"Geological Net Zero":

A proposal for a simple and globally effective international agreement on fossil carbon

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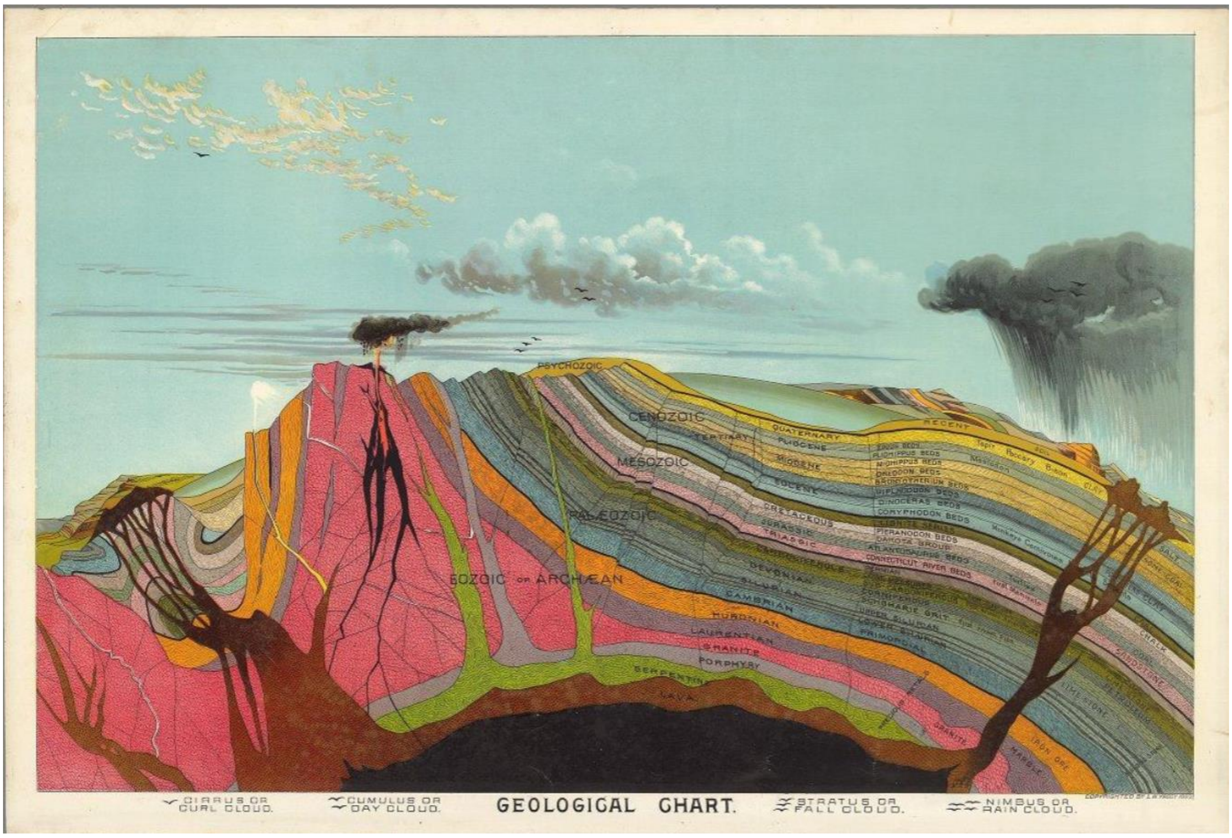

Earth section by L.W. Yaggi, 1893

Today, anthropogenic fossil carbon emissions are 25 to 100 times higher than volcanic emissions

SUMMARY

This article proposes a "geological net zero" resolution for COP26 (in November 2021 in Glasgow) that makes **producers** of fossil carbon responsible for the management of the life cycle of the carbon that they extract. The resolution is anchored in Earth System considerations: the integration and temporal harmonization of anthropogenic activities into the biogeochemical cycles of the Earth. This leads to a new view of carbon markets, with dependence on fossil carbon treated as a liability, not an asset.

Figure 1 : A broken clock & the geological and carbon cycles - Source: montage by the Author

Proposed geological net zero resolution:

For each quantity of fossil carbon extracted, the same quantity of carbon must be geologically sequestered in the same year.

This is to be achieved as soon as possible, consistent with a global carbon budget.

A supranational entity is to be formed and charged with supervising geological sequestration operations everywhere on the planet.

The adoption of this resolution would accelerate the transformation of fossil fuel extractive industries into industries of hydrogen production and geological sequestration of carbon; these industries could be able to geologically sequester more than half of the carbon extracted annually by the year 2030:

- Carbon must be sequestered as far upstream as possible in the fossil fuel extraction chain
- The geological sequestration of carbon will be accelerated by industrial integration with the production of blue hydrogen
- R&D efforts must be increased tenfold regarding
    - geological sequestration
    - the production of blue hydrogen
    - the production of natural hydrogen
- A new frontier is opening under our feet: that of geohydrogen and of mineral and energy flows from biogeochemical georeactors.

Informed about the fossil carbon footprint of the products they buy, consumers will be able to help accelerate the transition.

The modes of commercial transactions concerning fossil carbon must be changed:

- Carbon markets must rematerialize carbon; de-financialization is needed.
- These markets should exist physically at a local or regional level; it is not certain that a global market makes sense.
- Hydrocarbon and coal trading contracts will have to contain clauses committing the parties as to the physical fate of the fossil carbon extracted.

The start of massive operations for geological sequestration of carbon will allow:

- A smooth transition for producer countries.
- A transition within consumers' financial means.
- Economic risks of oil or electricity price shocks greatly reduced.
- Energy transition financial risk greatly reduced.

Implementation could be supported by the creation of a "Brown Climate Fund", driving the simplification of the complex web of existing taxes, subsidies, and fossil fuel financing, which would constitute a strong accelerator of transition.

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1. Context

Between 31 October and 12 November 2021, the twenty-sixth Conference of Parties to the United Nations Framework Convention on Climate Change (COP26) will take place in Glasgow, Scotland. Many organizations and delegations will be going there to make their voices heard and those of the public that they represent. Analysis of the main lines of their press releases gives cause to fear that the decisions taken have little chance of being in the real interest of the Earth, its climate, or its inhabitants.

Yet "*The Earth is crying out*", to use Bruno Latour's expression[1]. All experts, all associations, all ecological parties are unanimous. "*We have, within touching distance, in 20 years, a risk of the system going out of control, which we should never have got to*" adds Dominique Bourg[2] and many scientists. The IPCC, after 30 years of scientific synthesis work, has finally this 7 August confirmed[3] what many experience in their daily life or have been observing through climate data for decades: *"There is no doubt that human influence is warming the atmosphere, the ocean and the land. Widespread and rapid changes are taking place in the atmosphere, ocean, cryosphere, and biosphere".* The IPCC gives us the solution: we must *"limit cumulative CO2 emissions, achieve at least zero net CO2 emissions, as well as… strong, rapid and sustained reductions in methane emissions".*

So, there is fire and smoke everywhere! "*The alarms sounded, but they were disconnected one by one*"[4]. But where then is the source of the fire? The IPCC and the Deep Carbon Observatory[5] (2010-2020), based on the work of climate research organizations around the world, have now enabled us to know enough about the biogeochemical carbon cycle to confirm the fears expressed by Arrhenius[6] more than a century ago, and then by researchers within oil companies themselves more than 50 years ago[7]; already at that time it was suspected that fossil carbon emissions could cause climate change.

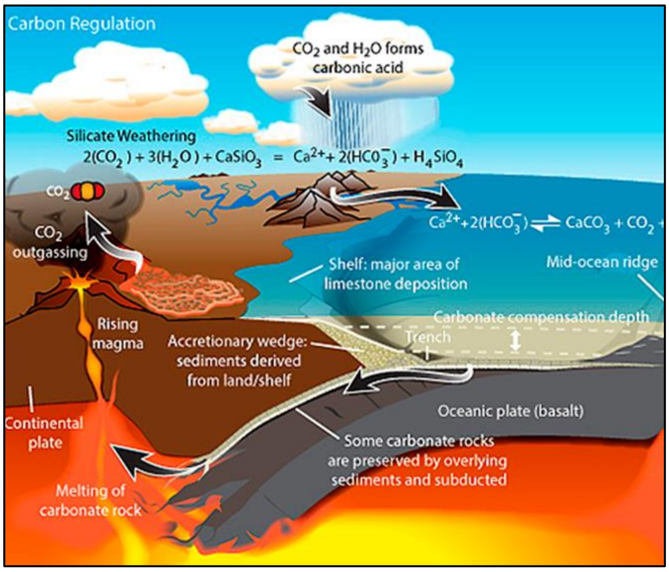

Figure 2 : Geologic and oceanic carbon cycle - Source John Garrett Wikipedia

With current data, quick and simple calculations[8] confirm clearly that they are the main cause of the disruption we see today. More precisely, depending on the assumptions chosen, they show that the combustion and leakage to the atmosphere of carbonaceous fossil materials release 25

[1] (Latour, 2015)
[2] (Bourg, 2021)
[3] (IPCC (AR6 working Group I), 2021)
[4] (Latour, 2015)
[5] (Alfred P. Sloan Foundation, 2021)
[6] (Wikipedia, 2021)
[7] (Greenpeace, 2021)
[8] Towards responsible circular fossil carbon industries: Upstream proposals to reduce demand and control supply - A working paper (Nicolas & Portolano, 2021)

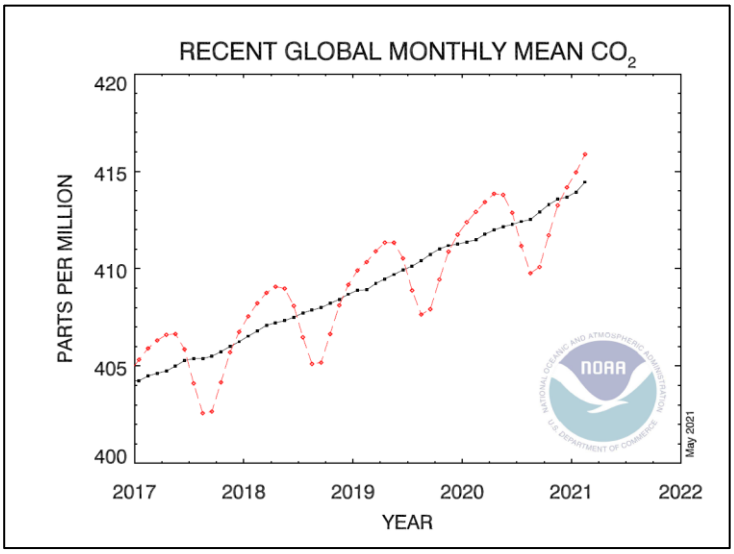

Figure 3: atmospheric CO2 content in Mauna Laua,Hawai – Source NOAA

to 100 times more greenhouse gases annually than volcanic emissions. However, we have recently learned that during previous geological eras, volcanic emissions less than current anthropogenic emissions were the cause of deep and lasting bioclimatic changes, or even a species extinction crisis.

It is urgent, but there is still time to act; if we stopped all fossil emissions tomorrow and implemented low-carbon measures affecting soil and forest management and human activities, we would have a good chance of leaving our descendants a planet with the infrastructures[9], environment and quality of life which we enjoy. An alternative solution, recommended here, would be to put in place measures allowing quantities of carbon that would otherwise enter the atmosphere (or has already done so) **to be geologically sequestered without delay** in quantities equivalent to, or even greater than, those extracted from the geosphere. And, in parallel, to implement measures allowing biospheric agents to absorb the excess atmospheric and oceanic carbon resulting from past human activities (adapted management of forests, soils, agriculture, the water cycle).

It is therefore with fossil emissions that we must start. Anything that can be done about other processes affecting the atmosphere, such as acting on agricultural and forestry practices to increase carbon storage in soils or forests, will be in vain if the source of the fire that we are burning remains alight, which we are maintaining by burning fossil fuels in the atmosphere without geological sequestration of an amount at least equal to that of the carbon extracted.

2. The proposed resolution

The Paris Agreement signed in December 2015 at COP21 was a major step forward in the fight against global warming in that it allowed nations to coordinate their actions. However, six years later, we still do not observe the slightest beginning of a downward turn in the curves of greenhouse gas concentration or global mean surface temperature: they are continuing their growth imperturbably, and have even accelerated, including during the year 2020 when COVID did cause a notable drop in emissions.

[9] It is perhaps already too late and at best we might then have the possibility of preserving the infrastructure that exists by adapting. Indeed, the climatic events of recent years and the long-term trends induced by global warming (rising coastal waters, for example) are changing the fundamental sizing parameters used in the design of civil engineering infrastructure and buildings. The statistical evolution of the time series of weather variables (Geert Jan van Oldenborgh, 2021) is leading to a modifying of the frequency and intensity of precipitation and wind as well as other parameters such as groundwater levels, thermal or humidity ranges. Thus structures designed to last for decades can instantly be destroyed or severely damaged at any time anywhere on earth. This may justify the use of the term "climate bombs" to describe climatic events which are becoming more and more common. (Geert Jan van Oldenborgh 2021)

"Geological Net Zero": An international agreement on fossil carbon

As a reminder, the Paris Agreement commits 154 countries and all the members of the European Community (signatory countries of the United Nations Framework Convention on Climate Change - Earth Summit in Rio de Janeiro in 1992).

It "*aims to strengthen the global response to the threat of climate change, notably by containing the rise in the average temperature of the planet to well below 2 °C above pre-industrial levels. To do this, the signatory states seek to achieve a global cap on greenhouse gas emissions as soon as possible, and to make reductions rapidly thereafter in accordance with the best scientific data available to achieve a balance between anthropogenic emissions by sources and anthropogenic removals by sinks of greenhouse gases during the second half of the century*".

It is therefore of a consensual nature but one which only commits the signatory countries to show good will and this only to the extent of their means or the aid they might receive from other signatories, whilst allowing them 35 years to achieve results!

This agreement has absolutely no direct impact on the actors at the origin of climate change who are the producers of hydrocarbons and coal; it is up to countries' governments to take the appropriate financial or regulatory measures so that the producers do what is necessary.

The COPs of the following years (COP22, 23, 24 and 25) did not change this landscape, with the results that we now see.

Enough is enough! It is now high time to call directly on the "fossil" actors to solve the principal aspect of the climate problem.

We therefore propose the adoption of a simple, common-sense resolution that directly involves the "fossil" players, in the same way as other industries already are, concerning their own impacts on natural cycles. We propose that the following legal obligation be imposed on the fossil fuel extraction entities:

"*For each quantity of fossil carbon extracted, the same quantity of carbon*[10] *must be geologically sequestered in the same year.*"[11]

This "geological net-zero" goal is to be achieved as soon as possible, consistent with a global carbon budget. This measure would affect the supply of fossil energy products, which would start to decrease due to the consequent increase in their production costs, which would include the cost of carbon capture and geological sequestration (CCGS).

[10] This is carbon accessible by biospheric agents, including humans: for example, atmospheric carbon, carbon from fossil fuels and derived products which can burn or be biologically broken down at any time, carbon present in matter organic (trees, plants, soils, plankton, etc.), etc. ...

[11] Within the framework of the COP, where an agreement can only concern countries, a resolution - to be defined - would require the signatory countries to commit themselves to imposing on extractive industries that the carbon resulting from the production of fossil fuels in their country be compensated by an equivalent quantity of geologically sequestered carbon, and this in a progressive manner, following a timetable in line with the Paris agreement. They could also penalize their fossil fuel suppliers who do not comply with the new agreement (for example, through a border tax on imported fossil carbon, which would be used to geologically sequester the same amount in less than a year).

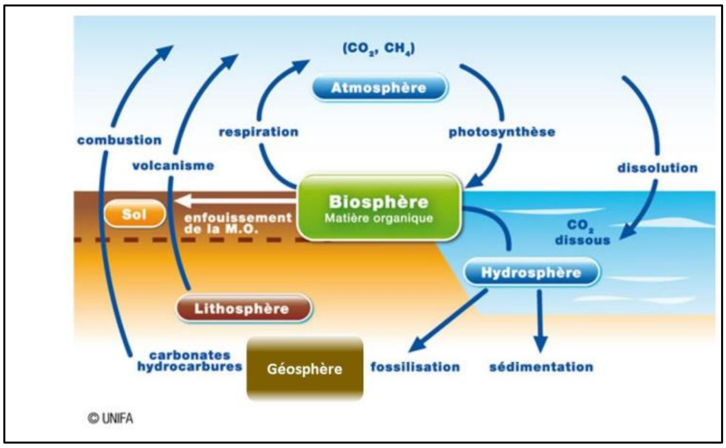

Figure 4: Carbon cycle - Source : UNIFA

It would be accompanied by a measure to reduce their demand by informing consumers of the fossil carbon footprint of the products they buy so that they can choose the least fossil carbon-intensive products if they wish.

The implementation of this resolution should be overseen globally by an independent supranational body, of the type that oversees the non-proliferation of nuclear weapons, whose role would be to inform international trade bodies, the public, associations, and authorities of progress in its implementation and to monitor and, if necessary, penalize offenders. **It would also ensure that the modes of sequestration implemented are implemented in ways that are adequately secure and not hazardous for current and future generations.**

This resolution is a common-sense measure for the ecological stewardship of the Earth. It requires major branches of industry to ensure that their activities are in line with the Earth's cycles and rhythms and that they do not interfere with these to the extent that they put the well-being of future generations at risk.

The industries extracting oil, coal, and other carbon-based geological materials such as limestone for cement will be able to adapt. And the financial and economic institutions will find the models to make it happen.

3. Benefits and implementation of the proposed resolution

Here are a few proposals and avenues of reflection designed to stimulate the creativity of these industries and of the participants in COP26.

3.1. Reinventing fossil fuel production

Hydrocarbons and coal currently account for about 80% of the world's primary energy supply. It seems difficult to imagine that we will be able to do without these substances until we have greatly exceeded the critical climate thresholds. To avoid this, it is therefore necessary to transform the fossil fuel production chain in depth.

3.1.1. Hydrocarbon production[12]

The hydrocarbon industry is, along with the coal industry and industrial practices in agriculture and livestock farming, one of the three main causes of climate degradation. It is a formidable industrial machinery that for more than a century has always been able to respond in less than 5 years to the economic, geopolitical, and industrial challenges that were posed to it. Part of the solution to the climate problem will come not by trying to marginalize it but on the contrary by confronting it with a new challenge: to continue to bring dense and easily accessible energy to consumers while securing their energy supply and now to complete the geochemical cycle of carbon.

To begin with, the proposed resolution should be imposed by regulation within a group of producing countries representing a significant fraction of the world's fossil fuel production.[13] Otherwise, the operational financial logic of multinational energy companies will force them to take advantage of national peculiarities to evade this newly established constraint; whatever regulations are put in place, the duty to maximize their shareholders' dividends will always make them move towards the least restrictive regulations. Regarding the adoption of the proposed resolution, countries whose economies are based on hydrocarbon production could see it as a solution to minimize the risk presented by the energy transition; their extractive economies could continue activities as soon as they have put in place the necessary infrastructure for geological carbon sequestration.

The energy power of hydrocarbons[14] is largely based on the hydrogen they contain[15]: in the combustion of natural gas (methane), for example, hydrogen – which is only 25% of the weight – contributes 60% of the energy released and carbon 40%. Hydrocarbons can also be seen as vectors for transporting hydrogen, the lightest and most widespread of them, methane, being one of the best vectors for transporting hydrogen... as soon as we know what to do with the carbon that carries it. It can be separated from hydrogen by various techniques whose cost increases rapidly as the carbon content of the treated effluent decreases. To be done at competitive costs, this must be done as far upstream as possible in the chain. This has several advantages:

- effluents with a higher carbon content are treated and processes are thus more efficient and less costly.
- the more favorable thermodynamic conditions (temperature and pressure) of the effluents at the wellhead can be taken advantage of (or even in the deposit itself for certain processes under development).

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[12]Readers wishing to keep abreast of the latest developments on this subject, which has been evolving very rapidly in recent months, may wish to refer to the latest publications of the CCS Institute, the Center on Global Energy Policy at Columbia University and the latest IEA reports, in particular (IEA, Special Report on Carbon Capture Utilization and Storage 2020) (IEA, Special Report on Carbon Capture Utilisation and Storage, 2020).
[13]An embryo of this group of countries could be constituted by those having made the following declaration (U.S. Department of Energy, 2021)in April 2021: "*Canada, Norway, Qatar, Saudi Arabia, and the United States, collectively representing 40 percent of global oil and gas production, will come together to form a cooperative forum that will develop pragmatic net-zero emission strategies, including methane abatement, advancing the circular carbon economy approach, development and deployment of clean-energy and carbon capture and storage technologies, diversification from reliance on hydrocarbon revenues, and other measures in line with each country's national circumstances.*" (U.S. Department of Energy 2021)
[14]Remember that hydrocarbons are essentially made up of chains of carbon atoms to which hydrogen atoms are attached and that they are mostly produced by the degradation of organic matter in the temperature and pressure conditions that exist at a depth of several thousand meters. The energy they provide comes from their oxidation (combustion) by the oxygen in the ambient air. This combustion produces mainly water and carbon dioxide.
[15] (Association des Consultants Pétrole Energie, 2021)

- the possibilities of sequestering the carbon in the very deposits from which it comes or in neighboring structures that will offer the same guarantees of geological safety of sequestration can be taken advantage of.
- means of control and monitoring can be called upon that use infrastructures and services that are already in place.

On the other hand, to be transported and delivered to the final consumer, if the latter is not on site, the co-produced hydrogen must be compressed, liquefied, or recombined with other transport vectors, such as nitrogen in the form of ammonia or adsorbed on solid compounds, for example based on magnesium. This new segment of the oil and gas industry can be shared with the equivalent segment of production and transport of green hydrogen from offshore wind turbines or solar farms. These same renewable energy production facilities can also be used to supply electricity to hydrocarbon production and sequestration operations, thereby significantly reducing their carbon footprint and improving their energy rate of return (EROEI)[16].

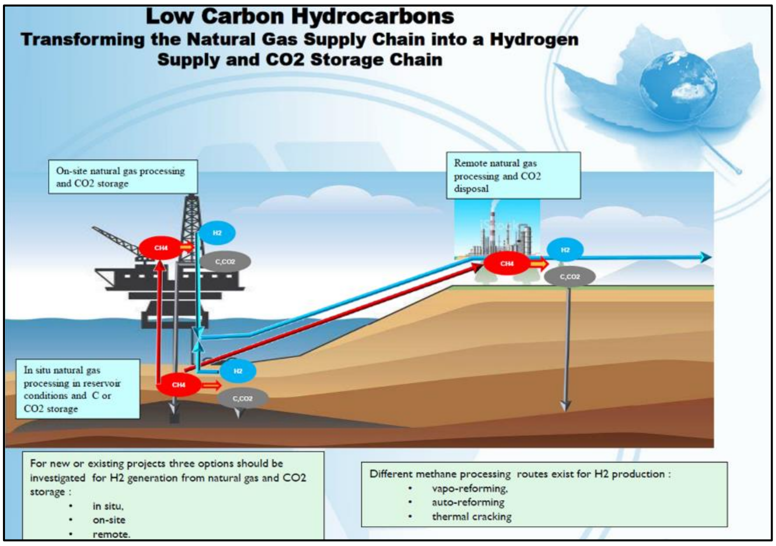

Figure 5 : in situ and on-site blue hydrogen production – Source EOSYS

3.1.2. Coal production

For coal, mainly used for power generation, experiments in carbon capture and geological sequestration on thermal power plant emissions have not been very successful so far, the main reasons being the cost of recovering the carbon from relatively low-carbon gases and the fact that nearby geological structures had to be newly tested and equipped to geologically sequester carbon.

Other routes can be considered. For example, many coal beds contain significant amounts of adsorbed methane. Some coal mines or deep and undeveloped coal beds could thus be converted into methane and hydrogen production centers, the latter being produced by reacting water and coal or methane at high temperature, using for this the heat of their combustion. The CO2 emitted can be re-injected into the coal beds where it easily displaces and replaces the co-produced methane.

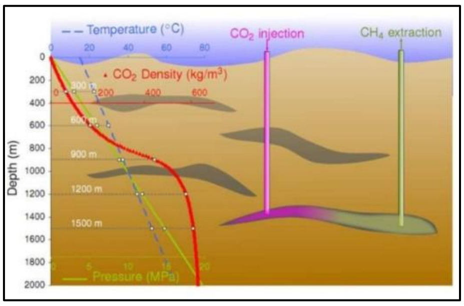

Figure 6 : Coal Bed Methane extraction by liquid CO2 sweeping – Source PhD Thesis of S. Nikoosokhan, U. Paris-Est

[16]EROEI: Energy Return on Energy Invested (Hall, Lambert, & Balogh, 2014)

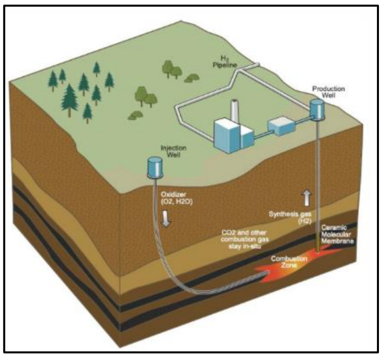

Figure 7 : H2 production by in situ combustion- Source Bureau of Economic Geology, Texas

Technologies have been developed over the past ten years to produce methane from layered coal deposits (Coal Bed Methane or CBM), taking advantage of the of horizontal drilling and fracking know-how developed by the shale oil and gas industry. The technical and economic contours of what is feasible in this area need still to be clarified. Experiments on the subject are advanced in China, the United States and Australia, but R&D resources have not been deployed on as large a scale as the oil and gas companies have put in the industrial development of the shale industry.

It is, however, a particularly crucial and sensitive subject because the use of coal is important and will remain so in many fast-growing countries or in exporting countries like Australia. In China and India in particular, it is of strategic importance for their energy supply, while at the same time placing these countries among the biggest emitters of CO2 into the atmosphere.

3.2. Diversifying geological capture and sequestration methods

3.2.1. CCGS from the hydrocarbon industry: CO2 in gaseous or liquid state (supercritical

The geological sequestration method that is now industrially operational is the injection of carbon dioxide in liquid form in a supercritical state into saline aquifers or hydrocarbon reservoirs at depths of between 4,000m and 1,000m. These techniques are mature[17]; they were initially developed more than 50 years ago to improve hydrocarbon recovery or to separate unwanted gases from hydrocarbon streams. It should be emphasized that these operations, if properly designed and operated, offer every guarantee of long-term security and safety. There is no shortage of structures in which to inject CO2 for sequestration.[18]

3.2.2. CCGS hubs[19]

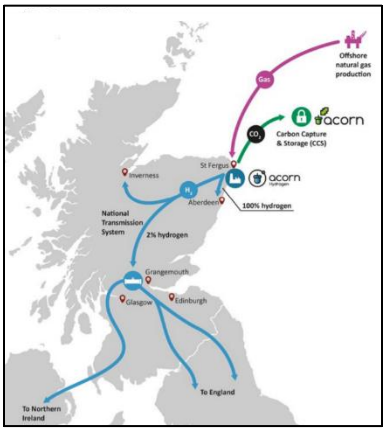

Figure 8: CCGS & H2 hub in Scotland - Source ACORN

The choice of CCGS projects depends on the proximity of the CO2 production site, the capture technologies that can be implemented and the quantities of carbon to be sequestered. This has recently led to the creation of industrial hubs in which the hydrogen needs, and CO2 effluents of several different industrial production units are consolidated: e.g. cement factories, iron and steel industries, metallurgy, refineries, power plants, fertilizers, greenhouses, and food processing units. The CO2 is collected and sent by pipeline to injection wells several tens or hundreds of kilometers away. Trucks and ships can also be used for CO2 transfers. Salt caverns can be used for CO2 sequestration or hydrogen storage. Such hubs have recently been developing very rapidly around the North Sea (Great Britain, Norway, Holland, Belgium), the Gulf of Mexico (Houston),

[17] (Kearns, Liu, & Consoli, 2021)
[18] Add CCGS structure atlas
[19] (Global CCS Institute, 2020)

the central plains of the United States, the Gulf states (Saudi Arabia, Abu Dhabi), Brazil, Australia and China.

3.2.3. Other modes of CCGS: solid carbon, carbonates, biomineralization, ecological redevelopment of land areas

Other methods of geological sequestration are under study. They can be classified into 3 categories:

Terrestrial surface processes. Examples:

- Promoting weathering of rocks,
- Restoration of sediment loads in watersheds through redevelopment
- Carbon absorbing cements,
- Artificial limestone aggregates[20],
- Mass production of carbon nanotubes (these emerging technologies appear to have a high growth potential, like solar technologies 20 years ago)[21],
- Sequestration in old mines or quarries of elemental carbon obtained by pyrolysis,

Lacustrine, coastal, or oceanic[22] processes: These are biotic and abiotic processes leading to the sedimentation of (organic) carbon-laden particles or to carbon fixation reactions on the ocean floor. Examples:

- Promotion of corals and shellfish on the bottom near the coast or on floating structures offshore,
- Promotion of planktonic growth in the middle of non-fertile oceans by upwelling deep water driven by pumps powered by solar and/or wind energy: this plankton feeds trophic chains and fixes carbon in the form of carbonate sediments formed from the shells of micro-organisms,
- Bio mineralization at the sea bottom,

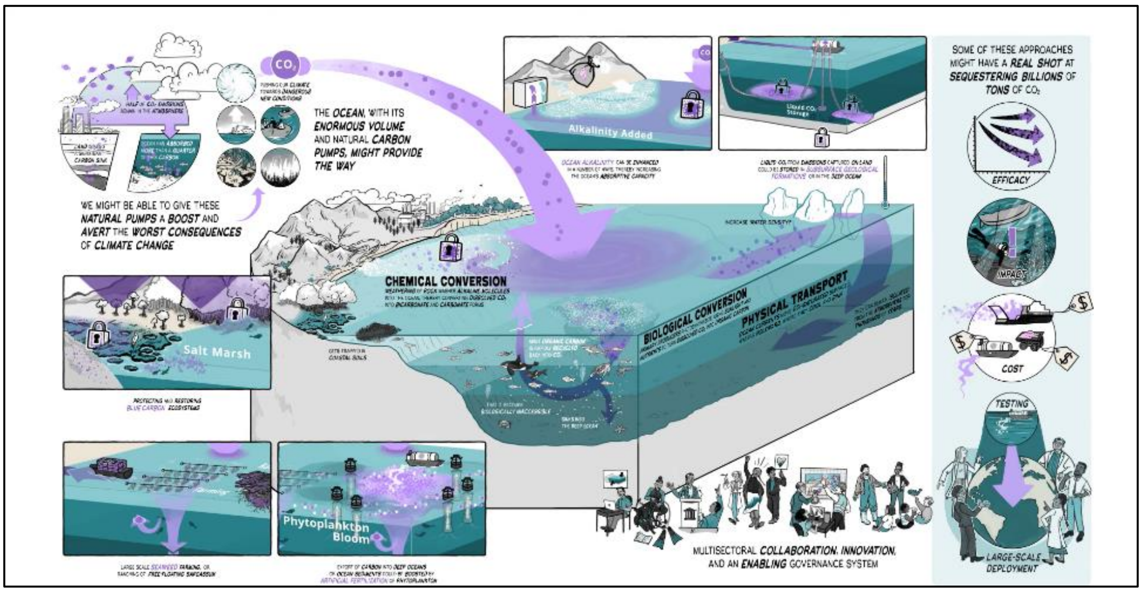

Figure 9 : options for CCGS in the ocean - Source www.oceancdr.net

[20] For example, see OCO Technologies - https://oco.co.uk/sustainable-construction-products/

[21] (Pasquali & Mesters, 2021)

[22] (Ocean CDR, s.d.)

- Oceanic permaculture: development of algae growths whose decomposition allows for biomineralization of carbon,
- Processes to increase ocean alkalinity: increased loading of alkaline sediment through coastal watershed management,

Subterranean processes. Examples:

- injection of liquid CO2 into the subsurface at a depth of more than 800m, where it remains hydraulically trapped, dissolves in water and/or binds chemically to the rock matrix.
- Decomposition (cracking) of natural gas into carbon and hydrogen, then sequestration of this carbon in solid form in old mines or quarries.
- Injection of carbonate solutions into fractured basic volcanic rocks (basalts) triggering a carbonate precipitation reaction in the fractures and geologically fixing the carbon.

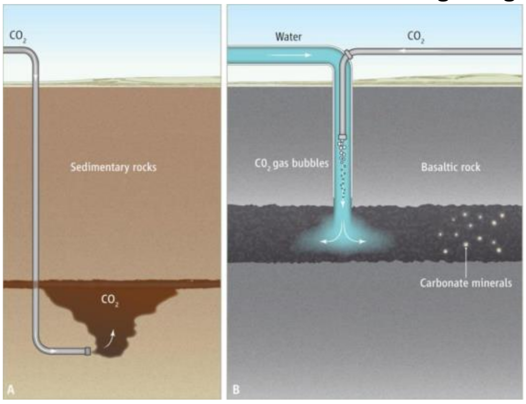

Figure 10 : Subterranean CCGS – Source Iceland GeoSurvey

Existing natural processes should thus be promoted through appropriate ecological management and redevelopment of natural environments.

Many other possibilities are being studied in laboratories and are only waiting to be tested in pilot schemes and then developed if successful.

The hydrocarbon and coal mining industries could thus become hydrogen production and carbon sequestration industries, and the industrial infrastructure they have built could even prove indispensable in lowering greenhouse gas levels in the atmosphere.

3.3. Consumer involvement: Fossil Carbon Footprint Indicator

To act directly on demand, it is proposed to introduce an indicator for consumers and industrial buyers that accompanies the existing or emerging indices of greenhouse gas emissions and carbon content of the products purchased[23]. This "Fossil Carbon Footprint Indicator", expressed as a percentage, indicates the proportion of fossil carbon in the total carbon that has been or will be used or mobilized in the development of the product and its consumption cycle, both in terms of the carbon energy used to produce, distribute or recycle/dispose of the product and the carbon it intrinsically contains.

A color code (black = fossil carbon, green = organic carbon) will allow consumers to know immediately if they are buying a product with a high fossil carbon content and to make their choices accordingly.

[23] (Nicolas & Portolano, 2021)

By default, a black code would be applied to all products. It would be up to manufacturers or suppliers to demonstrate to a control authority, to be instituted or existing, that the Indicator for their product is not equal to 100% (black).

3.4. Implications for financial and economic agents: should there be a carbon tax? What kind of carbon market is needed?

Economic and financial actors must give the economy and industry the means to function in symbiosis with natural carbon cycles. Several aspects are discussed below.

3.4.1. Supply-side policy: "Upstream" initiatives

Initiatives on oil and gas supply policy such as the "Supply side Policy" accompanied by Carbon Certificates or a Carbon Takeback Obligation (CTBO)[24] have been proposed for more than 12 years by oil specialists from the universities of Oxford, Edinburgh, and Oslo[25] and their implementation is being considered in countries such as Great Britain, Holland, or Norway. These initiatives have recently attracted the attention of Shell as well as renowned research centers in Australia, Germany, Norway, and Saudi Arabia.

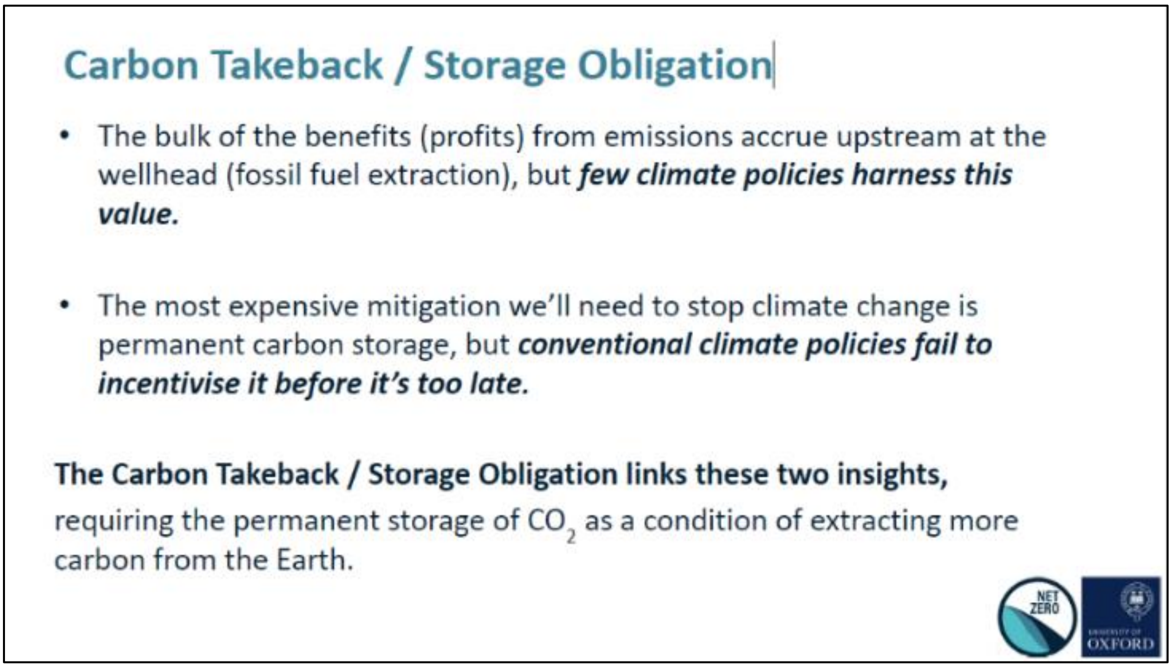

Figure 11 Basis of Carbon Takeback Obligation - Source NetZero & Oxford Institute

They aim to get hydrocarbon producers to participate directly in the financing of CCGS projects.

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[24] (Kuijper, Holleman, & van Soest, 2021)

[25] (Allen, Frame, & Mason, 2009) (Allen, Stuart Haszeldine, Hepburn, Le Quéré, & Millar, 2015) (Asheim, et al., 2019) (Kuijper, Holleman, & van Soest, 2021) (Zakkour, et al., 2021)

3.4.2. Upstream carbon tax

Another angle of approach, advocated in the same countries, consists in creating an upstream carbon tax at producer level which would supply funds intended to develop CCGS[26]projects. The downside compared to the carbon obligations cited above is that it is tempting for states to divert the proceeds from these taxes for other purposes and that in any case significant institutional evaporation risks exist in the management of these funds.

The upstream tax that would be required at the current stage to finance the CCGS projects is of the order of US$20 to US$45/barrel. This is to be compared with the price paid by the motorist at the pump, currently of the order of $300/barrel in France (September 2021) and with the market price of a barrel which has fluctuated over the last few months in a range of US$20-80/barrel. There is therefore a certain elasticity so that it is not the final consumer who fully finances the CCGS but that the other links in the oil and gas chain also participate, as well as the producing and consuming countries which levy significant taxes on both sides.

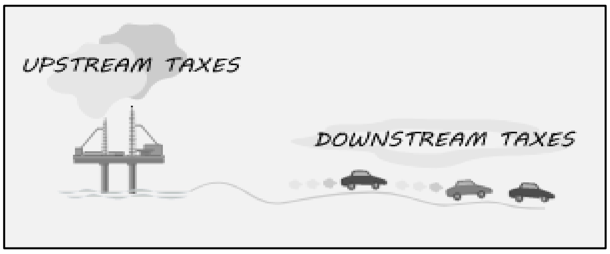

Figure 12 : Definition of upstream and downstream taxes - Source https://www.learn-economics.co.uk/

3.4.3. Carbon markets

The carbon price referred to is not the price of the carbon as such (fuel) but of the product of its combustion, the gas carbon dioxide (CO2).[27] Apart from a tiny fraction of what is produced, it is an externality, a substance that nobody wants. How then can we talk about a carbon market? Any producer of fossil carbon can calculate the cost of recovering and sequestering at the point of extraction the fossil carbon that it releases there. We can therefore define a local price for carbon at each extraction point: this is the price that the producer would be willing to pay to a service company to release him from his responsibility to return the carbon to its original geological cycle. If he can't find anyone to do it, or it's not economic for him to do it, his asset becomes stranded, temporarily, or permanently. It is therefore conceivable that local markets could be formed where fossil carbon extractors trade their carbon obligation and use service companies. A local price for fossil carbon and a local market are thus unambiguously defined. This is probably what the carbon hubs mentioned above will lead to. It is not certain that this will make it possible step by step to create a regional market, and even less so a global one, because the main cost element

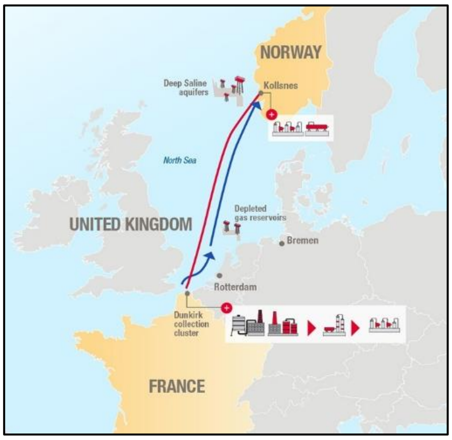

Figure 13 : carbon market driven by Norwegian CCGS – Source Total

[26]References available in (Nicolas & Portolano, 2021).

[27] Note that the coal price of US$ 100-200/ton is far from being able to incorporate the cost of sequestering the emitted atmospheric carbon: 1 ton of carbon emits 3.7 tons of CO2. If we were to include a cost of US$70/ton of CO2 for CCGS under current technical conditions, this would lead to an additional cost of US$256/ton of coal. Rather than closing coal fields, it is proposed to exploit them in a different way, underground, by developing technologies that allow the combustion of the carbon present in the coal and the adsorbed methane to be used in situ to produce hydrogen.

of carbon sequestration is its capture cost, and it is on the spot at the field, and even in the very field, from which this carbon is extracted that its capture costs the least.

We can also look at it from the point of view of consumers of fossil fuels: if their supplier can present them with a certificate of sequestration of the fossil carbon contained as well as the fossil carbon used in the extraction/transportation/refining/distribution of the product, they have no cause to have any concern. If not, the expensive services of an atmospheric carbon capture and sequestration company will have to be contracted by the region or state in which they make their purchase to take care of what their supplier has not done.

Figure 14 : European Carbon Border Tax – Source Tiao

In these schemes, there is neither a global nor regional carbon price, nor a carbon tax component for CCGS, nor a national or supranational entity imposing carbon quotas and opening the door to all kinds of fraud that have yet to be invented. Direct agreements between producers and buyers of oil and gas products may be sufficient to manage the physical carbon cycle locally or regionally.

3.4.4. Natural carbon cycles and carbon sequestration patterns

Another important area for reflection is the following: to what extent can an oil, gas or coal operator release himself from his carbon obligation by placing it in faster biospheric cycles than the one from which it comes, for example by planting trees that will only allow the geological sequestration of a tiny part of this carbon and may release it into the atmosphere a few decades later? Economic and financial rules and codes of practice still need to be established to manage the transition of carbon from a slow biogeochemical cycle to a faster cycle.

3.4.5. Transition to hydrogen

Today, based on IEA data, the hydrogen energy content of the burned hydrocarbons counts already for nearly half of the primary energy that they supply, as shows the figure below taken from (Pasquali & Mesters, 2021). Converting the hydrocarbon infrastructure into a hydrogen production infrastructure would allow the current energy transformation to be accelerated.[28] It would facilitate its metamorphosis initiated with the arrival of renewable energies. Their energy impact, it should nonetheless be recalled, remains minor for the moment: the rapid rise in capacity of renewable energies over the last 10 years has not yet been sufficient to affect the fossil fuel markets, and at the very most has only been able slightly to reduce their growth. The proposed placing of responsibility on upstream players would allow them to define and set up the industrial economic optimum between the share that goes to blue

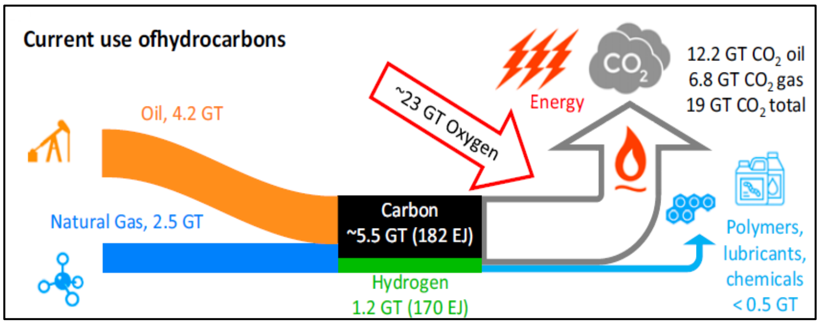

Figure 15 : Hydrogen energy content of hydrocarbons counts today for nearly half of the energy delivered by their combustion – Source Pasquali & Mesters, 2021

[28] (Association des Consultants Pétrole Energie, 2021)

hydrogen and the share that goes to green hydrogen[29], without the need for subsidies or market distortions. If these rules are well made, the conditions will be in place for the "invisible hand" dear to liberal economists to do its work; it will allow a smooth transition from a carbon economy to a green economy thanks to an arbitration or optimal combination, project by project, between blue hydrogen and green hydrogen. In the long run, given the natural decline of the hydrocarbon deposits, green hydrogen should end up predominating. However, hydrocarbon fields could see their operating life extended, and the quantities of hydrocarbons extracted significantly increased through the adoption of CO2 enhanced oil recovery (CO2-EOR process[30]) techniques, not only in the oil reservoir but also in an even larger underlying zone where there is a residual hydrocarbon saturation (ROZ, "Residual Oil Zone"[31]) that has not been exploited until now. Some fields could also be given a new lease of life (see footnote[32]) after the cessation of hydrocarbon exploitation. The recent recommendations of the IEA[33] and organizations such as the Carbon Tracker Initiative[34] not to bring new fields[35] into production could thus be followed: **primary or secondary hydrocarbon production with high carbon emissions would then be replaced by tertiary production with zero to highly negative carbon emissions.** This would contribute to mitigating the financial risk induced by the energy transition while opening up a prospective field of non-fossil geo-energy production possibilities that are currently absent from the energy transition debate (apart from geothermal energy, which currently plays a minor role). **The transition to a new renewable world that is re-rooted in its local lands or regions will not be possible by closing the barely explored frontier of what exists less than 5 kilometers from us, under our feet, in the lithosphere;** only recently have we started to understand that it is the seat of geochemical and energy flows that could hold happy surprises[36] for several generations.

3.5. Costs and financing of upstream decarbonization

The adoption of the principle of accountability of fossil carbon producers, accompanied by funding to sequester quantities of carbon equivalent to those they extract, could solve the problem of greenhouse gas emissions more quickly than is currently presented in the scenarios of the International Energy Agency (IEA) or the IPCC.

3.5.1. Additional cost due to integration of CCGS costs

Based on a geological carbon sequestration cost of US$70/ton CO2[37] (mainly in the form of investment

[29]Blue hydrogen: hydrogen produced from fossil fuels whose carbon is geologically sequestered. Green hydrogen: hydrogen produced from renewable energy sources.
[30] (Tenthorey, Taggart, Kalinowski, & McKenna, 2021)
[31] (Melzer, 2006)
[32]Former hydrocarbon fields can be converted into centers for carbon sequestration, geothermal heat production or extraction of mineral elements dissolved in associated waters (lithium, salt, potash, ...), or even centers for natural hydrogen or methane production by stimulating geochemical or biological reactions within the deposits. See for example the sites of the companies Proton Technologies (https://proton.energy/) and Cemvita (https://www.cemvitafactory.com/) and the "Endoterrestrials" (Fox, 2018) concept.
[33]"*No new oil and natural gas fields are needed in the net zero pathway*" - (IEA, Net Zero by 2050, 2021)
[34]https://carbontracker.org/
[35]Indeed, injecting CO2 into oil and gas fields would allow a significant proportion of them to achieve greater recovery while geologically sequestering large quantities of CO2 at the end of the operation.
[36]In particular about natural hydrogen flows (see for example the state of knowledge on the website https://www.hnatsummit.com/conference-program/)
[37]The cost of the CCGS is made up as follows: (IEA, Special Report on Carbon Capture Utilisation and Storage, 2020)$50/t CO2 for capture according to a process optimized for the co-production of hydrogen (this cost can

over 30 or so years), capturing and sequestering the approximately 33 billion tons of CO2eq[38] currently emitted by fossil fuel producers would cost US$2,310 billion per year, i.e., a total of US$69,300 billion over the 30-year amortization period used as a basis for the CCGS cost of US$70 /ton of CO2eq. This estimate, intended to give an order of magnitude of the effort to be made, is over-pessimistic and will never be realized for several reasons, and in particular:

- Capture technologies and the change in their implementation methods (upstream in production rather than downstream) have already started to lower capture costs; the CCGS installations built in the 2020s will be much less expensive than those built in the 2000s or 2010s.

- Other less expensive CCGS techniques not based on hydrocarbon technology are emerging.

- As soon as hydrocarbon prices include the sequestration cost of the associated carbon, they will increase, which will encourage their replacement by renewable energies and thus reduce the quantity of fossil fuels to be decarbonized.

Let us imagine, then, that we decide not to change anything in our way of life; renewable energy continues its progress thanks to the falling trend in its costs and the consumption of fossil energies remains unchanged. At most, coal-fired power plants are replaced by or converted to gas and the oil and gas sector takes full responsibility for the sequestration of its fossil emissions. Based on a hydrocarbon production of 216[39] million barrels of oil equivalent per day, (that is 79 billion barrels of oil equivalent per year), considering the sequestration of fossil carbon based on US$70/ton CO2 eq would have an impact of US$29/barrel for about thirty years, compared with an average price on the spot markets of US$70 and $300/barrel at the pump for the French motorist in September 2021.

The additional cost caused by the integration of the cost of carbon sequestration would certainly lead to some tensions on the markets and a readjustment of the apportionment of rent between the different actors of the hydrocarbon supply chain, but this would remain quite manageable in comparison with the variations in the prices of crude oil or gas over the last fifty years, which can reach several tens of dollars per barrel equivalent in a few months without there being any fatal disruption of supply to consumers.

3.5.2. Creation of a "Brown Climate Fund"?

To drive the ramp-up and ensure the monitoring of CCGS operations mentioned in section 2, a fund could be created to drive the financing of the investments required for CCGS: let us call it the "Brown Climate Fund" or BCF. The BCF would use its resources to de-financialize and materialize the current management of fossil carbon by dealing with physical and produced quantities of carbon and not with an abstract financial number ("carbon" price) remotely related to actual carbon emissions in an

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be lowered to $30/t CO2 if this hydrogen is co-produced directly in the form of ammonia, NH3) and $20/t CO2 for its transport and geological sequestration. These costs are mainly CAPEX, with OPEX accounting for about 5 to 10% of the total. (IEA, Special Report on Carbon Capture Utilisation and Storage 2020)

[38] Source IEA (IEA, https://www.iea.org/data-and-statistics, 2021)2018 data: in Gt CO2/year Total emissions 33.3 (of which coal 14.8, oil 11.4 Gt and gas 7.1 Gt) (IEA, https://www.iea.org/data-and-statistics 2021)

[39] Source IEA (IEA, https://www.iea.org/data-and-statistics 2021), 2018 data:
- in giga toe / year: total primary fossil fuels 11.5 (including coal 3.8, oil 4.5 and gas 3.2)
- in giga boe/year: total primary fossil fuels 79 (of which coal 26, oil 31 and gas 22)
- in million boe/day: total 216 million bpd (of which coal 71, oil 82 and gas 60)

abstract ETS (Emissions Trading Scheme). This will ensure that the funds invested in CCGS are used for physical carbon geological sequestration processes, following, for example, a scheme like that of the "Carbon Takeback Obligation" contracts mentioned above.

One main objective of the BCF could be to redirect financing that has tended to maintain the industry's stalled position about carbon emissions when it could be the driving force behind its decarbonization.

Examples of funds that could be partially or fully redirected by BCF interventions include:

- Between 2017 and 2019, the hydrocarbon industry in the G20[40] alone benefited from public subsidies estimated at US$584 billion[41] per year. These subsidies took the form of direct budgetary transfers, tax exemptions, aid for private consumption and investment, or direct public financing in state-owned enterprises. If extended outside the G20[42], this amount would be significantly higher.

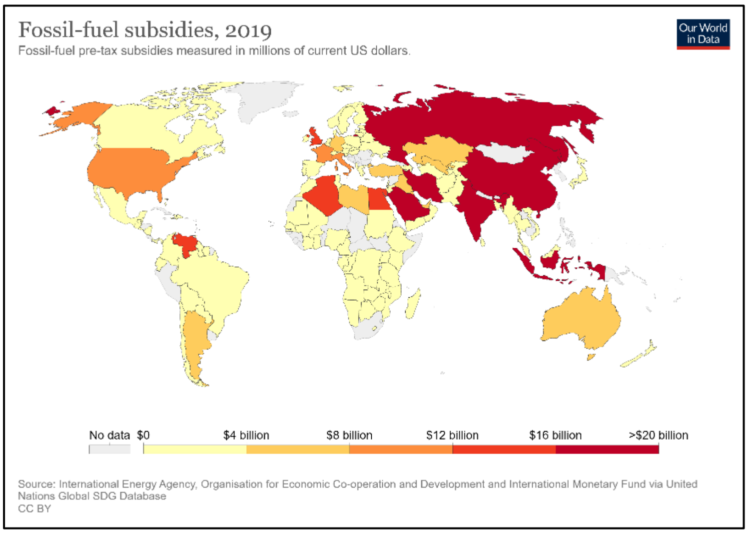

Figure 16 : Fossil fuel subventions 2019 - Source Our World in Data

- Moreover, according to IEA[43] figures, the total amount of investment in the oil and gas industries in 2019 was around US$750 billion for the upstream (extraction, processing, refining) and midstream (supply) segments. It could be appropriate to direct part of these investments towards the decarbonization of hydrocarbon production, such as the production of blue hydrogen or CO2-EOR+ tertiary recovery mentioned above.

- Funds linked to the financing of the coal industry could be redirected to CCGS.

[40]"G20 countries: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Turkey, Saudi Arabia, South Africa, Republic of Korea, the United Kingdom, the United States, and the European Union (EU)".
[41]Study financed by the Danish KR Foundation (International Institute for Sustainable Development, 2020)
[42]The G20 does not include major oil or gas producers such as Iran or those from the Middle East (excluding Saudi Arabia), North Africa, Africa (excluding South Africa), Latin America (excluding Brazil and Argentina) or much of Asia (excluding China, Japan, India, Indonesia and Korea).
[43] (IEA, https://www.iea.org/data-and-statistics, 2021)

As a comparison, it is interesting to note that the budgets envisaged for the energy transition for Europe alone total 1,115 billion Euros per year.[44]

For France, the cost of the energy transition is estimated at 70 billion euros per year[45]. Subsidies to fossil fuels are 35 billion euros per year.[46] Greenhouse gas emissions are 303 million tons equivalent per year[47]; if they were geologically sequestered or if a carbon compensation scheme was set up upstream with fossil energy suppliers for a cost of $70/t CO2, it would cost at the current dollar rate[48] a little less than 18 billion euros per year. It is not inconceivable therefore that France could consider a CCGS component in its climate policy, especially since this component could be the subject of long-term bilateral agreements with its fossil fuel suppliers, thus assisting them in their energy transition.

It therefore seems quite conceivable that by simply reorganizing the complex web of existing taxes and financing, more than 1,000 billion dollars globally could be directed each year towards decarbonizing the oil and gas industry and producing hydrogen. This would allow the sequestration of more than 14 Gt of CO2 per year within a few years and potentially by 2030, which would allow the low carbon transition to be undertaken without creating any 'oil' or 'electricity'[49] price shock, as seems to be happening in Europe now. This would go far beyond the recommendations of the IEA, which recommends that less than 50 billion dollars of public funds be devoted to CCGS in 2030. Considering the seriousness of the climate problem and the geopolitical tensions that its solution (and worse, its non-solution) might impose, the proposals suggested above are very reasonable.

Regarding coal, the situation is much less advanced; it requires innovations quickly followed by full-scale experiments, like the undertakings of the shale oil and gas industry. Nevertheless, we can reasonably count on the fact that if we put an "oil" level of resources into it, solutions will be found quickly, following the example of the meteoric growth experienced by the global shale oil and gas industry. Failing that, what is being done in Europe and North America could be generalized, i.e., accelerate the closure of coal fields by direct policy intervention or by subsidizing renewable energies or natural gas and the associated CCGS. It is this last hypothesis that has been considered in the reasoning above in this section.

3.6. Implication for emerging countries and oil-producing countries

The climate emergency is leading more and more Western funds to divest from the fossil fuel sector and move into the renewable energy sector. As nature abhors a vacuum, they are being replaced by less concerned funds from the "Carbon Zone", made up of countries such as Brazil, Mexico, Indonesia, China, India, Russia and most of the oil, gas and coal-producing countries of Eurasia, the Middle East and Africa; for these countries, which are generally experiencing strong demographic and/or economic growth, carbon-based fossil fuels are a guarantee of sustained growth, as was the case in the Western countries after the Second World War.

It is therefore necessary to propose provisions that do not penalize them, to define, in relation to the possibilities mentioned above, how the US$ 100 billion per year provided for in the Paris Agreement for the period 2015-2020 and managed by the Green Climate Fund (GCF[50]) could be allocated to the

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[44](Grandjean & Lefournier, 2021)
[45] (Grandjean & Lefournier, 2021)
[46](International Institute for Sustainable Development 2020)
[47] (IEA, https://www.iea.org/data-and-statistics, 2021)
[48] 1.18US$/Euro at10 September 2021
[49] (Geoffron, 2021)
[50] https://www.greenclimate.fund/

low-carbon transition of the poorest countries. Remember that only a small part of the announced funds has been distributed to date[51].

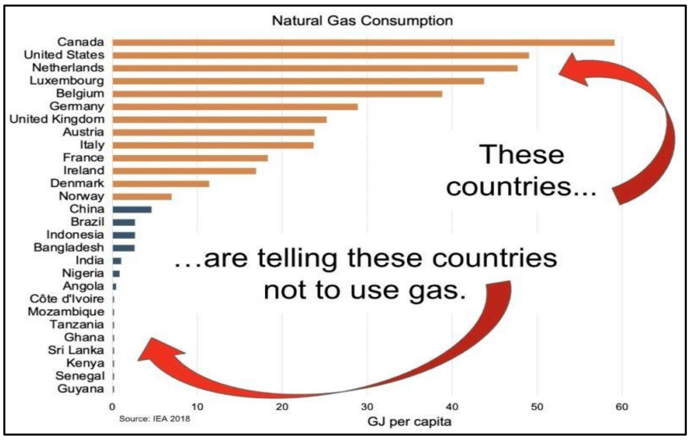

Figure 17 : Unfair deals? - Source (Widdershoven, 2021)

Note: countries in blue have stalled projects with important gas reserves waiting to be developed

Some carbon sequestration operations subject to very precise selection criteria could come under this fund[52], even if it has not yet financed any.[53] One could imagine it receiving an additional allocation for CCGS facilities and associated "midstream" infrastructure in producing countries or in countries receiving their production. These funds would be used to accelerate the implementation of integrated carbon management contracts between producers and buyers, along the lines of the "Carbon Takeback Obligation" scheme already mentioned. Buyers of products from these channels would then be guaranteed that the greenhouse gas emissions of the products purchased would be physically offset by the geological sequestration of equivalent quantities.

4. Legal aspects

An evolution of international law allowing for country-by-country legislative changes would help to strengthen the proposed carbon regulations.

Back in 2015, in preparation for COP21, the President of the French Republic, François Hollande, entrusted the former Minister of the Environment and Member of the European Parliament Corinne Lepage[54] with a mission consisting of "*establishing the rights of humanity, that is to say the right for all the inhabitants of the Earth to live in a world whose future is not compromised by the irresponsibility of the present*". A group of eminent specialists in international law and environmental law thus formed around her to propose a New Universal Declaration of Human Rights that *"serves present and future generations as well as Nature and the living world in general"*. The text was presented before the UN in April 2016 and has received signatures from about fifteen cities, bar associations from all over the world, NGOs, one state (the Comoros) and about fifty companies. It is not legally binding but has a strong symbolic and declarative value and can include constitutional provisions, as was the case for the Declaration of the Rights of Man and the Citizen of 1789. Yet, its implementation about the reduction of fossil emissions seems complicated.

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[51] (Green Climate Fund, 2021)
[52] (Vieweg & Noble, 2013)
[53] (Rassool, 2021)
[54] (Lepage, 2015)

"Geological Net Zero": An international agreement on fossil carbon

An approach that seems simpler to adopt and that corresponds more directly to the problem of fossil carbon, relying only on property rights, is proposed by Péter Szigeti[55]: any mineral contamination resulting from an extractive activity would generate the obligation to immobilize geologically and beyond the reach of surface biospheric agents equivalent quantities of contaminant. The advantage of this proposal is that it could be adopted by each country in a relatively simple way. **A resolution passed at COP26 recommending its adoption would be a useful lever**. Here is what Péter Szigeti proposes (personal communication):

The requirement to replace extracted fossil carbon with an equal amount of atmospheric carbon would arguably be the most important step towards a green (circular) economy. It could serve as a model for the entire economic and legal system, on its way to building sustainable circular economies.

Creating sustainable economic systems would certainly require transforming notions of personhood, ownership, and exchange,[56] harm and crime,[57] and many other fundamental concepts. Parts of this transformation are already underway. Several countries have recognized the personhood and rights of Mother Nature,[58] or of certain enduring features of the Earth such as forests,[59] mountains[60] or rivers.[61] The Dutch Supreme Court has judged that the Netherlands is acting in contravention of the right to life and the right to private life, family, and home, by not decreasing greenhouse gas emissions by at least 25% by 2021, compared to the 1990 baseline.[62]

The obligation to take back waste materials by primary producers has also been recognized under EU law.[63] A right to receive payment for environmentally beneficial effects stemming from specific land uses (or non-uses) has also been recognized, in New York State, Australia and Costa Rica among other places.[64] It is time to extend ecological protections even further.

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[55] (Szigeti, 2021)
[56] (Szigeti, 2021)
[57](Sands et al. 2021)
[58](Bolivia 2008; Ecuador 2008)
[59](Te Urewera Act 2014)
[60](Mount Taranaki Accord 2017)
[61](Salim v. Uttarakhand 2017; Columbian Constitutional Court 2016; Yarra River Protection Act 2017).
[62](Urgenda v. The Netherlands 2019)
[63](EU Directive 2012/19/EU ; EU Directive 94/62/EC)
[64](Salzman 2005)

5. Conclusions

Proposed geological net zero resolution:

For each quantity of fossil carbon extracted, the same quantity of carbon must be geologically sequestered in the same year.

This is to be achieved as soon as possible, consistent with a global carbon budget.

A supranational entity is to be formed and charged with supervising geological sequestration operations everywhere on the planet.

This could be done better than the IPCC and IEA best-case scenarios:

The fossil carbon source of global warming described as being like a fire at the beginning of this article could be smothered in less than 10 years by market-driven measures adapted to the geographical characteristics of the industrial players involved, the geological conditions of the fossil fuel deposits, and the methods and centers of geological carbon sequestration.

This could be done by implementing existing know-how and technologies, the effect of which could be accelerated by the emergence of new technologies and CCGS methods.

During this same period, it will also be possible to significantly reduce greenhouse gas emissions by adapting agricultural, livestock and forestry practices or by changing land use, as well as by reducing demand for fossil fuels through the decarbonization of transport, housing, and production methods.

By thinking in terms of the biogeochemical carbon cycle and setting up agreements that physically commit producers and buyers of fossil carbon to the quantities traded, it will be possible to direct investments towards strategic points in industry and business.

The result will undoubtedly allow warming to be limited to below the IPCC's most optimistic scenario!

This implies not polarizing the debate between fossil and non-fossil energy sources:

Only a geological solution can resolve the climate disequilibrium caused by the injection of fossil carbon into the atmosphere and the oceans. We have seen that the financial budgets to achieve this are of the same order as those envisaged for the energy transition to fully renewable energies and that they mainly require a reorganization and a redirection of the investments, taxes and subsidies that currently benefit the fossil industries. The resources and know-how of the current fossil fuel industries should not be discarded but redirected to deliver geological net zero.

It means adapting financial tools:

The world of finance must now invent new or promote existing the tools and make the proposals that allow the financial markets to reorganize towards these objectives. Implementation could be supported by the creation of a "Brown Climate Fund", driving the simplification of the complex web of existing taxes, subsidies, and fossil fuel financing, which would constitute a strong accelerator of transition.

We must resynchronize the rhythms of the economy with those of the Earth, to restore its natural metabolism:

Human activity has a strong impact on the biospheric carbon cycle, which is essential for life. The desynchronization that has existed since the start of the industrial era between human cycles and the Earth's natural cycles is manifesting its effects through climate disruption. Financial and economic tools must harmonize financial cycles, economic cycles, industrial cycles and natural (biogeochemical) cycles.

The ongoing energy transformation is a unique opportunity to re-establish a symbiotic relationship between the metabolism of human activities and the natural metabolism of the biosphere.

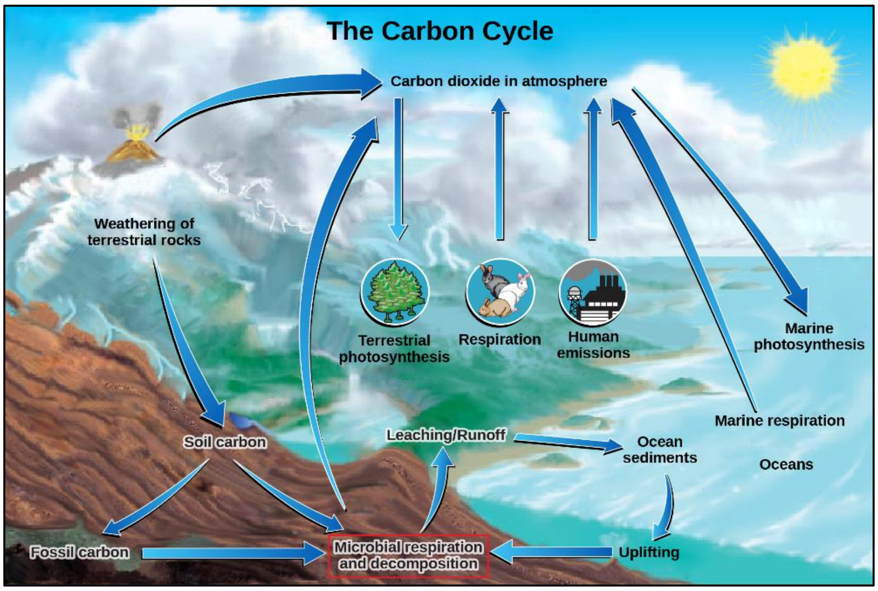

Figure 18 – THE END: back to the natural carbon cycle, the primary support for life - Source USGS

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