Advanced Science News

Achieving Gt/y CO2 Utilization with Negative CO2 Emissions

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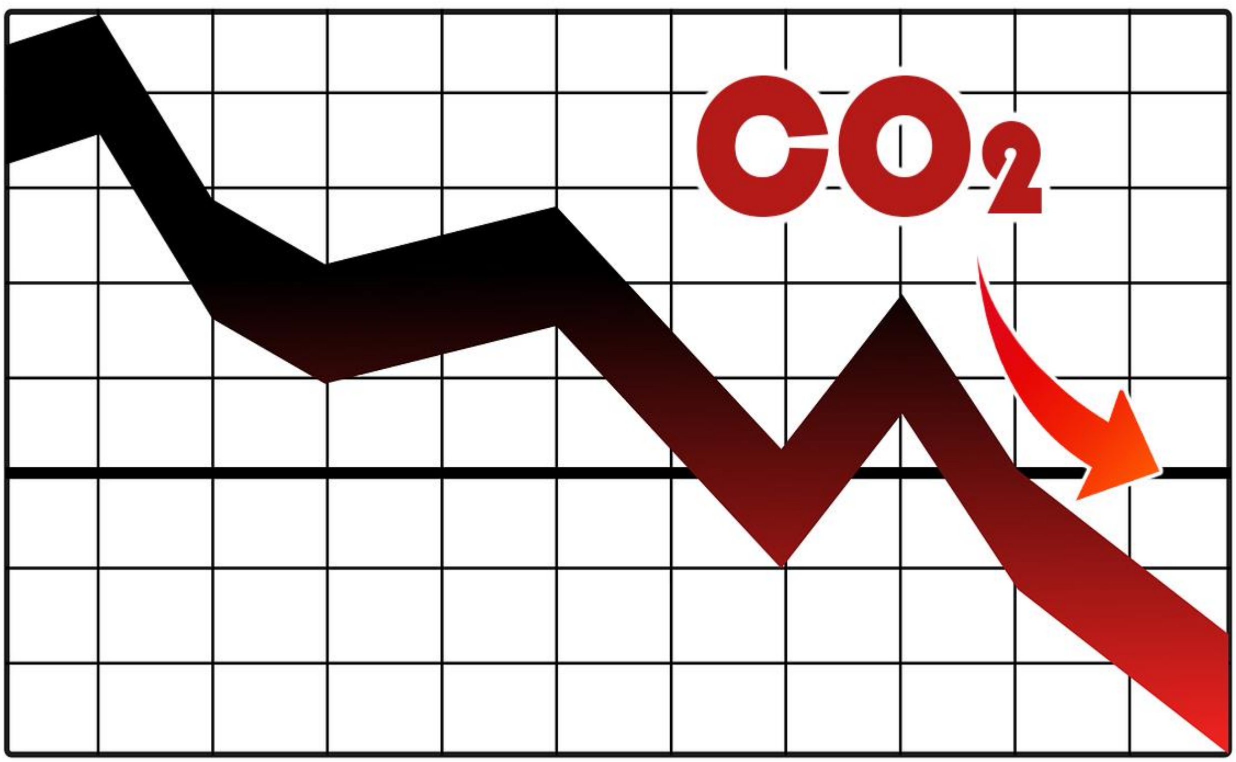

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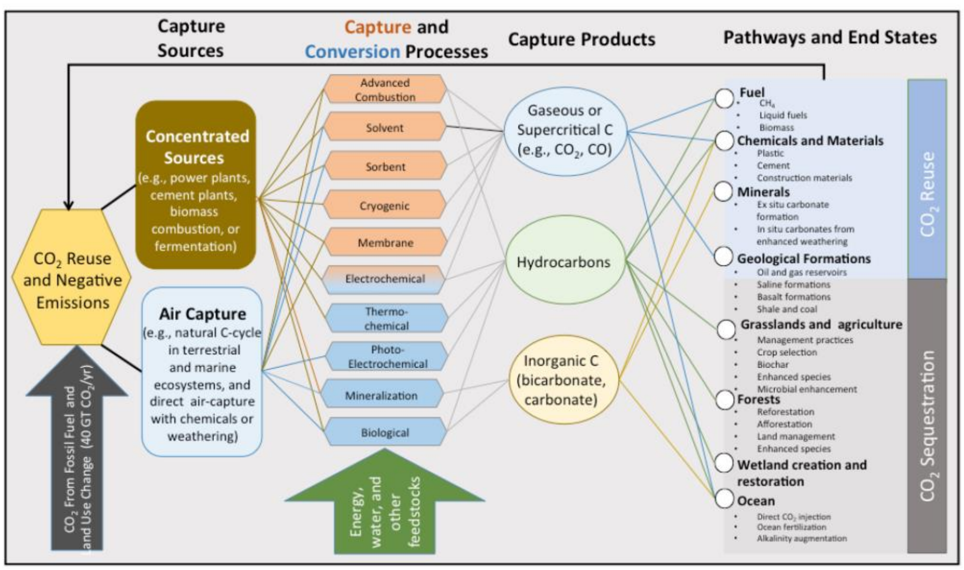

Figure 1. A whole systems approach involving sequestration and re-cycling of CO2 at the Gt/y scale to enable a negative CO2 emission landscape, [1].

Our global community has been tasked to define and implement a Manhattan style strategy for reducing CO2 emissions at the Giga Tonne scale. The vision to accomplish this heroic goal is a holistic paradigm, which makes use of all the technologies in the CO2 utilization toolbox that have the potential to achieve a net decrease in CO2 emissions at these gigantic scales.

At the outset, it is important to put the magnitude of this task in perspective. While a Giga Tonne of CO2 sounds like a lot of CO2, it only represents about 2.5% of current global emissions of around 40 Giga Tonnes per annum. Moreover, the emissions are distributed amongst various sources and locations around the world, so no one nation or system can solve this problem at the global level.

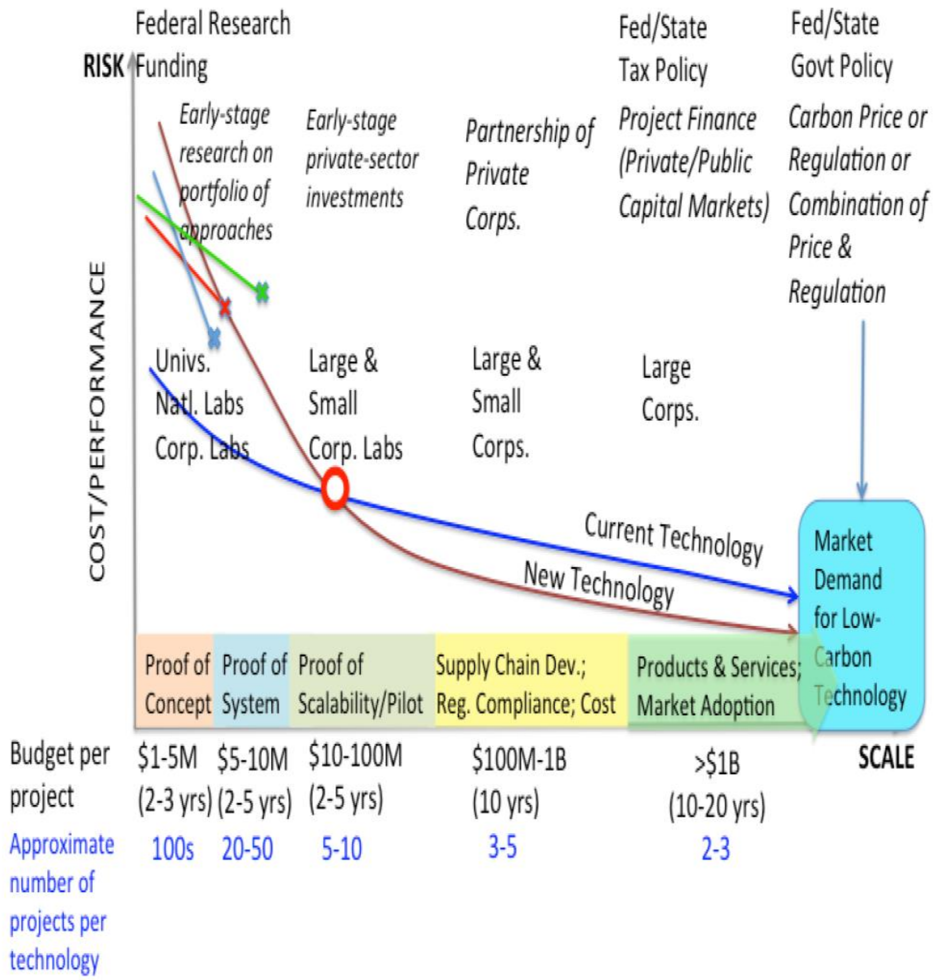

Figure 2. Gt/y CO2 utilization techno-economic learning curve. Note that new technologies that are superior in their performance and capability compared to current ones, could be the preferred technology based on cost, [1].

In the scenario of atmospheric CO2 concentrations rising to dangerous levels, negative emission CO2 utilization technologies could prove to be one of few known ways to avoid reaching a tipping point of irreversible catastrophic climate change consequences.

In this context, the Figure 1 embodies a 'whole systems' view of a negative CO2 utilization landscape, encapsulating all the cross-cutting chemistry and engineering options available today for achieving this lofty goal. The network of options begins with different CO2 capture sources, passes through various capture and conversion processes to diverse repositories and myriad products that include chemicals, materials, polymers, minerals and fuels, [1].

The practice of Gt/y CO2 utilization technologies raises very complex issues with no cure-all solution but rather one that will require integration of different pathways of the kind depicted in Figure 1. Choosing the best ways to utilize Gt/y amounts of CO2 will be contingent on geographic location, available infrastructure, the amount of CO_2 at source, and the type and value of CO_2 based products compared to fossil resourced alternatives. Assessment of the viability of each pathway will require a cradle-to-grave energy, carbon footprint and economic life-cycle-analysis, [1].

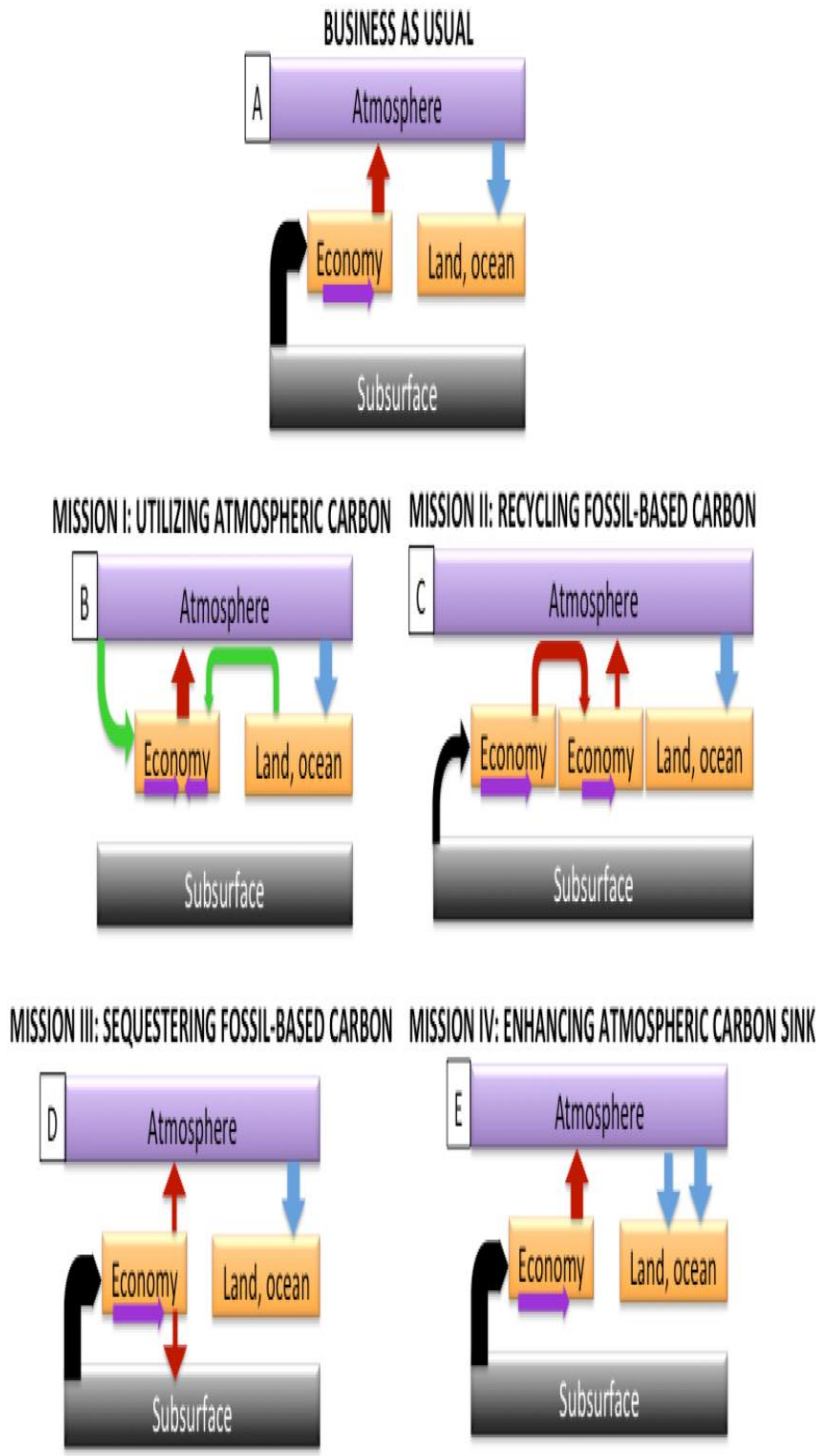

Figure 3. Illustration of schemes to transition a fossil intense to fossil free economy, [1].

To enable Giga Tonne CO_2 utilization processes with associated negative CO_2 emissions the following criteria are important: (i) Create an infrastructure able to de-fossilize the major CO_2 emitting industries, which include power generation, steel, concrete, agriculture, coal, oil and gas; (ii) Use renewable energy to capture, transport and convert the CO_2; (iii) Focus research and development and energy and economic analyses of those technologies that are deemed able to scale to at least 0.1 Gt/y; (iv) Evaluate large-scale engineering, investment, business, regulatory, risk, economic and policy models to attain a techno-economically feasible learning curve; (v) Understand and control the positive and negative consequences on the biosphere of Gt/y decreases of CO_2 levels in the atmosphere; (v) Put a price on CO_2 emissions to achieve Gt/y reductions; (vi) Train highly qualified people to make this whole systems approach to negative CO_2 emissions work at the Gt/y scale, [1].

This task will not be easy, quick or cheap. Lab-to-market-to-profit at the Gt/y scale has to surmount many hurdles that include science and engineering, demonstration to pilot scales, economics and regulations, supply chains and infrastructure development, business, risk and market research, and policy decisions at the city, regional, national levels. This is a 10-20-year journey, starting with million-dollar R&D investments and ending up having to finance the billion-dollar costs required for market adoption of products and services. The various stages of the techno-economic learning curve that illustrate these considerations are shown in the Figure 2.

Four different deployable approaches, denoted mission I-IV, envisioned to reduce CO_2 levels in the atmosphere, compared to a business-as-usual scenario, are encapsulated in Figure 3. The first utilizes atmospheric or land CO_2, the second recycles CO_2 from combustion, the third does not allow CO_2 into the atmosphere, and the fourth boosts land and ocean sinks. Each of these approaches forms one of the pathways in the network of the 'whole systems' approach for achieving Gt/y utilization of CO_2. It is possible to improve the effectiveness of these individual approaches to Gt/y CO_2 utilization by combining them together into more complex systems that could outperform the individual ones, [1].

It's the Real Thing – Modular CO_2 Refineries

Power-to-Gas, Power-to-Liquid and Gas-to-Liquid, are three gas-phase heterogeneous catalysis-based processes by which the greenhouse gases CO_2 and CH_4 can be converted into gaseous or liquid fuels, Figure 4.

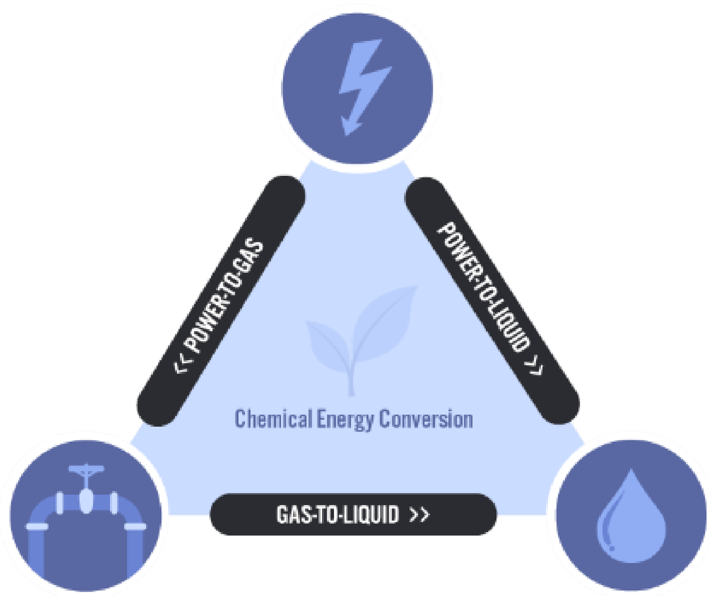

Figure 4. Chemical energy conversion processes, [2].

They all use renewable solar or wind electrical energy to drive (electro)-catalytic conversions whereby the electrical energy is stored in the form of chemical energy using the following processes:

(i) H_2 from H_2O by high efficiency steam electrolysis,

(ii) synthesis gas H_2/CO from CH_4 sources or from CO_2/H_2 by reverse water gas shift,

(iii) CH_4, CH_3OH or C_nH_{2n+2} from CO_2/H_2 or $CO_2/CO/H_2$ or CO/H_2 by methanation, methanol synthesis or Fischer Tropsch chemistry.

A spin-off company Ineratec (Innovative Chemical Reactor Technologies) birthed from research at Karlsruhe Institute of Technology, KIT, has recently commercialised innovative, compact and containerized chemical plants, which enable all of the above processes, [2].

They are modular CO2 refineries that convert CH4, CO2, H2O and H2 into gaseous and liquid fuels. The mandate of the company is to design, engineer, construct, commission and maintain the modules.

Their modular design enables Lego like construction of CO2 refineries over multiple length scales, from small units to industrial plants.

All of the aforementioned processes can be creatively integrated into these types of modular chemical plants, an example of which is shown in

Figure 5. Mobile synthesis unit for a compact containerized CO2 to fuel conversion plant [2].

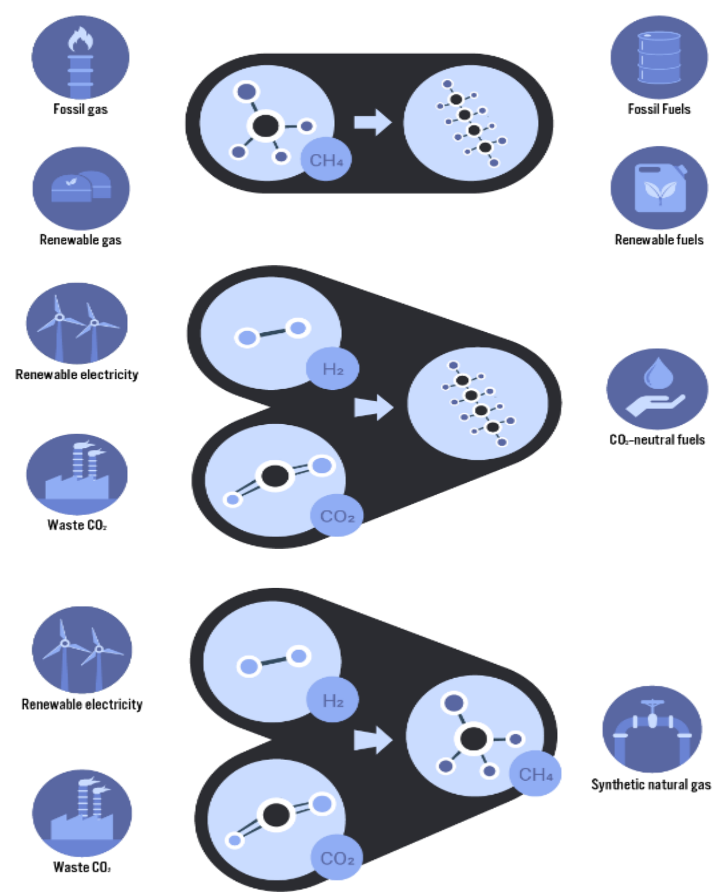

Figure 6. Gas-to-Liquid, Power-to-Gas, Power-to-Liquid processes, [2].

Figure 5. They all begin with capture and purification of CO_2 and production of H_2 or CO, powered by renewable electricity.

The Gas-to-Liquid process operates in two-stages, the first of which involves air oxidation of CH_4 into synthesis gas, sourced more often these days from biogas, sewage gas, or landfill gas. In the second step, the synthesis gas is converted into hydrocarbons by the Fischer-Tropsch synthesis, Figure 6. The Power-to-Gas process makes CH_4 from $CO/CO_2/H_2$ mixtures, which can advantageously be transported in existing pipeline infrastructure for use as a fuel, Figure 6. In the Power-to-Liquid process, similar to Power-to-Gas, the CO_2/H_2 is converted to synthesis gas, which is then used in the Fischer-Tropsch process to make synthetic fuels, Figure 6. At the time of writing, the aforementioned vision more-or-less delineates a roadmap for the development, implementation and commercialization of the most promising CO_2 utilization technologies.

The milestones on the road to the CO_2 refinery are the following: (i) basic-directed research, development and demonstration projects, (ii) academia, industry, national laboratory cooperation's, (iii) timelines, scaling, life cycle assessments and supply chains, (iv) private-public investments/ partnerships, (v) policy issues, and (vi) products and market opportunities.

These will all have to be developed and implemented in order to reduce to practice CO_2 utilization technologies that offer the potential to reduce CO_2 emissions and/or introduce negative emissions at the Gt/y scale.

A pragmatic and fast solution to the Gt/y CO_2 utilization challenge will require a systems-based approach that integrates the (i) science and engineering, (ii) economic and political, (iii) public, private and industry expertise of all stakeholders. The overriding goal of this holistic approach is to ensure that all stakeholders are meaningfully engaged in the portfolio of early to late stage technology development to minimise risk and maximise the opportunities for successful implementation of the plan.

Putting it all Together – Energy System of the Future

In 2015, a landmark investment of $329B in the global renewable energy industry, for the first time, surpassed that of fossil fuels. It seems the envisioned transition in our energy system, from non-renewable to renewable, is unstoppable.

Now we must now rise to the challenges of integrating a temporally fluctuating solar and wind renewable energy supply into a smart and secure energy infrastructure. An integrated system of this kind must be especially smart, to be able to generate, store, convert, control, regulate, transport and distribute a wide variety of renewable intermittent energy sources.

A pioneering example for the study of such a revolutionary energy system is Energy Lab 2.0, which is under development by three centers of the Helmholtz Association, on the Karlsruhe

Institute of Technology (KIT) campus in Southern Germany, [3]. Its goal is to investigate in a real-world laboratory setting, how to safely couple and control complex and sophisticated networks of renewable electricity, electricity storage, water electrolysis, heat and chemical energy carriers, Figure 7.

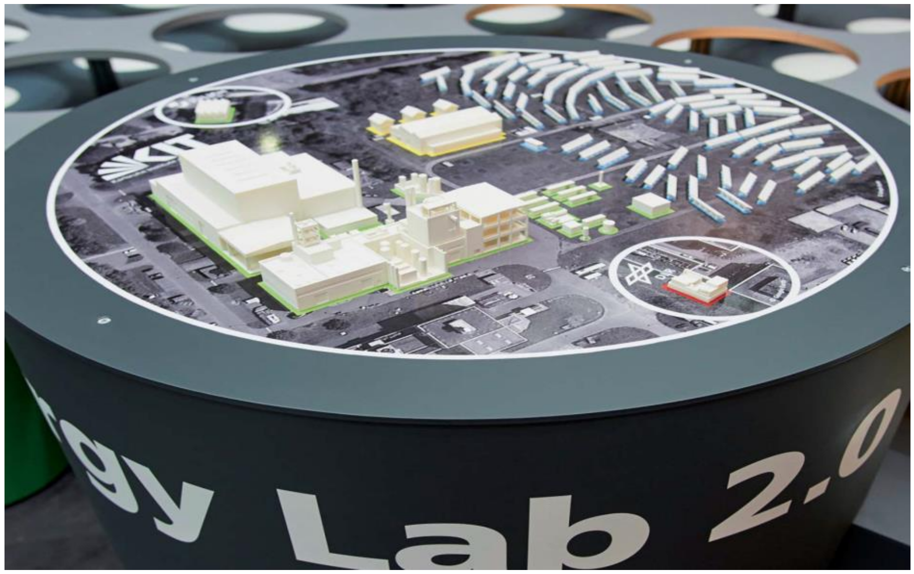

Figure 7. Energy Lab 2.0, [3].

Success in this endeavor is pivotal for enabling the transition from fossil to renewable energy supplies, in a smart grid system that has flexible fuels and loads, temporal fluctuations and geographical variations, in their provision and consumption of energy. For this energy system to generate, store and deliver power-to-heat, power-to-gas and power-to-fuel capabilities, it is necessary to cleverly interconnect and control, renewable forms of electricity, heat, gas and fuels for specific purposes.

The envisioned system will employ solar and wind electricity to produce gas and fuels from the catalysed reactions of H2 with CO2 and/or CO, where the H2 will come from H2O electrolysis, CO2 from renewable sources, and CO-H2 from biomass. Renewable electricity in this network of energy carriers will also be generated using gas turbines able to handle flexible fuels and varying loads, [3].

Decentralized CO2 Refineries built from Modular Transportable Plants

The futuristic vision of a fleet of modular CO2 refineries, powered by renewable forms of electricity, built from truck-size containers, transported, delivered and integrated on-site, to industries that have elected to convert their greenhouse gas emissions into synthetic fuels or easily transported liquid fuel precursors, is absolutely brilliant. This connects to the concept of mobile process equipment containers recently developed by chemical industry, Figure 8. Note that the container in Figure 8 is the mobile research lab whereas the real production containers making up the modular refinery would probably look different, as it would not need some of the features of the research lab container.

Development of the envisioned portable, versatile, self-contained, modular synthesis, testing and control systems will enable renewable heat, electrical or solar energy to be used at different industrial sites, to locally capture and purify carbon dioxide and generate hydrogen from water electrolysis. The subsequent conversion of the carbon dioxide and hydrogen into synthetic fuels, provides a novel and exciting paradigm for reducing greenhouse gas emissions, curbing global warming and ameliorating climate change.

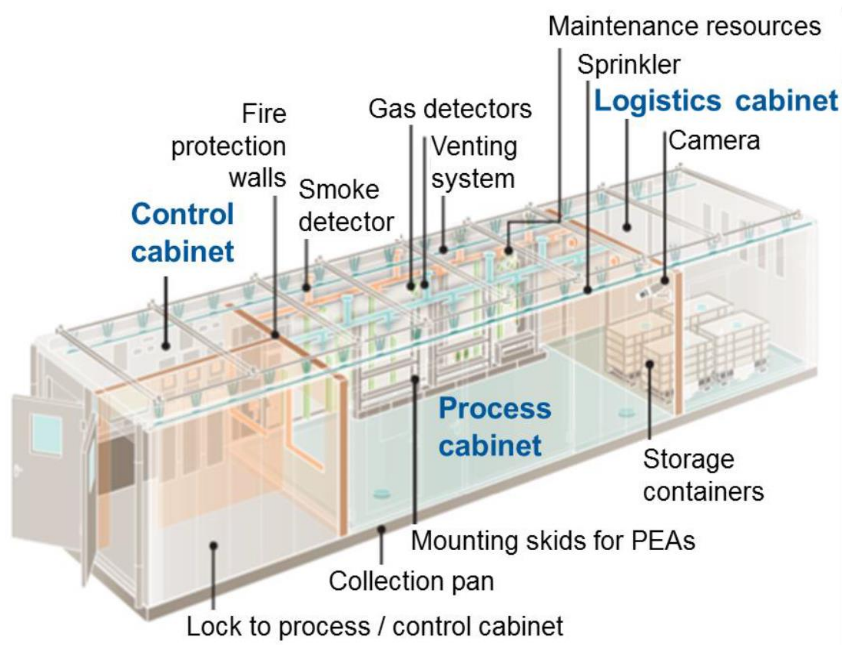

Figure 8. Transportable compartmentalized research container for validation of processes for converting carbon dioxide and water and renewable energy into synthetic fuels, on-site at greenhouse gas emitting industries, [4].

It's incredible to imagine that instead of having to collect and transport industrial greenhouse gas emissions to a CO2 refinery one can instead deliver modular CO2 refineries to the emitting industries. They could produce an easily transported liquid fuel on site, which can be shipped to a central facility for upgrading to the final product(s). This approach has the potential to solve many logistical problems that need to be broached in rising to the grandest challenge facing humanity today, climate change.

The transportable compartmentalised research container illustrated in Figure 8, modeled after Evonik's EcoTrainer, a complete self-contained chemical production complex on wheels [4], brings mobility, flexibility and versatility to Energy Lab 2.0 under construction at Karlsruhe Institute of Technology. Both of these technologies will prove to be key enabling components of the Energy Revolution, well underway in Germany, [3.4].

Imagine an industrial assembly line, manufacturing hundreds of thousands of these mobile CO2 processing containers, delivering and installing them into fossil powered industries all around the world, all tasked to efficiently and economically convert their greenhouse gas emissions into custom-made synthetic fuels.

We are "All" in it together

It's a tall order for society but let's face it, we are all in this world together and we must all now shoulder the Herculean responsibilities of caring for our Earth with the same degree of concern as we care for ourselves and our collective future. If we all work together, we can make it work and we can sustain all life on earth, as we know it today.

1. www.google.de/search?q=SEAB+Task+Force+Report+on+CO2+Utilization+and+Negative+Emissions+Technologies&ie=utf-8&oe=utf-8&gws_rd=cr&ei=ehlnWeqyHYHaU_35rPgF
2. www.ineratec.de/?lang=en
3. www.elab2.kit.edu/english/index.php
4. www.corporate.evonik.de/en/products/product-stories/Pages/chemistry-on-wheels.aspx

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