The energy transition up against the climate clock

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This article aims to shed light on what is at stake in the energy transition, beginning with a historical approach. It shows that the changes required to achieve the goals of the Paris Agreement are unprecedented compared to the mechanics of past transitions.

- The changes must occur in accordance with the pace of the climate clock, which is governed by the ever increasing amount of carbon present in the atmosphere ("carbon above"), whereas previous transitions have involved increasing the ability of societies to extract more and more fossil resources ("carbon below"), adding to the number of energy sources.
- Instead of the historical mechanism of stacking up energy sources, it is now necessary to develop a system whereby carbon-free sources are no longer simply added to existing sources, but replace fossil fuels altogether.
- Gains in energy efficiency must no longer lead, through falling relative prices, to higher energy consumption per capita, which greatly contributes to the escalation of emissions.

In conclusion, we propose adopting a holistic approach to the energy transition, making it easier to link strategies for mitigating climate change with strategies for combatting biodiversity loss.

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Introduction: a variable geometry concept

The concept of energy transitions emerged almost unnoticed following the oil shocks of the 1970s, in a book on the diversification of the energy mix,[i] then reappeared in the 1980s, following the oil countershock. The term came back into vogue, in the 2000s, with the rise in energy prices and growing awareness of climate change.

The fact that it is plural – energy transitions – rather than singular may be used to justify very diverse strategies. In the United States, the energy transition aims to reduce the country's dependence on hydrocarbon imports, and provides a justification for the large-scale exploitation of shale oil and gas, which may well prolong the use of fossil fuels.[ii] In the Middle East, the energy transition entails curing the region's economies from their addiction to oil rent. In emerging countries, its aim is to provide an increase in energy sources compatible with economic progress.

In Europe, the concept in theory justifies policies simultaneously aimed at reducing greenhouse gas emissions, promoting renewable energies and encouraging energy efficiency. But once we look a little closer, it is apparent that the package covers disparate national strategies: in the name of the energy transition, Germany has abandoned nuclear energy, the United Kingdom is seeking to re-adopt it and Poland wants to acquire it, while France wonders how it can reduce the proportion of nuclear in the national energy mix.

This malleability of the concept is dangerous because it can lead to undesirable futures with regard to the climate. The aim of the present issue of *Information & Débats* is to provide a rigorous formulation of the concept of energy transition and to clarify its links with climate change. In the first section, we revisit the historical analyses showing how previous transitions involved the stacking up of primary energy sources. The proliferation of sources led to an unprecedented increase in global energy consumption and to massive emissions of CO_2 into the atmosphere. The second section places the emphasis on the specificity of the low-carbon transition that will be needed to unstack these sources by giving up fossil fuels. Such a reversal will take time. Yet the amount of CO_2 already accumulated in the atmosphere means that there is very little time left. Reducing the discrepancy between the pace of eliminating fossil fuels and the countdown of the climate clock constitutes the major challenge of the low-carbon transition.

1. Past energy transitions: a history of accumulation

The concept of energy transition is often defined by the respective weight of the primary energy sources used in the system, commonly known as the "energy mix". For example, the global energy system shifted from the dominance of traditional biomass to that of fossil fuels at the beginning of the twentieth century, due to the growing contribution of coal, which accounted for 19% of the world's primary energy use in 1870, but 47% in 1900 and 55% in 1910 (Vaclav Smil).[iii] This analytic filter may also be applied to an isolated segment of the energy system: French electricity generation, which in thirty years transited from fossil fuels to nuclear energy in the latter part of the twentieth century.

This definition is often associated with the criterion of the time required for a new primary source to acquire a certain preponderance in the system, as suggested by Marchetti and Nakicenovic (1979)[iv] in a rather deterministic approach. For example, Smil (2017) estimates that it took more than a hundred years for coal to account for 25% of the global energy supply, while oil reached that proportion in eighty years – long time spans, also underlined by Peter Lund (2006).[v] This approach, however, is dependent on identifying start and end dates, regarding which there is often disagreement, as has been pointed out by Benjamin Sovacool (2017).[vi]

The energy mix approach, however, involves simplification and fails to reflect the inherent complexity of energy systems and the dynamics of their transformations.

What is an energy system?

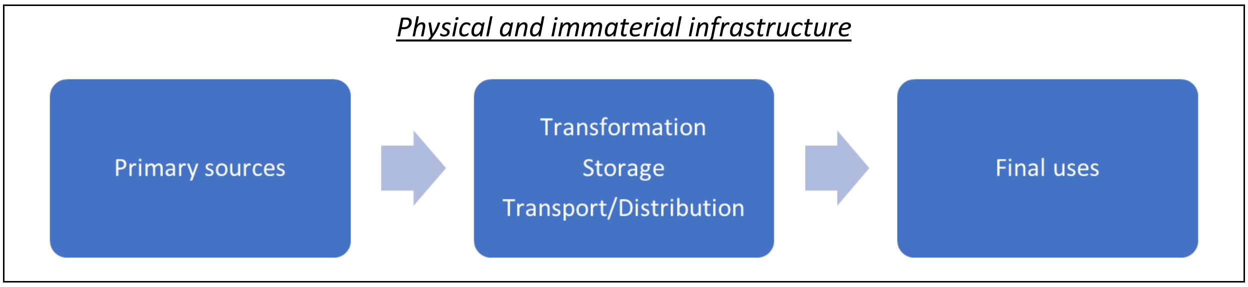
To understand the dynamics of energy systems, and therefore the right levers to change them, we need to have an adequate representation of them. An energy system is characterized by a complex set of interrelations that link primary sources to end uses (Figure 1).

End uses comprise energy consumption by households, businesses and municipalities, that meet a variety of social and economic needs, such as travel, heating, lighting and manufacturing. There is therefore a correlation between a society's production and consumption patterns and the amount of final energy it consumes. End uses can be linked to technologies that rely on a particular energy source over a long period of time. The invention of the internal combustion engine in the 1880s thus led to the expansion of the global automotive industry and the associated use of petroleum products.

A whole chain of equipment and infrastructure operates upstream of end uses that allows energy to be transformed, stored, and transported to consumers. These intervening links play a major role in the functioning of energy systems: without the invention of the steam engine by Watt in 1769, coal would not have taken off as it did in the nineteenth century, and without the invention of the turbine by Fourneyron in 1832, electricity would not have acquired the role it has played ever since.

Primary sources make up the system's energy mix. To measure this, we need to express the amount of energy used by end consumers in a common unit of energy. This operation raises conversion problems that depend on conventions, which in turn can lead to quite different results as regards the positioning of the electricity sector in the system (see Box "Primary energy, final energy, electrical energy").

Figure 1: Representation of an energy system



The concept of energy transition, defined as the set of transformations required to significantly modify the end uses, the mix of primary sources and the transformation/storage /distribution chain of an energy system, can now be characterized with greater rigour. Such a systemic vision underlies the work of authors such as Smil and Fouquet. It has also been popularized by Jeremy Rifkin's book on the "Third Industrial Revolution".[vii]

As historical analysis shows, this type of transformation affects the mix of primary sources together with end uses and intermediate links in the chain, and is spread out over long periods. Its pace is slowed in particular by the inertia of the physical and immaterial infrastructure on which the functioning of the system is based.

Primary energy, final energy, electrical energy: how are they measured?

Primary energy and final energy are traditionally distinguished in countries' energy balance sheets. The term primary energy covers the amount of energy available in a natural state prior to any transformation. The concept of final energy refers to the energy used to meet the needs of end consumers after the transformation of primary energy into secondary energies. Since the transformation and transportation process gives rise to losses, the quantity of primary energy entering energy systems is greater than the quantity of final energy available on exit.

To compare the different sources of energy, a common internationally agreed unit is used, namely the joule (originally defined as the amount of energy required to raise an apple by one metre in a field subject to the Earth's gravity). It is therefore necessary to use conversion coefficients between the different energy sources, which are calculated on the basis of their respective calorific content. Thus one kWh of secondary electricity produced from fossil fuels is equivalent to 3.6 MJ. Difficulties arise when it comes to converting kWh of "primary electricity" from nuclear or renewable sources into primary energy. Representation of the contribution of different sources to the energy supply depends in this case on the accounting method used. There are several such methods and the one chosen depends in practice on the convention adopted.[viii]

One approach involves directly calculating primary electricity production as primary energy without distinction between sources. The same conversion coefficient is applied to electricity from nuclear energy and renewables as electricity from fossil fuels (1kWh = 3.6 MJ), regardless of the energy used and how the electricity is generated. This method is used to produce UN energy balance sheets and IPCC scenarios.

An alternative approach is to calculate electricity generation from nuclear and renewables in terms of the amount of fossil energy it replaces. A yield of 38% for nuclear power is generally used, or 9.3 MJ for one kWh. This approach is used in the reports published by the World Energy Council, the US Energy Information Administration (EIA) and the BP group. Compared to the method used by the United Nations, it gives greater weight to nuclear energy and renewables in primary energy balance sheets.

A third approach involves treating electricity from nuclear energy and renewables differently. For the nuclear sector, calculation is based on substitution (10.9 MJ with a yield of 33%, since a third of the heat produced by a nuclear power plant is converted into electricity), while the same coefficient is applied to the primary and secondary electricity for the generation of electricity from renewables (3.6 MJ). This approach, commonly used by international organizations (International Energy Agency, Eurostat, etc.) and national balance sheets, is the one used in this article.

The accounting method chosen for electricity in primary energy is therefore not inconsequential and in particular it influences the calculation of energy intensity. For this reason energy intensity is usually measured in terms both of primary energy and of final energy.

Four historical transitions

The concept of energy transition can be broken down by sector, as for example by Fouquet (2010),[ix] and by geographical area. By analysing transitions at regional and sectoral scales, Sovacool (2017) refines the observations made by energy historians of the great inertia of energy systems and in particular of the time usually separating the emergence of innovations and when they produce their structural transformations. While such observations are relevant for certain sub-segments of the energy system, they cannot be easily be extrapolated to a global scale. It is this scale, however, that matters to the climate economist.

Drawing on Smil, we can identify four energy transitions that have shaped the history of societies. The first is the taming of fire, which enabled the human species to gain a major advantage over its competitors by using this energy for cooking, heating and eventually smelting metals. The second transition was the agricultural revolution, initiated by the Sumerians, who, by means of irrigation, were the first to increase agricultural yields and thereby support livestock and establish a settled way of life. In terms of energy, the agricultural revolution supplemented human muscle power with traction by domestic animals. For growing crops and transporting the harvest, productivity increased some four to six fold.

The third energy transition, beginning in Great Britain at the end of the eighteenth century, greatly increased the amount of energy used thanks to an additional primary source, namely coal, which replaced wood and the physical power of humans and domestic animals around 1900 and remained the world's main energy source until the mid-1960s. Although often viewed as the energy of the nineteenth century, coal did not play a significant role in the world energy system until 1880. Yet the innovations at the origin of its use were available from the middle of the eighteenth century. Thus some 150 years separated these technical innovations from the large-scale utilisation of coal, which then led to the transformation of the economic system.

The fourth energy transition was based on a cluster of innovations that emerged simultaneously during the last two decades of the nineteenth century. These innovations enabled electricity to be generated, transported and put to use for lighting and in industry and led to the development of the internal combustion engine powered by petrol or diesel. We see here two of the three major technical innovations identified by Gordon (2000,[x] 2012[xi]) in his analysis of the growth process. Indeed, the spread of these innovations was the driver of successive waves of growth during the twentieth century. Numerous products appeared as a consequence, from the washing machine – the first models of which came on to the market in 1907 in the United States – through to the computer and the various forms of transport in existence today. The accumulation of these goods transformed people's way of life and created the conditions for mass consumption, which until 1950 was limited to the industrialized countries, but progressively extended to the emerging countries thereafter. Here again, several decades separated the technical innovations, most of which emerged before 1900, and their impact on growth, which became fully apparent only after 1950.

Proliferating primary sources and the growth of energy consumption

A common feature of all these energy transitions is that new primary sources were added to the pre-existing ones, without replacing them. For this reason, the world has never consumed so much coal, "the energy of the nineteenth century", as it has since 2000 (Appendix 1). This additive system contrasts with the traditional view of energy transitions described by Marchetti and Nakicenovic (1979), in which the transition from one dominant energy to the next operates according to a logic of substitution. Yet this runs counter to the observed facts: energy transitions since the beginning of the industrial revolution have been based on a stacking up of primary sources, in which new energies come on stream without the existing ones being given up (Figure 2).

Figure 2. The energy system's past transitions: accumulation of primary sources

Primary sources	Transformation, Storage Transport/Distribution	Final uses
Biomass	Muscle power, firewood	Cooking + heating
	…+ animal haulage	…+ transport + agriculture + craft industry
Biomass + Coal	Steam engine (Watt)	Manufacturing, rail transport, shipping
…+ Fossil oil and gas: 80% of sources	Electricity, internal combustion engine, transport-distribution networks	Lighting, Mass consumption, Mobility of people and goods

Source: Authors, based on Smil (2017)

A second characteristic associated with the accumulation mechanism concerns the increasing energy density of the sources used. At equivalent volume, oil provides more energy than coal, which itself provides more energy than wood. Energy densities can also be expressed in terms of unit area. Thus past energy transitions have allowed human societies to produce increasing amounts of energy per unit area.

The most direct consequence of the stacking up of increasingly dense energy sources is the increasing amount of energy available per capita. Very slow during the first two transitions, this accelerated rapidly with the introduction of the new fossil sources of coal, oil and gas. Due to the demographic transition occurring at the same time, the result has been the unprecedented growth in energy consumption worldwide over the last two centuries.

At the beginning of the nineteenth century, the world population was about 1.2 billion people, each using an average of about 0.6 tonnes of oil equivalent (toe). At the dawn of the 20th century the population was 1.65 billion, with per capita consumption of 0.7 toe. Population growth coupled with the beginning of the exploitation of fossil sources led to a doubling of total energy consumption in the 19th century (Appendix 3).

The twentieth century, especially the second half, saw a tremendous acceleration of the energy transition, driven by the expansion of primary sources and the proliferation of uses linked to the spread of electricity, cars, chemicals derived from hydrocarbons, and so on. Average per capita energy consumption rose from 0.7 to 1.7 toe from the beginning to the end of the century. With the global population increasing more than fourfold, overall energy consumption increased by a factor of nine in the course of the twentieth century.

This trend continued during the first fifteen years of the twenty-first century, with total energy consumption rising by more than a third between 2000 and 2015, slightly faster than the world population. There was, however, a downturn in 2009, following the financial crisis, which lasted until 2017.

This fourth energy transition has by no means provided satisfactory access to electricity for everyone. In 2016, about a billion people (13% of the world's population) had no access to electricity and nearly three billion (41% of the world's population) were reliant on inefficient and highly polluting methods of cooking based on traditional biomass.[xii] Such unequal access reflects the global maldistribution of wealth: in 2016, average per capita consumption of energy worldwide was a little less than 2 toe, but for a North American it was 7 toe, for an Indian less than 1 toe and for a sub-Saharan African no more than 0.5 toe.

Energy transitions and relative energy prices

At the economic level, the last two transitions were triggered by an accumulation of physical and intangible capital, leading to massive productivity gains that spread through the energy system. This in turn resulted in epochal price movements affecting the production and use of energy.

In theory, fossil fuel prices should follow a long-term upward trajectory as the stock of reserves underground becomes increasingly scarce, in accordance with the process theorized by Hotelling.[xiii] Yet the price of fossil fuels, like that of most raw materials, has fallen in real terms since the beginning of the industrial revolution, thereby augmenting their use. This decline does not refute Hotelling's argument, but reminds us that the time frame in which it is situated necessarily involves technical progress, which in particular makes it possible to exploit an increasing fraction of the earth's resources under acceptable economic conditions.

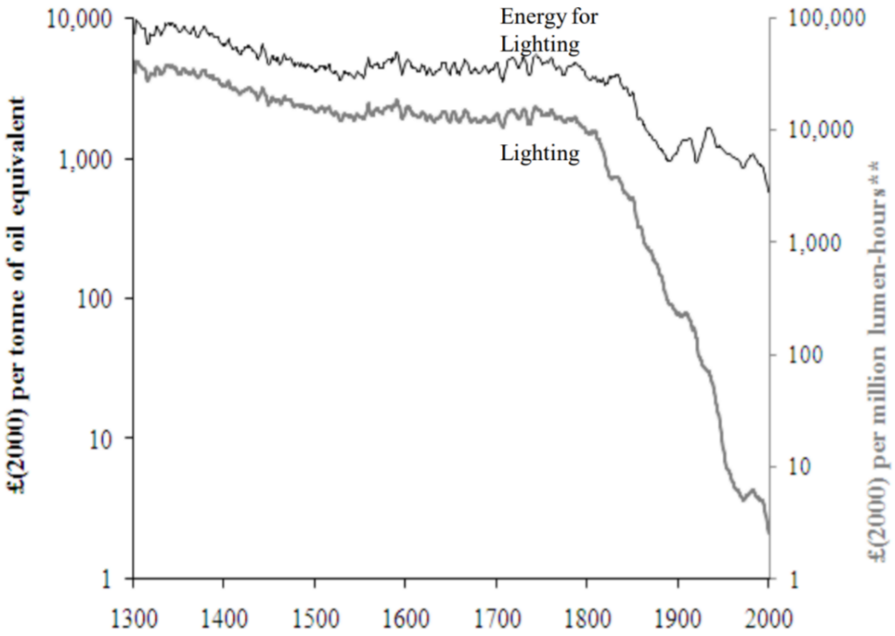
The price of oil, for example, relative to the general price level, fell for a century: from the first stages of exploration in Pennsylvania up until the 1970s. This decline was a powerful vector for the penetration of oil into the global energy mix. The two price shocks of 1973 and 1979-1981 marked the end of cheap oil and heralded a period of great instability in its price. Some saw it as the harbinger of an imminent "oil peak", extending a long tradition based on the "fear of shortage" inaugurated by Malthus and Ricardo for the stock of arable land, followed by Jevons for coal, the Club of Rome for all raw materials and more recently Bihouix[xiv] and Pitron[xv] for metal ores.

To understand the role of relative prices in transitions, more is needed than simply observing the price of primary sources. It is essential to distinguish, following Fouquet and Pearson (2012), the price of the sources used – for example, fuel for a vehicle – from the services provided by these sources, in this case, the number of kilometres that can be travelled. The discrepancy between the two prices measures energy efficiency. However, "even if, over a few years, the efficiency improvements and, thus, the differences between the trends in the prices of energy and energy services are small, over several decades or a century, the accumulated divergences can be very large." [xvi]

The evolution of lighting techniques provides a good illustration. Take the example of the lighthouse of the whales, located at the tip of the Ile de Ré in France (Appendix 4). The lighthouse originally used fish or whale oil, but light output was poor, because combustion of the oil tended to scorch the panes of the lantern. In 1736, fish or whale oil was replaced by coal, a change that improved the light output but required the transport of large quantities of coal. So once again there was a substitution, this time of mineral oil for coal. In 1854 the original structure was replaced by the present lighthouse, which is double the height. This lighthouse was one of the first to benefit from the step lens invented by Fresnel in 1822. Still in service, this system produces a much more powerful light, visible at up to 50 kilometres. The lighthouse ran on mineral oil until 1904, at which point the combustion system was replaced by a steam-powered generator. The lighthouse was connected to the electricity grid only in the 1950s. With electricity, the range of the lighthouse was again extended through the efficiency of the bulbs converting energy into light.

The link between the spread of innovations in lighting and relative prices has been closely studied by Fouquet and Pearson, using examples taken from the United Kingdom. Up until the early eighteenth century, the cost of lighting remained much the same, as the efficiency gains in the production and use of candles or oil lamps were very small. The emergence in the 19th century of new fossil fuel sources, coupled with changes in lighting techniques, altered the situation in two ways (Figure 3).

Figure 3: Evolution of the price of energy for lighting and the price of lighting



Source: Fouquet (2011)

* Five-year averages

On the one hand, the replacement of tallow, vegetable oils and whale oil by town gas, kerosene and subsequently electricity reduced the price of energy used for lighting to a huge extent between 1850 and 1920, and then more slowly and unevenly thereafter.

On the other, the technologies of the gas burner, the oil lamp and the incandescent bulb, which became commonplace in the 1930s, led to substantial efficiency gains and greatly reduced the price of lighting for consumers. In contrast to the efficiency gains observed for the supply of energy, these did not decline in the course of the twentieth century or the early part of the twenty-first century, in particular through the emergence of LEDs and other low energy bulbs.

All in all, efficiency gains in the transformation of energy into light, leading to a fall in relative prices, were the main driver of the spread of lighting. Coupled with improved efficiency in energy production, the decline in the price of lighting is certainly comparable to that of computer memory. Indeed it’s hard to decide between the price per lumen and the price per megabyte on that score!

The lever of productivity gains in the transformation of primary sources of energy into end uses is found in many areas, including heat production, industrial processes and transport, and played a crucial role in past energy transitions. Though lower relative prices it has greatly contributed to the spread and growth of new energy uses, which in turn have led to massive increases in CO_2 emissions.

Accumulation of CO_2 emissions

The accumulation of energy sources characteristic of past energy transitions is the main cause of the acceleration of anthropogenic greenhouse gas emissions. Around 1850 it began to result in an increase in the volume of CO_2 released into the atmosphere that has continued for more than a century and a half (Figure 4).

Until 1850, biomass was the mainstay of the energy system, supplemented to some extent by wind (windmills and sailing ships) and hydraulics (water power). The use of biomass lies within a short cycle in which combustion only releases into the atmosphere CO_2 previously stored in the plants. Along with the expansion of agriculture, cattle farming and to a lesser extent the need for timber, the use of biomass contributed to the clearing of forests. In the mid-nineteenth century forest clearance was occurring mainly in North America and Europe, where it accounted for than 90% of anthropogenic CO_2 emissions, estimated at two tonnes per capita annually.

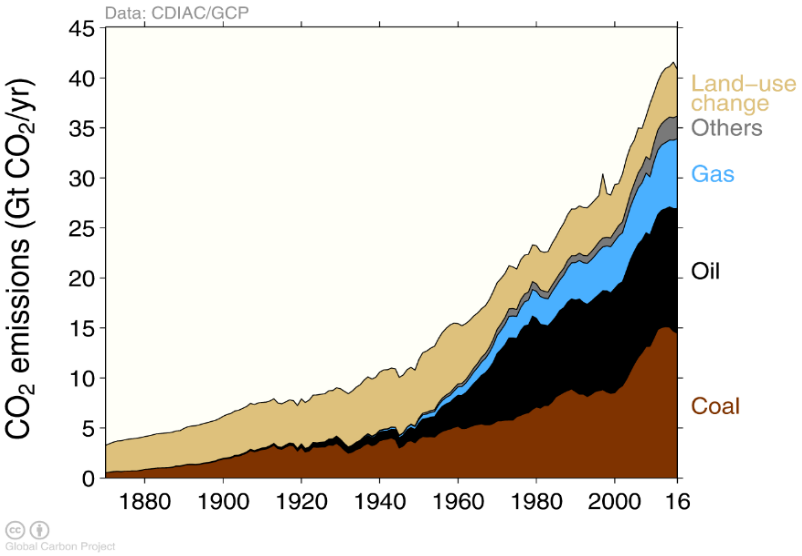
Changes in land use remained the main cause of CO_2 emissions until the middle of the twentieth century (Appendix 2). Emissions doubled between 1850 and 1950, driven largely by deforestation in the United States. The geography of deforestation then shifted to tropical forests. Emissions from fossil fuels increased rapidly up until the eve of the First World War, as a result of the growing use of coal. Emissions from the combustion of oil began playing a part after 1920, but the overall growth of emissions was constrained between 1910 and 1950 by setbacks to the world economy induced by the two world wars and the 1929 crash. In 1950, the combustion of fossil fuels and the production of cement accounted for average CO_2 emissions per capita of 2.2 tonnes, about as much as from forest clearance (Appendix 3). The developed countries accounted for some 80% of these emissions.

The phenomenon of cumulative sources became more pronounced after 1950. Population growth was accelerating. In addition, a growing proportion of the population was gaining access to mass consumption, which until 1970 had been limited to the developed countries but subsequently extended to the emerging countries. New fossil sources were entering the energy mix: first natural gas, then shale gas after 2000. Emissions associated with land use levelled off, but the dynamics of the stacking up of fossil fuels led to ever higher CO_2 emissions. Four sub-periods need to be considered separately.

The post-war period, described as “golden age” by the American economist Angus Maddison[xvii] and the “*trente glorieuses*” by the French economist Jean Fourastie[xviii], was characterized by rapid growth. Production of cars and trucks surged. This was the era of cheap oil, replacing coal as the primary source of CO_2 emissions in the late 1960s. Excluding deforestation, CO_2 emissions rose to 4.4 tonnes per capita in 1980, almost twice the figure for 1950 (2.2 tCO_2 per capita).

Between 1980 and 2000, growth began to be redistributed towards the emerging economies, but the shift was slowed by the debt crisis in Latin America and the implosion of the Soviet system. In developed countries, the rise in oil prices following the two oil shocks first advantaged natural gas, whose combustion emits significantly less CO_2 than coal for the same amount of energy produced, and to a lesser extent nuclear power. During these two decades, the increase in emissions was slower than population growth. At the turn of the century, the average emissions per capita amounted to 4 tonnes of CO_2, excluding deforestation.

Figure 4: Accumulation of CO_2 emissions by source



Source: Global Carbon Budget, 2017[xix]

The first decade of the twenty-first century saw a massive return to coal, driven by sustained growth in China and the needs of the electricity sector in many emerging countries, both large and small. The stacking up of sources was at a peak, because the demand for both gas and oil was driven by the strength of the cycle preceding the 2008 financial crisis. In ten years, CO_2 emissions from energy and industrial sources rose from 4 to 4.8 tonnes per capita. Growth rates were the highest since the "golden age", though with their main driver now shifting to the emerging countries.

The economic crisis and the reorientation of Chinese strategy in response to the rise of local pollution were the major causes of the slowdown in the first part of the decade 2010-2020, assisted by closures of coal mines and highly polluting plants, carbon pricing and massive investment in photovoltaic, wind and nuclear. At the same time, CO_2 emissions were declining in the United States as a result of the switch from coal to shale gas. Overall, CO_2 emissions from energy and industrial sources seem to have stabilized at around 36 billion tonnes (4.9 tCO_2 per capita) between 2014 and 2016, before increasing again in 2017.

Over the last two centuries, energy transitions have triggered a cumulative mechanism of stacking up new sources of CO_2 emissions never before encountered in human history. Between 1850 and 2017, the inhabitants of the planet have released slightly more than 2300 billion tonnes of CO_2 into the atmosphere, of which 40% have been emitted since 1990 and 28% between 2000 and 2017. The geography of these emissions has changed dramatically. Initially concentrated in Europe and North America, 80% of CO_2 emissions in 1980 still originated in the industrialized countries. By 2017, the proportion had fallen to below 40%.

The transition of the 21st century: the retreat from fossil fuels

In the preface to the French edition of his historical overview of the global environment, John McNeil returns to the main lesson learned from twenty years of academic research: "... in the early 90s, I thought that the event that had the most strongly marked global environmental history of the twentieth century had been the growth of the population. By the time I had completed this work, my opinion had changed. I now viewed the energy system based on fossil fuels as the key variable ... ."[xx]

If the stacking up of the three sources of fossil energy was the crucial feature of the twentieth century in terms of the environment and climate, unstacking these sources by eliminating fossil fuels will be the main task of the 21st century. This will be the principal challenge for the low-carbon transition, which is still in its early stages.

The end point of this fifth transition will in any case be a system entirely free of fossil sources. Indeed these sources are being progressively depleted in the course of their exploitation and it would take millions of years for them to be replenished naturally. In the very long term, the increasing scarcity of fossil fuels will result in a crippling rise in their cost, making them economically unusable. Hotelling's projection will eventually prevail. But if the implementation of the low-carbon transition is based solely on depletion of fossil reserves, far too much CO_2 will be released into the atmosphere compared to what it can absorb without major risk to the climate.

For the fact is that the Earth's crust contains much more exploitable fossil fuel reserves than the atmosphere can absorb without disrupting the climate system. The major problem of the twenty-first century is not the potential lack of coal, oil or gas. The problem is that over the last two hundred years mankind has developed enormous capacities for exploiting these three overly abundant sources of energy. Past energy transitions resulted from the need to overcome the scarcity of easily accessible fossilized carbon deposits. They were guided by "carbon below". Climate risk forces us to consider another stock, "carbon above", that is accumulating in the atmosphere and is disrupting the climate. The problem is no longer the scarcity of fossil deposits, but their excess. And it is this that must be curbed if global warming is to be mitigated. Compared to the energy transitions of the past, this necessity leads to a threefold reversal of perspective.

- Despite the inertia of the energy system, the shift must take place in accordance with the pace of the climate clock, which is regulated by the growing stock of "carbon above". Action in relation to this stock necessitates the use of three levers: reduction of CO_2 emissions; reduction of other greenhouse gas emissions; and increasing the sequestration capacity of carbon sinks.
- Rather than the stacking-up mechanism of the past, it is essential to institute a system in which carbon-free sources do not simply supplement existing sources, but instead replace fossil energies.
- Energy efficiency gains must no longer lead, through the fall in relative prices, to higher energy consumption per capita, which contributes significantly to the escalation of emissions.

It is on the basis of this threefold analytic grid that we must now analyse what is at stake in the low-carbon transition.

2. The low-carbon transition: how can we disaccumulate?

Since the publication of the first IPCC report in 1990, policymakers can no longer claim ignorance of the climate issue. The links between the carbon present in the atmosphere ("carbon above") and climate disruption are now well documented by the scientific community. This knowledge base was used as the basis for negotiations in the Paris Climate Agreement adopted in December 2015 (COP21).

Although the Paris Agreement contains few provisions to accelerate the low-carbon transition in the short term, it sets long-term goals for the international community: firstly, to limit global warming to "well below 2°C compared to pre-industrial levels";[xxi] and secondly, by the end of the century to achieve carbon neutrality, understood as a "balance between anthropogenic emissions by sources and their removals by sinks of GHGs".[xxii]

It is according to these two objectives, in principle pursued by the vast majority of countries ratifying the agreement,[xxiii] that the characteristics of an energy transition to mitigate global warming need to be analysed. In many ways this low-carbon transition will need to completely reverse the paths taken over the past two centuries.

The 2°C target: the time remaining

Agreement by policymakers on a mean temperature target is no more than a declarative operation until it has been translated into greenhouse gas emission ceilings that may not be exceeded. This link between the average temperature target and emission ceilings is documented in the IPCC Fifth Assessment Report,[xxiv] which calculates the "global carbon budget", defined as the cumulative CO_2 emission ceiling since 1870, which gives a two out of three chance of limiting global warming to 2°C.

The calculation is based on multiple assumptions, particularly with regard to non-CO_2 greenhouse gas emissions and the capacity of sinks. Rather than specify a single figure, the IPCC scientists have come up with a variation range, from which we will here use only the central value of 2900 billion tonnes of CO_2. At the time of the IPCC Fifth Assessment Report, about 1900 billion tonnes had been emitted since 1870, leaving a carbon budget of 1000 billion tonnes for achieving the 2°C target with a two-in-three probability. The editors of the report add: "Total fossil carbon reserves exceed this remaining amount by a factor of 4 to 7, with resources much larger still."[xxv] With regard to this analysis, McGlade and Ekins (2015)[xxvi] estimate that by 2050 one third of oil reserves, half of gas reserves and 80% of coal reserves will have to remain unused if the 2°C target is to be met.

The 2900 billion tonne ceiling is an amount that can vary, in particular according to the changing storage capacity of the oceans and biosphere for atmospheric CO_2. Research carried out in the framework of the Global Carbon Budget documents such changes over the period between two IPCC reports.[xxvii] On the basis of the ceiling, whose magnitude is unlikely to change much in the short term, it is possible to calculate the carbon budgets for different reference years.

In 1990, at the start of the climate negotiations, cumulative CO_2 emissions stood at slightly more than 1400 billion tonnes, an amount that at the prevailing rate of emissions left 52 years for the global carbon budget to be exhausted. Over the following twenty-five years this temporal margin signally failed to be put to good use in altering the trajectory of CO_2 emissions.

By 2017, the hands of the climate clock had inexorably moved on. Year by year, the flow of emissions is increasing the stock of CO_2 stock present in the atmosphere. The cumulative figure is now greater than 2200 billion tonnes. If the annual emissions level reached in 2017 does not decrease, the global carbon budget will be exhausted within the next fifteen years.

The time left on the climate clock is inescapably set by the laws of physics, biology and chemistry. It is therefore the ticking of the climate clock that will necessarily determine the pace of the low-carbon transition, despite the inertia of energy systems that will not vanish in the next few decades. On top of this specific feature of the low-carbon transition compared to the past transitions, there is also another: we will have to abandon the previous additive system in favour of a substitution system involving the rapid withdrawal of fossil sources.

Shifting from an additive system to a replacement system

When the price of gas traded on the Louisiana Henry Hub falls in the United States due to the exploitation of shale gas, a proportion of coal-fired power plants are shut down in favour of gas-fired plants, leading to a reduction in CO_2 emissions. We are here within a logic of substitution that is beneficial for the climate if we are reasoning strictly at the national level. But the unused coal resources do not necessarily stay in the ground. If the price of coal for export falls as a result of its greater availability, it can lead to a reverse process of substitution from gas-fired to coal-fired power plants which cancels out the initial effect, as was seen in Europe between 2011 and 2015. We then find ourselves back in the additive system, with its disastrous impact on the climate.

Consequently the real degree of substitution achieved must be viewed on a global scale. By way of illustration, consider three scenarios for the energy sector in 2050, based on the average amount of energy consumed per capita and the energy coming from fossil sources (Figure 5).[xxviii] If significant amounts of fossil energy could be produced without emitting CO_2, through carbon capture and storage technologies, they should be classified as carbon-free sources, along with renewables, biomass and nuclear energy. Each of these scenarios has been given a colour label reflecting its distance from the 2°C target.

Figure 5: Three scenarios for the energy sector in 2050

	1973	2015	2050 scenarios		
			RED	BLUE	GREEN
Energy consumption (toe per capita)	1.55	1.86	2.0	1.86	1.2
Proportion of fossil energies (%)	86.7	81.4	75	50	25
- Oil	46.2	31.7	20	10	2
- Coal	24.5	28.1	25	10	8
- Natural gas	16	21.6	30	30	15
CO_2 emissions (Gt)	14.5	32.3	40.6	23.3	7.9

Source: Christian de Perthuis, The Conversation, 2017

The red label indicates climate disaster, which is avoidable, in the view of Jean-Pierre Dupuy, if we are convinced it may actually occur.[xxix] This scenario arises from a continuation of past trends. Per capita energy consumption continues to increase, though it is very unequally distributed, with a billion people still without access to electricity in 2050. There is only a slow decline in the use of carbon sources, due to the inertia of coal and particularly to the soaring use of fossil gas. The proportion of fossil fuels in the energy mix slowly declines, though without any real substitution, for the fastest growing renewable energies have supplemented fossil fuels but not replaced them. Under the red scenario, global emissions increase by a quarter between 2015 and 2050. The world's "carbon budget" is exhausted in less than fifteen years, resulting in warming of 4°C or more by the end of the century.

The blue label describes the energy system based on the application of the Paris Agreement, involving voluntary commitments with no real constraints. The average per capita energy consumption is the same in 2050 as it was in 2015. The decline in per capita consumption in the high-income countries has been counterbalanced by increased energy access in the less advanced countries through decentralized renewable electricity grids. By 2050, land transport has freed itself from its addiction to oil. The proportion of fossil fuels has fallen to 50% of primary sources. But the substitution is only partial: the residual volume of oil and coal is still substantial. And the share of fossil fuel gas has in fact increased. Under the blue scenario, global emissions of energy-related CO_2 decrease by nearly 30% between 2015 and 2050, but their cumulative effect leads to overshooting the carbon budget by about 45%. Global warming lies in the middle of the 2°C-4°C range at the end of the century.

In contrast to the red scenario, under the green scenario there is an acceleration of the low-carbon transition. By 2050, energy uses of oil have become a by-product of its chemical uses. The use of coal and to a lesser degree of gas has greatly declined, and their replacement by non-carbon sources has been facilitated by the decline in per capita energy consumption, which is down to just over one tonne of oil equivalent. The world has seen a massive redistribution from the high-income countries, where energy consumption has fallen by more than half, to the less advanced countries, where the sharp decrease in storage costs and low-carbon electricity production, combined with the extension of grids to rural populations, has ensured sustainable quality access to electricity. Under the green scenario, CO_2 emissions in 2050 are only a quarter of what they were in 2015, but cumulative emissions have nonetheless exhausted the carbon budget. To fully contain the risk of global warming above 2°C, it would be necessary to switch to a negative emissions regime, in which annual gross emissions are less than the amount of CO_2 sequestered by carbon sinks, before the end of the century.

Red, blue, green? Which path are we taking? The red scenario, which continues the historical pattern of stacking up energies, can no longer be viewed as the route we are destined spontaneously to follow. Economic forces (lower costs of renewables and electricity storage), social pressure (public awareness of fossil fuel-related health damage) and political initiatives (altered policies in the wake of the Paris Agreement) should durably spare us that particular outcome. But in which direction are we heading?

The “politically correct” Paris Agreement leads, in the best of cases, to the blue scenario, under which new carbon-free sources expand rapidly but only partially replace coal and oil and do not reduce the share of fossil gas. This scenario must now be viewed as inadequate, in that it falls far short of the target of keeping warming below 2°C.

To achieve the 2°C target, we need to aim for the green, disaccumulation scenario, under which high-income and emerging countries rapidly withdraw fossil sources from their energy systems and the less developed countries increase their access to energy without reproducing the historical patterns of adding new fossil sources. This twofold movement is possible only if efficiency gains speed up and are distributed in a completely new way.

The fair distribution of energy efficiency gains

The primary criterion for differentiating energy systems in 2050 is the amount of energy consumption per capita. Under the blue scenario, consumption stabilizes between 2015 and 2050, despite its never having done so over a comparable period at any point during the twentieth century. Under the green scenario, average per capita energy consumption falls by a third, an even greater departure from the historical norm, that would allow energy sources to be disaccumulated and would give a reasonable chance of stabilizing warming by the end of the century.

It is important to analyse the mechanisms underlying the fall in per capita energy consumption. For such a fall may equally well reflect either a worsening of energy impoverishment or a virtuous mechanism whereby efficiency gains are redistributed.

The green label could well apply to a world where the unequal distribution of resources and the polarization of wealth in the hands of a minority actually increases between 2015 and 2050. Energy savings would then come on the one hand from the spread of low-carbon production and consumption standards in the high-income countries, using processes that are inaccessible to a large part of the global population and on the other from the failure of energy development and access programmes in the less developed countries. The two levers for the decline in consumption would be the rationing of purchases and the lack of access to basic energy services. We are dealing here with a climate-friendly low-carbon transition, but one lacking a social safety net, and thus diametrically opposed to the principles of inclusion often associated with “green growth”.[xxx]

To escape this scenario, we need to imagine redistribution at the macroeconomic level of the benefits of growth from countries with high and intermediate living standards to less developed countries, following a pattern similar to that advocated by Tim Jackson.[xxxi] In this way, productivity gains would be redirected towards meeting the basic needs of low-income countries and populations, which would mean bringing to an end the accumulation of superfluous goods and services in the hands of the wealthy. A real social revolution, no less. In terms of the low-carbon transition, this has two implications.

- Prioritizing access to basic energy services in the less developed countries. This goal is clearly specified in the sustainable development roadmap adopted in 2015 within the framework of the United Nations. As with the case of health studied by Angus Deaton,[xxxii] inequalities in access to energy can only partially be explained by income gaps, and reducing them requires acting on multiple socio-economic and regulatory variables.[xxxiii] At comparable living standards, countries that have broadly disseminated basic care obtain the best results. In terms of energy, the reduction of renewable energy costs and digitization provide the technical means to speed up access to basic services for the majority of people. But progress is still slow, both for access to electricity and for improving traditional cooking practices, which is by far the leading source of global air pollution-related mortality.
- Proactively addressing the social component of the low-carbon transition, in terms of employment and living standards. The withdrawal from fossil fuel will result in significant financial losses in countries with abundant fossil resources and will involve professional retraining in fossil fuel consuming countries. The economic instruments introduced to accelerate the low-carbon transition are often anti-redistributive. This is the case for carbon taxes, which, in the absence of support measures, disproportionately affect households with low purchasing power.[xxxiv] But at the same time carbon taxes provide sufficient revenues to more than counteract these regressive effects.[xxxv] Similar anti-distributive effects are found in many systems aimed at promoting the low-carbon economy. For example, renewable electricity feed-in tariffs that have been set at levels above market prices, and whose additional cost is financed by a tax paid by all electricity consumers, has very often led to the subsidization of wealthy households by low-income households.

The reduction of inequality is only one of the measures enabling energy efficiency gains to facilitate the low-carbon transition. The other is to circumvent the well-known “rebound effect”.

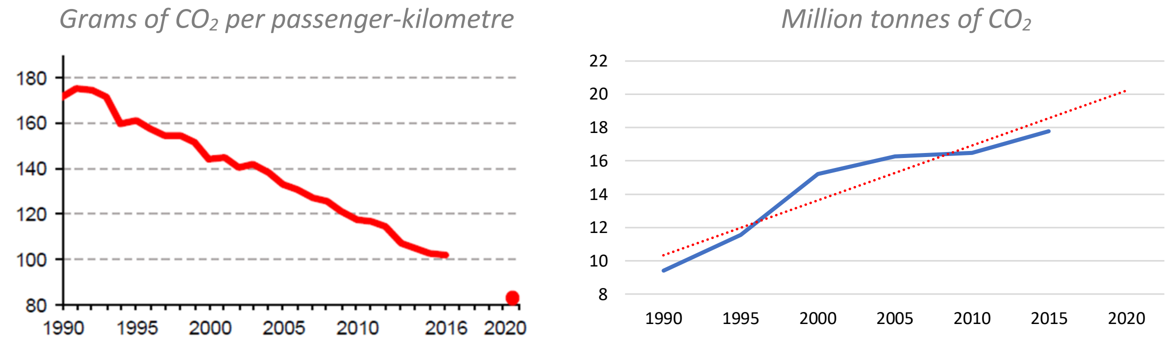
Distribution of energy efficiency gains: the rebound effect

The rebound effect was presciently described by Jevons in 1856: “It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.”[xxxvi] The rebound effect may be defined as the portion of efficiency gains used by economic agents to increase the amount of energy consumed, which is why it is the bane of policies aimed at controlling energy demand through energy efficiency.

In France, for example, it has been shown that households making improvements to the energy performance of their homes actually increase their energy consumption by up to 60%, and that this often allows “constrained” households to enhance their level of comfort.[xxxvii] But this phenomenon very much limits the effects of residential thermal renovation policies primarily intended to reduce energy consumption and CO_2 emissions.

In very fast-growing sectors, such as international air transport, this rebound effect is even more pronounced. Between 1990 and 2016, CO_2 emissions per passenger carried almost halved as a result of efficiency gains by airlines. But over the same period, emissions from international air transport doubled, making it the sector with the highest growth of CO_2 emissions in the entire economy (Figure 6).

Figure 6: CO_2 emissions from French international air transport 1990-2015



Grams of CO_2 per passenger-kilometre

Million tonnes of CO_2

Source: Authors, DGAC and IEA data

In the case of air transport, as in that of coal described by Jevons or of light analysed by Fouquet, efficiency gains induce spectacular increases in energy consumption through lower prices. The rebound effect is thus greater than 100% and in fact acts as a driver of the sector though the increase in induced demand. This dynamic of opening up markets through lower prices is central to the functioning of the economic system. If we want to make energy efficiency a lever for the low-carbon transition, we must provide powerful economic incentives to counteract a mechanism underlying much of the growth observed in the twentieth century.

To counter the spiral of the rebound effect, Von Weizsäcker (2009) proposes a tax system that would tax productivity gains and thereby prevent the long-term decline in the relative prices of energy and raw materials encouraging their use. “We have suggested increasing the prices of energy and of another primary energy resources by as many percentage points as the energy and resource productivity has increased in the previous year. Adjustments may be made using taxes and should begin one month after the statistical data of energy and materials productivity gains in the previous year is available […] This system of increase should be preferably be made binding for 50 years or more.”[xxxviii]

Apart from the practical difficulty of implementing it, this mechanism has two disadvantages. Firstly, it runs the risk of reducing incentives to raise productivity: economic agents are hardly likely to increase productivity if all the resulting gains are appropriated by the state. Secondly, it encourages energy savings but not energy substitution, which is a key driver of the low-carbon transition. It is therefore worthwhile exploring another way of countering the rebound effect, namely carbon pricing.

From an oil rent economy to a carbon rent economy

Ever since the visionary work of Pigou (1920), economists have regularly justified the use of carbon pricing instruments on the basis of efficiency criteria: a green tax allows environmental costs to be internalized and marginal costs to be equalised, thus helping reduce the total cost of action to protect the environment.

The issue of carbon pricing goes well beyond the effectiveness of action. Since the beginning of the 2010s, the low-carbon transition has been facilitated by lower costs for renewables and energy storage. In 2010, a bid to produce solar energy could be won with a price of around $180 per kWh. In 2018, bids are won at levels that have fallen as low as $30.[xxxix] A six fold price reduction, comparable to the falls in the price of the lumen or the megabyte analysed above.

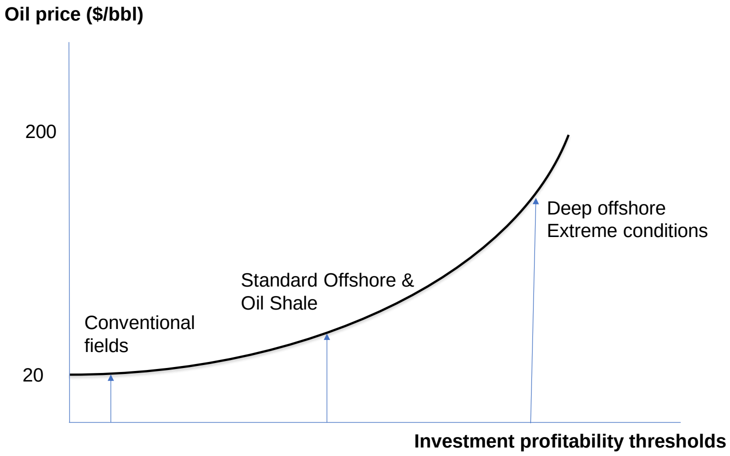
These relative price declines will continue stimulating investment in renewable electricity generation and encouraging the automotive industry to speed up the shift toward electric models. This dynamic takes us away from the red scenario and put us on the trajectory of the blue label. But it still conforms to the logic of accumulation, in which carbon-free sources only partially replace fossil fuels, which will resist for as long as possible. To accelerate the pace of the low-carbon transition and hasten the withdrawal of fossil energies, the relative price scale needs to be changed by means of carbon pricing.

Take the example of oil. Its economics is based on rent, which has two sides: scarcity rent and differential rent. It is this two-sidedness that may well prolong its exploitation beyond what would otherwise be the case.

When the relative scarcity of oil increases, for geological or geopolitical reasons, the price per barrel soars, and may exceed $100, as in 2008 or 2013. Higher prices tend to have a negative impact on the economy because they act as an indirect tax on consumers. On the other hand, they are favoured by environmental activists: the rise in the price per barrel makes consumers economise and find substitutes. Such reasoning is valid enough in the short term. But at the same time, rising oil prices increase the scarcity rent captured by producers, which encourages them to invest in new capacity and unconventional extraction technologies and thus augment the potential for CO_2 emissions in the medium and long term.

The increased supply finally catches up with demand, which has in the meantime been slowed by the price increase, and causes a further drop in prices. This is the cyclical phenomenon of “oil counter-shocks”. The decrease in price stimulates demand, causing CO_2 emissions to rebound, which is bad news in the short term for the climate, especially as producers reveal unsuspected resilience to lower prices. This is where the second aspect of the oil rent – differential rent – comes into play. In fact the great majority of producers pocket a second bonus, resulting from the difference between their operating costs and those of fields that are less accessible or produce lower quality oil. When the price per barrel drops to $20, less well-located producers suffer. But the Ghawar field in Saudi Arabia is still very profitable, with its cost of production in the range of 5 to 7 dollars a barrel. Its operator is not about to leave the market...

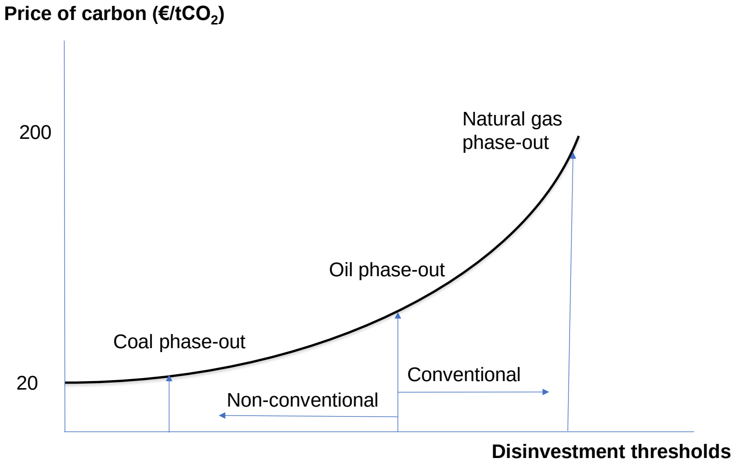
Figure 7: The economics of oil rent



The double-sidedness of oil rent also applies to other fossil fuels whose exploitation is based on the economic rules formalized by Hotelling. This rent dynamic leads to the prolongation of their use. If we are to disaccumulate energy sources, we need to bypass the exploitation of fossil sources by switching from an oil rent economy to a carbon rent economy.

The lynchpin of the carbon rent economy is the value given to climate protection through a CO_2 price. This price is a cost that will necessarily apply to all anthropogenic CO_2 emissions. It does not matter whether it is introduced into the economy through a tax, a cap-and-trade market or, less overtly, a set of standards. The important things is that is should provide the right incentives on both the supply side and the demand side.

Figure 8: Economics of carbon rent



On the consumer side, the introduction of a carbon price causes an increase in the cost of different energy sources in proportion to their respective CO_2 content. Two incentives result from this measure: first, an incentive to economise on energy, the average cost of which is increasing; and second, an incentive to replace the most CO_2-emitting sources by carbon-free or low-carbon sources. This mechanism has been applied in Sweden, where a carbon tax of more than €120/tCO_2 makes the use of fuel oil or gas from fossil sources prohibitively expensive, and these are virtually no longer used in heating networks. As a result, Sweden emits half as much CO_2 per capita for heating buildings as Spain, where the climate is far warmer.

In a carbon-rent economy, virtuous consumer incentives are no longer counterbalanced by a counter-effect of expanding fossil-producing capabilities on the producer side prompted by rising prices. Once the carbon price becomes the guiding light of the energy transition, carbon rent takes precedence over oil rent. It becomes increasingly less profitable to invest in fossil fuels as the cost of CO_2 rises, unless carbon capture and storage technologies allow the use of fossil energy from CO_2 to be dissociated from emissions. The rising cost of CO_2 thus turns both producers and consumers away from CO_2-emitting fossil sources.

While carbon pricing is an appropriate tool for speeding up the exit from fossil fuels and moving towards energy sobriety, its practical application is much more problematic with regard to biomass and more generally “living carbon”. For the aim of “carbon neutrality” is closely bound up with the key role of agriculture and forestry in the energy transition.

The goal of carbon neutrality

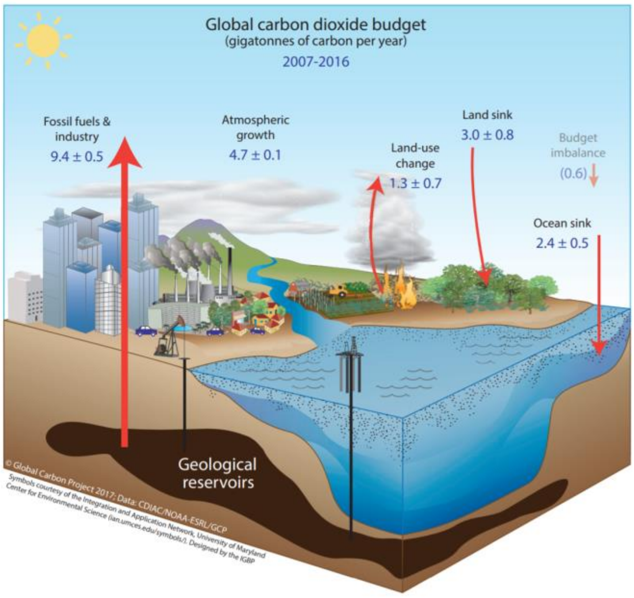
The second long-term target introduced by the Paris Agreement is “carbon neutrality”, which involves limiting emissions of greenhouse gases into the atmosphere to what can be absorbed by natural or man-made CO_2 sinks. This results in a net zero emissions regime, which stabilizes the concentration of greenhouse gases in the atmosphere – in other words, the right control variable for acting on global warming. The target of neutrality is therefore relevant if it can be translated into concrete objectives for the different Parties to the Agreement.

Like other European countries, France has adopted this objective of carbon neutrality by 2050, without, however, clarifying the implications of transposing the global objective to the scale of a country or group of countries. This objective is often linked to the possibility of creating artificial sinks storing CO_2 by means of carbon capture and storage technologies. But the main issue regarding carbon neutrality lies elsewhere, and primarily concerns the role of agriculture and forestry in sequestering carbon or emitting it into the atmosphere, depending on how these sectors are managed.

Let us suppose that at the global level, the energy transition has been effectively translated into a permanent exit from fossils fuels and that in 2050 the energy system emits no more a single tonne of CO_2. Let us also suppose that emissions related to industrial processes have been completely eliminated, for example through CO_2 capture and storage techniques. Would we then have succeeded in eliminating greenhouse gas emissions into the atmosphere?

The answer is no, for there would still be emissions associated with agriculture, forestry and the management of organic waste, which account for more than a quarter of global greenhouse gas emissions. These activities all play a part in the “living carbon” cycle, which covers everything produced by photosynthesis and is at the origin of food chains. For the most part, their emissions do not consist of CO_2 from the combustion of fossil fuels, but are composed of methane and nitrous oxide mainly released by agriculture and the destocking of CO_2 caused by deforestation and the tillage or erosion of soil (Figure 9).

Figure 9: The global carbon cycle



Source: Global Carbon Budget, 2017

The decarbonisation of the energy system therefore only marginally affects emissions from "living carbon" sectors. And it could even have the reverse effect if it causes land-use changes that alter the absorption capacity of natural carbon sinks, since most renewable sources produce less energy per hectare than fossil (or nuclear) sources.

Take the example of energy biomass. The use of traditional biomass, the main source of energy in the less advanced countries, leads in many cases to excessive withdrawals that the natural environment is unable to replenish. "Fuelwood" is thus a significant source of tropical deforestation. This traditional source will be lost if the low-carbon transition is accompanied by real progress in energy access. But it could be replaced by withdrawals that are even more destructive for the natural environment if fossil sources are incautiously replaced by industrial uses of biomass.

Along with the risk of destabilization of food balances, this is the main limitation to the expansion of first-generation biofuels. Subsidized on a large scale in the United States and Europe, these programmes have a far greater carbon footprint than Brazil's from by-products of sugar cane. The carbon balance for these programmes is clearly negative because of its deforestation effects when palm or coconut oil is used as a raw material. This risk of overexploitation of the resource is found in projects for converting coal-fired power plants to biomass.[xl] Given the number of coal plants to be converted around the world, the resources required would be considerable. This is why the potential effects of conversions that have been made in the United Kingdom, for example, or those under discussion for the Gardanne and Cordemais plants in France must be carefully assessed. If poorly controlled, massive replacement of coal by wood would lead to overexploitation of the natural environment, which would not be able to provide the fuel needed without increasing the emission of CO_2 into the atmosphere.

Agriculture, on the other hand, can produce large amounts of energy by promoting the conservation of the natural environment, through agroforestry or the methanization of agricultural waste. Hedgerow rebuilding and maintenance has great potential in areas where the development of field crops has occurred at the expense of plant cover. Methanization improves the management of livestock manure and encourages intercropping practices that reduce soil erosion.

The goal of carbon neutrality therefore introduces a new dimension into the low-carbon transition. It is necessary to address both fossilized carbon in the energy system and living carbon that can either supply food chains or provide energy sources. This dimension of the energy transition raises unknown issues, as if energy, food and deforestation were disjoint sets. In addition, living carbon is the main sink capable of increasing the sequestration of atmospheric CO_2 in the coming decades.

Investment in sinks: biodiversity in the service of the low-carbon transition

At the international level, the main change in land use affecting the carbon cycle is tropical deforestation, which results in destocking of CO_2. Varying from one year to the next, tropical deforestation accounts for around 10% of global greenhouse gas emissions. The main cause of this massive release of CO_2 is the destruction of forest for growing crops and raising livestock. To combat tropical deforestation, it is essential to deal with its agricultural causes, as exemplified by Brazil, which has managed to more than halve the rate of deforestation by curbing the cultivation of soybeans and cattle rearing in Amazonia.[xli]

The capacity of the biosphere to store carbon also depends on how farmers and ranchers use the land: permanent grassland, hedgerows, and intercropping help store carbon in the soil; the erosion of bare land, ploughing and excessive use of chemicals deplete its living matter and release CO_2.

In cases where soils are severely degraded and poor in living matter, there is considerable potential for CO_2 storage if the trend is reversed by appropriate agricultural practices. This potential is particularly high in the Sahel and semi-arid zones of Africa, where the restoration of agricultural soils could at the same time combat food insecurity by increasing yields per hectare. The “4 per 1000” initiative launched at the 2015 Paris climate conference could play a part here if it results in action at the local level.[xlii]

In contrast, in cases where soils are already saturated with CO_2, such as in the peat bogs of the Indonesian forest, there is no additional storage potential. The right strategy is then to protect these natural environments so as to conserve the accumulated carbon.

Such a reorientation of agriculture and forestry could in the long term be a vital component of a successful transition to carbon neutrality, as well as having beneficial effects on the diversity and health of the natural environment.

Investment in carbon sinks capturing CO_2 from the biosphere will not involve massive investment in new large-scale industrial processes. It primarily calls for investment in natural and human capital, drawing on varied scientific resources in order to understand the complex functioning of ecosystems and involving a multiplicity of experiments by actors in the territories concerned. For farmers, it is also a training issue: practising biocontrol to protect crops requires a much higher level of technical knowhow than is required for the application of chemicals, the inputs of which are generally specified by their manufacturers. All this is far cry from the misleading retrograde image sometimes associated with organic farming.

It is difficult to quantify the potential effect of the CO_2 that is removed from the atmosphere in this way. What matters for the climate is solely the net increase in atmospheric CO_2 that can be absorbed by the natural environment. By construction, this quantity cannot grow indefinitely. Investing in carbon sinks therefore lies within a perspective of transition, since additional CO_2 capture becomes pointless once the gross emission sources are eliminated from the system, in accordance with a global programme based on the fundamentals of the circular economy.[xliii]

On the other hand, investment in the restoration of carbon sinks has beneficial effects in the longer term. It involves re-establishing positive dynamics within the natural environment in order to enhance its regenerative capacity on the basis of biological diversity. In short, it is also an investment in the fight against the loss of biodiversity, one of the other major natural regulation systems seriously disrupted by human activity. It is therefore a particularly important aspect of the path toward carbon neutrality.

Conclusion: for a holistic approach to the low-carbon transition

The low-carbon energy transition that is now beginning will concern both the energy system and agriculture and forestry, which are an integral part of it: by supplying people with calories on a daily basis, agriculture provides what can be called the primary energy system. Including this primary function in the energy system gives a clearer view of what is at stake in the low-carbon transition.

Virtually the only sources of energy until the beginning of the 20th century, agriculture and forestry initially supplied the human species with food energy. The first energy transition was based on the control of fire, which was used for cooking, heating and smelting metals. The rearing of livestock following the establishment of settled society introduced a second energy transition, in which human muscle power was supplemented by animal traction and the feeding of livestock became a major energy supply source for transport and tilling the soil.

Over the last two centuries, fossil sources have vastly increased the amount of energy consumed and have multiplied the uses it has been put to. This fossilized carbon was initially a living stock of carbon that took tens of millions of years to transform into exploitable deposits. In two centuries, the earth’s inhabitants have totally short-circuited geological time, which explains the magnitude of the disturbance caused by this rapid release of CO_2.

In both cases, the primary source of the energy system emerges after photosynthesis has transformed the solar energy falling on the planet into living carbon, with a gap of millions of years separating fossil energy from living energy. Any attempt to rebalance the system on the basis of these post-photosynthesis sources alone would quickly lead to unmanageable conflicts between energy use, food use and other uses on a planet that will soon have a human population of more than nine billion. This is why the exit from fossil fuels can only occur subject to two conditions: the massive reduction of waste in the use of energy and the introduction of new non-carbon sources.

Among the substitutes for post-photosynthesis sources, wind, hydraulics, and marine currents, all of which have long been used in windmills and sailing vessels, can increase their contribution without creating any major disruption. The potential of nuclear energy, through fission and possibly fusion in the future, is and will be burdened by the numerous problems of risk management associated with its use. This leaves solar power, the capture of energy prior to photosynthesis, which, as Smil (2017) makes clear, “is the only form of renewable energy whose total terrestrial flux far surpasses not only today demand for fossil fuels but also any level of global energy demand realistically imaginable during the 21st century (and far beyond)[xliv].

This global vision integrating agriculture and forestry introduces the complexity inherent in living systems, which makes it difficult to include agriculture and forestry in carbon pricing schemes designed to accelerate the exit from fossil sources. But it does allow us to better assess the progress of the low-carbon transition, involving unprecedented transformation for human societies. These shifts will variously involve making energy choices on “carbon above” – the quantity of which varies according to gross emissions but also according to the capacity to strengthen carbon sinks through the protection of biodiversity; moving from a logic of stacking up primary energy sources to a logic of substitution involving a rapid exit from fossil sources without a negative rebound effect on the natural environment as a result of the overexploitation of energy biomass; and seeking to reduce per capita energy consumption, both in terms of the energy needed to feed people and the energy used for transportation, heating, lighting and so on.

These general guidelines may be inflected in accordance with the situation applying in different countries. In the case of France, they could profitably inform a public debate that is still overly focussed on the role of nuclear power in the electric mix, as shown by the consultation with citizens carried out on the occasion of the "Multiannual Energy Programme".[xlv] They could also help clarify the concept of carbon neutrality, which was surreptitiously introduced into the objectives of the French climate plan without any citizen or parliamentary consultation. Lastly, they would give greater coherence to public policy, which appears to treat action to combat global warming on the one hand and the fight against the loss of biodiversity on the other as two separate issues.

Appendix 1 – Energy consumption by source (Mtoe)

	Coal	Oil	Gas	Other	Total	Fossil fuel share (%)
1800	9			520	529	2%
1850	53			676	729	7%
1900	536	17	6	596	1 133	49%
1910	810	37	13	652	1 462	59%
1920	920	83	22	761	1 681	61%
1930	948	164	56	909	1 857	63%
1940	1 084	248	82	1 024	2 109	67%
1950	1 180	510	196	1 439	2 618	72%
1960	1 445	1 039	419	2 344	3 790	77%
1970	1 622	2 218	933	4 185	5 807	82%
1980	2 075	2 866	1 346	5 507	7 581	83%
1990	2 447	2 947	1 840	6 542	8 989	80%
2000	2 496	3 358	2 239	7 679	10 175	80%
2010	3 900	3 690	2 964	8 901	12 801	82%
2015	4 152	4 020	3 218	9 511	13 663	83%

Source: Data from V. Smil (2017)

Since 1800, the stacking up of primary sources has been the engine of energy transitions. New sources are added to the pre-existing ones, without replacing them. Moving from this additive system to a substitution system will be the main challenge of the low-carbon transition.

Appendix 2 – CO_2 emissions by source ($MtCO_2$)

	Coal	Oil	Gas	Land use + Cement	Total	Share of energy emissions (%)
1850	198			2 548	2 746	7%
1900	1 889	59	11	4 215	6 174	32%
1910	2 853	125	26	4 548	7 552	40%
1920	3 091	286	40	4 492	7 910	43%
1930	3 161	557	103	5 105	8 926	43%
1940	3 729	840	154	5 870	10 593	45%
1950	3 924	1 551	356	6 011	11 842	49%
1960	5 170	3 113	832	6 672	15 788	58%
1970	5 706	6 744	1 808	5 443	19 700	72%
1980	7 096	8 881	2 703	4 686	23 366	80%
1990	8 650	9 138	3 762	5 518	27 069	80%
2000	8 533	10 466	4 727	5 791	29 517	80%
2010	13 979	11 393	6 219	6 988	38 579	82%
2015	14 690	12 270	6 843	7 935	41 738	81%

Source: DIAC data

The energy transition that has been going on for two centuries has led to a massive increase in energy-related emissions, which accounted for 81% of total CO_2 emissions in 2015, compared to just under half in 1950 and less than a third at the beginning of the last century.

Appendix 3 – Population, energy consumption and CO_2 emissions per capita

	World population (in millions)	Energy consumption (toe per capita)	CO_2 emissions (tCO_2 per capita)	of which energy emissions (tCO_2 per capita)
1800	900	0,59	*nd*	*nd*
1850	1 200	0,61	2,3	0,2
1900	1 650	0,69	3,7	1,2
1910	1 700	0,86	4,4	1,8
1920	1 860	0,90	4,3	1,8
1930	2 070	0,90	4,3	1,8
1940	2 300	0,92	4,6	2,1
1950	2 536	1,03	4,7	2,3
1960	3 033	1,25	5,2	3,0
1970	3 701	1,57	5,3	3,9
1980	4 458	1,70	5,2	4,2
1990	5 331	1,69	5,1	4,0
2000	6 145	1,66	4,8	3,9
2010	6 958	1,84	5,5	4,5
2015	7 383	1,85	5,7	4,6

Source: Data from V. Smil (2017), CDIAC and UN

Population growth and increased per capita fossil fuel consumption are the two main drivers of anthropogenic CO_2 emissions into the atmosphere.

Appendix 4 – Lighthouse of the Whales (Phare des Baleines)

Source: https://www.iledere.com/

The tower of the whales (on the left in the photo) was one of the first lighthouse to come into service in France. It was commissioned by Colbert, then Secretary of State for the Navy, and completed in 1682 under the supervision of Vauban. Originally fuelled with fish and whale oils, it then switched to coal and oil, which marginally improved its effectiveness. The current lighthouse (on the right in the photo) came into operation in 1854. Its electrification took place at the beginning of the last century and it was connected to the electricity grid in the 1950s. Its range was considerably increased through the Fresnel lens *and subsequently by using bulbs that are much more efficient in converting energy to light.*

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