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Energy in a changing climate

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Abstract. Warming of the Earth's climate represents the "great challenge" of our times that may even undermine the subsistence of humankind on the planet. This paper reviews the causes and effects of climate change due to the anthropogenic activities. Since energy production constitutes the main source of climate-forcing anthropogenic emissions, a particular emphasis is given in the paper to the energy system transition to meet the objectives of the Paris Agreement, the international treaty signed in 2015 under the auspices of the United Nations Framework Convention on Climate Change, aimed at reducing the risks and effects of climate change on the global society.

Keywords. Climate change, anthropogenic emissions, energy system transition, IPCC, Paris agreement.

1. THE EARTH'S CLIMATE SYSTEM

The term "climate" (from the ancient Greek word *klima*: inclination) refers to the meteorological and environmental conditions in a given geographical area averaged over a long period of time, typically 30 years or more, as defined by the World Meteorological Organisation (WMO).

The Earth's climate system includes different components, sometimes referred to as "compartments", which interact dynamically with each other: atmosphere, ocean, Earth surface, cryosphere and biosphere, the life on the planet, including mankind. The system evolves with time, influenced both by an internal dynamics and by external factors called climate forcings. Climate forcing can either be due to natural phenomena (natural forcing) or to anthropogenic activities, in the latter case defined as anthropogenic forcing.

The "engine" of the Earth's climate is the Sun. The Earth's surface, in fact, receives energy from the Sun, 50% of which in the visible part of the electromagnetic spectrum. Part of the incident radiation is reflected back to space by the Earth's surface and by the clouds. The fraction of reflected energy is defined "albedo". The Earth's albedo is on average approximately 0.3 (30% of the solar energy is reflected back to space), but varies considerably in different areas of the globe depending on the nature of the surface: snow and ice, sea surface, vegetation, desert, urban areas, etc. To balance the absorbed incoming energy, the Earth must radiate the same amount of energy back to space. Because the Earth is much colder than the Sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum. The Earth reaches therefore an equilibrium temperature where absorption and emission are balanced (Fig. 1).

But in the atmosphere are naturally present certain atmospheric constituents such as water vapour, carbon dioxide (CO_2), methane (CH_4) nitrous oxide (N_2O) and other compounds that absorb a significant fraction of the infrared radiation emitted by the Earth. The absorbed energy is then re-emitted in all directions thus contributing to the warming of the lower levels of the atmosphere causing the so-called (natural) greenhouse effect, in analogy with the heat trapping effect of the glass walls in a greenhouse illuminated by the Sun that increases the temperature of the air inside (Fig. 1). These absorbing species are therefore cumulatively called greenhouse gases (GHGs).

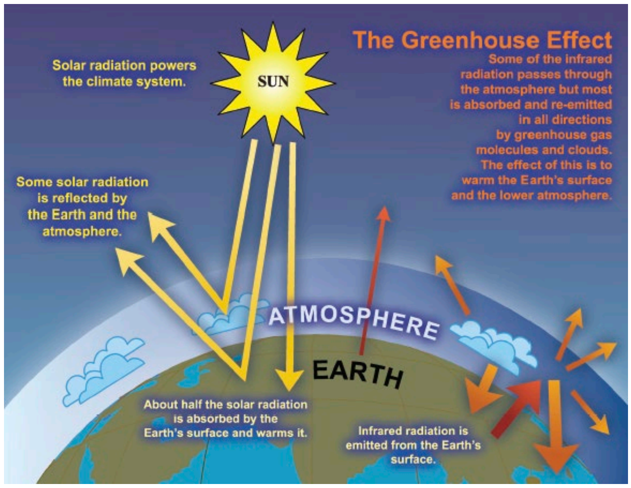

Figure 1. Schematic representation of the Earth's climate system and the greenhouse effect (from Le Treut et al., 2007).

In the absence of an atmosphere the radiative equilibrium temperature of the Earth would be purely a function of the distance of the Earth from the Sun and of the surface albedo that is -18°C. But, as a consequence of the natural greenhouse effect, the average surface temperature of the Earth is ca. 15°C, 33°C higher than the radiative equilibrium temperature.

It is easy to understand that, in the absence of the natural greenhouse effect, the life on the planet would not have developed, at least not in the way we now experience.

2. THE ANTHROPOCENE

After the end of the last glaciation, ca. 12.000 years ago, the warmer temperatures caused by the natural greenhouse effect favoured, with the development of agriculture, the emergence of our civilization.

Since the onset of civilisation, man has modified the natural environment to make it more suitable to his needs, e.g. clearing large forested areas transformed into agricultural land. Until recent times, however, the world population was quite limited in number and the technologies available were relatively primitive, therefore the impact of humans on the environment had been quite limited both quantitatively and spatially.

But for the past two centuries or so the effects of humans on the global environment have increased dramatically. During the past two centuries, the human population has increased tenfold to more than 7 billion and is expected to reach 10 billions in this century. Humans exploit about 30 to 50% of the planet's land surface and use more than half of all accessible fresh water. Energy use has grown 16-fold during the twentieth century, causing 160 million tonnes of atmospheric sulphur dioxide (SO_2) emissions per year, more than twice the sum of its natural emissions. More nitrogen fertilizer is applied in agriculture than is fixed naturally in all terrestrial ecosystems; nitric oxide (NO) production by the burning of fossil fuel and biomass also overrides natural emissions. Fossil fuel burning and agriculture have caused substantial increases in the concentrations of GHG, CO_2 by 40% and CH_4 by more than 150%, reaching their highest levels over the past 800 millennia (Crutzen, 2002).

For all these reasons the Nobel Laureate Paul Crutzen and the biologist Eugene Stoermer suggested that the Holocene, the geologic epoch initiated with the end of the last glaciation has come to an end and that it seems appropriate to assign the term Anthropocene to the present geological epoch in many ways dominated by human activities (Crutzen and Stoermer, 2000).

There are different views concerning the beginning of the Anthropocene. While Crutzen and Stoermer had dated the beginning of the Anthropocene with the beginning of the industrial revolution in mid-18th century, Ruddimann (2013) has put forward the idea that mankind has started modifying the natural environment at least 9,000 years ago with the large deforestations to get cultivable land. Finally, more recent discussions have determined that the beginning of the Anthropocene as a geological epoch should be dated to the early 1950s, corresponding to the "Great Acceleration" after the 2nd World War, marked by a major expansion in human population, large changes in natural processes, the development of new materials and of the international trade (Lewis and Maslin, 2015).

3. CLIMATE CHANGE IN THE ANTHROPOCENE

Human activities contribute to climate change by causing changes in the atmosphere of the amounts of greenhouse gases and other gaseous and particulate components, with the largest contribution deriving from the burning of fossil fuels. Since the beginning of the industrial era, the overall effect of human activities on climate has been a warming influence and the human impact now greatly exceeds that due to natural processes, such as solar changes and volcanic eruptions (Forster et al., 2007).

The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), published in 2014, reports that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcing agents together. In fact, the best estimate of the human-induced contribution to warming is similar to the observed warming over the same period (Fig. 2).

The observed surface temperature change in Fig. 2 is shown in black; the attributed warming ranges (colours) are based on observations combined with climate model simulations, in order to estimate the contribution of an individual external forcing to the observed warming. The 5 to 95% uncertainty range is superimposed to the bars.

Human-induced warming has now reached on average 1°C above pre-industrial levels in 2017, increasing at a rate of 0.2°C per decade, but warming greater than the global average has already been experienced in many regions and seasons (Allen et al., 2018).

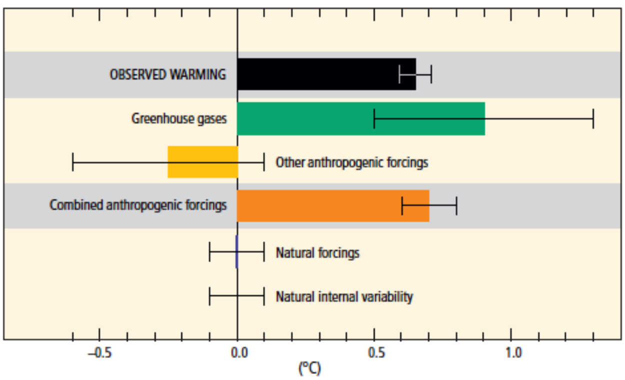

Figure 2. Comparison between the observed increase of global mean temperature (GMST) over the period 1951-2010 and the estimated anthropogenic contribution. The black bar is the observed GMST over the period, while the green and yellow bars represent the modelled contribution of GHGs and other climate forcers (mainly atmospheric aerosols that exert a cooling effect on climate; Fuzzi et al., 2015), respectively. The orange bar is the sum of the two (green + yellow) representing the total modelled temperature increase due to anthropogenic emissions. As can easily be seen, the modelled and observed GMST increase are very close to each other, taking into account the uncertainty ranges of the different quantities (the 5 to 95% uncertainty range is reported on top of each bar). The natural contributions to GMST increase and the internal variability of the Earth's climate system are minimal, if not negligible (from IPCC 2014).

3.1. Anthropogenic GHG emission

The main GHGs deriving from human activities are the above-mentioned CO_2, CH_4 and N_2O. These gases accumulate in the atmosphere, causing concentrations to increase with time. Significant increases of all these components have occurred in the industrial era (Fig. 3), with an even higher increase staring from the 1950s (the Great Acceleration). All of these increases are attributable to human activities (IPCC 2014).

Between 1750 and 2011, the cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 $GtCO_2$. About 40% of these emissions have remained in the atmosphere (880 ± 35 $GtCO_2$), the rest was removed from the atmosphere and stored on land (in plants and soils) and in the ocean that has absorbed about 30% of the emitted anthropogenic CO_2. What is more important, about half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred over the last 40 years.

CO_2 is not, as previously mentioned, the only GHG emitted by human activities, and Fig. 4 reports the glob-

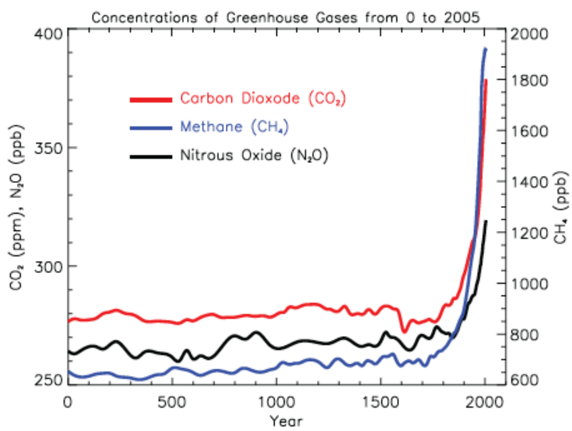

Figure 3. Atmospheric concentrations of the most important GHGs over the last 2,000 years. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb) (from Forster et al., 2007). Present GHG concentrations (2017) are: CO_2 = 406 ppm, CH_4 = 1859 ppb, N_2O = 330 ppb (WMO, 2018).

al annual anthropogenic GHG emissions expressed as CO_2-equivalent (CO_2-eq). The global GHG emission in 2010 amounted to 49 Gt CO_2-eq.

The main drivers of anthropogenic GHG emissions are the population increase and the increasing energy needs of our society. Some figures illustrate the combined effects of the evolution of these two parameters.

At the time when agriculture emerged, about 10,000 B.C., the population of the world was estimated a few millions, growing to a couple of hundred millions by year 1 A.D.. Around 1800 the world population had reached one billion, with the second billion achieved in only 130 years (1930), the third billion in 30 years (1960), the fourth billion in 15 years (1974), and the fifth billion in only 13 years (1987). During the 20th century alone, the population in the world has grown from 1.65 billion to over 6 billions.

On the other hand, the world per-capita energy consumption, that amounted to some 20 GJ per year at the beginning of the 19th century has now reached ca. 80 GJ per year (Tverberg, 2012).

3.2. Anthropogenic GHG emissions by economic sector

All human activities cause the emission in the atmosphere of GHGs, and Fig. 5 reports the global anthropogenic GHG emissions from different economic sectors in 2010 (IPCC, 2014).

As can be seen from the figure, energy production constitutes the anthropogenic activity with the highest share of GHG emission (35%).

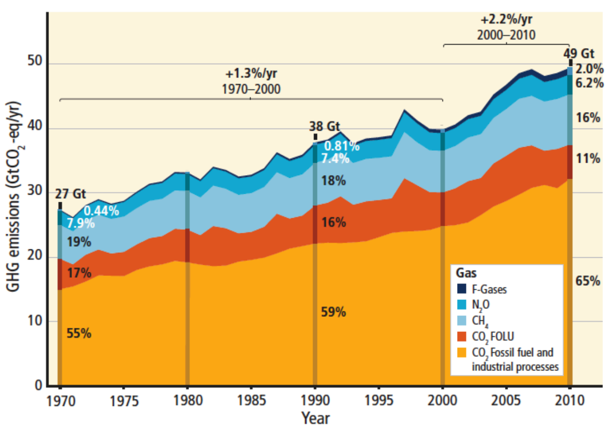

Figure 4. Total annual anthropogenic GHG emissions in gigatonnes of CO_2-equivalent per year ($GtCO_2$-eq/yr) for the period 1970 to 2010 by gases: CO_2 from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use (FOLU); CH_4; N_2O; gases covered under the Kyoto Protocol (F-gases) (from IPCC, 2014).

4. THE EFFECTS OF CLIMATE WARMING

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. The 5th IPCC Assessment Report has described in great detail the observed effects on the basis of some main climatic parameters (IPCC, 2014).

4.1. Temperature increase

Global warming (presently +1°C GMST with respect to the preindustrial period) is already negatively influencing the agricultural yields, thus affecting food security (Zhao et al., 2017). At the same time, the increase of seawater temperature is influencing the marine ecosystems and biodiversity. At present, the worldwide effect on human health of climate warming has been relatively small, although an increased heat-related mortality has been reported (e.g. the 2003 heat wave in central-southern Europe). Climate warming is also altering the precipitation regimes of several regions with effects on water availability and agricultural yields (Steffen et al., 2015).

4.2. Sea level rise

Over the period 1901–2010, global mean sea level rose by 0.19 m (0.17 to 0.21). This is mainly due to gla-

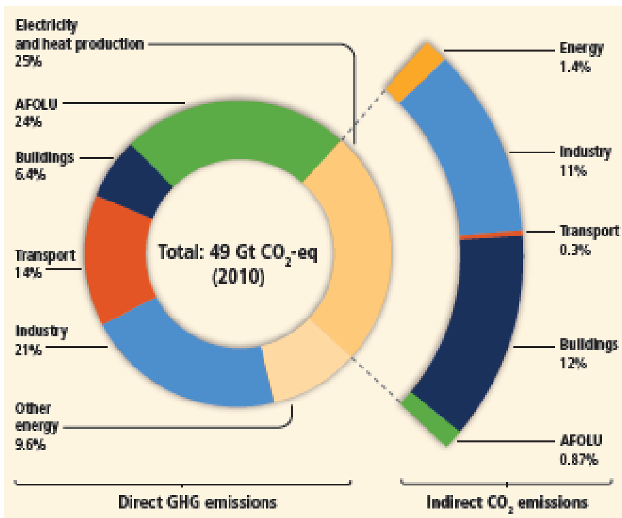

Figure 5. Total anthropogenic GHG emissions in $GtCO_2$-eq/yr) from different economic sectors in 2010. The circle shows the shares of direct GHG emissions in percentage of total emissions form the five main economic sectors. The pullout shows how shares of indirect CO_2 emissions from electricity and heat production are attributed to sectors of final energy use (IPCC, 2014).

cier mass loss and ocean thermal expansion (IPCC, 2014). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia. Sea level rise is threatening all coastal areas with risk of flooding and the need of relocating the affected population (Nicholls et al., 2011).

4.3. Melting of glaciers

Over the last two decades, the Greenland and Antarctic ice sheets have been loosing mass and glaciers have continued to shrink almost worldwide, contributing on the one side to sea level rise, and on the other threatening freshwater availability in many regions of the world (IPCC, 2014).

4.4. Extreme events

The impact of recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires reveal significant vulnerability of some ecosystems and many human systems to current climate variability. Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructures and other consequences for human wellbeing (IPCC, 2014).

5. THE PARIS AGREEMENT AND THE MEANS FOR THE IMPLEMENTATION

The policy actions to be implemented in order to limit the effects on the human society of the climate warming that is already happening fall under two broad categories:

- *mitigation* – measures aimed at reducing the emission of GHGs and other climate forcers (energy efficiency, decarbonisation, more efficient agricultural practices, etc.);
- *adaptation* – technological and infrastructural measures that allow contrasting the effects of climate change in progress.

Since more than 25 years the United Nations Framework Convention on Climate Change (UNFCCC) has been working on a global treaty that could reduce the GHGs emissions to contrast climate change. Finally, on December 12, 2015, within the 21st UNFCCC Session, 196 Countries, responsible for 95% of global GHG emission, approved the so called "Paris Agreement" that deals with GHG emissions mitigation, adaptation, and finance and that will formally start in the year 2020. The long-term overall goal of the Paris Agreement is to keep the increase in global average temperature to well below 2 °C above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, since this would substantially reduce the risks and effects of climate change.

IPCC was then invited by the UNFCCC to provide a Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways contained in the Paris Agreement. This Report was actually prepared and presented in October 2018 (IPCC, 2018).

The headline statements reported below from the Summary for Policymakers highlight some of the main conclusions of the report (IPCC, 2018). For a guide to the treatment of uncertainty within the IPCC reports, reference is made to Mastrandrea et al., (2010).

5.1. Understanding global warming of 1.5°C

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*).

Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are unlikely to cause global warming of 1.5°C (*medium confidence*).

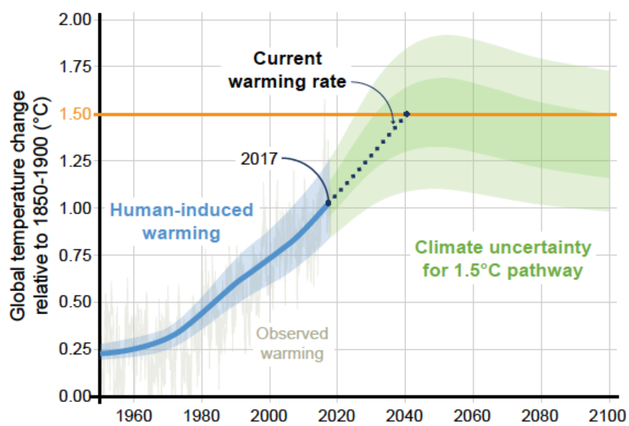

Figure 6. Human-induced warming reached approximately 1°C above pre-industrial levels in 2017. At the present rate, global temperatures would reach 1.5°C around 2040. Stylized 1.5°C pathway shown here involves emission reductions beginning immediately, and CO_2 emissions reaching zero by 2055 (from Allen et al., 2018).

Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*).

5.2. Projected climate change, potential impacts and associated risks

Climate models project robust differences in regional climate characteristics between present-day and global warming of 1.5°C, and between 1.5°C and 2°C. These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*).

By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depend on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*).

On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans (*high confidence*).

Limiting global warming to 1.5°C compared to 2°C is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected

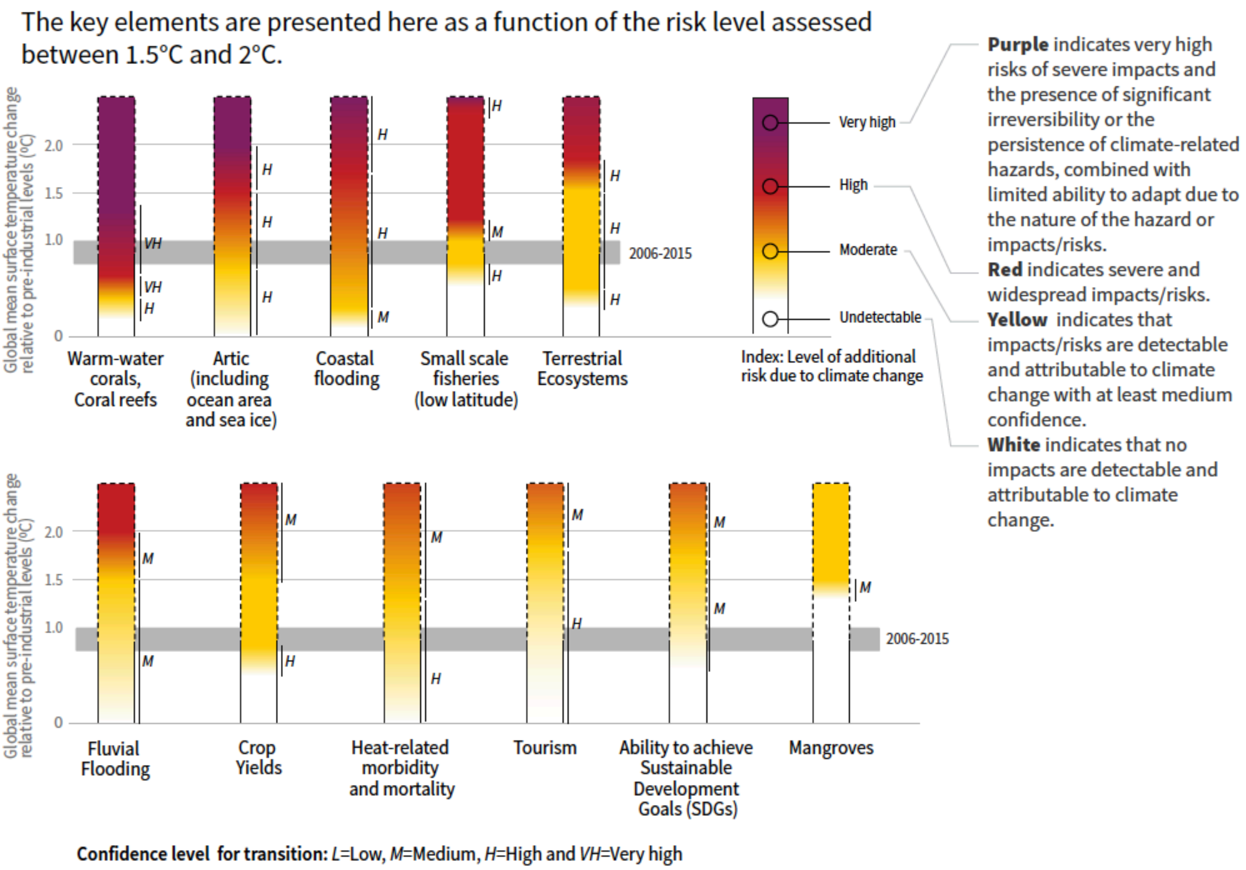

Figure 7. The dependence of risks and/or impacts associated with selected elements of human and natural systems on the level of climate change, highlighting the nature of this dependence between 0°C and 2°C warming above pre-industrial level (from Hoegh-Guldberg et al., 2018).

to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef ecosystems (*high confidence*).

Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There is a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*).

5.3. Emission pathways and system transitions consistent with 1.5°C global warming

Two main pathways can be followed for limiting global temperature rise to 1.5°C above pre-industrial levels: i) stabilizing global temperature at 1.5°C or ii) global temperature temporarily exceeding 1.5°C before coming back down later in the century. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C, CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C (*high confidence*).

Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant up-scaling of investments in those options (*medium confidence*).

All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*).

6. ENERGY SYSTEM TRANSITION TO MEET THE OBJECTIVES OF THE PARIS AGREEMENTS

Realizing a 1.5°C-consistent pathway would require rapid and systemic changes on unprecedented scales in: i) the energy system, ii) land and ecosystem management, iii) urban and infrastructure planning, iv) the industrial system. As previously stated, the energy system constitutes the anthropogenic activity with the highest share of GHG emission and in this section mitigation and adaptation options related to the energy system transition will be reported, derived from the IPCC 1.5°C Report (de Coninck et al., 2018).

To limit warming to 1.5°C, mitigation would have to be large-scale and rapid. Transformative change can arise from growth in demand for a new product or market, such that it displaces an existing one. This is sometimes called "disruptive innovation". For example, high demand for LED lighting is now making more energy-intensive, incandescent lighting near obsolete, with the support of policy action that spurred rapid industry innovation. Similarly, smart phones have become global in use within ten years. But electric cars, which were released around the same time, have not been adopted so quickly because the bigger, more connected transport and energy systems are harder to change. Renewable energy, especially solar and wind, is considered to be disruptive by some as it is rapidly being adopted and is transitioning faster than predicted. But its demand is not yet uniform. Urban systems that are moving towards transformation are coupling solar and wind with battery storage and electric vehicles in a more incremental transition, though this would still require changes in regulations, tax incentives, new standards, demonstration projects and education programmes to enable markets for this system to work (de Coninck et al., 2018).

Different types of transitions carry with them different associated costs and requirements for institutional or governmental support. Some are also easier to scale up than others, and some need more government support than others. The feasibility of adaptation and mitigation options requires careful consideration of multiple different factors. These factors include:

- whether sufficient natural systems and resources are available to support the various options (environmental feasibility);
- the degree to which the required technologies are developed and available (technological feasibility);
- the economic conditions and implications (economic feasibility);
- what are the implications for human behaviour and health (social/cultural feasibility);
- what type of institutional support would be needed, such as governance, institutional capacity and political support (institutional feasibility).

An additional factor (geophysical feasibility) addresses the capacity of physical systems to carry the option, for example, whether it is geophysically possible to implement large-scale afforestation consistent with the 1.5°C requirements (de Coninck et al., 2018).

6.1. Renewable energy

The largest growth driver for renewable energy has been the dramatic reduction in the cost of solar photovoltaic (PV). Solar PV with batteries has been cost effective in many rural and developing areas and small-scale distributed energy projects are being implemented in developed and developing cities where residential and commercial rooftops offer potential for consumers becoming producers (prosumers). The feasibility of renewable energy options depends to a large extent on geophysical characteristics of the area considered. However, technological advances and policy instruments make renewable energy options increasingly attractive in most regions of the globe. Another important factor affecting feasibility is public acceptance, in particular for wind energy and other large-scale renewable facilities that raise landscape management challenges, but financial participation and community engagement can be effective in mitigating resistance (de Coninck et al., 2018).

6.2. Bioenergy and biofuels

Bioenergy is renewable energy from biomass, while biofuel is biomass-based energy used in transport. There is high agreement that the sustainable bioenergy potential in 2050 would be restricted to around 100 EJ/yr. Sustainable deployment at higher levels, in fact, may put significant pressure on available land, food production and prices, preservation of ecosystems and biodiversity, and potential water and nutrient constraints. Some of the disagreement on the sustainable capacity for bioenergy stems from global versus local assessments. Global assessments may mask local dynamics that exacerbate negative impacts and shortages while, at the same time, niche contexts for deployment may avoid trade-offs and exploit co-benefits more effectively. The carbon intensity of bioenergy is still a matter of debate and depends on several factors such as management, direct and indirect land-use change emissions, feedstock considered and time frame, as well as the availability of coordinated policies and management to minimize negative side effects and trade-offs, particularly those around food security (de Coninck et al., 2018).

6.3. Nuclear Energy

The current deployment pace of nuclear energy is constrained by social acceptability in many countries due to concerns over risks of accidents and radioactive waste management. Though comparative risk assessment shows health risks are low per unit of electricity production and land requirement is lower than that of other power sources, the political processes triggered by societal concerns depend on the country-specific means of managing the political debates around technological choices and their environmental impacts. On the other hand, costs of nuclear power have increased over time and the current time lag between the decision date and the commissioning of plants is presently between 10 and 19 years (de Coninck et al., 2018).

6.4. Energy storage

The growth in electricity storage for renewables has been around grid flexibility resources. Battery storage has been the main growth feature in energy storage over the last few years mainly as a result of significant cost reductions due to mass production for electric vehicles. Although costs and technical maturity look increasingly positive, the feasibility of battery storage is challenged by concerns over the availability of resources and the environmental impacts of its production. Research and demonstration of energy storage in the form of thermal and chemical systems continues, but large-scale commercial systems are still rare. Renewably derived synthetic liquid (like methanol and ammonia) and gas (like methane and hydrogen) are increasingly seen as a feasible storage options for renewable energy, producing fuel for use in industry during times when solar and wind are abundant. The use of electric vehicles as a form of storage has also been evaluated as an opportunity, and demonstrations are emerging, but challenges to up-scaling remain (de Coninck et al., 2018).

7. CONCLUSION

Warming of the Earth's climate is a scientifically proven reality and represents the "great challenge" of our times that may even undermine the subsistence of our specie on the planet. Scientists have proven unequivocally that climate warming is already taking place and that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC 2014). It is then up to the policy makers to undertake the appropriate and timely actions for the mitigation of and the adaptation to climate warming that is already underway. In addition to political actions, citizen's behavioural attitudes are also important for mitigation of global warming: mobility choices, dietary habits, waste management, household management, etc..

It is also certain that several aspects of climate change will persist for centuries and that an effective endeavour for contrasting this phenomenon involves a commitment for many generations to come: higher emissions today imply the need of a higher decrease tomorrow, with higher economic and social costs.

Today, the global society has already available the scientific knowledge and most of the technologies needed to effectively contrast climate change, and the strategies to be put in place depend solely on political and economic choices. In any case, it should be considered that the social and economic costs of inaction towards climate change mitigation and adaptation are definitely higher than those for implementing the necessary mitigation and adaptation measures (Stern, 2007; Ricke et al., 2018).

ACKNOWLEDGEMENTS

This review paper builds largely on various Reports of the Intergovernmental Panel of Climate Change, to some of which I have contributed. These Reports have analysed and assessed several tens of thousands peer-reviewed papers on the different aspects of climate change. The use of statements and figures from these Reports is acknowledged since it has made possible the drafting of this paper.

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