Introduction

Optimizing the design of the root national CO2 network is vital for achieving a cost-effective project with future expandability. This abstract shows example of challenging traditional approaches proposed by design offices. This achieved optimization of World's largest CO_2 collection (23 MMTPA), compression and sequestration network serving current and future users in their significant roles toward decarbonization. Not only does this help achieve Saudi Arabia's net-zero targets but also paves the pathway for blue-hydrogen energy transition.

The subject mega project builds an expandable national decarbonization grid consisting of CO2 collection, compression/pumping, and sequestration system that provides carbon abatement services to nearby CO2 emitters. All collected CO2 from emitters is compressed/pumped in centralized dry gas compression plants to the required pressures for sequestration. The first-phase design seeds all future phases as they would be expansions building on its design. Hence it is essential to consider all possible options including non-traditional solutions. A common 'traditional' perception is that transportation of CO2 is best done in supercritical phase. Another traditional concept is the use of integrally-geared compressors for CO2 compression duties. These and other ideas were considered and challenged meticulously to arrive at the presented final 'out-of-the-box' solution achieving minimal cost and optimal flexibility.

The Traditional Approach to Compressed CO2 Gas Transport

Traditional designs for CO2 compression and transportation typically default to supercritical compression and transportation of CO2 in dense phase [1]. This 'supercritical' phase of CO2 means it has to be compressed to a pressure above the critical pressure, which occurs at a pressure higher than 73.8 bar and a temperature of more than 31.1°C for pure CO2, before it is transported [2][3]. This default preference of supercritical CO2 is believed to be based on lower pressure losses associated with transporting dense phase fluid which has lower viscosity and shear losses compared to liquids; i.e. dense-phase fluid vs. liquefaction options. This is true when compared to liquids, however, it doesn't hold when comparing dense phase to gas-phase (sub-critical) as the advantages from lower viscosities and associated lower pressure drops are similar. Another basis for the default preference of supercritical CO2 transportation is the smaller volumetric flows for dense phase fluid when compared to gas phase. This means supercritical dense-phase CO2 fluid transportation require smaller diameter pipes due to the having lower volumetric flows comparable to the gas-phase. Although this is generally true, it fails to realize that dense-phase transportation requires high pressure compression/pumping to reach supercritical phase and thick-walled pipelines to withstand that pressure. The high-pressure compression/pumping costs considerable CAPEX and OPEX. Moreover, thick-walled pipelines require significant amount/tonnage of steel plus a much longer schedule for welding /construction, aside from sourcing and availability restrictions. All of this means that this traditional approach may not be the most cost-effective solution and must be evaluated on case-by-case basis applying all details of the specific CO2 Capture, Compression & Sequestration (CCS) project. A third common 'traditional' perception related to compression is the use of integrally-geared compressors for the required CO2 compression duties, often followed by a pump in series as last stage before transporting through a pipeline. Although this was the concluded 'optimum' solution among 10 other options considered in a project done by the author over 10 years ago, it is still recommended not to make it a standard for all projects as process and site conditions could vary significantly. Instead, case-by-case analysis should be required in every project.

From the above discussion, it becomes obvious that the traditional defaults become more challengeable as, for example, CO2 flows increase and pipeline lengths decrease. In any case, the author recommends that optimization and inclusion of all options should be considered for every project as there are many other parameters (e.g. ambient temperatures, CO2 contaminants, cooling water availability) that differ significantly from one project to the other and could influence the techno-economic evaluation results.

One of World's Largest CO_2 CCS Projects

This subject 23 MTPA CCS project in Jubail is led by Saudi Aramco as a Joint Venture with Linde and SLB. Specifically, this project has a collection network with an initial 30 MTPA capacity that encourages emitters to join and achieve the Kingdom's short-term target of 44 MTPA of CO2 by year 2035 [4]. This impressive 23-30 MTPA capacity in a single location exceeds the current world-leading projects of Aramis, NL (22 MTPA) and Humber, UK (18 MTPA). It is also worth noting that the Huston Hub, which has non-confirmed commitments for the overall targeted 100 MTPA by 2040, is a cluster of multiple sites and projects.

The Jubail CCS starts with up to 11 MTPA installed compression capacity by 2027, and with succeeding phase adding compression to achieve the 23MTPA sequestration capacity, while the collection network already boasts a 30 MTPA capability that can be further increased with future emitters. Figure 1 below depicts the main segments of the final system design and their capacities. The dotted lines encapsulate the three main segments of the subject project. The first is the collection network which consists of compression and treatment plants for Saudi Aramco emitters, main CO2 collection pipeline, and connections to other emitters. This network design's max capacity is 30 MTPA, but a provision for future emitters of direct connection to the second segment (compression hub) allows for an even further increase in capacity. The second segment is the central compression/pumping having multiple trains that can be increased to accommodate sequestration capacities. Details of this segment will be discussed further in a dedicated section within this paper. The third and final segment is the sequestration transportation and injection scope. This overall design aims to strike a balance between expandability, flexibility and on-time investment or minimal initial investment. The total capacity can be even further increased by simply tying in additional emitters to the compression hub, increasing compression capacity and adding transport pipeline (or pumping station) and sequestration site.

The first phase of design development typically done during early FEED sets the seed for all future phases as they typically consist of expansions building on the first-phase structure. This is why it is essential during the early FEED stage or even earlier to consider all possible options of both traditional and non-traditional solutions that can be used, instead of proceeding with typical perceptions and only traditional concepts.

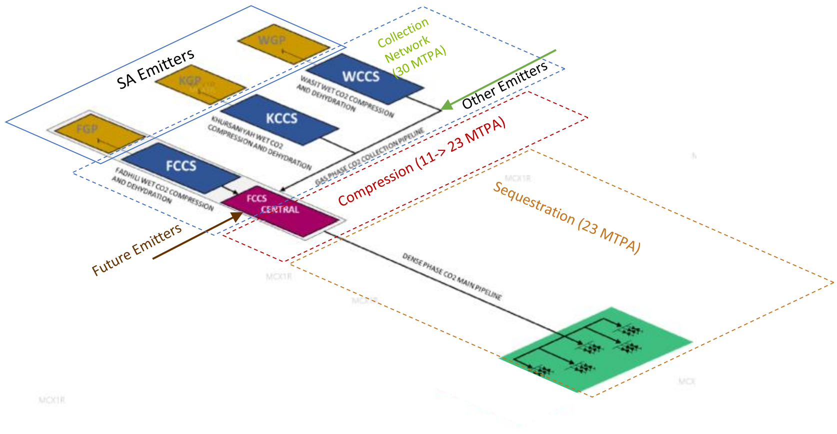

Fig. 1 — Main Segments of Jubail CO2 CCS Hub

Base Case and Design Optimization

This section will discuss the 'Base Case' design and the main challenge posed by the author which resulted in considering multiple options specifically for the collection network and compression/pumping hub scopes. This paper will not delve into optimizations executed to arrive at the transport/sequestration scope details as that was carried using typical project scope optimization methodologies. Similarly, the emitted gas treatment typical process studies and scope optimization is outside the interest of this paper.

Base Case Description: The base case configuration is to obtain dense phase CO2 supplies by emitters to the collection network. Each emitter is responsible for their capture, compression and treatment/dehydration facilities to produce 'within-specifications' CO2 at 1,450 psig supercritical conditions. The CO2 specifications have many details but primarily require CO2 content to be a minimum of 98% purity with less than 50ppm of water. All of this means that significant compression of CO2 is required at each emitter, with dehydration plant falling between the process stages of compression; i.e. wet compressor stages (WC) followed by dehydration then comes the dry compressor (DC) stage(s) to reach dense phase state pressures. The 30-inch sized, 900 LBS-rated collection network pipeline then delivers all the dense phase CO2 collected from emitters to a centralized pump hub. The Pump hub then boosts the dense phase CO2, after cooling it via a chiller (CH) to achieve a manageable density (or specific gravity), from the received pressure to the required pipeline inlet pressure (3,790 psig) to transport the supercritical fluid through a 230km pipeline and deliver it to the injection wells. For the first phase flows, 3 dense-phase pumps (DP) would be required to run plus one spare to ensure availability. The Base Case design and considered main alternative options are shown in Figure 2 below. Note that process optimization for the Saudi Aramco emitters concluded to use of temperature swing adsorption (TSA) technology for the process dehydration package to dehydrate wet CO2 gas after the wet compression train to achieve the gas specifications water content limit of less the 50ppm.

Alternative Options Considered: The author identified significant opportunity for both cost savings and encouraging decarbonization by lowering the collection network pipeline pressure and relocating the high-pressure (supercritical) compression to the common compression/pumping hub instead of the complexities and costs of having multiple 'smaller' dry gas compressors in each emitter's CO2 collection and compression facility. This entailed that the collection network pipeline would be larger in diameter (48-inch sized, 300 LBS rating) and operating in gas phase. This challenged the traditional approach mentioned in the above section which defaults to dense-phase transport of CO2 across-the-board for all pipelines, including that of the collection network.

Supporters of the traditional approach thought that the smaller size of a dense-phase pipeline will always be cheaper than a larger size gas phase pipeline. That view fails to realize that allowing gas phase collection, instead of imposing dense-phase/supercritical pressures on the CO2 emitters, greatly simplifies the compression requirements and reduces cost and execution time, thus encouraging emitters and facilitating their earlier participation in CO2 abatement. Since only relatively low-pressure compression would be required form the emitters, this gives them the flexibility to consider multiple compression technologies with well-proven references and allows more suppliers (better competitiveness) and lower costs. Plus, centralizing the high-pressure compression is more efficient as fewer total number of compressors are used with higher efficiency. Moreover, on the collection pipeline cost and execution aspects, the lower pressure pipeline requires less steel tonnage (30% less in this case) and significantly reduced welding scope (50% less passes, treatments and inspections) which translates in considerably lower cost and schedule. Despite this clarity, the author had to defend this proposal at numerous meetings with contractors and all stakeholders until all were convinced; the meetings delved into multiple disciplines including facilities planning, scheduling, cost estimation, process engineering, project management, flow assurance, electric engineering, corrosion engineering, and of course rotating equipment engineering. One important issue to note is the mitigation of free water formation in the gas phase pipeline which was done in this case by limiting water content to 50ppm and designing pipeline temperatures and pressures for avoidance of free water formation at various flows and extreme conditions. An advantage for dense phase CO2 transport is the tolerance of higher moisture content, but that also needs a pre-treatment process similar to gas phase transport. With gas phase collection and centralization of the high-pressure compression/pumping in mind, several sub-options were considered. These options, lettered A to D are shown along with the Base Case design in Figure 2. These options are discussed briefly in the following sub-sections.

Option A: Liquefaction + Pumping: In this option, the collected and dehydrated CO2 is taken through a phase change by sub-cooling to a temperature of around 1.7F. this liquefaction process allows subsequent pumping to the required transport pipeline inlet pressure of 3790psig. In a similar configuration to the base case, 3 pumps would be running with one standby in option A. The number of pumps is determined by limiting the pump size to be reasonably supported with references and avoid risks of prototyping. Even though this option offered a considerable reduction in energy consumption compared to the base case, it was ruled out due to non-condensable gases in the captured streams and arguable need of additional capital investment for separation/comingling process plants, despite expectation that the pumps would be able to handle this minor gaseous content.

Option B: Centralized Dense Phase Compression + Water Cooling + Pumping: In option B, the collected and dehydrated CO2 is compressed by the dry compressor to a pressure of approximately 1900 psig. This high pressure allows a cooling tower (CT), which is simpler cooling compared to base design and option A, to be used for achieving high enough density (about 0.6~0.7 specific gravity) to enable use of a referenced pump design for the last stage of pressure boost. The CT design outlet temperature is around 110 F due to the relatively high site ambient air temperatures. The final pumping stage achieves the required transport pipeline inlet pressure of 3790psig. As the duty (and power) in pumping is reduced in option B compared to base design and option A, 2 pumps would be required running with one standby to achieve target availability. This option offers similar energy consumption compared to the base case but with a considerable reduction in capital investment.

Option C: Centralized Dense Phase Compression + Air Cooling + Pumping: In option C, the collected and dehydrated CO2 is compressed by the dry compressor to a pressure of approximately 2700 psig. This higher pressure only requires air cooling, which is simpler and lower cost compared to all previous options, to be used for achieving the targeted density (about 0.6~0.7 specific gravity) to enable use of a referenced pump design for the last stage of pressure boost. Of course, the use of air cooling instead of water comes at the expense of higher power required for compression. The air cooler design outlet temperature in this case is around 140 F, which is governed by high site ambient air temperatures. The final pumping stage achieves the required transport pipeline inlet pressure of 3790psig, but with a further reduction in pump duty/power which reduces the required number of pumps in option C compared to option B. In this option, only one pump would be required running with one pump as standby to achieve target availability. This option offers marginally higher energy consumption compared to the base case but with even further reduction in overall capital investment.

Option D: Centralized Dense Phase Compression with Air Inter-Cooling: In this option, the collected and dehydrated CO2 is compressed to the final required transport pipeline inlet pressure of 3790psig by the dry dense-phase compressors; the compression of course has to be done in two process stages with intermediate cooling (inter-cooling) due to compressor high discharge temperature limitations. Due to the scarcity of water and targeted low capital investment, air cooling is used in this option for the inter-cooling duty between the process compression stages. The inert-stage pressure is not specified as it leaves room for optimization by compressor suppliers. This option offers comparable energy consumption to that of the base case but with the highest reduction in capital investment.

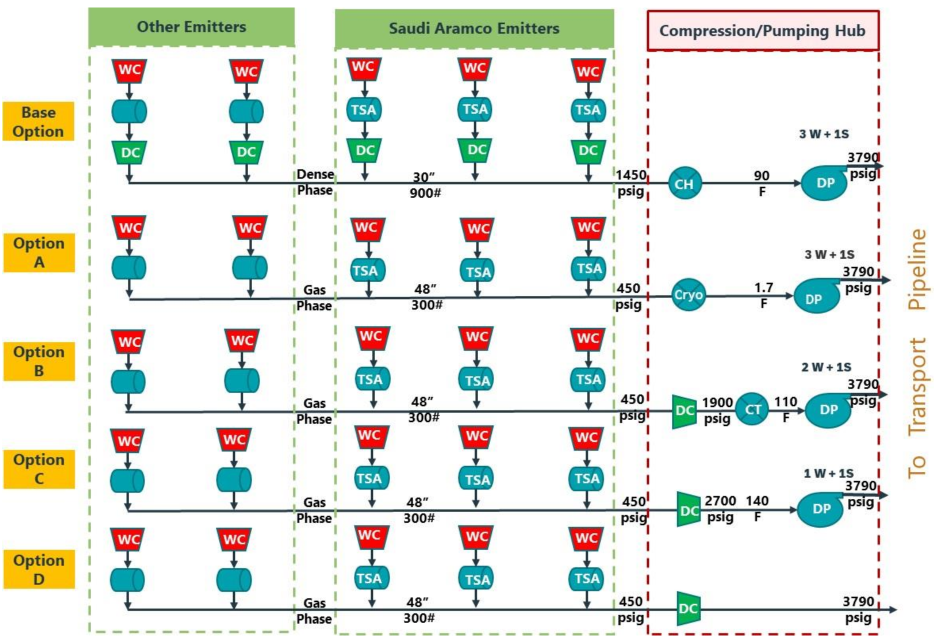

Fig. 2 — Main Collection and Compression Options Considered

Final Selected Design

The selected design was Option D as it offers over 22% CAPEX reduction plus many other advantages in safety, risk mitigation and decarbonization facilitation. Table 1 below shows a comparative Risk & Opportunities matrix between the base case design and the final selected design of Option D.

Table 1— Comparative Risk/Opportunities Matrix between Base Design and the selected design (Option D).

Risk/Opportunities	Base	Option D	Remark
CAPEX saving Kingdom perspective	Red	Green	Significant CAPEX saving in option-D over base case
CAPEX/OPEX redistribution	Yellow	Green	Minimal capture cost transfer to transport. OPEX advantage.
Collection network 2-ph flow/corrosion risk	Green	Yellow	Tighter water spec for option-D
Safety risk from CO2 leak	Yellow	Green	High pressure and dense phase CO2 leak (Jubail Area)
Project execution complexity	Yellow	Green	Higher equipment counts and execution scope in Base case
Equipment Prototype Risk	Red	Yellow	More dense-phase Compressors + dense phase pumps in Base

Red: High Risk (worst), Yellow: Medium Risk , Green: Low Risk (best)

Further Optimization

After the selection of Option D, the author pursued further optimization of the train configuration and inter-stage parameters. In particular, comparative efforts focused on sizing the first compression stage to achieve various inter-stage pressures and temperatures (with controlled cooling) in order to arrive at optimal and referenced compressible fluid parameters for 2^{nd} stage compression, or nearly incompressible fluid parameters for referenced pump as final stage. The objective was to maintain or reduce CAPEX of Option D but with less energy consumption. The optimization resulted in the train configuration shown in figure 3 below, which has comparable CAPEX but with approximately 20% lower power/sizing than Option D. This train configuration has a double ended motor driving a compressor for 1^{st} stage pressure boost from one end and a pump driven via fluid coupling from the other end for achieving the last stage of pressure boost before the dense phase CO2 fluid is sent through the transportation pipeline. The fluid coupling or (starting clutch) is mainly used during startup to ensure that pump is only run after reaching stable supercritical conditions in the compressed CO2 fluid. The intercooling between the compressor and pump stages is done with air due to the scarcity of water and incremental cost if a water cooling system is added.

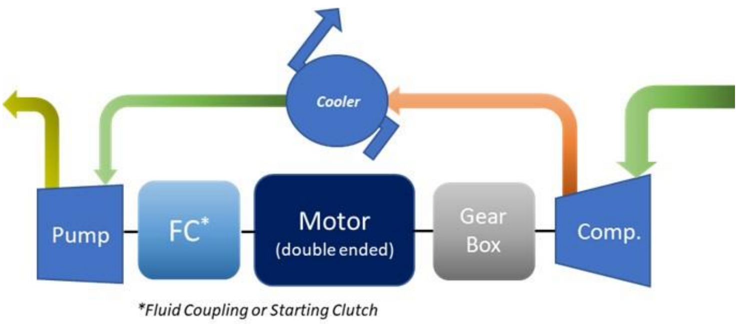

Fig. 3 — Recommended Optimized High Pressure (Dry) Compression/Pumping Train Configuration

Conclusion

As CCS projects could differ significantly from one place to another, having different configurations and process parameters, it would be logical to conduct detailed case-by-case analysis and not apply preferences or preconceptions even if based on past projects. A one-size-fits-all approach here would not result in neither optimum CAPEX no OPEX. The advantages of challenging the base design proposed for the grass-root Jubail CCS project were discussed in details in above sections of this paper. Specifically, challenging the preconceived thought that transport of CO2 must always be in a dense phase (supercritical) state proved fruitful and resulted in easier decarbonization country-wide, significantly lower capital investment and more efficient operation. The recommended design (Option D, with the optimized train configuration in Figure 3) is to obtain dry CO2 gas supply from emitters to the collection network, which delivers it in the gas phase to a centralized compression/pumping hub that boosts it to supercritical pressures required to deliver and sequester the CO2 at injection wells. Final achievements of the subject optimization can be summarized as follows:

- Optimized collection pressures for National CO2 grids that maximizes benefits to all emitters and encourages de-carbonization/CO2 abatement
- Comparative Techno-economic analysis that proves Gaseous phase collection/transportation is superior.
- Best compression/pumping options for very large duties in Arabian Gulf ambient/environmental conditions.

References

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