7 AFFORDABLE AND CLEAN ENERGY

Clean Energy Transition Challenge: The Contributions of Geology

Cristina Rodrigues, Henrique Pinheiro and Manuel Lemos de Sousa

1. Introduction

In order to discuss the global topic of the clean energy transition, it is essential that strategies by world decision makers are clearly understood. International agencies and European Union (EU) institutions have developed and implemented significant programs, as described below. The first European strategy on climate was developed in 1991 through the creation of the European Commission and Climate Program. Later on, in 1997, the Kyoto Protocol was designed, the main goal being to stabilize atmospheric concentrations of GHGs at a level that would prevent dangerous interference with the climate system. Since then, several initiatives have been promoted, such as the reports of the UNFCCC and the first (2000) and second (2005) European Climate Change Programmes, which included the need to identify the most environmentally and cost-effective policies and measures that would allow Europe to cut its GHGs, and to apply carbon capture and storage (CCS) technologies as part of the efforts. The agreements currently in force are as follows:

(i) In 2015, with the Paris Climate Agreement, a global political action plan was developed to put the world on track to avoid climate change, highly supported by the idea of keeping the increase in the global average temperature to well below 2 °C (or ultimately 1.5 °C) above pre-industrial levels. To reach this main goal, it was established that renewable energies should embody a higher share of the global energy matrix, as well as nuclear energy.
(ii) In 2019, the European Green Deal was established, with one of the main targets focusing on climate change, through actions to be developed by the EU. The use of "green hydrogen" and carbon neutrality are seen as priorities for a clean and circular economy.

Given the above context, one should ask how best to respond to the mentioned political agreements whilst taking into account the actual and forecast global and European energy demand, notwithstanding the fact that the world energy supply is, and will continue to be, highly dependent on fossil fuels, for both technological and economic reasons, at least in the short and medium terms. Accelerated, rapid innovation and invention will certainly be the catalysts in developing non-fossil fuel alternatives to energy production, so long as they are sustainable and affordable and can reduce the time frame for achieving the goals of clean energy and almost neutral emissions.

Consequently, in the authors' view, the need to implement the energy transition strategy, meaning to shift the global energy sector from fossil fuel based to zero-carbon energies by the second half of the 21st century, should be a main goal, allowing for growth in the global energy demand to continue whilst addressing climate change concerns and targets. The energy transition has to be implemented in a conscious and coherent manner in order to achieve the clean and circular economy concepts. This means that strong efforts in technology and policy are required, capable of turning non-fossil fuel energy production into competitive and sustainable economically viable sources. Therefore, analysis of the cost of climate change mitigation versus the cost of the energy transition is a must, given the costs of renewable energy solutions, and those of batteries and hydrogen energy (Nordhaus 2018).

If one accepts the general framework described above, and in order to accomplish the main goal of the Paris Climate Agreement, which is to reduce CO_2 emissions in order to keep the global temperature rise well below 2 °C (or even 1.5 °C), we insist that it is indispensable to use the contribution of geology in the application of carbon capture and storage, as well as in underground energy storage technologies, and to do so as soon as possible.

The main goal of this chapter is to discuss the energy and climate sectors, given the need to develop a workable international strategy for a clean energy transition by considering the contribution of geology in the application of carbon capture and storage, as well as in underground energy storage technologies, and to do so as soon as possible.

Energy transition is a well-known subject discussed at all climate and energy meetings. It is also one of the most controversial topics, and therefore an almost impossible mission in seeking to establish successful and acceptable international economic, technical, political and social measures. To better address the energy transition thematic, it is pertinent to highlight and to clarify several related subjects, which are discussed in the present manuscript. This approach begins with a general overview of the international energy and climate strategies implemented in recent decades, and the global and European decisions focusing on the politically binding and non-binding measures established to meet the greenhouse gas (GHG) reduction targets are also highlighted. In the second section, the topic of climate change is presented, with emphasis on the need to contextualize climate change in the geological evolution of planet Earth. The third topic addressed is the energy transition target in order to fulfill the current global energy demand. Finally, the role that geology can play, and will play, in the energy transition strategy is assessed, making it clear that this ambitious target will not be reached without a strong contribution from geology.

2. Overview on International Energy and Climate Strategies

The energy transition was recently established as one of the key solutions to climate change mitigation, which involves shifting from a system based on fossil fuels (oil, natural gas and coal) to one dominated by variable renewable energies. However, the starting point in discussing the energy transition topic goes back, at least, to 1979 with the First World Climate Conference held at Geneva (Conference of Experts on Climate and Mankind), where climate change was recognized as a serious problem. Rightly or wrongly, climate change is considered to be intimately related to the increase in GHGs, of which carbon dioxide (CO_2) is a constituent, despite its relevance, for example, to agricultural production (Dayaratna et al. 2020). CO_2 is acknowledged as playing an important role in the atmospheric temperature of the Earth, and therefore a CO_2 increase can contribute to a gradual warming of the lower atmosphere, especially at high latitudes. It is assumed that anthropogenic activity, including the exploitation and burning of fossil fuels, deforestation and changes in land use, has a fundamental role in the amount of CO_2 increase in the atmosphere and, consequently, in increasing GHG concentrations. The Declaration of the First World Climate Conference established a main goal "to foresee and prevent potential man-made changes in climate that might be adverse to the well-being of humanity" (WMO (World Meteorological Organization) 1979, p. 3). Additionally, it was also advised to implement efforts to reduce fossil fuels in the world energy matrix by including nuclear and renewable energies.

In the late 1980s and early 1990s, several intergovernmental conferences focusing on climate change occurred, in which both scientific and policy subjects were discussed, and the ultimate conclusion reached was the need to establish a global climate action plan.

In 1990, although established in 1988, the Intergovernmental Panel on Climate Change (IPCC) released its First Assessment Report, which scientifically confirmed the climate change issue, allowing governments to adapt their policy decisions. The Second World Climate Conference, also held in 1990, established a framework treaty on climate change, the final declaration of which did not specify any international targets for reducing CO_2 emissions, but a number of principles were defined that were included in the Climate Change Convention. The Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC) was approved later (December) in 1990.

Only in 1991 was the first European community strategy created on climate change, establishing the need to limit CO_2 emissions and to improve energy efficiency as main objectives. The specific action plan was as follows:

(1) To create a directive to promote electricity from renewable energy;
(2) To promote voluntary commitments by car markets to reduce CO_2 emissions by 25%;
(3) To propose taxation of energy products.

The United Nations Framework Convention on Climate Change (UNFCCC) was signed at Rio de Janeiro in 1992, which was established as the main international treaty on fighting climate change, in order to prevent dangerous human-made interference with the global climate system. A global agreement was required to implement UNFCCC strategies; therefore, in 1995, the first Conference of the Parties (COP1) took place in Berlin, and finally in 1997, in Kyoto (Japan), the Kyoto Protocol, an extension of the UNFCCC, was signed. Nevertheless, the Kyoto Protocol was only implemented in Montreal (Canada) in 2005, with the main goal to stabilize atmospheric concentrations of GHGs at a level that will prevent dangerous anthropogenic interference with the climate system. This was to be achieved by cutting GHGs to 5% below 1990 levels, by the 2008–2012 period. The Kyoto Protocol legally binds industrialized countries and economies in transition and the EU to emission reduction targets. Targets for the first commitment period (2008–2012) of the Kyoto Protocol covered emissions of the six main GHGs, namely CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6) (Wigley 1998). It was established that the Party's assigned amount is the maximum amount of emissions, measured as equivalent in CO_2, that a Party could emit during a commitment period.

The COP meetings continue to take place on a regular basis with the main goal to discuss, in detail, the rules for the implementation of the Kyoto Protocol by setting up new funding and planning instruments for adapting and establishing an outline for technology transfer.

As it is well known, the EU has long been committed to international efforts to reduce climate change and felt the responsibility to set an example through the creation of strong policies in Europe. To ensure the development of a comprehensive package of the most environmentally effective policies and measures to reduce GHG emissions, the EU established the European Climate Change Programme (ECCP). Two ECCP plans were developed in the period from 2000 to 2005. The first ECCP, established in 2000, was responsible for examining an extensive range of policy sectors and instruments with potential for reducing GHG emissions, by creating several working groups, namely, energy supply, energy demand, energy efficiency in end-use equipment and industrial processes, transport and research, among others, but the most important and innovative one was emissions trading. Each working group had to identify different options for reducing GHG emissions based on cost effectiveness, seeking the promotion of energy security and air quality as a final target. The second ECCP, launched in 2005, after four years of implementation of the first ECCP, aimed to further identify cost-effective options for reducing GHG emissions that would promote economic growth increase and job creation. Learning from the first period of the ECCP, when priorities allowed identifying five main working groups (energy supply, energy demand, transport, non-CO_2 gases and agriculture), it was possible in the second ECCP period to add new working groups, namely, aviation, CO_2 and cars, adaptation to the effects of climate change, reducing greenhouse gas emissions from ships and carbon capture and storage. In this second program, additional measures were taken, such as promoting the use of renewable energies in heating applications.

As it has become clear, the 21st century has been marked by new energy and climate challenges, in which the EU has played a leading role in identifying potential efficient solutions, although mainly political ones. The European energy/climate strategy has led to the development of several initiatives, namely, "Europe 2020" (EC (European Commission) 2007a), "European Strategic Energy Technology Plan (SET-Plan)" (EC (European Commission) 2007b), "Energy 2020: a strategy for competitive, sustainable and secure energy" (EC (European Commission) 2010), "The EU energy policy: engaging with partners beyond our borders" (EC (European Commission) 2011c), "Energy Roadmap 2050" (EC (European Commission) 2011b), "Directive on energy efficiency" (EC (European Commission) 2011a), "Guidelines for trans-European energy infrastructure" (EC (European Commission) 2011e) and "Smart grids: from innovation to deployment" (EC (European Commission) 2011d) (Rodrigues et al. 2015).

During this period, in order to ensure the security of supply and competitiveness and, at the same time, to promote decarbonization of the energy system, aiming at reducing GHG emissions, mainly CO_2, the EU identified and recommended six European industrial initiatives for implementation: wind, solar, bioenergy, smart grids, nuclear fission and carbon capture and storage (CCS) (EC (European

Commission) 2007b). It was then clear that to meet the goals of the "Limiting Global Climate Change to 2 °C: the way ahead for 2020 and beyond" (EC (European Commission) 2007a) report by reducing CO_2 emissions will not be possible without geological sequestration/storage (Rodrigues et al. 2015; D'Amore and Bezzo 2017). As a result, on 23 April 2009, the European Parliament and the European Council unveiled Directive 2009/31/EC (Directive on Geological Storage of CO_2) (EC (European Commission) 2009), in order to define a regulatory framework for geological sequestration/storage of CO_2 regarding the conditions to deliver "storage permits" proposed by the Kyoto Protocol (2005) whilst promoting the vision of global environmental integration. Nevertheless, it is pertinent to mention that over the years, COP negotiations have been quite controversial. In fact, the COP15 meeting, in 2009 at Copenhagen, was recognized as disappointing for several reasons:

(1) It failed to set the basic targets for reducing global annual emissions of GHGs up to 2050;
(2) It did not secure commitments from countries to meet the emissions targets collectively;
(3) The target agreement was not binding.

It is indisputable that the first period of the Kyoto Protocol (2008–2012) failed, due to deficiencies in the structure of the treaty, such as the time frame of the agreement and the choice to establish a five-year commitment period which would start ten years after being signed, the exemption of developing countries from reduction requirements and the lack of an effective progressive emissions trading system (Rosen 2015). It is well known that the Kyoto Protocol was condemned from the beginning, given that it did not include the world's largest and fastest growing economies, for example, China, which was excluded from binding targets, and the fact that the United States of America (USA) did not sign the agreement.

A second commitment period (2013–2020) to the Kyoto Protocol was agreed in 2012, in the so-called Doha Amendment (UN (United Nations) 2012). This amendment included new commitments for Annex I Parties to the Kyoto Protocol, a revised list of GHGs which included one more GHG (nitrogen trifluoride—NF3) and amendments to several articles of the Kyoto Protocol which needed to be updated. During the first period of the agreement, a 5% reduction in GHGs was established, but the second commitment period was really ambitious by establishing a reduction in GHG emissions by a least 8% below 1990 levels. Flexible market mechanisms were created in the second Kyoto Protocol period, which were based on a trade of emissions permits, namely, international emissions trading, clean development mechanisms and joint implementation by the Parties. As a matter of fact, the commitment period established by the second Kyoto Protocol agreement to meet the GHG emission reduction target was rather ambitious and too short, and when associated with the energy demand increase, it led to a new GHG emissions strategy. In fact, the main goal became the removal of GHGs from the atmosphere, even if GHG emissions are not reduced. In this perspective, these new mechanisms motivated GHG abatement techniques using the most cost-effective processes, such as CCS technologies (UN (United Nations) 2012).

The Paris Agreement, adopted at the Paris Climate Conference (COP21) in 2015, is the first international legally binding global climate change agreement set out to avoid dangerous climate change. This agreement was recognized as a key point between policies and climate carbon neutrality before the end of the 21st century, which implied reaching the following targets (UN (United Nations) 2015):

(1) To limit the increase in the global average temperature to well below 2.0 °C, or even 1.5 °C, above pre-industrial levels;
(2) To reach the global emissions peak as soon as possible, which has already been accomplished in Europe and North America but will, most likely, take longer for developing countries;
(3) To undertake a rapid reduction in emissions using the best available science knowledge to achieve an efficient balance between emissions and removals in the second half of the 21st century;
(4) To strengthen the ability of countries to deal with the impacts of climate change, through appropriate financial programs and new technology frameworks.

In 2019, the European Green Deal (EGD) was proposed to transform the EU into a modern, resource-efficient and competitive economy and therefore the world's first carbon-neutral continent by 2050. The action plan established by the EGD aimed to increase the efficient use of all resources by moving to a clean and circular economy, to restore biodiversity and to cut pollution. In fact, the EGD is not a law that will put all countries on track to achieve climate change goals, but one of its main targets is to propose a European Climate Law to transform this political commitment into a legal obligation through the revision of the EU Regulation (EU) 2018/1999 (EC (European Commission) 2020b). The EGD has been seen as a powerful tool to combine efforts to reduce GHG emissions and, at the same time, to prepare Europe's industry for a climate-neutral economy. In this perspective, hydrogen has been considered as a key priority for addressing both the EGD and Europe's clean energy transition (EC (European Commission) 2020a). The EU Hydrogen Strategy is seen as a prevailing strategy to increase electricity production from renewable energy, and since hydrogen does not emit CO_2, it can play an important role in decarbonizing the industry. However, this energy scenario change will not be an easy task, given that hydrogen energy represents a small fraction of the world energy matrix, and it is still largely produced from fossil fuels, mainly from natural gas and coal. Consequently, the main goal of the hydrogen strategy is to decarbonize hydrogen production and expand its use into sectors where it can replace fossil fuels. The EU proposed an additional program, the Digital Transformation (EU (European Union) 2021), which seems capable of accelerating the energy transition by making power-generating assets more efficient, through grid modernization processes that make the system more secure and resilient, and that assist the industry in providing sustainable and affordable power to final consumers.

Summarizing, the transition energy issue has been subjected to several approaches in recent decades, but it is an international consensus that countries are not doing nearly enough to transition to non-fossil fuel energy sources. Undoubtedly, it is quite a hard task to accomplish a net zero-carbon economy by 2050, and to keep the world temperature increase to 2 °C, or even 1.5 °C. However, it is pertinent to state that this 2 °C target was a political decision, perceived by the public as a realistically achievable and acceptable goal, but it was never clearly advocated and recommended as a safe level of warming through a scientific assessment (Knutti et al. 2015). Additionally, transition energy has negative implications for cohesion and social inclusion of all countries, since several regions (Eastern and Southeastern European countries) will be obliged to make great investments, while other countries (Western Europe and North America) will be encouraged to reduce carbon-intensive industries which will imply infrastructure adaptations. In conclusion, to reach net zero emissions by 2050, the EU needs to agree and ratify a consistent climate change strategy, with strong and rapid investments, which must be accompanied and supported by innovation in science and technology. In fact, several studies are in place that are focused on climate change mitigation, including understanding the influence (if any) of solar variability on surface air temperature (Soon et al. 2015).

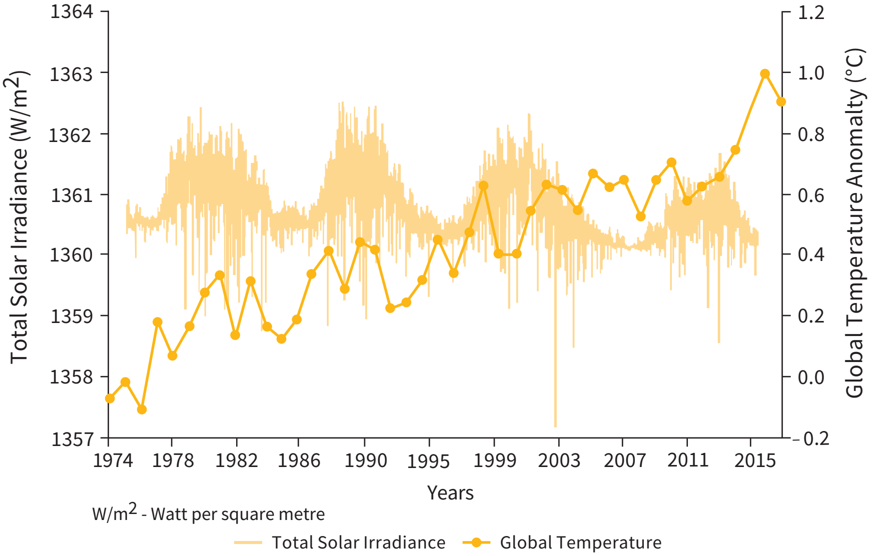
3. Climate Change: Is It the Problem?

As previously mentioned, climate change was identified as a serious problem back in 1979, during the First World Climate Conference, which was globally accepted as a result of the increase in GHG emissions. It was recognized that GHGs affected the energy balance of the global atmosphere, ultimately leading to an overall increase in the global average temperature.

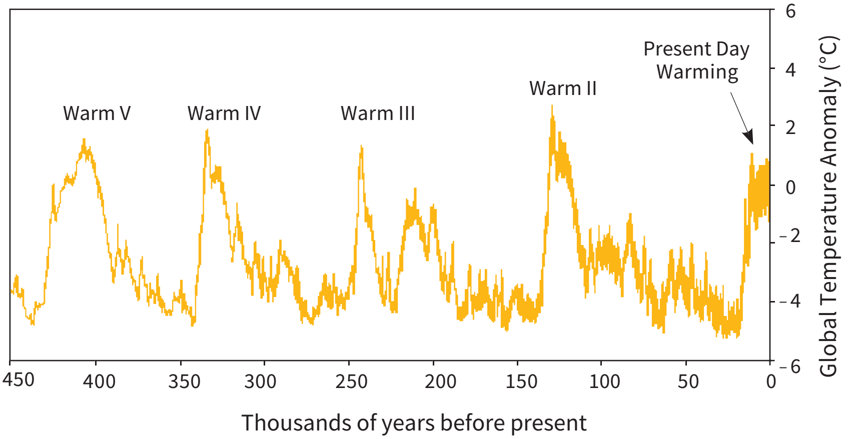
First of all, it is pertinent to clearly understand the concept of climate change used worldwide, and to accomplish that goal, the crucial role of two entities must be highlighted, namely, the UNFCCC and the IPCC. However, both entities have different approaches to the climate change definition, and, surely, this inconsistency in the concept is one of the main reasons for the international standoff on a climate policy, leading to a lack of decision making regarding updating policies on climate and energy strategies. The UNFCCC established that "climate change is directly or indirectly attributed to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (UN (United Nations) 1992, p. 3). The IPCC defined climate change as any change in climate over time, whether due to natural variability or induced by human activity (Rahman 2013).

The definition of climate change is a nontrivial and contentious exercise and, therefore, can be understood as the most complex and controversial question in the entire science of meteorology and climatology. In fact, several specialists (Allen 2003; Werndl 2016) argue that there are no strict criteria to justify the use of the expression climate change, and therefore its understanding remains unclear. As a result, the concept of climate change is often roughly employed and, consequently, may lead to considerable confusion regarding the existence and extent of global warming.

Undeniably, climate change means, a priori, a change in the statistical distribution of weather patterns in the long term, which may take place over decades (traditionally 30 years), but such changes and variations are typically studied over significantly longer periods of time, as shown through geological studies covering millions of years. In fact, the Earth's climate has changed in the course of the geological evolution, even before human activity could have played a role in its transformation. Thus, climate change consists of temporary changes in climatic conditions (temperature, precipitation and wind, among others), which can encompass changes in both average conditions and changes in variability. Since planet Earth's climate is naturally variable in the geological time scale, the long-term characteristics—specifically average temperatures—are controlled by the Earth's energy balance over time. In the last million years, the climate has naturally shown fluctuations between warm periods and glacial ages, which are strongly correlated with the natural Milankovitch cycles, established between 1920 and 1942 (Tarling 2010). According to Milankovitch, these oscillations are related to orbital changes, which, in turn, are controlled by three elements: eccentricity, obliquity and precession. These elements also have different periodicities, which affect not only the gravitational field of the Earth's surface but also the intensity and distribution of solar radiation that reaches the upper atmosphere. In this context, what is understood today as climate change, meaning changes produced by anthropogenic activities, is, from a geological time scale perspective, natural climate change (Figure 1). In fact, it appears that the role of human activity in the climate change increase can be addressed as a time scale-dependent subject (Figure 1).

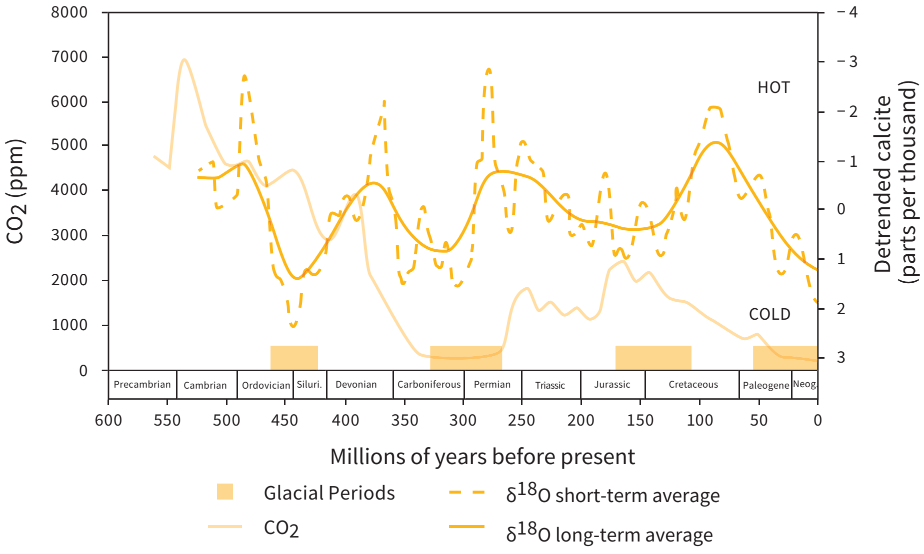


(a)



(b)

Figure 1. *Cont.*



(c)

Figure 1. Historical temperature of planet Earth: (**a**) 44-year interval (adapted from Augustin et al. 2004); (**b**) 450,000-year interval (adapted from Augustin et al. 2004); (**c**) 542,000-year interval. Source: Graphics by authors, adapted from Veizer et al. (2000), Berner and Kothavala (2001) and Moore (2019).

Herbert and Fischer (1986) and Park and Herbert (1987), by studying paleoclimatic periodicities in a geologic time series, stated “there is overwhelming evidence for cyclicity at about 2 cycles/m, corresponding to Milankovitch oscillations with periods near from 100 thousand of years” (Park and Herbert 1987, p. 14,037). This type of study will greatly improve our understanding of the role of orbital oscillations in climate change, and, consequently, it could help in defining a time scale which will allow measuring the components and their variability over short periods (Schwarzacher 1993; Giraud et al. 1995; Crowley and Berner 2001; Stenni et al. 2010).

In the present work, the concept of climate change is not addressed with the commonly fatalistic approach, where it is considered to be promoted by GHG emissions, these being responsible for an overall increase in the global average temperature; rather, GHG emissions are seen to correspond to local changes susceptible only to influencing the environment at the scale of humanity’s lifetime.

As it stands, one pertinent question arises: why is it that CO_2 is taken as the most dangerous GHG in the atmosphere? According to the Environmental Protection Agency (EPA), and other international entities (IPCC and UNFCCC), the most dangerous GHGs are CO_2, CH_4, nitrous oxide (N_2O) and fluorinated gases (e.g., chlorofluorocarbons, hydrochlorofluorocarbons). It is assumed that an anthropogenic source is responsible for almost all of the increase in GHGs in the atmosphere in recent centuries, mainly attributing CO_2 and CH_4 emission increases to general activities in the fossil fuel sector, whereas those of nitrous oxide and fluorocarbons to other human activities. Table 1 depicts some of the main characteristics of the major GHGs, in which it is quite perceptible that CO_2 is not the most dangerous GHG, since its lifetime can be a few days when it is quickly absorbed by the ocean surface, but some part will remain in the atmosphere for thousands of years; instead, CH_4 and N_2O have a more worrying lifetime average. Therefore, CH_4 plays a more negative role in the atmosphere than CO_2.

Additionally, Figure 2 shows that CH_4 concentrations (between ~300 and 800 ppmv) in the atmosphere have always been higher than CO_2 concentrations (between 160 and 300 ppmv)—actually, more than double. Yet, again, how are these two GHGs' emissions closely related to anthropogenic activities? Several studies using data going back 800,000 years in time, extracted from ice cores located at Dome C in Antarctica (Jouzel et al. 2003; Jouzel et al. 2007; Pol et al. 2010; Kang and Larsson 2013; Persson 2019), have shown what had been proposed by Herbert and Fischer (1986), meaning that consistent fluctuations in CO_2 and CH_4 concentrations exist, and these rising and falling CO_2 and CH_4 concentrations coincide with the onset of ice ages (low CO_2 and CH_4) and interglacial (warm) periods (high CO_2 and CH_4). Indeed, these periodic fluctuations are promoted by changes in the Earth's orbit around the sun, the so-called Milankovitch cycles (Figure 3).

A worrying scenario of an uncontrolled increase in CO_2 emissions due to anthropogenic activities, mainly related to the burning of fossil fuels, has been presented by the IPCC (Intergovernmental Panel on Climate Change) (2013). Actually, Figure 4 displays a common projection of the atmospheric CO_2 concentration measured during the last 800,000 years until the present day, showing that the last few years are clearly marked by a strong increase in the CO_2 concentration. Again, this fatalistic approach is related to the time scale used, 800,000 years, which is negligible from the geological scale point of view. Actually, taking into consideration Figure 1c, the time scale (800,000 years) used in Figure 4 could be understood as a "few minutes" from the geological scale perspective, and consequently, the approximately 4600 million years of planet Earth's evolution, which is intimately connected to the warm and cold periods identified by Milankovitch, is completely neglected.

Table 1. Major GHGs and their main characteristics.

GHG	Major Sources	Average Lifetime in the Atmosphere	Global Warming Potential	
			20 Years	100 Years
Carbon dioxide	Burning fossil fuels (oil, natural gas and coal), solid waste and trees and wood products; changes in land use; deforestation and soil degradation.	A few days to thousands of years	1	1
Methane	Production and transport of fossil fuels; livestock and agricultural practices, mainly rice fields; anaerobic decay of organic waste in municipal solid waste landfills.	12.4 years	84	28–36
Nitrous oxide	Fertilizers, deforestation, burning biomass.	121 years	264	265–298
Fluorinated gases	Industrial processes and commercial (aerosol sprays, refrigerants) and household uses, and they do not occur naturally.	A few weeks to thousands of years	Varies (the highest is sulphur hexafluoride at 15,000)	Varies (the highest is sulphur hexafluoride at 23,500)

Source: Table adapted from IPCC (Intergovernmental Panel on Climate Change) (2013).

It is now pertinent to mention the concept highlighted in 2013 by the IPCC (Intergovernmental Panel on Climate Change) (2013), "Climate Numerical Models", as well as "Earth System Models", which are embodied as the modern environmental and climate science approaches to enable a full understanding of natural systems and their sensitivities (Haywood et al. 2019; Voosen 2021). Different sources of uncertainties in climate change models have been reported, namely, anthropogenic and natural factors. Among the main anthropogenic factors are radiative forcing due to GHGs, and changes in population size and distribution, urbanization, energy system production and consumption and land use. The natural factors are mainly related to major volcanic eruptions, which can be responsible for the injection of small aerosol particles into the stratosphere, and changes in the radiation emitted by the sun (Giorgi 2010; Mitchell et al. 2020; Pielke 2020; Shaviv 2008). The IPCC (Intergovernmental Panel on Climate Change) (2013) stated that the concept of climate models is an attempt to assess the effects, risks and potential impacts associated with anthropogenic GHG emissions, which will allow scientific assessment of mitigation and societal adaptation strategies. Nevertheless, if the idyllic situation of immediately stopping CO_2 emissions were a reality, most of the warming and, consequently, its climate impacts would persist for many centuries. These irreversible changes are often misunderstood and are currently disregarded in most climate models. The irreversibility on time scales is at least hundreds of years, meaning that planet Earth is a multiparameter system in a dynamic equilibrium, and implying that climate change resulting from past emissions, even in the absence of future emissions, constitutes a global commitment for many future generations. Additionally, acknowledging that climate change will simply persist for centuries to millennia due to the long lifetime of CO_2 in the atmosphere is a key point in decision makers' strategies (Knutti et al. 2015).

Another relevant subject, commonly discussed on climate change forums, is the general rise in the sea level around the world (Figure 3). According to the IPCC (Intergovernmental Panel on Climate Change) (2013), the long-term effects of the global average temperature increase are responsible for the general rise in the sea level, resulting in the inundation of low-lying coastal areas and the possible disappearance of some island states, and the melting of glaciers, sea ice and Arctic permafrost. Actually, as already mentioned in this work, climate change corresponds to cyclic natural modifications, such as underwater volcanism, which significantly contributes to the overall increase in temperature, mainly in the oceans. In this regard, on the matter of underwater volcanism, it is worth emphasizing that a recent and remarkable scientific study, with the credibility of MIT (Huppert et al. 2020), although already discussed by others (Johnson et al. 2018), has highlighted what geologists empirically already knew, but that is now supported by rigorous geophysical observations and measurements. As is well known, volcanic islands do not last forever, and their longevity can differ significantly; for example, some islands such as the Canary Islands located in the Atlantic Ocean are more than 20 million years old, while the Galapagos Islands located in the Pacific Ocean have already drowned. Recently, it has been demonstrated that the formation and longevity of volcanic islands are intimately related to the movement of tectonic plates and their relationship with mantle plumes (hotspots). Nevertheless, to determine the actual age of each island, including those that have drowned, the direction and speed at which tectonic plates are moving in relation to the swell uplift underneath need to be measured, as does the length of each swell, which is formed when the mantle plume raises the seafloor. The unavoidable drowning of all volcanic islands over time is a natural phenomenon, which depends on the tectonic plate's speed and the size of the mantle plumes, and therefore it is not, in any way, related to an eventual rise in the sea level.

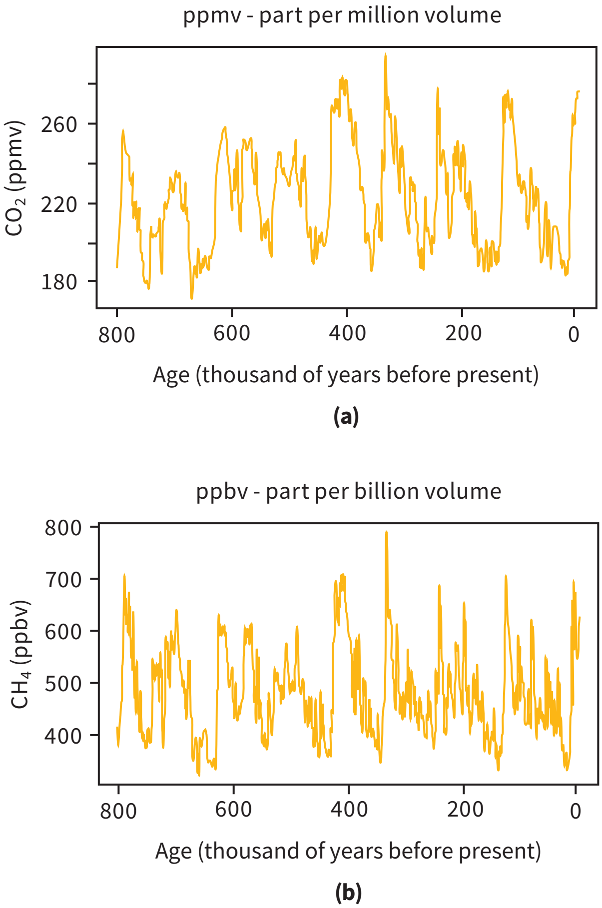


Figure 2. Atmosphere concentrations over the past 800,000 years before the present (1950): (**a**) CO_2; (**b**) CH_4. Source: Graphics by authors, adapted from Persson 2019.

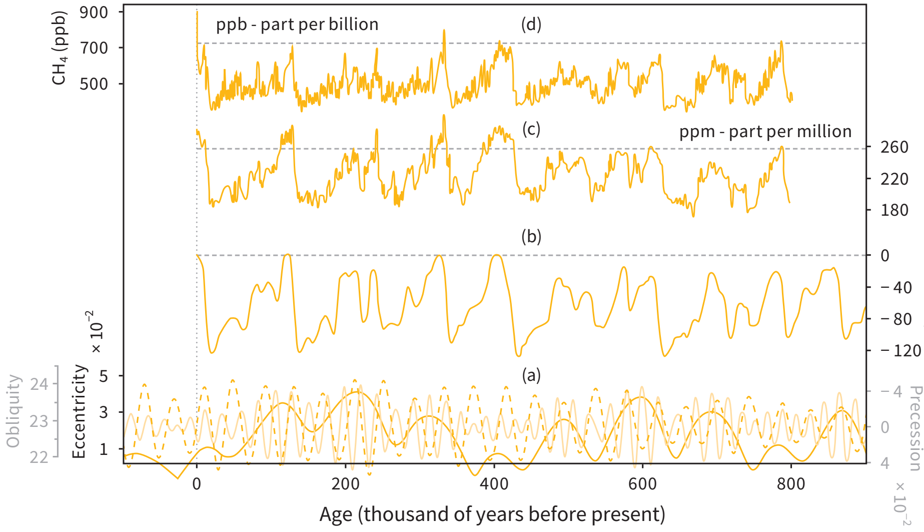


Figure 3. Variability over 800,000 years before the present (1950) of: (**a**) orbital parameters; (**b**) sea level; (**c**) CO_2 concentration; (**d**) CH_4 concentration. Source: Graphic by authors, adapted from Pol et al. (2010).

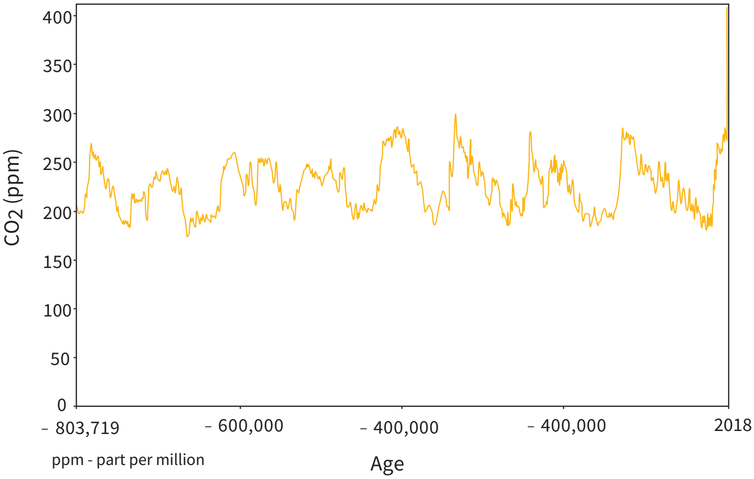


Figure 4. Atmospheric CO_2 concentration during the last 800,000 years. Source: Graphic by authors, adapted from Ritchie and Roser (2017).

One of the key mistakes made when dealing with climate change questions, and consequently the cause of worldwide controversial opinions, is the consideration that the climate change increase is due to anthropogenic sources, resulting from, above all, the use of fossil fuels (Giorgi 2010; Pielke 2020). Even if it is true that fossil fuel activities play a relevant role in the increase in GHG emissions and require mitigation, it is not true that they are the only cause, nor even the most dominant one. Be that as it may, in the second decade of the 21st century, questions related to climate change gained a greater acceptance by private and/or public entities, specifically as a result of the change in the definition or the perspective of the "climate change" concept. Actually, this change consists in a paradigm shift supported by the idea that climate change is no longer a cause of environmental degradation, but a requirement for sustainable development.

The Paris Conference (COP21) represents the culmination of the convergence of efforts of different players, with the main goal of reducing CO2 emissions, and therefore limiting the global average temperature increase, which will allow meeting the net zero GHG emissions target, in the second part of the 21st century.

4. Energy Transition and Energy Demand

In the Conference of the Parties meetings (COP22—Marrakech, COP23—Bonn, COP24—Katowice and COP25—Madrid) held after the Paris Conference (COP21, 2015), it was emphasized that the future of climate change mitigation involves the processes of decarbonization and energy transition. The urgent need to align the use of fossil fuels and climate goals was also recommended because a radical energy transition requiring a far more predominant use of renewable energies can never be achieved in the short and medium term. With the current state of knowledge, it is not even possible to imagine, in a sustainable (economic and technical) way, a world energy supply exclusively from renewable sources.

The energy transition is not only related to the production of renewable energy, with the main goal to replace fossil fuels in the world energy supply, but it is also seen (IPCC (Intergovernmental Panel on Climate Change) 2013) as a long-term investment opportunity that will transform the entire energy system over the next 30 years and beyond. This means that significant investments across the entire value chain are required, namely, in clean energy generation, transmission and distribution networks, energy storage and electric transport infrastructure.

The EGD (EC (European Commission) 2019) is a set of policy initiatives which combines the twin effort of reducing GHG emissions and preparing Europe's industry for a climate-neutral economy, to be conducted through the implementation of renewable energy sources. The EGD stands for a tech-driven energy revolution that will rapidly replace all hydrocarbons, and Kovac et al. (2021) went further by assuring that such an energy transition process is already being implemented. This unrealistic "new energy economy" scenario is confident that the technologies of wind and solar power and battery storage are undergoing innovative development in computing and communication technologies, to the extent that it will dramatically reduce costs and increase efficiency (Mills 2019). Given the intermittency of renewable energy sources, highly dependent on weather conditions and the number of hours of day light, energy storage has an essential role in the general energy transition framework.

In this context, the European Commission launched a new initiative entitled "A hydrogen strategy for a climate-neutral Europe" (EC (European Commission) 2020a). Hydrogen energy is, today, seen as a key priority to achieve the EGD and, consequently, Europe's clean energy transition. The relevant role of the new carbon-neutral system scenario is, evidently, related to the fact that hydrogen energy production does not emit CO_2, as it uses renewable energy sources, and that almost no air pollution is generated when it is used. Additionally, hydrogen energy can play a crucial role in the renewable energy storage sector, and it can be used as a feedstock, as a fuel, as batteries and in many other industrial applications, such as in the transport, power and building sectors.

However, how is hydrogen energy generated? Hydrogen energy is produced through a chemical process known as electrolysis, which uses an electrical current to separate the hydrogen from the oxygen atoms in water. There are different processes to produce hydrogen energy which are associated with a wide range of emissions, depending on the technology and energy source used, namely: electricity-based hydrogen (any type of electricity source); renewable hydrogen or clean hydrogen (renewable electricity source); fossil-based hydrogen (fossil fuel as an electricity source); fossil-based hydrogen with carbon capture (fossil fuel as an electricity source using carbon capture technologies); low-carbon hydrogen (any type of electricity source associated with fossil-based hydrogen with carbon capture); and hydrogen-derived synthetic fuels (gaseous and liquid fuels on the basis of hydrogen and carbon) (EC (European Commission) 2020a).

Presently, hydrogen represents a small fraction of the global and EU energy matrix, and according to IRENA (International Renewable Energy Agency) (2019), future projections on the breakdown of renewables used in the total final energy consumption in 2050 indicate that hydrogen energy will continue to account for only 3% (Figure 5).

Despite this reality check, for hydrogen energy to contribute to climate neutrality, it will need to achieve a far larger scale, and its production must be a fully decarbonized process, meaning that hydrogen must be generated from renewable hydrogen (clean hydrogen or green hydrogen) using electricity generated from renewable sources. In such a process, hydrogen energy is produced without emitting CO_2 into the atmosphere, with water vapor being the only emission. The renewable hydrogen process is quite complex, requiring the following requisites: (1) the water used must contain salts and minerals to allow electrical conductivity, and (2) two electrodes must be immersed in the water and connected to an electrical power source. Ultimately, the dissociation of hydrogen and oxygen atoms will occur when the electrodes attract ions with opposite charges.

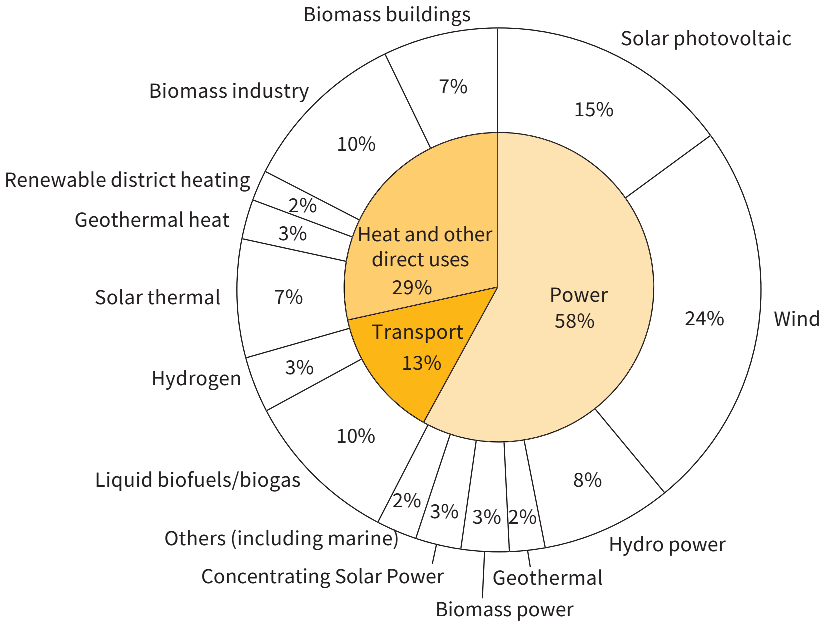


Figure 5. Breakdown of renewables use in total final energy consumption in 2050. Source: Graphic by authors, adapted from Gielen et al. (2019).

However, there are unavoidable questions about the viability of clean hydrogen relating its high production and storage costs (Figure 6), the difficulty of transport over long distances and the energy losses during conversion processes (Bossel et al. 2003), and, today, hydrogen energy is still largely produced from fossil fuels (Figure 7).

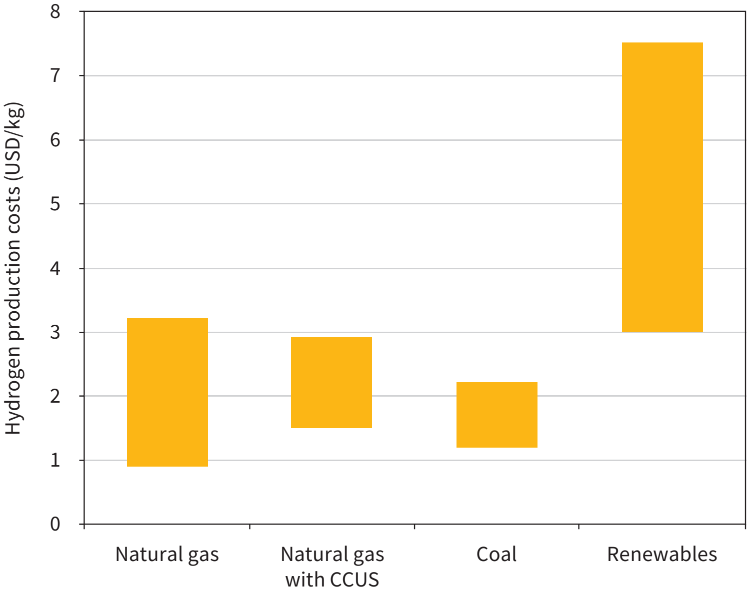


Figure 6. Hydrogen production costs by production source in 2018. Source: Graphic adapted from IEA (International Energy Agency) (2019).

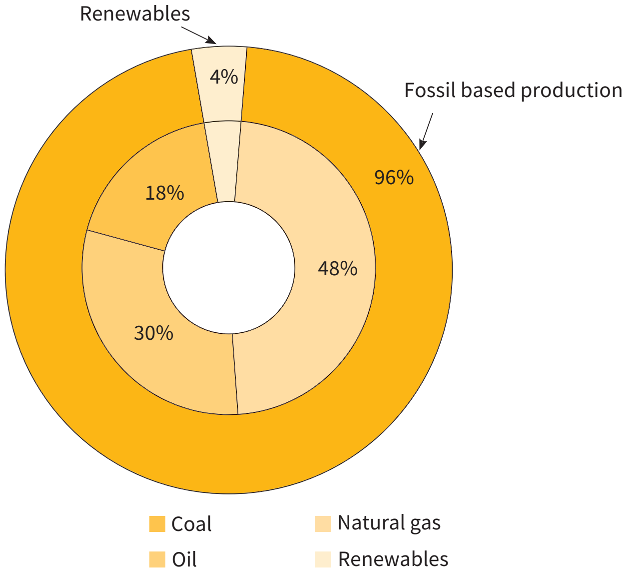


Figure 7. Hydrogen production by major sources. Source: Graphic by authors, adapted from Molloy and Baronett (2019).

Of the four major sources used for commercial production of hydrogen, three require fossil fuels: (1) steam methane reformation (SMR), (2) oil oxidation and (3) coal gasification (Figure 7), and therefore emit CO_2. These three processes are referred to as gray hydrogen production. Nevertheless, if the production of hydrogen is accompanied by CO_2 capture and storage, it is then referred to as blue hydrogen (EC (European Commission) 2020a). However, the effectiveness of CO_2 capture (maximum 90%) needs to be taken into consideration.

The fourth source is renewable electrolysis, generating so-called green hydrogen, the only process that does not emit CO_2 (Figure 8).

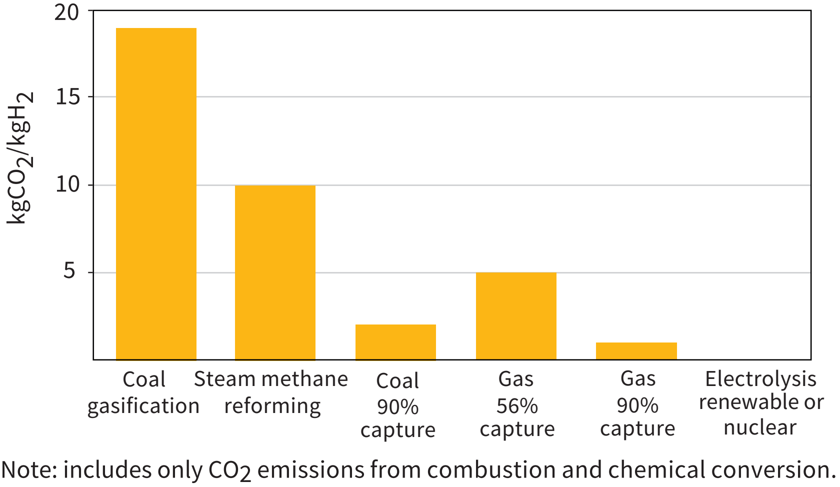


Figure 8. CO_2 emissions by hydrogen production process in 2019. Note: Includes only CO_2 emissions from combustion and chemical conversion. Source: Graphic by authors, adapted from Bartlett and Krupnick (2020).

In the extremely complex and high-cost scenario of the hydrogen sector, Germany aims for the European leadership in carbon capture and storage, and to produce hydrogen from natural gas, and has launched a new hydrogen strategy with a clear focus on green hydrogen production (BMWI 2020). To achieve carbon neutrality by 2050, Germany greatly relies on the energy transition strategy, keeping in mind that gaseous and liquid energy sources will continue to be an essential part of Germany's energy supply, with the expectation that hydrogen energy will play a key role in enhancing and completing the energy transition.

There is no doubt that, today, green hydrogen (renewable hydrogen) is not cost competitive against fossil-based hydrogen and, in particular, fossil-based hydrogen with carbon capture and storage, which is highly dependent on natural gas prices. The EC (European Commission) (2020b) stated that costs for renewable hydrogen are declining quickly and will continue to get cheaper, with the cost of the electrolysis process having already reduced by 60% in the last ten years. Therefore, there is an expectation that cost-competitive renewable hydrogen will eventually be achieved if accompanied by cost-competitive renewable energy.

In this optimistic scenario, where the generation of renewable energy will quickly become cheaper, the matter of intermittency comes to mind, as does the imperative need for cost-effective and reliable energy storage.

Schernikau and Smith (2021) highlighted the enormous difficulties and practical issues related to one source of renewable energy—solar photovoltaic panels. They focused on Germany as a case study and showed that supplying Germany's electricity demand entirely from solar photovoltaic panels (located in Spain, the optimal region for the production of solar energy due to the high direct normal solar irradiation), considering several adjustment factors (peak power, backup peak, transmission loss, winter capacity, etc.), would require a total area of approximately 35,000 km^2 (7% of Spain´s surface area) covered with solar photovoltaic panels. Such a scenario would equate to an installed capacity of 2000 GW, which is almost three times more than the worldwide capacity installed in 2020 (715 GW). In addition, one cannot ignore the fact that solar photovoltaic panels last, on average, 15 years and would require replacement every 15 years. Schernikau and Smith (2021) further estimated that the annual silicon and silver requirements for such a scenario would require close to 10% and 30% of the current global production capacity, respectively. This seems to be an unrealistic and unachievable scenario which will worsen once we add estimations of resource requirements for the production and installation of battery backup systems. Advancing this scenario to cover about 40% (200,000 km^2) of Spain with solar photovoltaic panels in order to supply the entire European electricity demand, as suggested by Schernikau and Smith (2021), how would all the energy produced be stored?

In fact, the EC (European Commission) (2020b) stated that energy storage is the key factor in promoting an increase in renewables into the global and EU energy matrix. Battery electricity storage has been established as a vital technology in the world' transition to a sustainable energy system, and its worldwide acceptance is also connected to specific advantages, namely, its fast response capability, sustained power delivery and geographical independence (Yang et al. 2018). Despite the major improvements in the battery sector, it seems that selecting the battery energy storage system sizing methodology, which is clearly dependent on the renewable energy system used, is the biggest challenge of the entire process. Given the difficulty for a single battery energy storage system to produce capable and reliable renewable energy independent of electricity provided through main grids, unless an oversized generator and storage capacities are utilized, new battery systems are being developed. Javed et al. (2020) proposed a hybrid pumped and battery storage (HPBS) system, in which "the battery is only used in order to meet very low energy shortfalls considering the net power deficiency and state of charge, while pumped hydro storage works as the main storage for high energy demand" (Javed et al. 2020, p. 1).

On the subject of batteries, how many would be needed to store the world renewable energy demand? The study by Schernikau and Smith (2021) was a realistic analysis of 14 days of energy storage backup for Germany during the winter period. For this period, Germany will require approximately 45 TWh of battery storage. However, producing the required storage capacity from batteries using current technology would require the full production of 900 Tesla Gigafactories, such as the Nevada Gigafactory (Mills 2019), working at full capacity for an entire year. Additionally, for the annual replacement of batteries, an extra output of 45 Tesla Gigafactories, corresponding to a full production of 2.25 TWh, will be required. To gain a general idea of what these numbers actually mean, the global battery production in 2020 was 0.5 TWh. Another key point on batteries is the future demand, and the rate of demand, for specific raw materials (such as lithium, copper, cobalt, nickel, graphite, rare earths, bauxite, iron and aluminum), leading to a dramatic increase in production, which would significantly affect the global mining sector. The mining chain comprises several processes from prospecting to extraction, transportation and processing, requiring significant amounts of energy. Mills (2019) suggested that the energy equivalent of 100 barrels of oil is required to produce a single battery that can store the equivalent of one barrel of oil. Additionally, today, natural gas accounts for more than 70% of the energy used to produce glass required to build solar photovoltaic planes, and if wind turbines are used to supply half the electricity in the entire world, 2000 Mt of coal would be required to produce the concrete and the steel needed to build the wind equipment (Mills 2020), knowing that the annual production of coal in 2019 was approximately 8000 Mt (IEA (International Energy Agency) 2020). Therefore, how will the clean energy system process work if a dramatic increase in the production of raw materials is required to produce green energy, which in themselves have negative environmental and health impacts, with high amounts of energy being required, which actually originates from fossil fuels?

Despite all the production issues related to battery systems, it is obvious that the raw materials required to produce battery storage systems will soon dominate the global production of minerals. In fact, today's production of lithium batteries already accounts for about 40% of all lithium and 25% of cobalt, meaning that, in the near future, global lithium mining would have to expand by at least 500% (Mills 2019). This analysis leads to another essential question—does planet Earth have enough raw materials to fulfill the production of batteries that the market will demand? The study by Schernikau and Smith (2021) clearly assists in answering this key point, by using the Germany case study. As mentioned, a 14-day battery storage solution for Germany would imply 45 TWh of battery storage production, using Tesla's newest technology, and consequently a 7000–13,000 Mt demand for raw materials. Battery replacement would require a capacity production of 2.25 TWh, implying a 400–700 Mt demand for raw materials. For example, 1,800,000 t of lithium production would be needed, knowing that the 2020 global production was 230,000 t, meaning feeding Germany's battery storage systems would require a lithium supply which is 5.6 times greater than the current global production (Figure 9). In the case of cobalt, another essential mineral used in the production of batteries, 225,000 t of cobalt production would be required, but the current global production is about 120,000 t, meaning Germany's battery storage production would demand 1.9 times more than the 2020 global production (Figure 9). To conclude on this matter, considering the current global production of raw materials, the Germany case study clearly demonstrates that the use of renewables, in the form of solar photovoltaic panels and/or wind energy, is a rather unrealistic solution for Germany or for the world—simply put, the rate of demand for raw materials, coupled with the energy demand that goes with their extraction and processing, current technology and the immediate environmental impact typically associated with mining and processing, is totally impractical and unaffordable, especially given the time frame proposed by international organizations such as the EU and the IPCC (Table 2).

Table 2. Global reserves of most important raw materials by country.

Country	Reserves			
	Cobalt (kt)	Lithium (kt)	Nickel (kt)	Graphite (kt)
Argentina		2000		
Australia	1100	1500	19,000	
Brazil	78	48	10,000	72,000
Canada	240		2900	
Chile		7500		
China	80	3200	3000	55,000
Colombia			1100	
Cuba	500		5500	
Democratic Republic of the Congo	3400			
Guatemala			1800	
India				8000
Indonesia			4500	
Madagascar	130		1600	940
Mexico				3100
New Caledonia	200		8400	
Philippines	250		3100	
Russia	250		7900	
South Africa	30		3700	
Turkey				90,000
United States of America	23	38	160	
Zambia		270		
Zimbabwe		23		
Other countries	610		6500	960
World total	7000	14,000	80,000	230,000

Source: Table adapted from EC (European Commission) (2018).

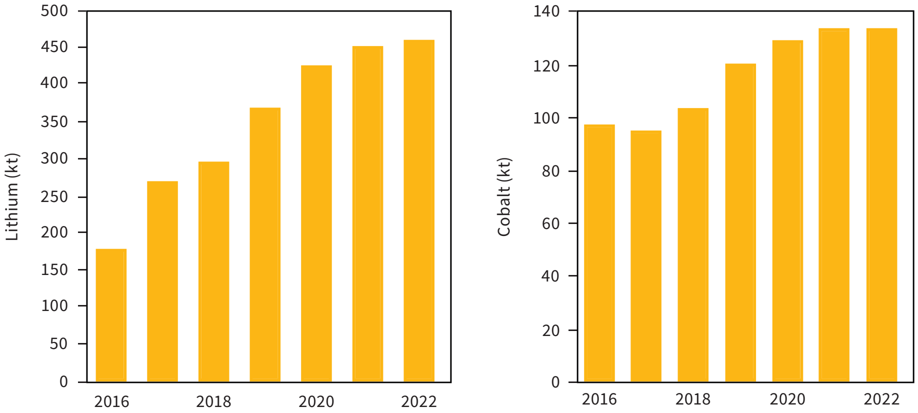


Figure 9. Lithium and cobalt global production from 2016 until 2022. Source: Graphics by authors, adapted from Metso: Outotec (2021).

Ultimately, the world needs to sustain its energy supply and growth while significantly reducing emissions, and the following question remains: how can this be achieved when world energy consumption continues to increase as a result of population increase, industrialization and improved quality of life?

A 30% increase in world energy consumption is expected between 2014 and 2035, mainly related to the rapid growth of emerging economies, amongst which China and India account for half of this increase (Figure 10). Yet, an apparent mistake is consistently made, intentionally or not: that of discussing the global energy matrix based on the EU and/or the USA case studies, relegating the rest of the world, its populations and, above all, its energy needs and development rights to an obscure platform.

International policies, as well as the targets established in international treaties, namely, the Paris Agreement, play a very powerful role in the evolution of the world energy sector and may even cause real deviations in the evolution of the global energy matrix. In the current energy scenario (Figure 11), it is clear that fossil fuels will continue to play an important role in the global energy matrix. GECF (Gas Exporting Countries Forum) (2017) still projects that approximately 75% of global primary energy consumption will be met by fossil fuels (oil, natural gas and coal) in the year 2040, despite a decrease of 6% being projected between 2014 and 2040. There are expectations that a substantial increase in nuclear and renewable energies will occur, corresponding to approximately 25% of the world energy matrix. Renewable energies are the primary energy sources with the highest growth, from 13% in 1990 to 18% in 2040. Despite this promising renewable energy scenario, direct use of fossil fuels is, and is expected to remain, the dominant energy source in the modern world. Mills (2019) suggested that in order to completely replace fossil fuels over the next 20 to 30 years, knowing that half a century was needed for global oil and gas production to expand by 10-fold, global renewable energy production would have to increase by at least 90-fold, and this is an unrealistic proposition even when substantial financial efforts are involved. It is therefore quite obvious that the global energy demand will not allow the Paris Agreement targets to be met, especially with the current energy and climate strategies, which lack binding agreements and carbon markets, as with those proposed in the Kyoto Protocol.

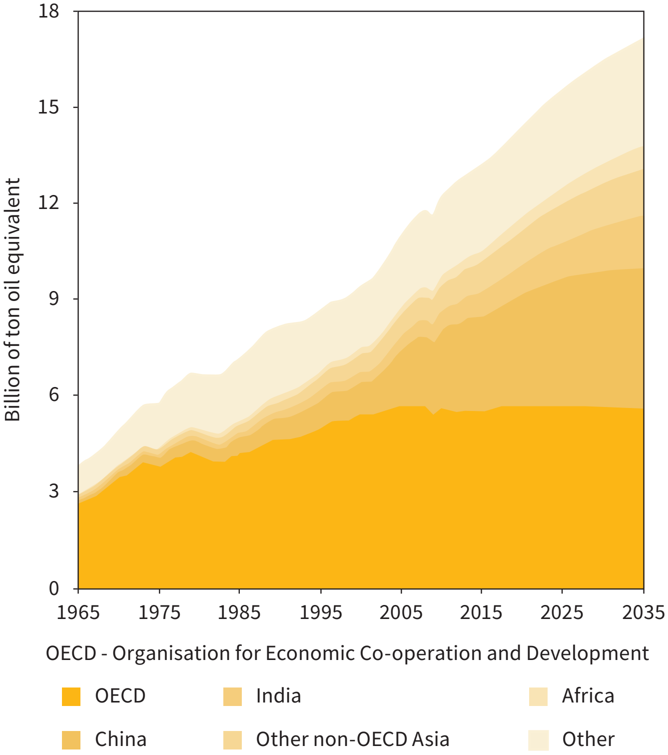


Figure 10. World energy consumption by region. Source: Graphic by authors, adapted from BP (British Petroleum) (2017).

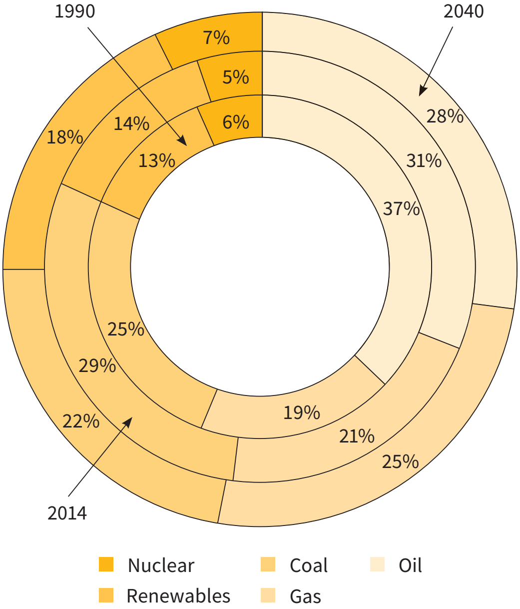


Figure 11. Evolution of shares of global primary energy, between 1990 and 2040. Source: Graphic by authors, adapted from GECF (Gas Exporting Countries Forum) (2017).

Returning to the IEA's assumed goal to achieve net zero CO_2 emissions by 2050, we are of the view that, even with the enormous financial and technological efforts that are continuously made, it is unlikely that total decarbonization of the energy sector in the envisaged timespan will be achieved. In fact, full decarbonization of the energy sector would imply an urgent and rapid deployment of available technologies, but above all, worldwide use of technologies that are not on the market yet. These new technologies are mainly related to battery storage systems, hydrogen electrolyzers and direct air capture and storage systems (IEA (International Energy Agency) 2021). As previously mentioned, there is still much to be conducted in the implementation process of new technologies, from the availability of raw materials to energy efficiency and cost competitiveness. For the implementation of new technologies, three main scenarios on global CO_2 emissions have been proposed and projected, namely, business-as-usual, rapid transition and net zero (BP (British Petroleum) 2020). Additionally, BP (British Petroleum) (2020) and IEA (International Energy Agency) (2021) stated that the global CO_2 emissions peak has already been reached (Figure 12), mainly due to the impact of COVID-19, and they will not return to their pre-pandemic levels. Nevertheless, it is important to keep in mind that the previous projections are significantly different from these new proposals; actually, BP (British Petroleum) (2017) projected an increase in global CO_2 emissions of 13% between 2014 and 2035 (Figure 13), which is far from the targets of achieving a 30% reduction by 2035, as proposed by the Paris Agreement.

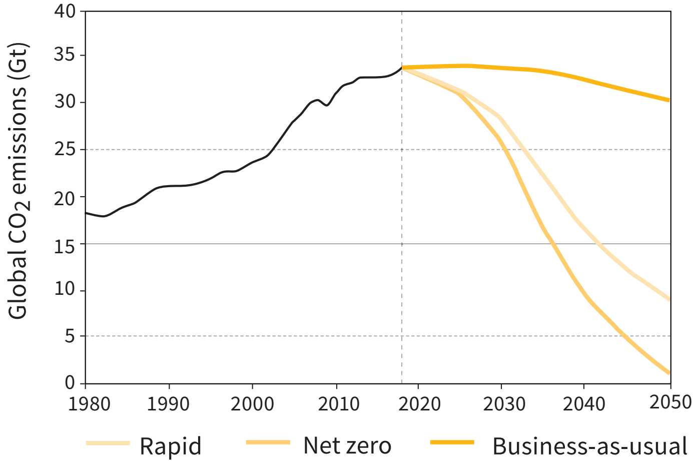


Figure 12. Global CO_2 emission scenarios. Source: Graphic by authors, adapted from BP (British Petroleum) (2020).

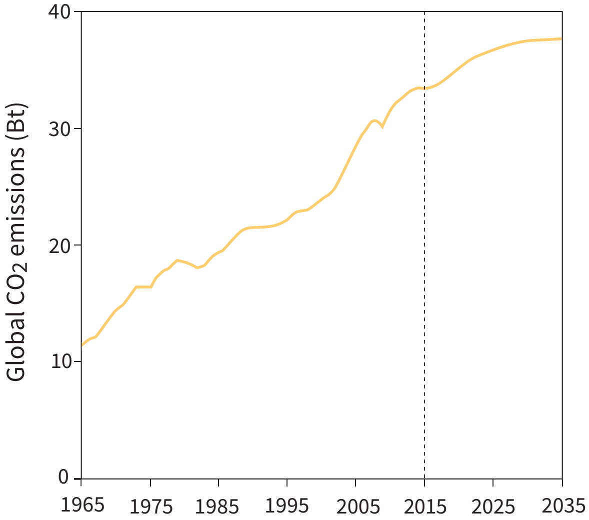


Figure 13. Global CO_2 emission projection. Source: Graphic by authors, adapted from BP (British Petroleum) (2017).

The three CO_2 emission scenarios presented by BP (British Petroleum) (2020) are supported by differences in economies, energy policies and social preferences. One main subject that has been discussed since the Kyoto Protocol is the establishment of carbon prices and, consequently, the carbon market. The business-as-usual scenario assumes carbon price increases of USD 65/t in developed countries and USD 35/t in emerging countries by 2050. Instead, both the rapid transition and net zero scenarios assume a substantial increase of USD 250/t in developed countries and USD 175/t in emerging economies by 2050.

The business-as-usual scenario corresponds to the global CO_2 emission projection if government policies, technologies and social preferences continue working in the usual way, as seen recently. In this scenario, projections address CO_2 emissions above 30 Gt in 2050, showing a slight decline of 10% between 2020 and 2050, which is far from the carbon-neutral target established by the European Commission.

The rapid transition scenario is based on a series of policy measures, led by a significant increase in carbon prices and supported by more targeted sector-specific measures, such as a significant shift away from traditional fossil fuels to non-fossil fuels, led by renewable energy, in order to achieve a more diversified global energy matrix (Figure 14). This rapid scenario projection suggests a 70% decline by 2050, which is consistent with the Paris Agreement targets of limiting the rise in the global average temperature to well below 2 °C above pre-industrial levels (Figure 12).

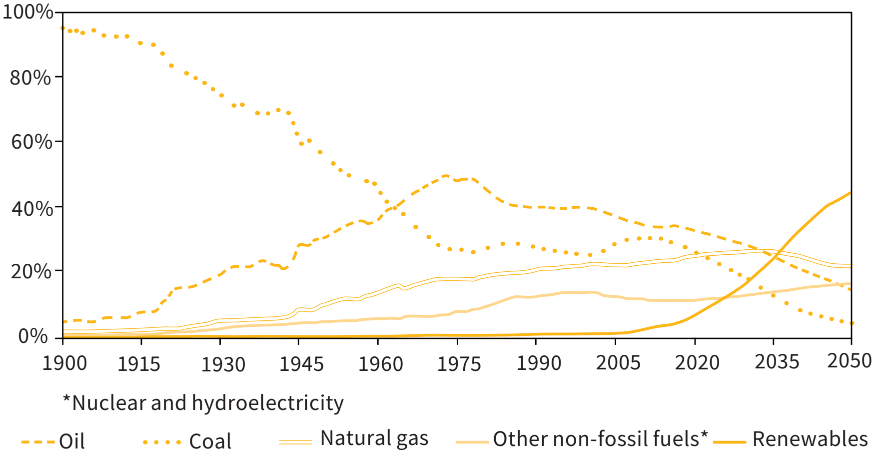


Figure 14. Shares of primary energy in the rapid transition scenario. Source: Graphic by authors, adapted from BP (British Petroleum) (2020).

The net zero scenario assumes that the policies in the rapid transition scenario are reinforced by significant shifts in social behaviors and preferences. Nevertheless, this scenario believes that an accelerated energy transition cannot be achieved based only on government policies, and that binding strategies need to be established. The net zero scenario suggests a deep decline by over 95% in global CO_2 emissions by 2050, which will allow meeting the global average temperature rise of well below 1.5 °C above pre-industrial levels.

At this moment, it is quite obvious that achieving a carbon-neutral energy system by 2050 will be a challenging task, requiring enormous efforts by all stakeholders, spanning social, economic, political and technological points of view. From the technological perspective, besides developments in new energy systems, it is undeniable that carbon capture and geological storage, so-called CCS technologies and specifically carbon capture utilization and storage (CCUS) technologies, must be included, as suggested by the Paris Agreement, as one of the potential solutions to meet the targets of carbon neutrality by 2050.

5. Geology Contribution to an Efficient Energy Transition

The contribution of geology on the path to achieving an efficient energy transition has different approaches. The first and inherent approach deals with the important role that geology plays in understanding climate change in the general context of planet Earth's evolution, which will offer potential tools to calibrate our future climate models. Three other major geological "contributors" are directly linked to reducing GHG emissions in this overall energy transition framework, namely, (1) mineral raw materials to build renewable energy equipment, (2) underground geological structures for hydrogen storage and (3) underground geological storage structures for CO_2 abatement.

The main target of the energy transition is to shift energy production from fossil fuels to non-fossil sources, meaning that the ultimate goal is to base the global energy matrix on CO_2-free energy sources. These CO_2-free energy sources and technologies, such as wind, solar, biomass or geothermal, require the exploration and exploitation of mineral raw materials for their deployment, with the obvious and often seriously detrimental consequences of the environmental impacts. Additionally, raw materials are not only needed for the construction of renewable energy equipment, such as solar photovoltaic panels and aeolian turbines, but also for building battery energy storage systems, considering the variability and intermittency of renewable sources.

Another important contribution from geology is related to the need for energy savings and efficiency, commonly associated with hydrogen energy production, which can be achieved by managing the heat and cold demand using underground storage structures (Dalebrook et al. 2013). Hydrogen energy is considered the key priority of carbon-neutral energy systems, due to its regenerative and environmentally friendly features. Nevertheless, hydrogen energy has two major inherent problems: its production and storage. Hydrogen energy production is complex, and it is not a cost-competitive energy, which must be produced from water or even hydrocarbons (Dalebrook et al. 2013). Hydrogen has a low critical temperature of -251.15 °C, meaning that hydrogen is a gas at ambient temperature and atmospheric pressure; therefore, its storage implies a reduction in an enormous volume of hydrogen gas (Züttel 2003). Despite the significant issues in hydrogen production, hydrogen storage in large quantities is arguably the most challenging part of the entire hydrogen energy chain. Hydrogen storage in itself is not the main problem, a subject already addressed by several authors in recent decades (Yartys and Lototsky 2004; Zhou 2005; Niaz et al. 2015), and six different methods have already been sufficiently implemented, namely, (1) high-pressure gas cylinders (up to 800 bar), (2) liquid hydrogen in cryogenic tanks (at -252.15 °C), (3) adsorbed hydrogen on materials with a large specific surface area (at -173.15 °C), (4) absorbed hydrogen on interstitial sites in a host metal (at ambient pressure and temperature), (5) chemically bonded hydrogen in covalent and ionic compounds (at ambient pressure) or (6) oxidation of reactive metals (e.g., Li, Na, Mg, Al, Zn) with water, and hydrogen is already stored in underground salt cavities in the UK and the USA. Nevertheless, the hydrogen storage issue can be avoided when hydrogen production is supported by fossil-based hydrogen processes, namely, blue and gray hydrogen processes, usually reflecting an efficient alignment between production and consumption, where production occurs at the site of an industrial consumer, and usually where significant hydrogen storage is not required. The main issue is the large-scale storage of hydrogen commonly required for green hydrogen production, which is powered by intermittent renewable energies. For storing temporally large volumes of renewable energy surplus, geological options probably have the lowest cost and represent the best solution (Schoenung 2011; Heilek et al. 2016; Tarkowski 2017; Andersson and Grönkvist 2019; Karakilcik and Karakilcik 2020). Four specific geological options have been evaluated: salt caverns, depleted oil fields, depleted gas fields and deep saline aquifers. In fact, these geological options are commonly used in technological processes of CO_2 abatement, which will be discussed later in this section. Figure 15 shows a scheme for hydrogen production and storage when using 100% renewable energy sources.

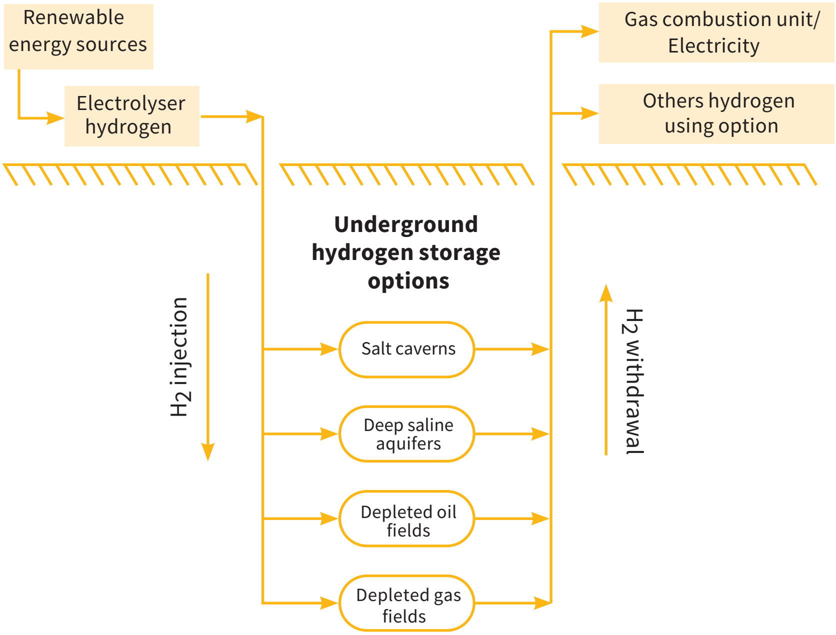


Figure 15. Renewable energy system scheme with an underground geological hydrogen storage facility. Source: Graphic by authors, adapted from Tarkowski (2019).

Salt caverns, which are built in underground salt domes, are the most mature option for geological storage facilities for hydrogen (Ozarslan 2012; Lemieux et al. 2020; Liu et al. 2020). Several advantages are attributed to salt caverns, such as their storage efficiency given that only a small fraction of the hydrogen injected is unable to be extracted from the geological structure, their lack of contaminants and, lastly, one of the most crucial advantages, their high-pressure operating systems, enabling a rapid discharge when hydrogen is needed (IEA (International Energy Agency) 2019). In this context, large-scale underground geological structures will play a crucial role in the hydrogen energy economy as integrated power plants with grids that rely mainly on renewable energy sources.

The last geological contribution, and perhaps the most controversial in recent years to reduce GHG emissions, mainly CO_2, is represented by CCS technologies (Figure 16). CCS technologies (Bui et al. 2018) were well studied at the beginning of the 21st century, resulting in several well-established geologic screening criteria for "pure" sequestration/storage of CO_2. As previously mentioned, a European regulatory framework for geological sequestration/storage of CO_2 (Directive 2009/31/EC, Shogenova et al. 2014) was defined in 2009. Directive 2009/31/EC was prepared for pure sequestration solutions in deep saline aquifers, and it was rapidly understood that they could be one of the largest potential technical storage solutions to reduce CO_2 emissions (Celia et al. 2015; Khan et al. 2021), but economically unviable, mainly due to the lack of investor-motivating measures.

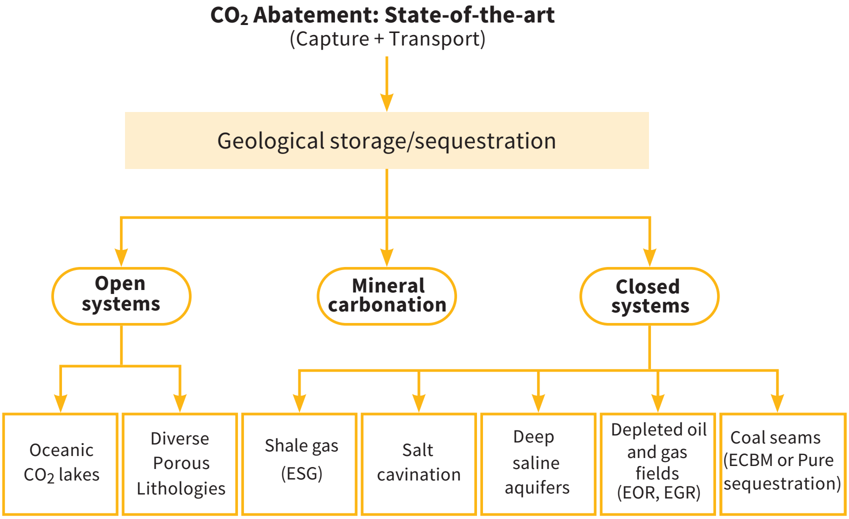


Figure 16. Geological storage solutions for CO_2 abatement. Source: Graphic by authors, adapted from Lemos de Sousa et al. (2008).

The subject became so important that the European Commission requested the European Academies Science Advisory Council (EASAC) to address the subject of carbon capture and storage in Europe (EASAC (European Academies Science Advisory Council) 2013). A similar important concern was developed by Chinese experts (Jiang et al. 2020). It became clear that to address CCS technologies, the key point would be to transform these technologies into an effective economic approach (D'Amore and Bezzo 2017; Kapetaki and Scowcroft 2017; Shogenova et al. 2021). The term "CO_2 utilization" was seen as the obvious solution, which allowed for the definition of three main categories: CCUS—hydrocarbon resource recovery, CCUS—consumptive applications and CCU—reuse (non-consumptive) applications (CSLF (Carbon Sequestration Leadership Forum) 2012).

In CCUS—hydrocarbon resource recovery (EOR), CO_2 is used to enhance hydrocarbon (oil and gas) production, which may partly compensate for the initial cost of CCS and contribute to the implementation of long-term CO_2 storage in other geological facilities, such as deep saline aquifers. The CCUS—consumptive applications involve the formation of minerals, also designated as mineral carbonation, which results in CO_2 storage by "locking up" the carbon component in the structure of the new mineral formed. In CCU—reuse (non-consumptive) applications, the temporarily stored CO_2 is also not directly consumed, and instead, the CO_2 is reused or used only once while generating some additional benefit.

Additionally, in 2015, the Paris Conference (COP21) highlighted that CCS is one of the key promising technologies that can effectively contribute to reducing CO_2 emissions in the power generation sector, even if CO_2 utilization options are used.

Nonetheless, in this section, the main goal is to highlight the role of geological sites in reducing CO_2 emissions, and in such cases, those that allow for CO_2 utilization. Therefore, considering the geological solutions for CO_2 abatement that are presented in Figure 16, four main groups can be identified, namely, (1) depleted oil fields (CO_2 enhanced oil recovery—CO_2-EOR), (2) CO_2 enhanced gas recovery (CO_2-EGR), (3) shale gas reservoirs (CO_2 enhanced shale gas—CO_2-ESG) and (4) coal seams (CO_2 enhanced coalbed methane—CO_2-ECBM). There are several key criteria for CO_2 storage projects that must be reached, which are different for each of the geological solutions but supported by the same general assessment procedures, namely, risk assessment; monitoring, reporting and verification requirements; reservoir simulations; accounting for the amount of CO_2 that can be stored; post-injection monitoring and site closure; economics evaluation; social context analysis; and legal and regulatory issues (Ajayi et al. 2019; MRI (Mitsubishi Research Institute) 2020). Certainly, the amount of CO_2 that can be stored in a geological site is one of the most important criteria in the whole key criteria list; thus, in this context, coal seams could play a major role in the CCUS technology framework.

Coal is a porous medium reservoir characterized by a unique organic microstructure, which allows for a CO_2 storage volume that is much higher than its pore volume capacity (Rodrigues and Sousa 2002), due to its adsorbed inherent features. The dominant adsorption characteristics of coal mean that CO_2 is mainly stored in the internal surface area of pores, in a condensed form, which is very close to the liquid state. Therefore, reservoirs characterized by organic microporous media signify higher internal surface areas and, consequently, higher storage capacities (Rodrigues et al. 2015). The main attribute that justifies coal as the better storage site option and, at the same time, the most permanent and secure solution for CO_2 storage in the medium–long term is its high organic matter content (greater than 50% in weight) (ISO 11760 2005). Besides the CO_2 storage capacity, the CO_2 injectivity rate is also a relevant criterium to select a geological site. The low CO_2 injectivity of a coal seam, due to its low permeability (usually lower than 5 millidarcy—mD), is undeniably an unfavorable key parameter suggesting not to use ECBM as the most economically viable CCUS technology.

CO_2-EOR projects have the largest potential of the various CO_2 utilization options, and they are the most used to date. In fact, they have been used on a commercial scale since the 1970s, totalling more than 100 commercial and pilot/demonstration projects (Ajayi et al. 2019). Yet, due to amazing improvements in the shale gas sector in recent years (Soeder and Borglum 2019), it is possible to consider CO_2-ECBM as an economically viable solution for CCUS technologies. These improvements are intimately related to horizontal drilling technologies, which involve a special form of directional drilling, typically through a formation at a well inclination of 90° from the vertical, using air hammers with rotation, and with directional control by means of bent housing motors. The well is drilled vertically until the reservoir's calculated depth is reached, and then the well is drilled to turn at an angle that is steadily increased until the well becomes parallel with the reservoir (Jiang et al. 2017; Guo et al. 2018). The long laterals of horizontal wells increase the reservoir–well contact, allowing for significant improvement in the reservoir's CO_2 injectivity and therefore in hydrocarbon production, which avoids the commonly but extremely expensive multi-well drilling approach used in the past.

Over the years, CCS technologies have been applied worldwide to both CO_2 pure sequestration and to CO_2 utilization. Nevertheless, due to the costs involved in the entire process, the most implemented type has been the CCUS technologies. According to the Economic Forecasting and Policy Analysis (EPPA) model developed by the Massachusetts Institute of Technology, which takes into account several pre-requisites to perform the assessment of storage capacity (MRI (Mitsubishi Research Institute) 2019), the word's total accessible geological CO_2 storage capacity is estimated to be between 8000 and 55,500 Gt, depending on the estimation scenario. The EPPA model includes the implementation of several CCS technologies, from CO_2 pure sequestration to CO_2 utilization projects. Considering the pre-requisites needed to address an efficient assessment of a site storage capacity, eighteen regions were selected for the model (Table 3). This model presents two distinct approaches: (1) a lower estimation, where a storage capacity factor of 0.037 Gt of CO_2 stored per 1000 km^3 of the sedimentary basin is used, and (2) an upper estimation, where a storage capacity factor of 0.26 Gt of CO_2 per 1000 km^3 of the sedimentary basin is used. Therefore, this EPPA model, taking into consideration the annual global CO_2 emission projections proposed by BP (British Petroleum) (2020), which stated that the global

CO_2 peak was reached in 2020, with annual total CO_2 emissions of approximately 35 Gt (Figure 12), implies that in the lower estimation scenario, the global storage capacity will be able to store the emitted CO_2 for approximately 228 years, and in the upper estimation scenario, CO_2 abatement through CCS technologies would take place over approximately 1585 years.

CCS technologies seem to be a plausible option in the short and medium term to reduce CO_2 emissions in the industrial sector. Actually, these technologies are currently known as the technological solution that will allow fighting for the global climate change targets, meaning to achieve carbon neutrality by 2050, despite several challenges related to costs, infrastructure and incentives that must be overcome. Significant progress has been made in recent decades; in fact, one of the first CCS projects in the USA, initiated in 1972, remains operating, in which CO_2 is captured in a fertilizer facility (Enid Fertilizer) and utilized in an EOR project (CSLF (Carbon Sequestration Leadership Forum) 2019). However, it has been during this last decade that the implementation of CCS projects has increased worldwide. The facility classification system proposed by CSLF identified two major categories based on their annual CO_2 capture capacity, namely, large-scale CCS facilities (capture capacity over 0.4 Mt/year), and pilot and demonstration CCS facilities (capture capacity less than 0.4 Mt/year) (CSLF (Carbon Sequestration Leadership Forum) 2019). Yet, a new CCS facility classification system was proposed by Global Status of Global CCS Institute (2020), which, besides the general pre-requisites list (CSLF (Carbon Sequestration Leadership Forum) 2019), is mainly supported by the commercial return while operating parameter. Therefore, this new classification established the following categories: (1) commercial CCS facilities, and (2) pilot and demonstrative CCS facilities. Today, there are 65 commercial CCS facilities and 34 pilot and demonstration CCS facilities around the world, but mainly located in North America, Europe and Asia. From the 65 commercial CCS facilities, 26 are operating, and they can capture and permanently store around 40 Mt of CO_2 per year. In the present scenario, it is only possible, when using CCS technologies, to provide a CO_2 abatement of approximately 0.11% of the 35 Gt of current annual CO_2 emissions in the entire world.

At this stage, it is quite clear that significant improvements are required throughout the entire energy chain in order to achieve carbon neutrality by 2050.

Gates (2021) was quite emphatic about the different approaches required for meeting reduction targets by 2030 and net zero targets by 2050. If the world is to go for the latter, he proposed both what can be done and what needs to be done. One thing is absolutely essential, and that is innovation at various levels, in order to create and roll out breakthrough technologies that can assist in reaching the ultimate goal by 2050. It is hoped that CCS technologies will play an essential role through this challenge.

Table 3. EPPA global storage capacity by region.

Region	Estimated Storage Capacity (Gt) Lower Estimation (0.037 Gt/1000 km^3)	Upper Estimation (0.26 Gt/1000 km^3)
Africa	1563	10,986
Australia and New Zeland	595	4184
Dynamic Asia	119	834
Brazil	297	2087
Canada	318	2236
China	403	2830
Europe	302	2120
Indonesia	163	1144
India	99	697
Japan	8	59
Korea	3	24
Other Latin America	606	4257
Middle East	492	3454
Mexico	138	967
Other East Asia	272	1911
Other Eurasia	485	3410
Russia	1234	8673
United States of America	812	5708
Global	7910	55,581

Source: Table by authors, adapted from MRI (Mitsubishi Research Institute) (2019).

6. Conclusions

Whilst the world seeks to better understand climate science and significantly improve on climate models, predictions and interpretations of data relevant to so-called climate change, besides addressing the sustainability of resources, and the reduction in emissions, in an effort to protect the environment, factors such as energy economics, security and cost of supply must be properly addressed at all times.

In an ever-changing world, highly dependent on hydrocarbon-based energy sources, seeking to transition to new so-called cleaner sources, energy security concerns are heightened and the risks for disruption increase significantly. Such a transition needs to be as unincumbered as possible and should take into account the energy return on energy investment (EROEI) in order for sensible measures and policies to be put in place and succeed in delivering the end result. Current investments significantly favor renewables, but it seems as if work is being conducted at the expense of a major increase in additional natural resources and space, adding to even more environmental pressures. New renewable technologies will continue to raise the problem of waste disposal and recycling, adding further to the global concern of pollution and waste management, with a direct impact on nature, land and human and animal life. Under-investment in the old economy in favor of the new economy will result in disruption to the energy supply chain, recently referred to as the "revenge of the old economy" (Gillespie 2021), with all the economic impacts and consequences that accompany it.

In conclusion, it is quite obvious that the energy transition system, mainly supported by the idea of replacing fossil fuels, which are still responsible for about 80% of global primary energy in 2021, by renewable sources, is an essential step required by the global energy sector, in order to try to meet the targets of carbon neutrality by 2050, which is considered to be a difficult, if not impossible, task to reach. This subject has been discussed since the 1970s and was strongly raised with the implementation of the first Kyoto Protocol commitment, but the current global climate scenario is far from the main target, that is, net zero emissions.

The general analysis presented in this manuscript seeks to consider the different aspects relating to climate and to global energy demands. The energy transition must be conducted in a gradually and consistent manner to avoid massive disruptions to the energy and human development chains whilst seeking to ameliorate the impacts of climate change. Evidently, innovation and new developments need to come into play to accelerate the pace of change well beyond the impact seen from the current suit of alternative energy sources, namely, renewables. In this approach, fossil fuels will most likely continue to share the global energy matrix, although they will start decreasing, but most likely not in the medium term. To achieve carbon neutrality by 2050, a significant and intense multi-disciplinary effort in all sectors is required, with radical changes or improvements to cause a significant reduction in fossil fuel consumption that can only result from processes that are not available as of yet. This may include the likes of hydrogen, and perhaps an increased nuclear contribution to the energy matrix, but much work is required in a very short period of time (30 years).

The contribution of geology to the energy transition phase, which forms part of the drive to achieve the target of zero carbon by 2050, is multi-faceted. Batteries required to store energy produced from intermittent renewable sources require mineral raw materials. Large-scale facilities required to store large volumes of hydrogen can be provided by geological structures, such as salt caverns, depleted oil and gas fields and deep saline aquifers. Finally, given that a rapid energy transition to a fossil fuel-free energy system is presently impossible, CO_2 will continue to be emitted, and the most efficient solution to reduce CO_2 emissions into the atmosphere is to apply CO_2 abatement technologies, such as CCS technologies, by selecting the best underground geological structures through a set of key criteria.

Author Contributions: Each author contributed with an equal amount of expertise and discussions in the development of the present investigation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are indebted to Fundação Fernando Pessoa for supporting this investigation in the scope of the research program of the FP-ENAS Research Unit. Thanks, are also due to Patrícia Moreira for her competent contributions to the literature research, and to the final organization of the reference list.

Conflicts of Interest: The authors declare no conflict of interest.

References

Ajayi, Temitope, Jorge Salgado Gomes, and Achinta Bera. 2019. A review of CO_2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. *Petroleum Science* 16: 1028–63. [CrossRef]

Allen, Myles. 2003. Liability for climate change. *Nature* 421: 891–92. [CrossRef] [PubMed]

Andersson, Joakim, and Stefan Grönkvist. 2019. Large-scale storage of hydrogen. *International Journal of Hydrogen Energy* 44: 11901–19. [CrossRef]

Augustin, Laurent, Carlo Barbante, Piers R. F. Barnes, Jean Marc Barnola, Matthias Bigler, Emiliano Castellano, Olivier Cattani, Jerome Chappellaz, Dorthe Dahl-Jensen, Barbara Delmonte, and et al. 2004. Eight glacial cycles from an Antarctic ice core. *Nature* 429: 623–28. [PubMed]

Bartlett, Jay, and Alan Krupnick. 2020. *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions*. Report 20–25. Washington, DC: Resources for the Future.

Berner, Robert A., and Zavareth Kothavala. 2001. GEOCARB III: A revised model of atmospheric CO2 over Phanerozoic time. *American Journal of Science* 301: 182–204. [CrossRef]

BMWI. 2020. *The National Hydrogen Strategy*. Berlin: Federal Ministry for Economic Affairs and Energy, pp. 1–32.

Bossel, Ulf, Baldur Eliasson, and Gordon Taylor. 2003. The Future of the Hydrogen Economy: Bright or Bleak? *Cogeneration and Competitive Power Journal* 18: 29–70. [CrossRef]

BP (British Petroleum). 2017. *BP Energy Outlook: 2017 edition*. London: British Petroleum, p. 103.

BP (British Petroleum). 2020. *BP Energy Outlook: 2020 edition*. London: British Petroleum, p. 157.

Bui, Mai, Claire S. Adjiman, André Bardow, Edward J. Anthony, Andy Boston, Solomon Brown, Paul S. Fennell, Sabine Fuss, Amparo Galindo, Leigh A. Hackett, and et al. 2018. Carbon capture and storage (CCS): The way forward. *Energy & Environmental Science* 11: 1062–176.

Celia, Michael Anthony, Stefan Bachu, Jan Martin Nordbotten, and Karl W. Bandilla. 2015. Status of CO_2 storage in deep saline aquifers with emphasis on modeling approaches and practical simulations. *Water Resources Research* 51: 6846–92. [CrossRef]

Crowley, Thomas J., and Robert A. Berner. 2001. Paleoclimate: Enhanced: CO_2 and Climate Change. *Science* 292: 870–72. [CrossRef]

CSLF (Carbon Sequestration Leadership Forum). 2012. *CSLF Annual Meeting, 24–26 October 2012, Perth, Australia*. Bergen: Carbon Sequestration Leadership Forum.

CSLF (Carbon Sequestration Leadership Forum). 2019. *Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIIs)*. Chatou: Carbon Sequestration Leadership Forum.

D'Amore, Federico, and Fabrizio Bezzo. 2017. Economic optimisation of European supply chains for CO_2 capture, transport and sequestration. *International Journal of Greenhouse Gas Control* 65: 99–116. [CrossRef]

Dalebrook, Andrew F., Weijia Gan, Martin Grasemann, Séverine Moret, and Gábor Laurenczy. 2013. Hydrogen storage: Beyond conventional methods. *Chemical Communications* 49: 8735–51. [CrossRef] [PubMed]

Dayaratna, Kevin D., Ross McKitrick, and Patrick J. Michaels. 2020. Climate sensitivity, agricultural productivity and the social cost of carbon in FUND. *Environmental Economics and Policy Studies* 22: 433–48. [CrossRef]

EASAC (European Academies Science Advisory Council). 2013. *Carbon capture and storage in Europe*. (EASAC Policy Report 20). Halle (Saale): German National Academy of Sciences Leopoldina, p. 86.

EC (European Commission). 2007a. *Limiting Global Climate Change to 2 °C: The Way Ahead for 2020 and Beyond*. [COM (2007) 2 Final]. Brussels: European Commission, p. 13.

EC (European Commission). 2007b. *Towards a European Strategic Energy Technology Plan*. [COM (2006) 847 Final]. Brussels: European Commission, p. 12.

EC (European Commission). 2009. *Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the Geological Storage of Carbon Dioxide*. Brussels: European Commission.

EC (European Commission). 2010. *Energy 2020: A Strategy for Competitive, Sustainable and Secure Energy*. [COM (2010) 639 Final]. Brussels: European Commission, p. 20.

EC (European Commission). 2011a. *Energy Efficiency Plan 2011*. [COM (2011) 109 Final]. Brussels: European Commission, p. 16.

EC (European Commission). 2011b. *Energy Roadmap 2050*. [COM (2011) 885 Final]. Brussels: European Commission, p. 20.

EC (European Commission). 2011c. *On Security of Energy Supply And international Cooperation—"The EU Energy Policy: Engaging with Partners beyond Our Borders"*. [COM (2011) 539 Final]. Brussels: European Commission, p. 19.

EC (European Commission). 2011d. *Proposal for a Regulation of the European Parliament and of The Council on Guidelines for Trans-European Energy Infrastructure and Repealing Decision No 1364/2006/EC*. [COM (2011) 658 Final]. Brussels: European Commission, p. 48.

EC (European Commission). 2011e. *Smart Grids: From Innovation to Deployment*. [COM (2011) 202 Final]. Brussels: European Commission, p. 12.

EC (European Commission). 2018. *Report on Raw Materials for Battery Applications*. [SWD (2018) 245/2 Final]. Brussels: European Commission, p. 47.

EC (European Commission). 2019. *The European Green Deal*. [COM (2019) 640 Final]. Brussels: European Commission, p. 24.

EC (European Commission). 2020a. *A Hydrogen Strategy for a Climate-Neutral Europe*. [COM (2020) 301 Final]. Brussels: European Commission, p. 23.

EC (European Commission). 2020b. *Proposal for a Regulation of the European Parliament and of The Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulation (EU) 2018/1999 (European Climate Law)*. [COM (2020) 80 Final-2020/0036 (COD)]. Brussels: European Commission, p. 25.

EU (European Union). 2021. Regulation (EU) 2021/694 of the European Parliament and of the Council of 29 April 2021: Establishing the Digital Europe Programme and repealing Decision (EU) 2015/2240. *Official Journal of European Union* 2021: L166/1–L166/34.

Gates, Bill. 2021. *How to Avoid a Climate Disaster—The Solutions We Have and the Breakthroughs We Need*. New York: Penguin Random House, p. 257. ISBN 978-0-241-44830-4.

GECF (Gas Exporting Countries Forum). 2017. *Global Gas Outlook 2017*. Doha: Gas Exporting Countries Forum, p. 96.

Gielen, Dolf, Francisco Boshell, Deger Saygin, Morgan D. Bazilian, Nicholas Wagner, and Ricardo Gorini. 2019. The role of renewable energy in the global energy transformation. *Energy Strategy Reviews* 24: 38–50. [CrossRef]

Gillespie, Todd. 2021. Energy Crisis Is Old Economy's Revenge, Says Goldman's Currie. *Bloomberg News*. Available online: https://www.bnnbloomberg.ca/energy-crisis-is-old-economy-s-revenge-says-goldman-s-currie-1.1658513 (accessed on 25 October 2021).

Giorgi, Filippo. 2010. Uncertainties in climate change projections, from the global to the regional scale. *EPJ Web of Conferences* 9: 115–29. [CrossRef]

Giraud, Fabienne, Luc Beaufort, and Pierre Cotillon. 1995. Periodicities of carbonate cycles in the Valanginian of the Vocontian Trough: A strong obliquity control. *Geological Society Special Publications* 85: 143–64. [CrossRef]

Global CCS Institute. 2020. *The Global Status of CCS 2020 - CCS Vital to achieve Net-Zero*. Melbourne: Global CCS Institute, p. 44.

Guo, Chaohua, Mingzhen Wei, and Hong Liu. 2018. Study of gas production from shale reservoirs with multi-stage hydraulic fracturing horizontal well considering multiple transport mechanisms. *PLoS ONE* 13: e0188480. [CrossRef]

Haywood, Alan M., Paul J. Valdes, Tracy Aze, Natasha Barlow, Ariane Burke, Aisling M. Dolan, Anna S. von der Heyd, Daniel J. Hill, Stewart S. R. Jamieson, Bette Lou Otto-Bliesner, and et al. 2019. What can Palaeoclimate Modelling do for you? *Earth Systems and Environment* 3: 1–18. [CrossRef]

Heilek, Christian, Philipp Kuhn, and Maximilian Kühne. 2016. The Role of Large-Scale Hydrogen Storage in the Power System. In *Hydrogen and Fuel Cell*. Edited by Johannes Töpler and Jochen Lehmann. Berlin: Springer, pp. 21–37.

Herbert, Timothy D., and Alfred G. Fischer. 1986. Milankovitch climatic origin of mid-Cretaceous black shale rhythms in central Italy. *Nature* 321: 739–43. [CrossRef]

Huppert, Kimberly L., J. Taylor Perron, and Leigh H. Royde. 2020. Hotspot swells and the lifespan of volcanic ocean islands. *Science Advances* 6: 1–8. [CrossRef]

IEA (International Energy Agency). 2019. *The Future of Hydrogen Seizing Today's Opportunities*. Report Prepared by the IEA for the G20 Japan. Paris: International Energy Agency, p. 203.

IEA (International Energy Agency). 2020. *Renewables 2020: Analysis and Forecast to 2025*. Paris: International Energy Agency, p. 171.

IEA (International Energy Agency). 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Special Report. Paris: International Energy Agency, p. 223.

IPCC (Intergovernmental Panel on Climate Change). 2013. *Climate Change 2013: The Physical Science Basis*. Working Group I Contribution to the IPCC Fifth Assessment Report. Cambridge: Cambridge University Press, p. 203. Available online: www.ipcc.ch/report/ar5/wg1 (accessed on 28 June 2021).

IRENA (International Renewable Energy Agency). 2019. *Global Energy Transformation: A Roadmap to 2050*. Abu Dhabi: International Renewable Energy Agency, p. 52.

ISO 11760. 2005. *Classification of Coals*. Geneva: International Organization for Standardization, p. 9.

Javed, Muhammad Shahzad, Dan Zhong, Tao Ma, Aotian Song, and Salman Ahmed. 2020. Hybrid pumped hydro and battery storage for renewable energy based power supply system. *Applied Energy* 257: 114026. [CrossRef]

Jiang, Tingxue, Xiaobing Bian, Haitao Wang, Shuangming Li, Changgui Jia, Honglei Liu, and Haicheng Sun. 2017. Volume fracturing of deep shale gas horizontal wells. *Natural Gas Industry B* 4: 127–33. [CrossRef]

Jiang, Kai, Peta Ashworth, Shiyi Zhang, Xi Liang, Yan Sun, and Daniel Angus. 2020. China's carbon capture, utilization and storage (CCUS) policy: A critical review. *Renewable and Sustainable Energy Reviews* 119: 1–15. [CrossRef]

Johnson, Markes E., B. Gudveig Baarli, Mário Cachão, Eduardo Mayoral, Ricardo S. Ramalho, Ana Santos, and Carlos M. da Silva. 2018. On the rise and fall of oceanic islands: Towards a global theory following the pioneering studies of Charles Darwin and James Dwight Dana. *Earth-Science Reviews* 180: 17–36. [CrossRef]

Jouzel, Jean, Françoise Vimeux, Nicolas Caillon, Gilles Delaygue, Georg Hoffmann, Valerie Masson-Delmotte, and Frederic Parrenin. 2003. Magnitude of isotope/temperature scaling for interpretation of central Antarctic ice cores. *Journal of Geophysical Research* 108: 4361. [CrossRef]

Jouzel, Jean, Valerie Masson-Delmotte, Olivier Cattani, Gabrielle Dreyfus, Sonia Falourd, Georg Hoffmann, Bénédicte Minster, Julius Nouet, Jean-Marc Barnola, Jérôme Chappellaz, and et al. 2007. Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years. *Science* 317: 793–96. [CrossRef] [PubMed]

Kang, Jian, and Rolf Larsson. 2013. What is the link between temperature and carbon dioxide levels? A Granger causality analysis based on ice core data. *Theoretical and Applied Climatology* 116: 537–48. [CrossRef]

Kapetaki, Zoe, and John Scowcroft. 2017. Overview of Carbon and Storage (CCS) demonstration project business models: Risks and Enablers on the sides of the Atlantic. *Energy Procedia* 114: 6623–30. [CrossRef]

Karakilcik, Hatice, and Mehmet Karakilcik. 2020. Underground Large-Scale Hydrogen Storage. In *Accelerating the Transition to a 100% Renewable Energy Era*. Edited by Tanay Sidki Uyar. Istanbul: Springer, Volume 74, pp. 375–92.

Khan, Chawarwan, Julie K. Pearce, Suzanne D. Golding, Victor Rudolph, and Jim R. Underschultz. 2021. Carbon Storage Potential of North American Oil & Gas Produced Water Injection with Surface Dissolution. *Geosciences* 11: 123–32.

Knutti, Reto, Joeri Rogelj, Jan Sedláček, and Erich M. Fischer. 2015. A scientific critique of the two-degree climate change target. *Nature Geoscience* 9: 13–18. [CrossRef]

Kovac, Ankica, Matej Paranos, and Doria Marcius. 2021. Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy* 46: 10016–35. [CrossRef]

Lemieux, Alexander, Alexi Shkarupin, and Karen Sharp. 2020. Geologic feasibility of underground hydrogen storage in Canada. *International Journal of Hydrogen Energy* 45: 32243–59. [CrossRef]

Lemos de Sousa, Manuel, Cristina Fernanda Rodrigues, Maria Alzira Dinis, and Gisela Marta Oliveira. 2008. *Overview on CO_2 Geological Sequestration*. Porto: Universidade Fernando Pessoa.

Liu, Wei, Zhixin Zhang, Jie Chen, Deyi Jiang, Fei Wu, Jinyang Fan, and Yinping Li. 2020. Feasibility evaluation of large-scale underground hydrogen storage in bedded salt rocks of China: A case study in Jiangsu province. *Energy* 198: 117348. [CrossRef]

Metso: Outotec. 2021. Battery Metals. Available online: https://www.mogroup.com/commodities/battery-metals/ (accessed on 28 June 2021).

Mills, Marker P. 2019. *The "New Energy Economy": An Exercise in Magical Thinking*. New York: Manhattan Institute, p. 23.

Mills, Marker P. 2020. *Mines, Minerals, And "Green" Energy: A Reality Check*. New York: Manhattan Institute, p. 19.

Mitchell, Dann M., Yuen Tung Eunice Lo, William J. M. Seviour, Leopold Haimberger, and Lorenzo M. Polvani. 2020. The vertical profile of recent tropical temperature trends: Persistent model biases in the context of internal variability. *Environmental Research Letters* 15: 1–11. [CrossRef]

Molloy, Patrick, and LeeAnn Baronett. 2019. The Truth about Hydrogen, the Latest, Trendiest Low-Carbon Solution. Available online: https://www.greenbiz.com/article/truth-about-hydrogen-latest-trendiest-low-carbon-solution (accessed on 28 June 2021).

Moore, Patrick. 2019. *The Positive Impact of Human CO2 Emissions on the Survival of Life on Earth*. Winnipeg: Frontier Centre for Public Policy, p. 30.

MRI (Mitsubishi Research Institute). 2019. *Think & Act. Corporate Communications Division*. Tokyo: Mitsubishi Research Institute, Available online: https://www.mri.co.jp/en/about-us/info/group_report/index.html (accessed on 5 July 2021).

MRI (Mitsubishi Research Institute). 2020. *FY2019 Study on the Infrastructure Development Project for Acquisition of JCM Credits (International Cooperation in CCUS) Report*. Environment and Energy Division. Tokyo: Mitsubishi Research Institute, p. 310.

Niaz, Saba, Taniya Manzoor, and Altaf Hussain Pandith. 2015. Hydrogen storage: Materials, methods and perspectives. *Renewable and Sustainable Energy Reviews* 50: 457–69. [CrossRef]

Nordhaus, William. 2018. Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies. *American Economic Journal: Economic Policy* 10: 333–60. [CrossRef]

Ozarslan, Ahmet. 2012. Large-scale hydrogen energy storage in salt caverns. *International Journal of Hydrogen Energy* 37: 14265–77. [CrossRef]

Park, Jeffrey, and Timothy D. Herbert. 1987. Hunting for Paleoclimatic Periodicities in a Geologic Time Series with an Uncertain Time Scale. *Journal of Geophysical Research: Solid Earth* 92: 14027–40. [CrossRef]

Persson, Erik K. 2019. What Is the Link Between Temperature, Carbon Dioxide and Methane? A Multivariate Granger Causality Analysis Based on Ice Core Data from Dome C in Antarctica. Master's thesis, Uppsala University, Uppsala, Sweden.

Pielke, Roger. 2020. *Understanding the Great Climate Science Scenario Debate*. New York: Forbes, Available online: www.forbes.com/sites/rogerpielke/2020/02/03/understanding-the-great-climate-science-scenario-debate/?sh=5f3251bb26a7 (accessed on 11 October 2021).

Pol, Katy, Valérie Masson-Delmotte, Sigfús Johnsen, Matthias Bigler, Olivier Cattani, Gael Durand, Sonia Falourd, Jean Jouzel, Bénédicte Minster, Frédéric Parrenin, and et al. 2010. New MIS 19 EPICA Dome C high resolution deuterium data: Hints for a problematic preservation of climate variability at sub-millennial scale in the "oldest ice. " *Earth and Planetary Science Letters* 298: 95–103. [CrossRef]

Rahman, Muhammad Ishaq-ur. 2013. Climate Change: A Theoretical Review. *Interdisciplinary Description of Complex Systems* 11: 1–13. [CrossRef]

Ritchie, Hannah, and Max Roser. 2017. CO_2 and Greenhouse Emissions. Our World in Data CO_2 and Greenhouse Gas Emissions Database. Available online: https://ourworldindata.org/atmospheric-concentrations (accessed on 28 June 2021).

Rodrigues, Cristina F., and Manuel J. Lemos de Sousa. 2002. The measurement of coal porosity with different gases. *International Journal of Coal Geology* 48: 245–51. [CrossRef]

Rodrigues, Cristina F., Maria A. P. Dinis, and Manuel J. Lemos de Sousa. 2015. Review of European energy policies regarding the recent "carbon capture, utilization and storage" technologies scenario and the role of coal seams. *Environmental Earth Sciences* 74: 2553–61. [CrossRef]

Rosen, Amanda M. 2015. The Wrong Solution at the Right Time: The Failure of the Kyoto Protocol on Climate Change. *Politics & Policy* 43: 30–58.

Schernikau, Lars, and William Hayden Smith. 2021. How Many km^2 of Solar Panels in Spain and How Much Battery Backup Would It Take to Power Germany. Available online: https://ssrn.com/abstract=3730155 (accessed on 2 May 2021).

Schoenung, Susan M. 2011. *Economic Analysis of Large-Scale Hydrogen Storage for Renewable Utility Applications*. Alburquerque: Sandia National Laboratories, p. 41.

Schwarzacher, Walther. 1993. Milankovitch cycles in the pre-Pleistocene stratigraphic record: A review. *Geological Society Special Publications* 70: 187–94. [CrossRef]

Shaviv, Nir J. 2008. Using the oceans as a calorimeter to quantify the solar radiative forcing. *Journal of Geophysical Research* 113: 1–13. [CrossRef]

Shogenova, Alla, Kris Piessens, Sam Holloway, Michelle Bentham, Roberto Martínez, Kristin M. Flornes, Niels E. Poulsen, Adam Wójcicki, Saulius Sliaupa, Ludovít Kucharič, and et al. 2014. Implementation of the EU CCS Directive in Europe: Results and development in 2013. *Energy Procedia* 63: 6662–70. [CrossRef]

Shogenova, Alla, Nicklas Nordback, Daniel Sopher, Kazbulat Shogenov, Auli Niemi, Christopher Juhlin, Saulius Sliaupa, Monika Ivandic, Adam Wojcicki, Jüri Ivask, and et al. 2021. Carbon Neutral Baltic Sea Region by 2050: Myth or Reality? Paper present at the 15th Greenhouse Gas Control Technologies Conference, Abu Dhabi, United Arab Emirates, March 15–18; p. 12.

Soeder, Daniel J., and Scyller J. Borglum. 2019. The evolutionary U.S. shale plays. In *The Fossil Fuel Revolution: Shale Gas and Tight Oil*. Amsterdam: Elsevier, pp. 109–35.

Soon, Willie, Ronan Connolly, and Michael Connolly. 2015. Re-evaluating the role of solar variability on Northern Hemisphere temperature trends since the 19th century. *Earth-Science Reviews* 150: 409–52. [CrossRef]

Stenni, Barbara, Valérie Masson-Delmotte, Enricomaria Selmo, Hans Oerter, Hanno Meyer, Regine Röthlisberger, Jean Jouzel, Olivier Cattani, Sonia Falourd, Hubertus Fischer, and et al. 2010. The deuterium excess records of EPICA Dome C and Dronning Maud Land ice cores (East Antarctica). *Quaternary Science Reviews* 29: 146–59. [CrossRef]

Tarkowski, Radoslaw. 2017. Perspectives of using the geological subsurface for hydrogen storage in Poland. *International Journal of Hydrogen Energy* 42: 347–55. [CrossRef]

Tarkowski, Radoslaw. 2019. Underground hydrogen storage: Characteristics and prospects. *Renewable and Sustainable Energy Reviews* 105: 86–94. [CrossRef]

Tarling, Donald Harvey. 2010. Milankovitch Cycles in Climate Change, Geology and Geophysics. Paper present at the 6th International Symposium on Geophysics, November 11–12, Tanta, Egypt, pp. 1–8.

UN (United Nations). 1992. *United Nations Framework Convention on Climate Change*. (Document FCCC/Informal/84: GE.5-62220 (E) 200705). New York: United Nations, p. 24.

UN (United Nations). 2012. *Kyoto Protocol to the United Nations Framework Convention on Climate Change, Kyoto, 11 December 1997. Doha Amendment to the Kyoto Protocol, Doha, 8 December 2012. Adoption of Amendment to the Protocol*. New York: United Nations, p. 41, [Reference: C.N.718.2012.TREATIES-XXVII.7.c (Depositary Notification)].

UN (United Nations). 2015. *Paris Agreement*. New York: United Nations, p. 25.

Veizer, Ján, Yves Godderis, and Louis M. François. 2000. Evidence for decoupling of atmospheric CO_2 and global climate during the Phanerozoic eon. *Nature* 408: 698–701. [CrossRef] [PubMed]

Voosen, Paul. 2021. Climate panel confronts implausibly hot models. *Science* 373: 474–75. [CrossRef] [PubMed]

Werndl, Charlotte. 2016. On defining climate and climate change. *The British Journal for the Philosophy of Science* 67: 337–64. [CrossRef]

Wigley, Tom M. L. 1998. The Kyoto Protocol: CO_2, CH_4 and climate implications. *Geophysical Research Letters* 25: 2285–88. [CrossRef]

WMO (World Meteorological Organization). 1979. *World Climate Conference—A Conference of Experts on Climate and Mankind*. Geneva: Declaration and Supporting Documents, p. 50.

Yang, Yuqing, Setphen Bremner, Chris Menictas, and Merlinde Kay. 2018. Battery energy storage system size determination in renewable energy systems: A review. *Renewable and Sustainable Energy Reviews* 91: 109–25. [CrossRef]

Yartys, Volodymyr A., and Mykhaylo V. Lototsky. 2004. An Overview of Hydrogen Storage Methods. In *Hydrogen Materials Science and Chemistry of Carbon Nanomaterials*. NATO Science Series II: Mathematics, Physics and Chemistry. Edited by Turhan Nejat Veziroglu, Svetlana Yu. Zaginaichenko, Dmitry V. Schur, Bogdan Baranowski, Anatoliy Petrovich Shpak and Skorokhod Valery Volodimirovich. Dordrecht: Springer, Volume 172, pp. 75–104.

Zhou, Li. 2005. Progress and problems in hydrogen storage methods. *Renewable and Sustainable Energy Reviews* 9: 395–408. [CrossRef]

Züttel, Andreas. 2003. Materials for hydrogen storage. *Materials Today* 6: 24–33. [CrossRef]