Breakthrough Carbon Capture: Exploiting Trade-Offs

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Despite the considerable on-going research into a variety of pre- and post-combustion carbon capture and storage technologies, there is concern that these programs will not achieve the required optimal solutions suitable for timely implementation at costs that are acceptable to the consumer.

If economically viable carbon capture solutions are to be achieved within environmentally acceptable timescales, a considerable amount of truly paradigm-shifting, breakthrough thinking may be required to support the current initiatives – right? Perhaps not. This article offers an alternative approach that shows how recent technological innovation methodologies might be used in this arena. We discuss the importance of identification and resolution of trade-offs and compromises as being the primary driving force of innovation. We examine a number of key trade-offs present in the current carbon capture technologies and propose conceptual-level strategies based on already known solutions to equivalent trade-offs from other sectors.

Background

Within the European Union (EU) there is a clear understanding that in order to meet its 20 percent CO_2 reduction (from 1990) by 2020, the post-2012 Kyoto period will require significant additional technology developments to meet the required average one-percent-per-year emission reduction. There is also agreement that probably one of the greatest impacts in reducing CO_2 emissions will be made by introducing zero emission fossil fuel power plants that include carbon dioxide capture and storage. Cost effective CO_2 capture and storage may also prove an essential element both for the production of sufficiently large quantities of hydrogen in the transition to the "hydrogen economy" and in the use of so called "clean coal."

Thus, significant EU funds are being directed toward R&D projects that demonstrate various technology options for the capture, compression, transportation and storage of CO_2 from power plants. Table 1 lists a sampling of such programs.

Table 1: Selection of EU Funded CO_2 Capture, Compression and Storage Projects

Program	Focus	Size	Completion
CO_2 Sink	Full-scale underground CO_2 storage test site	18.5 MEuros	March 2009
Encap CO_2: Enhanced Capture of CO_2	Pre-combustion technologies for enhanced capture of CO_2 in large power plants – 90 percent capture rate and 50 percent capture cost reduction	22 MEuros	2010
CACHET: CO_2 Capture and Hydrogen	Develop technologies to reduce significantly	13.5 MEuros	2008

Production from Gaseous Fuels	the cost of CO_2 capture from natural gas with H_2 production		
HYPOGEN	Phase 1 feasibility study, DYNAMIS preparing for large-scale H_2 production from decarbonized fossil fuels with CO_2 geological storage	Phase 1: 7.5 MEuros Overall: 1.3 BEuros	Phase 1: 2008 Overall: 2015
CO_2ReMoVe	Separation of CO_2 from natural gas at oil and gas operations in the North Sea, southern Saharan desert and in Germany, followed by compression and re-injection	15 MEuros	(Unknown)
CO_2 Capture Project (CCP)	Technologies to reduce the cost of CO_2 separation, capture and geologic storage from combustion sources such as turbines, heaters and boilers	Industry-funded (50 MEuros?) with EU support for sub-projects	Phase 2: 2008
CASTER (CO_2 from capture to storage)	Esbjerg power plant, 1 ton CO_2/hour	Part of CCP	Operational since March 2006
Full listing available at http://www.co2captureandstorage.info/cont_europe.php			

The project literature makes it clear that a diversity of opinions exists regarding the optimal technology and that operational costs of the alternatives are of significant concern. Current costs of carbon capture vary with the technological processes, scale and geography, but are on the order of 40 to 60 Euros per ton of CO_2. A typical cost analysis undertaken using the cost analysis tool GESTCO has shown that storage costs could be on the order of one Euro/ton and pipeline transportation about 5 Euros/ton.[2,3] The remaining costs (typically 45 Euros) are those associated with the capture technology itself.

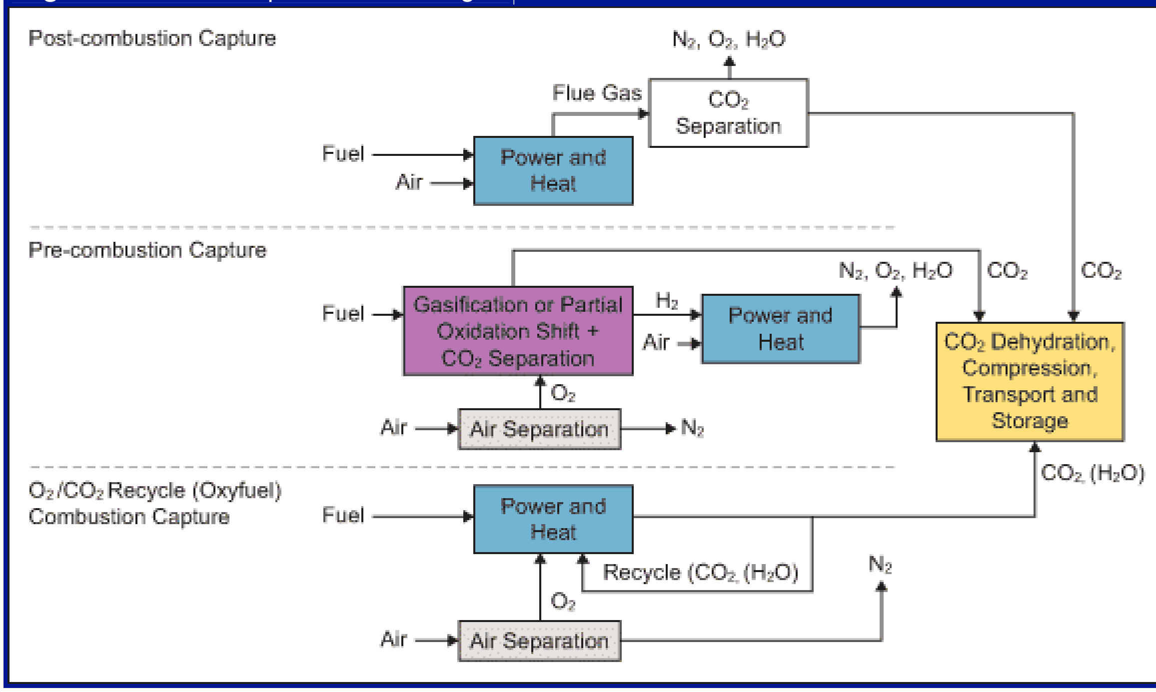
Current EU research targets for the cost of CO_2 capture vary from 20 Euros per ton to a range of 20 to 30 Euros per ton.[4,7] It is assumed that these targets are market-derived and represent costs that would be acceptable to the consumer. After allowing 6 Euros/ton transport and storage, this suggests a typical commercially realizable capture target of 19 Euros/ton. This is equivalent to a technology cost reduction of about 55-60 percent over current levels within a time span of as little as three years and as many as eight years (depending on individual programs).

The innovation breakthrough opportunities are, therefore, considered to be primarily in the area of the cost reduction of capture technology.

CO_2 Capture Technologies

A conceptual understanding of the current capture technologies will help with considering breakthrough potential. Let's go through the basics. (A useful overview of capture methodologies is provided in reference.[8])

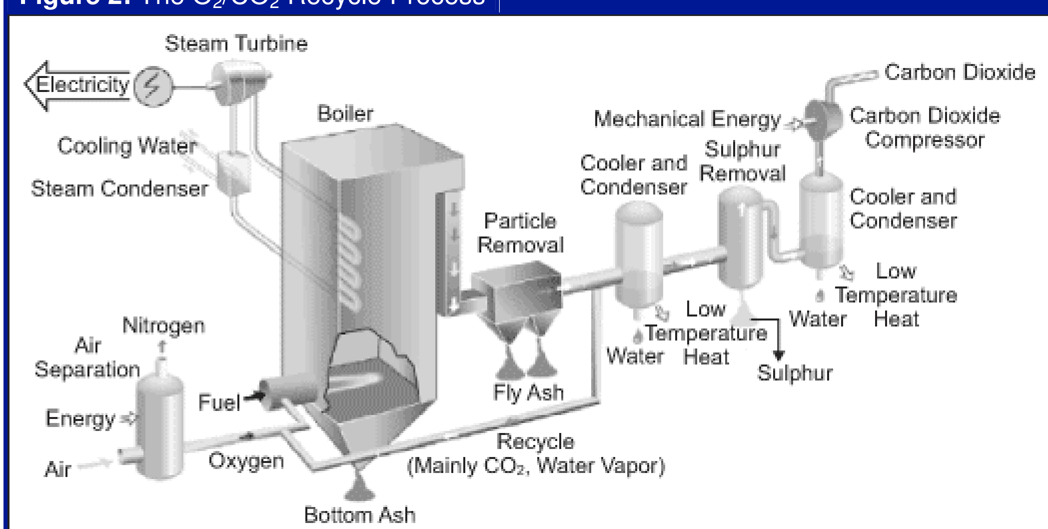
Figure 1: Carbon Capture Methodologies



O_2/CO_2 Recycle

In the O_2/CO_2 recycle process, the fuel is combusted with almost pure oxygen that has been mixed with recirculated flue gas. The recirculation serves to moderate the combustion temperature. The resulting flue gas from the process is a practically pure stream of CO_2 and water, the latter separated through condensation.

Figure 2: The O_2/CO_2 Recycle Process

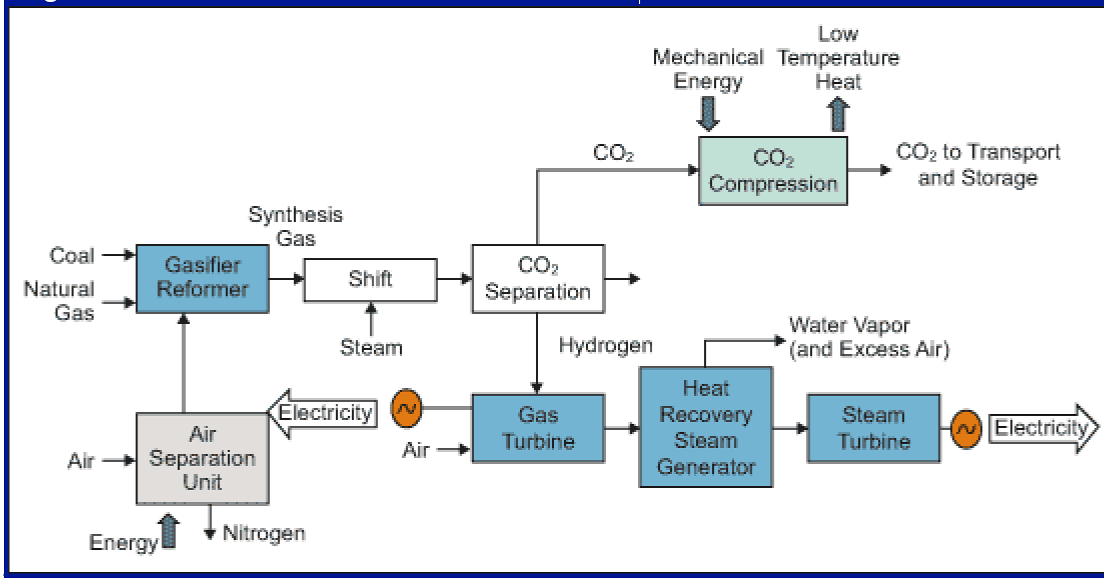


The reported challenges involved with the O_2/CO_2 recycle approach relate to individual process efficiencies that contribute to the overall efficiency of power generation. Current research is looking at alternative methods of oxygen separation (such as metal oxide-doped ceramic membranes and ways of recovering the low temperature process heat.[5]

Pre-Combustion Capture

Using oxygen and steam, the fuel (natural gas or solid fossil fuels) can be separated into CO_2 and H_2 through the so-called water gas shift reaction. CO_2/H_2 separation can be enabled through the use of, for example, vanadium membranes with ultra-thin palladium layers (Eltron membranes) or "hydrogen transport membranes." The hydrogen generated is directly used for power generation with gas turbines or even fuel cells. This integrated reforming combined cycle (IRCC) process has its analog for solid fossil fuel in the integrated gasification combined cycle (IGCC).

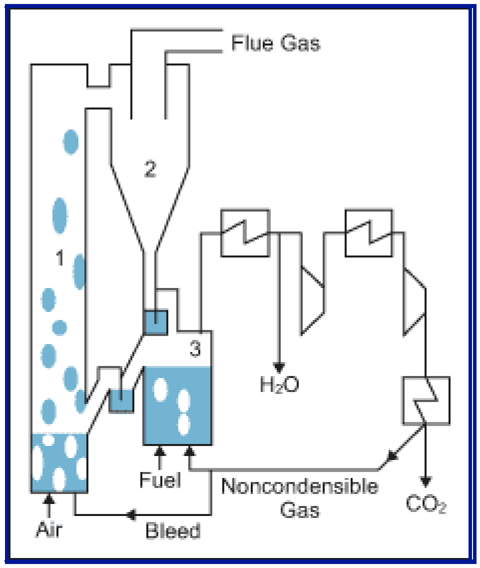
Figure 3: Pre-combustion Water Gas Shift Process



An alternative pre-combustion technology is chemical looping, in which the combustion oxygen is transferred to the fuel via an intermediate metal oxide that acts as an oxygen carrier (as explained in references 6 and 9):

Fuel reactor: $4MeO + CH4 \gg 4Me + 2H_2O + CO_2$
Air reactor: $4Me + 2O_2 \gg 4MeO$

Figure 4: Alternative Pre-combustion Process – Chemical Looping



Post-Combustion Capture

This area focuses on making cost-effective improvements to the already used solvent-based CO_2 absorption systems through the development of new solvents (amines) and system optimization. This approach is applicable for use in existing power plants although it decreases the efficiency of generation by 15-25 percent and currently increases the power cost by up to 50 percent. Alternatives that are under consideration include using the calcium cycle, cryogenic separation, membranes or solid adsorbers. The calcium cycle uses quicklime as the capture medium, which yields limestone, which can be subsequently reheated, thereby releasing its stored CO_2 and producing quicklime for re-use.

At the Elsam coal-fired power station in Denmark, a post-combustion absorber-based CO_2 capture unit has been installed within a pilot plant as part of the Castor project.[10] The flue gases are directed to an absorber, where they are mixed with a solvent. The solvent captures the CO_2 ("enriched") since it has a greater affinity with CO_2 molecules than with the flue gas constituents (such as nitrogen). The CO_2 trapping efficiency is reported to be nearly 90 percent. Solvent regeneration is undertaken through heating to 120°C, in order to break the bonds between the CO_2 and the solvent, so that it can be reused within the system.

Breakthrough Solution Methodology

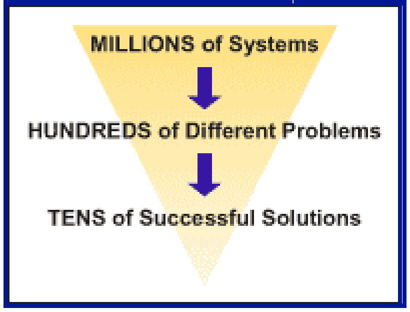
The carbon capture problem is still in its infancy in many ways. Nevertheless, progress is happening, and certain breakthroughs in, for example, some of the membrane technology have created step-change improvements.

Step-change breakthroughs have been the focus of extensive programs of research that have generated a considerable number of case studies.[11] These case studies have been gathered from a broad spectrum of technology and scientific disciplines, primarily through the reverse engineering of solutions found in the global patent database, but more generally through the detailed examination of any form of true innovation.

One of the aims of this research has been to establish whether there are repeatable patterns and, therefore, reproducible solution archetypes within innovation. In essence, the objective has been to uncover the "DNA" of breakthrough innovation itself. Perhaps surprisingly, some distinct patterns began to emerge in even the very early stages of the research – in fact, in the first 50,000 or so innovation exemplars. The subsequent analyses have in some ways merely served to reinforce and refine these initially identified patterns.

The research has highlighted that there is a considerable amount of "reinventing the wheel" taking place across different disciplines: A problem identified and solved in one industry sooner or later appears and is solved again in another. Frequently, because the two industries tend to use different terminology, the two solutions are derived independently of one another. The extent of this wheel reinventing the wheel phenomenon is illustrated in Figure 5.

Figure 5: Re-inventing the Wheel



Currently, around 95 percent of all attempted innovations will fail for one reason or another. Reverse engineer the failure and you'll discover there are almost as many ways to get things wrong as there are failures. Study the successful innovations, on the other hand, and you'll see two things. First, there's s considerable overlap in terms of the types of problems being tackled (strength vs. weight being one such classic example). Second, and perhaps more surprisingly, there are very few ways of deriving successful solutions.

One of the key characteristics of a step-change breakthrough solution is that it involves the identification and challenge of some form of trade-off or compromise. Breakthroughs, thus, tend to occur when problem solvers refuse to accept the compromise; to continue with the previous example, that higher strength must equate to higher weight. When a problem solver finds a way to simultaneously increase strength and decrease weight, we have the basis for a breakthrough. Likewise, when we increase strength and decrease cost or increase strength and use less material, the status quo is again challenged. Breakthroughs happen when problem-solvers stop looking for the "optimization" solutions and start looking for the ones that seek to "eliminate" the trade-offs.

Some of the most significant breakthroughs occur when existing solutions from one industry are translated into another. Think, for example, of the Dyson vacuum – which took a well known industrial separation process and translated it into a domestic cleaner. Or consider the more recent Sanyo "zero-detergent" washing machine, which likewise transfers a well-known industrial cleaning means (in this case ultrasound) from one discipline to another. An effective heuristic here is to think of someone who has a more extreme version of your problem, since they are likely to have already identified a solution. The main difficulty in making these kinds of connections is that it is not always easy to make the cross-industry analogies and connections.

Step-change breakthroughs also tend to follow distinct and repeatable patterns. Jumps that occur in one industry are also very likely to occur in others. These patterns occur because inevitably when we make a step-change advance to solve one problem, sooner or later another problem arises, and this problem eventually also has to be solved.If these findings are true – and we can only aim in this article to intrigue readers enough to want to explore the topic further – there are significant potential implications for the carbon capture problem. One of those implications is that someone somewhere has already solved the problem. Another is that the patterns of evolution of other solutions can help point the direction that current carbon capture technologies can be expected to follow. Both of these implications are difficult to believe.

Application of Systematic Innovation to Carbon Capture

By way of a crude demonstration of the potential, it is possible to focus on an aspect of a carbon capture problem and examine what emerges. As we've described, an important characteristic of a breakthrough solution is that it identifies and challenges a trade-off or compromise. There can be little doubt that there are significant unresolved compromises in and around the carbon capture arena. At the highest level, these may be seen as a conflict between knowing how to sequester carbon and knowing how much it will cost to achieve that aim. Challenging a conflict at this kind of abstract macro-level is likely to prove inconclusive, and so it is frequently helpful to zoom in and look at some of the contributing factors to this overall cost-capability conflict.

One such aspect might be seen to involve the membranes used in the pre-combustion hydrogen – carbon dioxide separation concepts. According to recent patents granted in this area, a key conflict with these membranes is a parallel desire to have a high membrane surface area (in order to assist in the ability to transfer the hydrogen from one side of the membrane to the other) and – knowing that the vanadium or other equivalent materials required to act as the membrane material is expensive – to minimize the amount of material required.[12]

Although the specifics of this particular membrane material are unique to the carbon capture problem, the generic high-surface-area vs. minimum-amount-of-material conflict is not. Many other industries and problem solvers have had to tackle this generic problem. When we study what these people have done, even though the specifics of their particular situation may again be unique, what the research reveals is that they have all used a relatively small set of strategies to successfully challenge the trade-off:

- Segment the expensive material into smaller pieces
- Incorporate asymmetries into the system
- Incorporate composite material structures
- Incorporate 3-D curvatures into the membrane design
- Apply high frequency vibrations

Clearly these strategies are generic. Asymmetry, for example, could mean a whole series of different things. Fortunately (or unfortunately, depending on your perspective), only someone with domain knowledge of the hydrogen separating vanadium membrane is likely to know how asymmetry may help to solve the problem. An outsider familiar with the general strategies may be able to make suggestions such as differential thickness of membrane or different porosities or different sizes of porosities or protruding surfaces, but they can't know if or how any might help to solve the specific problem.

On the other hand, one of the other things the non-domain specialist can do is to go back to the original source of the general strategies – in this case a patent database – and use the words suggested in those strategies as search words. To demonstrate this procedure, we might take the unlikely sounding "apply high frequency vibrations" idea and use that as a way of searching for situations where others have used it to solve a surface area vs. amount of material problem.

Conducting such a search within the specifics of the vanadium membrane reveals nothing – suggesting that this strategy has not yet found its way into this sector. Searching more generally, however, reveals that it is frequently used in other areas. These areas include catalysis in the petrochemical and pharmaceutical sectors and fuel spray nozzles in both jet engine and automotive industries. These sectors contain the same area vs. amount-of-material conflict. Incorporation of ultrasound or similar ultrasonic fields have been extremely effective in improving effectiveness. The authors have little domain knowledge about vanadium membranes and little detailed knowledge about the likely efficacy of incorporating some kind of ultrasonic or other high frequency vibration to the specific problem. We do, on the other hand, have some knowledge of the catalysis and fuel spray nozzle problems, and we do know that ultrasound can deliver a thousand-fold improvement in performance.

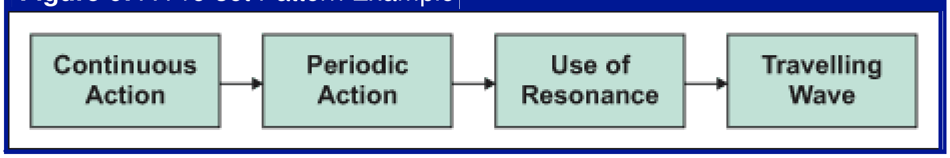
We also know that as soon as we solve one problem, another problem will arise. Typically, this next problem is expressed as a "Yes, but…" statement – usually spoken by the domain experts. "Yes, but" is often used as a way of halting discussion of a solution direction. In the systematic innovation methodology, however, knowing that certain problems always follow others, we can be reasonably certain that whatever the new contradiction created by the "Yes, but…" someone somewhere will also have solved that new problem. Applying ultrasonic vibration to a delicate vanadium membrane sounds like it will present a fatigue and component life problem. But we're not the only people who have had to tackle what is now a new "vibration vs. life" conflict. Which in turn implies: whatever other conflicts we might be able to find in and around any aspect of the carbon capture problem, someone, somewhere has already been thinking about how to solve that conflict.

Finding the Untapped Potential

Research suggests that all systems evolve in only a relatively few number of pre-set patterns (of which so far we have found 37). In the preceding section, we explored how a vanadium membrane may make a number of step-change jumps in order to resolve a particular conflict (surface area vs. amount of material). This is not the only conflict to surround the design of this component. While we may not know what all of the other conflicts might be, we do know what the trend patterns are likely to look like.

Figure 6 illustrates one pre-set pattern. It's a trend that describes how actions that begin as continuous are likely to advance to incorporate pulsations, and that the frequency of these pulsations is likely to increase up to a point where a resonant frequency of some form is found.

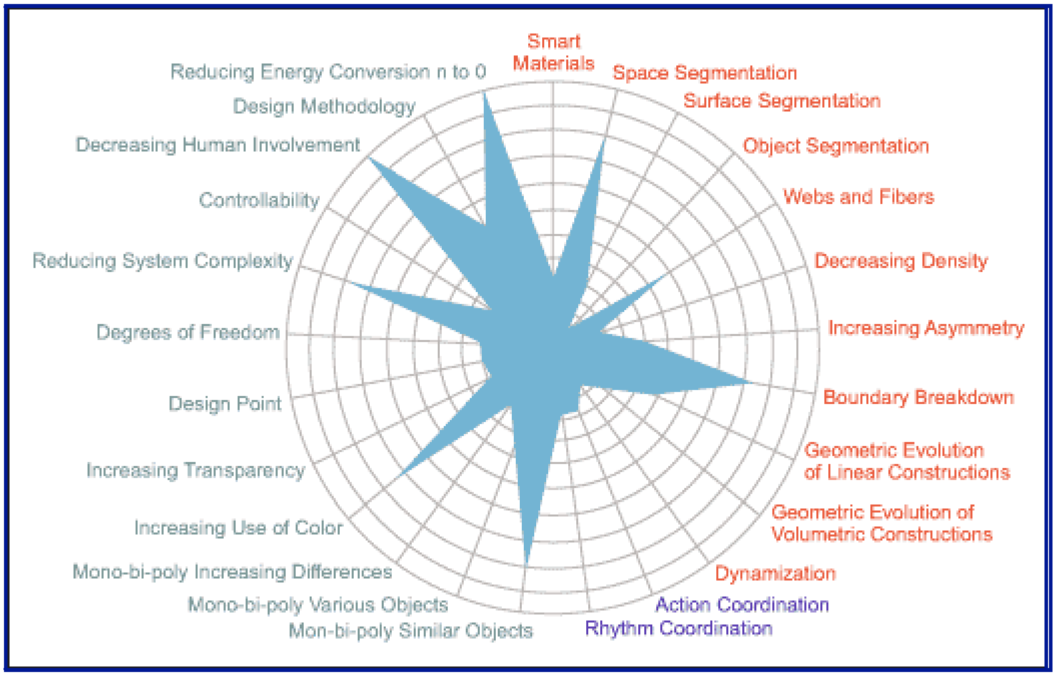
Figure 6: A Pre-set Pattern Example



A look at the vanadium membrane patents in the U.S. patent database reveals that the current designs are at the first stage of this progression, "continuous action." Should the ultrasonic vibration idea turn out to be practically viable, then the system will make the predicted jump to the second or third stage of the trend.

The "Yes, buts" that might prevent the system from advancing along this particular trend are in turn likely to be solved by one or more jumps along any of the other (36) step-change trend patterns. A useful thing to do, therefore, is to make the same sort of comparison as described for the pulsation trend above and to map where the current membrane designs reside along these other trends. Figure 7 illustrates the results of this analysis for a typical state-of-the-art membrane. Each of the spokes on the radar plot represents one of the step-change trend patterns. The shaded region then represents how far along each of those trends the current designs have evolved.

Figure 7: Example of Results for Given Analysis



The meaning of each of these trend patterns and the current position of the membranes along each is beyond the scope of this paper (see reference 13 for more details on the trend patterns). What is important to register here is the amount of unshaded white space on the plot. This unshaded area gives an impression of how many step-change advances observable in other industries have not yet been made in the vanadium membrane sector. In all this white space (or "blue ocean," to use the fashionable vernacular) represents around 45 jumps that have not yet been exploited. Whether these jumps represent a sufficient advance to make carbon capture via the vanadium membrane route an economically viable proposition remains to be seen.

Conclusion

This article does not propose any specific solutions to the carbon capture problem, but rather suggest to the domain experts that if they can identify the critical trade-offs and compromises, there exists a considerable database that suggests that someone somewhere has already been thinking about and possibly solved a similar problem.

Meanwhile, it is our belief that a trend pattern analysis of components in other candidate carbon capture technologies will reveal similar levels of untapped potential, and thus open the possibility that at least one will get us where we need to be.

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