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COMPREHENSIVE REVIEW OF CARBON EMISSIONS

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KA203 - Strategic Partnerships for higher education

PART I

Impacts of climate change on the environment and human societies

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1. Introduction

This report is part of the first intellectual output (IO1) of the Erasmus Goes Green project. Its objective is to provide a general overview of the main current and potential future impacts of anthropogenic greenhouse gas emissions. It is based on state-of-the art knowledge and builds on much of the previous synthesis reports provided by the Intergovernmental Panel of Climate Change (IPCC) and the European Environment Agency (EEA). The report is divided into four sections. Section 2 describes the functioning of the climate system and the basic principles of the greenhouse effect with a focus on the present-day anthropogenic emissions of the main greenhouse gases. Section 3 outlines the impact of these emissions on the different components of the climate system. The impacts of climate change on the environment and on human societies are addressed in sections 4 and 5 respectively.

2. Human influence on the climate system

2.1 The climate system

Climate is usually defined as the long-term weather average. More rigorously, the IPCC defines the climate as a statistical description in terms of mean, trends and variability of meteorological variables (temperature, humidity, wind speed, atmospheric pressure and precipitation) over a long-time period, generally thirty years as recommended by the World Meteorological Organization. However, depending on the period under study, the reference period may range from months to thousands or even millions of years.

The climate system (also referred to as "the Earth system" in the following) includes five components: the atmosphere, the ocean, the cryosphere, the biosphere and the upper lithosphere. The driving force of the Earth system is the absorption of solar energy by the Earth's surface. The excess energy received at the equator is redistributed towards the high latitudes through atmospheric and oceanic circulations. Incoming solar radiation is mainly concentrated in short wavelengths (i.e visible wavelengths). A part of this radiation does not reach the surface and is either absorbed by the atmosphere or directly reflected back to space. Around half of the incoming shortwave radiation is absorbed by the Earth. To ensure the thermal equilibrium, the absorbed solar energy is compensated by a long wave energy flux (i.e. in the infrared wavelengths) emitted towards the atmosphere. This long wave radiation is partly reflected back to space, but the greater part is trapped by the atmospheric constituents, that are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases (GHGs), clouds and aerosols. These constituents also emit long wave radiations in all directions, but ~95% are emitted downwards causing a further warming of the Earth's surface and the lower layers of the atmosphere. This process is called the greenhouse effect.

2.2 Drivers of the climate system

The climate system is influenced by natural external forcings (e.g. changes in orbital parameters of the Earth, natural greenhouse gases, modulations of solar cycles, volcanic activity, tectonic changes) and by anthropogenic activities. Any change in these natural or anthropogenic forcings induces a change in the climate response. This response also depends on internal variability processes, such as the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO). In addition, climate changes may also be amplified (i.e. positive feedback) or mitigated (i.e. negative feedback) by the interactions between the different components of the Earth system.

Climate drivers act at different time scales. As an example, tectonic changes have affected the Earth's climate on time scales of a few tens to several hundred million years. Glacial-interglacial cycles have been driven by changes in orbital parameters of the Earth and variations of natural GHG in the atmosphere from around 180 ppm[1] to 280 ppm between glacial and interglacial periods respectively. Over the last millennium, it has been advanced that variations in solar and volcanic activities could have been responsible for climate fluctuations such as the Medieval Warm Period or the Little Ice Age. However, today, the effects of anthropogenic greenhouse gas emissions on the present-day climate greatly exceed the effects due to known changes in natural processes.

2.3 Greenhouse gas emissions

The main GHGs (H_2O, CO_2, CH_4 and N_2O) are naturally present in the atmosphere. They are emitted through evaporation (H_2O), volcanic eruptions and forest fires (CO_2), wetlands and various fermentation processes (CH_4), and from micro-organisms in soils and oceans (N_2O). All these GHG are responsible for the greenhouse effect which is a natural phenomenon without which the Earth's surface temperature would be around -18°C. However, since the beginning of the industrial era in 1750, massive amounts of greenhouse gases (GHGs) have been discharged in the atmosphere through the combustion of fossil fuels (oil, gas, coal), deforestation, agriculture, intensive livestock breeding and fertilizer production. Besides water vapor (H_2O), the main GHGs are water carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) produced by the photodissociation of N_2O. Other GHGs, produced exclusively by human activities are fluorinated gases used in refrigeration and air conditioning systems, as well as in aerosol cans. According to the Intergovernmental Panel of Climate Change (IPCC, 2007), "*most of the observed increase in global mean surface temperature from 1951 to 2010 is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*".

The anthropogenic contribution of water vapour is considerably much less than the natural evaporation. Moreover, water vapour is rapidly removed from the atmosphere (~10 days) through precipitation. Therefore, it is not considered as a primary driver for climate change. However, due to the increased water holding of warmer air, water vapour has the potential to amplify global warming. This process is known as the water vapour feedback. Carbon dioxide is the most abundant GHG after water vapor, and has the longest residence time in the atmosphere (several hundreds of years). Its atmospheric concentration increased by more

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[1] 1 ppm = One part per million. This unit is used to refer to as a mass fraction (1 ppm = 1 mg/kg =10^{-6}). In the same way, 1 ppb is defined as one part per billion (1 ppb = 1µg/kk = 10^{-9})

than 46% between 1750 and 2019, rising from 277 ppm to 410 ppm, a level never attained over the last 800,000 years as indicated by Antarctic ice core records. Similarly, methane and nitrous oxide have experienced dramatic increases: 164 and 22% respectively in 2016-2017 relative to 1750.

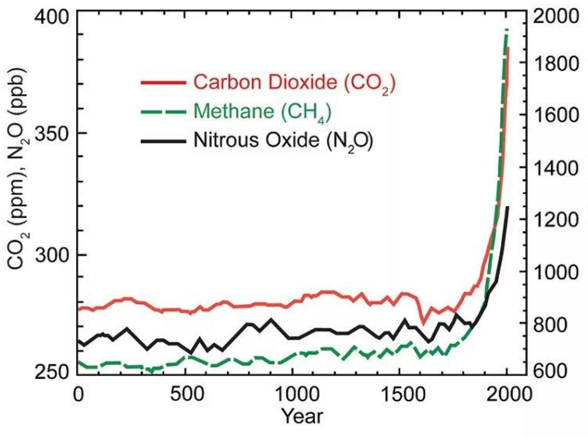

Figure 1: *Evolution of the atmospheric concentrations of the three main greenhouse gases (CO_2, CH_4, N_2O) over the last two millennia (0-2000 years). This figure illustrates the sharp increase in GHG concentrations from the beginning of the industrial area. Source : IPCC (2007).*

Today, around 86 % of atmospheric CO_2 comes from fossil fuel emissions and 14% from deforestation. Around 23% are dissolved in the ocean and 31% are buried in soils or used by vegetation for photosynthesis (Friedlingstein et al., 2020). These carbon sinks help to modulate global warming by removing carbon from the atmosphere. However, almost half of the CO2 emissions (46%) remain in the atmosphere. This fraction could be increased in the future. Indeed, as deforestation is becoming more and more widespread, there are less available plants to absorb CO_2. Moreover, oceans are not infinite reservoirs and may therefore no longer be able to absorb fossil emissions if they were to keep on growing.

3. Observed and projected changes in the climate system

3.1 Changes in surface temperature

The effect of GHG increase in the atmosphere has been proved to be the dominant cause of the observed global warming since the second half of the 20th century. Increase in surface temperature was estimated in 2017 around 1.0°C above pre-industrial levels, with a likely range between 0.8°C and 1.2°C (Allen et al. 2018) and a warming trend of about 0.2°C per decade. According to the National Oceanic and Atmospheric Administration (NOAA, 2021), the last decade (2011-2020) was 0.82°C warmer than the 20th century (1901-2000) average, making it the warmest decade on record. This magnitude of warming is almost half of the 2°C warming that is compatible with the global climate stabilization target of the EU and the ultimate objective of the UNFCCC. The warming is generally greater than average over land areas while most ocean regions are warming at a slower rate.

The NOAA (2021) ranked the year 2020 as the second warmest year on record (+0.98°C compared to the pre-industrial reference period), just behind the year 2016 (+1.00°C). This makes 2020 the 44th consecutive year since 1977 with global land and ocean temperatures above the 20th century average. However, this warming was not uniform with differences from one continent to the other and between land and oceanic areas.

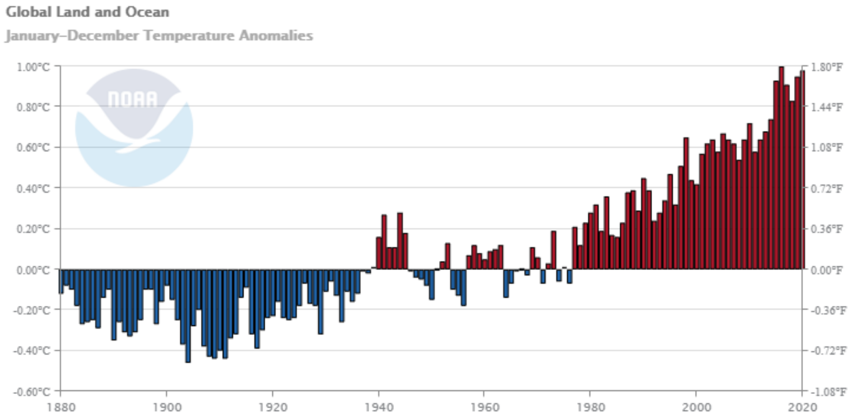

Figure 2: *Mean annual difference of surface air temperature relative to the 20th century average (1901-2000). Blue bars indicate colder than average temperatures and red bars indicate warmer temperatures (Source: NOAA).*

Over land areas, the 2020 warming (+1.59°C) even exceeded that of 2016 (+1.54°C). The largest continental warming in 2020 has been observed in Europe with 2.16°C above the 20th century average, surpassing the previous 2018 record by 0.28°C. It appears to be the 24th consecutive year having a near-surface temperature above the average. Reconstructions show that the recent decades in Europe are the warmest for at least 2 000 years and they lie significantly outside the range of natural variability. Over the period 2006-2015, the average annual temperature over land areas increased by 1.45 to 1.59°C with respect to pre-industrial times. This increase is larger than the increase in the global mean surface temperature. However, this masks large regional and seasonal disparities. In winter, the greatest warming is observed in northern and central Europe, where departures from the 1981-2010 climatological mean up to 3°C have been recorded. Conversely, the Iberian Peninsula warmed mostly in summer.

Climate models require information about future emissions or concentrations of GHGs and other climate drivers. For the fifth assessment report of the IPCC (IPCC, 2013), a set of four scenarios (the representative concentration pathways) has been defined by their approximate radiative forcing in 2100 relative to year 1750. These scenarios are labelled RCP2.6, RCP4.5, RCP6 and RCP8.5 and correspond to an additional radiative forcing in 2100 of 2.6, 4.5, 6 and 8.5 W/m^2 respectively[2]. They include economic, demographic, energy and climate considerations.

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[2] The RCP scenarios have been built with models including economic, demographic, energy and climate considerations. RCP2.6 is a mitigation scenario which peaks at around 3W/m^2 before 2100 and

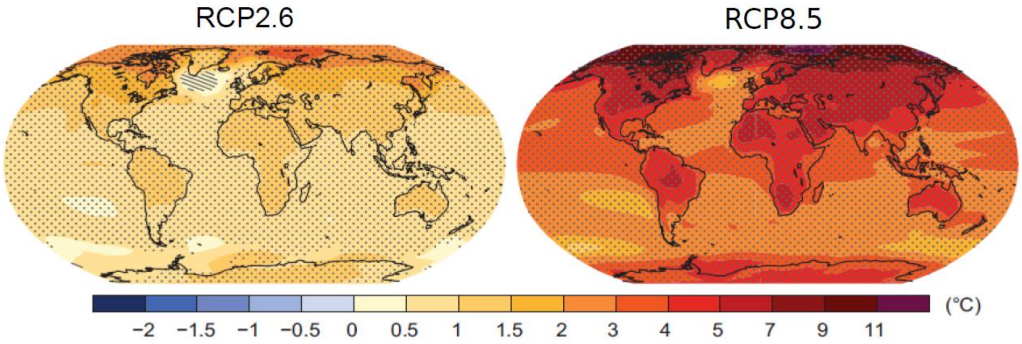

Figure 3: *Annual mean surface temperature change in 2081-2100 (relative to 1986-2005) provided by the CMIP5 multi-model mean for the RCP2.6 (left) and RCP8.5 (right) scenarios. Black dots indicate regions where the temperature change greatly exceeds the internal variability and where at least 90% of the models agree on the sign of change. Hatched areas indicate regions where the mean is small compared to the internal variability. These maps indicate a greater warming for the Arctic region (up to 11°C) and a greater warming over the continents compared to the oceans. Adapted from IPCC 2013.*

Global climate models project further increases in the global mean surface air temperature over the 21st century (Hartmann et al., 2013). Until 2030-2040, the amplitude of warming does not differ so much between the scenarios. However, at longer time scales (from 2040 onwards), the warming rate becomes strongly dependent on the representative concentration pathways. According to the CMIP5[3] ensemble mean, the only scenario limiting the warming below 2°C within the 21st century (relative to 1850-1900) is the RCP2.6 scenario, illustrating the importance of climate policies. Compared to the climatological baseline reference period (1986-2005), the projected warming averaged over 2081-2100 is between 0.3 and 1.7°C with RCP2.6 and between 2.6 and 4.8°C with RCP8.5. These numbers represent the 5th and the 95th quantiles respectively. This means, for example, that 95% of the individual CMIP5 models project a warming of 4.8°C with RCP8.5 and less than 5% simulate a warming below 2.6°C.

The EURO-CORDEX initiative (Jacob et al., 2014) provides high resolution (50 km and 12.5 km) regional climate simulations for Europe under the medium (RCP4.5) and the highest emission scenario (RCP8.5). The projected warmings in 2071-2100 (relative to 1971-2000)[4] obtained with these regional simulations are 1-4.5°C with RCP4.5 and 2.5-5.5°C with RCP8.5 (Fig. 4).

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then declines. RCP4.5 and RCP6 stabilize after 2100 at 4.5 and 6.0 W/m^2 after 2100 and RCP8.5 reaches 8.5 W/m^2 in 2100 and continues to rise afterwards. The corresponding atmospheric GHG concentrations (in terms of CO2 equivalent) are respectively around 490, 650, 850 and 1390 ppm

[3] Climate Model Intercomparison Project, Phase 5 (Taylor et al., 2012).

[4] Note that the reference periods are different from those considered in the global mean CMIP5 ensemble

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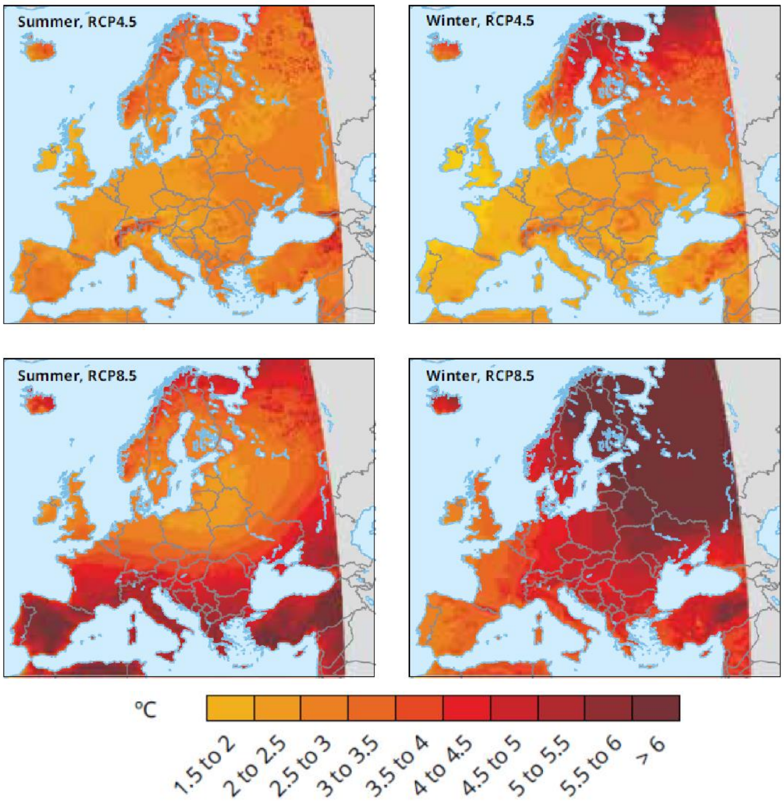

***Figure 4:** Projected changes in European summer (left) and winter (right) surface air temperature (in °C) for the RCP4.5 (top) and RCP8.5 (bottom) scenarios for the period 2071-2100 relative to 1971-2000.*
Model simulations are based on the multi-model ensemble average of the regional simulations from the EURO-CORDEX initiative. Adapted from EEA (2017).

For southern Europe, the strongest warming is projected to occur in summer, especially in the Iberian Peninsula where it could exceed 6°C. Conversely, these high warming amplitude could be seen in winter for northern and northeastern Europe (Jacob et al., 2014).

3.2 Changes in the hydrological cycle

Because increased temperatures favour evaporation, global warming has a direct influence on the hydrological cycle (precipitation, evaporation, runoff). Moreover, the water holding capacity of the air increases with temperature by about 7% per 1°C of warming, leading to a greater amount of water vapor content in the atmosphere. More intense precipitation is thus expected along with increased risks of flooding. However, there is no clear evidence of positive or negative trend in precipitation change averaged over global land areas, partly because of large interannual and decadal variability. In addition, large uncertainties exist regarding precipitation changes due to insufficient in situ measurements in some regions that are difficult to access and to uncertainties in algorithms used to convert direct spatial observations into precipitation rates. However, large scale patterns of precipitation change stand out, although they are only attributed with only low or medium confidence. Different data sets suggest that precipitation has increased in the tropics and subtropics (30°S-30°N), reversing the drying trend observed from the mid-1970s to the mid-1990s. The mid- and high-latitudes of the

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northern hemisphere also show an overall increase in precipitation, although, for the latter, the magnitude differs among datasets (Hartmann et al., 2013).

Average precipitation shows no significant change in Europe since the 1960s. However, at the sub-continental scales, large differences can be observed. In particular, there is a noticeable contrast between north and south. Observations indicate significant increases in annual precipitation in Scandinavia (up to 70 mm/decade in Norway) and the Baltic states, and strong decreases in southern regions, particularly in South of France and the Iberian Peninsula (up to 40 mm/decade). In central Portugal, the decrease is even more pronounced and reaches 90 mm/decade. In summer, drying extends over most parts of the Mediterranean Basin while increases have been reported in some northern regions (EEA, 2017 and references therein).

This north/south contrast is projected to be amplified in the future (Jacob et al., 2014). Results from the EURO-CORDEX consortium show that under the RCP8.5 scenario, annual precipitation rates in 2071-2100 are projected to decrease in the southernmost regions and increase in most northern and central Europe with the largest increase (relative to 1971-2000) occurring in Scandinavia and northeastern Europe (> 30%). In summer, regions of increased precipitation rates are less extended southwards and central Europe shows no significant change. By contrast, rainfall deficit extends over all the countries bordering the Mediterranean Sea and the North Sea with decreases ranging from 10-20% for UK, Belgium, Netherlands, west Germany to 30-40 % for the Iberian Peninsula, southern France, western Italy coast and Greece (Fig. 5).

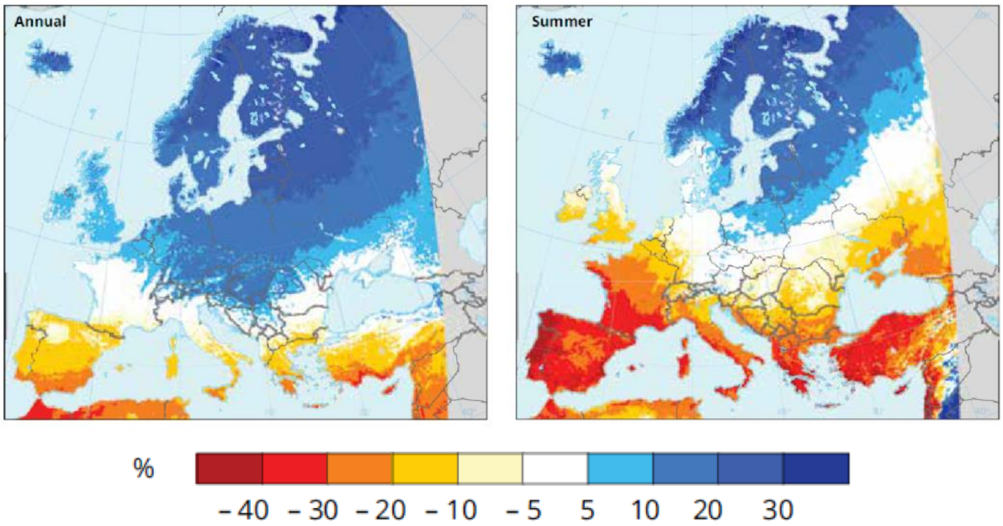

Figure 5: *Projected changes in annual (left) and summer (right) precipitation (%) in the period 2071-2100 compared to the baseline period 1971-2000 for the forcing scenario RCP8.5. Model simulations are based on the multi-model ensemble average of RCM simulations from the EURO-CORDEX initiative. Adapted from EEA (2017).*

3.3 Changes in extreme events

The increase in the global surface temperature and changes in the hydrological cycle are expected to affect the frequency and intensity of extreme events, such as heat waves, heavy precipitation, droughts, flooding cyclones and storms.

3.3.1 Hot extremes

Observations indicate a continued increase in heat extremes for land areas for the last three decades. These extremes are characterized by more frequent warm days and nights and more frequent heat waves. They also have strong direct impacts on human health and well-being, as well as on society (e.g. through decreased labour productivity), ecosystems (e.g. through forest fires) and agriculture. In particular, heat waves exacerbated by the urban heat island effect and air pollution can have devastating impacts on human health in urban areas.

In Europe, the maximum daily temperatures have shown significant upward trends and the number of unusually warm days has increased by up to 10 days per decade since 1960 in most of southern Europe and Scandinavia. Large areas have experienced intense and long heat waves since 1950, most of which occurred after 2000 (in 2003, 2006, 2007, 2010, 2014, 2015, 2018 and 2019). The severity of a heat wave depends on its duration, its relative intensity (how much hotter than the mean temperature at a given location) and its amplitude. The most severe European heat waves have been characterized by the persistence of extremely high temperatures at night (Russo et al. 2015). Summer 2003 was certainly one of the most striking examples with temperatures up to 40°C in some regions. However, in 2019, for example, two successive episodes occurred in June and July affecting the entire continent. But one of the most affected countries was France where temperatures above 46°C were recorded.

Climate model projections performed under all RCP scenarios agree on increases in heat wave frequency and magnitude for most European regions in the course of the 21st century (Ouzeau et al. 2016). Temperatures, such as the ones experienced in different parts of Europe in 2003 and 2019 will become much more common in the future. Under the RCP8.5 scenario, very extreme heat waves are projected to occur every two years in the second half of the 21st century, with a greatest frequency in southern and south-eastern Europe (Russo et al. 2014). According to Ouzeau et al. (2016), the duration and intensity of the 2003 event could be much lower than the strongest heat waves that could occur over 2071-2100. Unless appropriate climate policies are adopted, 90% of the summers in southern, central and north-western Europe will be warmer than any summer in the 1920-2014 period under the RCP8.5 scenario (Lehner et al., 2018).

3.3.2 Heavy precipitation events

Despite uncertainties due to non-uniform data coverage, the majority of observation-based studies suggest that heavy precipitation events have become more intense and more frequent in Europe on average. However, there are large differences across regions and seasons. Studies generally agree that heavy precipitation has become more intense in northern and West Central Europe, although changes are not always statistically significant. In southern

Europe, there is only low confidence for an increasing trend of heavy precipitation, although sub-daily events are observed in regions where the mean precipitation decreases (Westra et al., 2014 and references therein).

Global warming is projected to lead to a higher intensity of precipitation and longer dry periods in Europe (Hartmann et al., 2013). Projections show an increase in heavy daily precipitation in most parts of Europe in winter during the 21st century with increases of up to 30 % in north-eastern Europe. In summer, an increase is also projected in most parts of Europe, but decreases are projected for some regions in southern and south-western Europe (Jacob et al., 2014).

3.3.3 Wind storms

Storms may lead to significant damages on population, infrastructures and natural systems. In the North Atlantic and northwestern Europe, the most severe storms occur primarily in winter. They are characterized by high wind speeds and may be often accompanied by extremes of precipitation. In mid-latitudes, storms affecting large parts of land areas are referred to as extra-tropical cyclones. They develop from low-pressure weather systems that originate from the temperature gradient between the poles and the tropics. The storm tracks (i.e. the path of storms over time) depend on many factors such as land-sea contrasts, surface air temperature, topography and variability in the large-scale atmospheric circulation. The dominant mode of atmospheric variability in the North Atlantic is the North Atlantic Oscillation (NAO) defined as the pressure difference between the Icelandic low and the Azores high. When the pressure difference increases, more pronounced storms with high wind speeds are observed in northern Europe, while a weak pressure gradient leads to a displacement of the storms towards the Mediterranean basin.

Wind measurements are often inhomogeneous. This is due for example to instrumental changes, environmental influences, changes in the frequency of measurements and to various techniques of measurements. This leads to contradictory results and prevents from drawing robust conclusions about the trends of the intensity and the frequency of storms until the middle of the 20th century. Most models neither indicate a clear trend for the storm activity in the mid-latitude regions, but agree on an increase in northwestern Europe and the Baltic Sea (Hartmann et al., 2013, Feser et al., 2014). Despite large model uncertainties, it is now widely accepted that under global warming, the storm tracks shift polewards and eastwards (e.g. Ulbrich et al., 2009, Zappa et al., 2013, Yin et al., 2005). Moreover, modelling studies generally agree on an increase in the intensity of storms in northern, northwestern and Europe over the 21st century.

3.4 Impacts on cryosphere

The cryosphere includes snow, mountain glaciers and ice sheets, sea ice, permafrost, frozen lakes and rivers, and contains more than 70% of the Earth's freshwater reservoir. It is very sensitive to climate change and interacts in various ways with the other components of the climate system over a wide range of time (from seasonal to a hundred thousand years) and spatial scales. The extent of snow and ice surfaces has a direct influence on the energy balance of the Earth’s surface. Fresh snow reflects between 80 and 90% of incident solar radiation. The snow cover reduction due to warming decreases the fraction of solar energy reflected back to space, and thus, increases the absorption of incoming radiation, thereby increasing warming, which in turn accelerates snow melting. This effect is known as the albedo feedback. Another important aspect of snow cover is the role it plays in thermal insulation. In winter, snow covered ground cools much less quickly than bare ground, hence the importance of snow depth for plant and animal life. Finally, melting snow and/or ice in spring and summer requires a high latent heat of fusion, so that the snow cover represents a significant heat loss for the atmosphere during the melting season. Changes in sea ice thickness also modifies the energy exchanges at the air-sea interface and act on the strength of the thermohaline circulation by changing the density of sea waters (when sea ice is formed, salt is rejected and the water density increases).

The Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) states that *“over the last decades, global warming has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers, reduction in snow cover, and Arctic sea ice extent and thickness, and increased permafrost temperatures”.*

3.4.1 Snow cover

Observations reveal that snow cover has decreased in spring and summer since the 1920s, with an even more striking decrease since the end of the 1970s. According to the special IPCC report on Ocean and Cryosphere (IPCC, 2019), the snow season duration has declined in nearly all regions, especially at lower elevations by 5 days per decade on average. Over the period 1967-2015, snow cover extent has decreased by about 7% in the Northern hemisphere in March and April (47 % in June). In Europe, the observed reductions are even almost twice larger with13 % for March and April and 76 % for June between 1980 and 2015 (EEA 2017). Over the 21st century, these trends are projected to be enhanced in the Northern Hemisphere. In Europe, decreases in snow cover are projected to range from 4 to 12% for the low emission scenario (RCP2.6) to 20 to 35 % for the high emission scenario (RCP8.5). Snow cover duration will likely follow a similar trend with reductions of about 10 days for RCP2.6 and 40 days for RCP8.5 (Brutel-Vuilmet et al. 2013). In European mountains, decrease in snow mass could range from 30 to 95 % depending on the altitude and the emission scenario (Steger et al. 2013, Scmucki et al. 2015, Soncini and Bocchiola 2011, Lopez-Moreno et al. 2009, Frei et al., 2018).

3.4.2 Glaciers

Regional analyses have shown that, until around 2000, the average mass balance[5] cumulated over all European glaciers was close to zero, with significant mass losses for Alpine glaciers being compensated for by advances of glaciers in western Norway stemming from a sharp increase in precipitation. From the year 2000 onwards, the Norwegian glaciers began to

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[5] The mass balance of a glacier is the difference between the mass gained by snow deposition and the mass lost by melting.

retreat in response to the increase in temperature. Over the period 2003-2009, the most negative mass balances occurred for glaciers located in Central Europe and low latitude areas. In the Alps, glaciers have been retreating since the mid-nineteenth century. Projections suggest during the 21st century a substantial reduction of the ice volume of European glaciers located below 2000 m. In central Europe, Scandinavia and Caucasus glaciers will have lost between 60% to 80% of their mass at the end of the 21st century depending on climate scenario (Hock et al., 2019).

3.4.3 Sea ice

The extent and thickness of sea ice are the two indicators of sea ice conditions. Typically, the average Arctic sea-ice extent ranges from 14 to 16 × 10^6 km^2 at the end of winter (7 to 9 × 10^6 km^2 at the end of summer). Over the last two decades, surface air temperatures in the Arctic region have increased by more than twice the global average. One striking result was the record reached in 2012 with a minimum sea ice coverage of 3.4 × 10^6 km^2 (i.e. 20% below the previous record of 2007). On September 15 2020, the annual minimum of Arctic sea ice was 3.74 × 10^6 km^2, making it the second lowest in the 42-year-old satellite record.

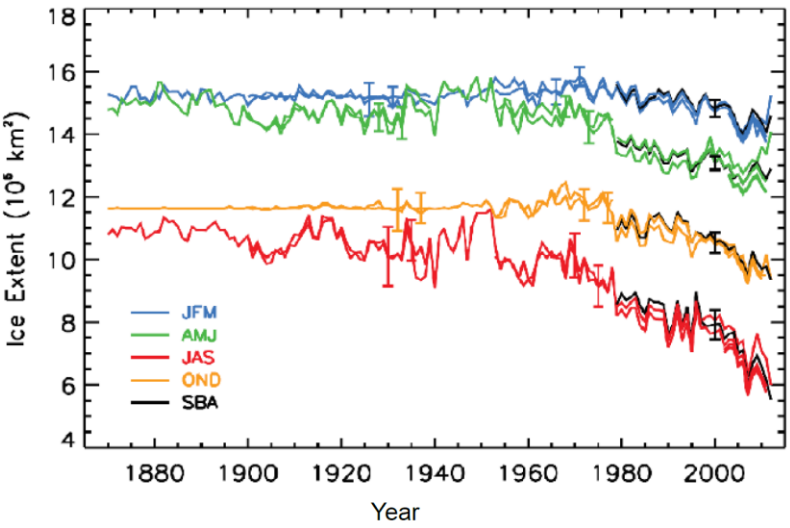

Figure 6: *Evolution of Arctic seasonal sea-ice extent from 1870 to 2011. Data from the different seasons are shown in different colors to illustrate variation between seasons (blue : January-February-March; green: April-May-June; red: July-August-September; orange: October-November-December). The black lines correspond to data coming from the Scanning Multichannel Microwave Radiometer and passive microwave data from the Special Sensor Microwave Imager (Source: IPCC, 2013).*

General circulation models clearly highlight a sea-ice decline in the course of the 21st century, the dominant factor being the rising summer temperatures (Notz and Stroeve, 2016). Projections of average reductions in Arctic sea ice extent for 2081–2100 compared to 1986–2005 range from 43% (RCP2.6) to 94% (RCP8.5) in September. For a 1.5°C global warming, sea ice in September is likely to be present at the end of the century with only ~1% chance of

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individual ice-free years (Jahn, 2018; Sigmond et al., 2018). After 10 years of 2°C warming, more frequent occurrence (10-35%) of an ice-free summer Arctic is expected (IPCC, 2019). However, there is a large spread between models in the timing at which these ice-free conditions will occur and their duration during the summer season (Notz and SIMIP community, 2020).

The evolution of sea ice around the Antarctic is more uncertain. Models project a decrease in sea ice extent ranging from 16% for RCP2.6 to 67% for RCP8.5 in austral summer for 2081–2100 compared to 1986–2005. There is, however, low confidence in those values because of the wide inter-model spread and the inability of almost all of the available models to reproduce the mean annual cycle, the interannual variability and the overall increase of the Antarctic sea ice coverage observed during the satellite era (IPCC, 2013).

3.4.4 Polar ice sheets

The mass balance of the ice sheets[6] depend on changes in snowfall, atmospheric temperatures which act on surface melting, and ocean warming which enhances the basal melting under the ice-shelves. Eventually, this may lead to the dislocation of ice shelves and to iceberg calving. This causes an inland retreat of the grounding line (i.e. the limit beyond which ice starts to float), and subsequently, an acceleration of the upstream grounded ice[7]. Present-day ice sheets are important reservoirs of freshwater and have the potential to raise sea-level by ~ 60 m if they were to melt completely. In recent decades, the contribution of Greenland and Antarctic ice sheets to sea-level rise amounts to 18.2 mm (IMBIE team, 2018, 2019).

In the early years of the 1990s, the Greenland ice sheet gained mass in the interior because of increased snowfall. However, since the mid-1990s, in situ and remote sensing observations have clearly demonstrated that the ice sheet has been losing mass and that this process now affects all the sectors of the ice sheet. The mass loss is partitioned between surface melting due to increased temperatures (~52%) and increased ice discharge due to dynamic processes. (~48%). Between 1992-1997 and 2007-2012, the rate of mass loss has increased from -26 ± 27 Gt/yr to 275 ± 27 Gt/yr (IMBIE team, 2019). After a record mass loss in summer 2012 of more than 600 Gt (Nghiem et al. 2012), Greenland has seen a slight decrease in the short-term mass loss trend. However, in 2019, Greenland has experienced an exceptional melting season with a mass loss estimated to 560 Gt (Tedesco and Fettweis, 2020).

In the Antarctic ice sheet, surface melting is negligible and mass loss is mainly driven by dynamic ice discharges resulting from enhanced ice flow of marine-terminating glaciers. Over the period 1992-2017, the rate of mass loss has increased from 49 ± 67 Gt/yr to 219 ± 43 Gt/yr with contributions coming mainly from the West Antarctic ice sheet and, to a lesser extent, from the Antarctic Peninsula. It has long been considered that the East Antarctic ice sheet

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[6] For ice sheets, an additional contribution of ice mass losses come from iceberg calving and from submarine melting of floating ice (also called ice-shelves).

[7] As opposed to floating ice, grounded ice is the ice resting on bedrock.

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was gaining mass due to increased precipitation, despite no firm consensus being established (Velicogna and Wahr, 2006; Ramillien et al*.,* 2006). However, recent studies suggest that some sectors are also affected by mass loss. As a result, the rate of change in ice-sheet mass is estimated to be +11 ± 58 Gt/yr in 1992 (mass gain) and - 28 ± 30 Gt/yr (mass loss) in 2017 (IMBIE, 2018). Using a different technique, Rignot et al*.* (2019) estimate an even larger mass loss from EAIS with a strongly reduced uncertainty.

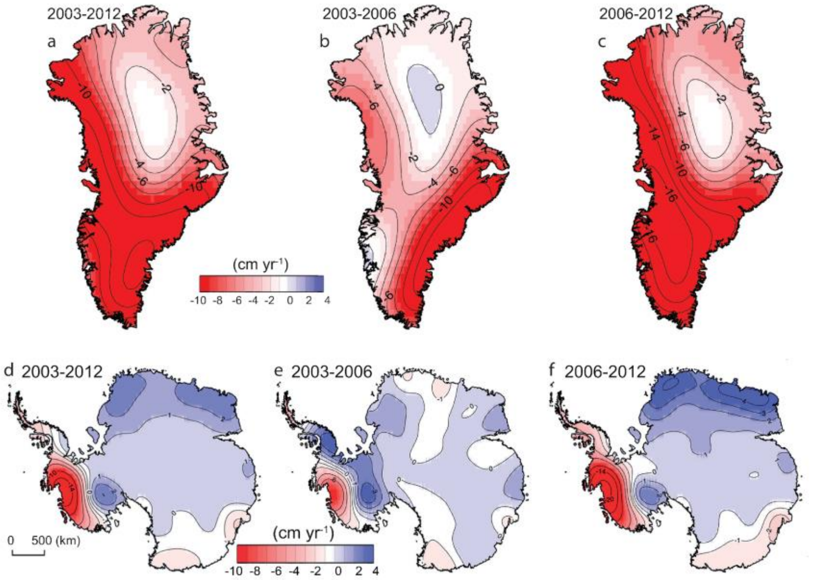

Figure 7: *Temporal evolution of ice loss in Greenland (top) and Antarctica (bottom) determined from gravimetry observations from the GRACE satellite, shown in centimeters of water per year for the periods 2003–2012, 2003–2006 and 2006–2012, color coded red (loss) to blue (gain) (Source: IPCC, 2013).*

Ice sheet melting is accompanied by possible changes in albedo and therefore in the surface energy balance, which in turn can lead to changes in the mass balance of the ice sheets. Another consequence of the melting and/or mechanical destabilization of the ice sheets, concerns the freshwater flux released in the ocean. Locally, this release leads to a decrease in ocean surface temperatures, a change in sea ice cover and a reduction of ocean density in the vicinity of ice sheets. Density changes also cause a disruption of large-scale ocean circulation by altering deep-water convection. For example, meltwater from Greenland has the potential to weaken the Atlantic Meridional Overturning Circulation. These changes can have effects in regions far from the polar zones.

3.4.5 Permafrost

Permafrost is defined as soil that remains permanently frozen for at least two consecutive years. It is topped by a so-called ‘active layer’ that thaws each summer, and whose thickness can vary from a few centimeters to hundreds of meters, depending on altitude and latitude. At present, permafrost covers about 24% of the northern hemisphere continental areas. It is found mainly in polar and circumpolar areas and in mountain regions at lower latitudes (e.g. Chile, the Alps, the Himalayas). It can also be found in the seabed of the Arctic Ocean in the continental shelf areas.

In the Arctic region, measurements of ground temperatures indicate that permafrost temperatures have increased from the mid-1970s to 2010 from 0.15 ± 0.03 to 0.82 ± 0.07 °C per decade. Over the last decade, data from various boreholes extending from Svalbard to the alps indicate a regional warming of permafrost of 0.5-1.0°C. Continuous monitoring over 5–7 years shows warming down to 60 m depth and current warming rates at the permafrost surface of 0.04–0.07 °C/year, with greatest warming in Svalbard and northern Sweden (EEA, 2017). One of the main consequences of permafrost warming is the increase in thickness of the active layer, although some permafrost areas exhibit only modest thickening or even a thinning. Indeed, a study based on the analysis of 169 circumpolar and mid-latitude sites revealed that only 43.2 % of them have experienced an increase of the active layer thickness since the 1990s (Luo *et al.,* 2016). In some European sites, increasing depth of the active layer has also been observed but there is great spatio-temporal variability from one site to the other ranging from a few tenths of cm/yr to more than 10 cm/yr.

Permafrost areas are very sensitive to the rate of warming and will very likely continue to thaw across Europe in the coming decades. Projections indicate substantial near-surface permafrost degradation and thaw depth deepening over much of the permafrost area. Projections based on the ensemble of CMIP5 climate models yield a reduction of near-surface permafrost area in the northern hemisphere between 37 ± 11% for RCP2.6 and 81±12% for RCP8.5 over the 21st century.

Thickening of the active layer is a matter of great concern since it may have large consequences on the stability of the surface due to the melting of shallow ice. Potential impacts include thaw settlement, soil creeps, slope failures and ponding of surface water. All these features can cause severe damages to infrastructures, such as roads, dams or structural building foundations but also to vegetation. In forested areas, thaw modifies the hydrological conditions and can lead, for example, to the destruction of tree roots, causing drastic changes in the ecosystems. Another consequence of permafrost degradation is the release of CO2 and CH4 gases to the atmosphere due to decomposition of organic matter by bacteria. The magnitude of the thaw related feedback is unknown but one study suggests that 232-380 billion tons of CO_2 equivalent could be emitting by 2100 (Schurr and Abbott, 2011), acting thereby as a strong positive feedback on global warming. The total amount of carbon stored in the permafrost has been estimated at 1 672 Gt, which is about twice the amount of carbon in the atmosphere.

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3.5 Impact on the ocean

3.5.1 Oceanic heat content

In response to carbon emissions from human activities, ocean heat content has increased, at least since the 1950s. Oceanic warming represents approximately 93% of the Earth's warming and it has been estimated that ocean heat uptake has doubled since the 1970s with the two-thirds of the observed increase occurring in the upper layer (0 – 700 m). Over the 1971-2010 period, the ocean warmed at a rate of 0.11 ± 0.02°C per decade by 75 m, decreasing to 0.015°C per decade by 700 m. There is also evidence for warming in deeper layers (700 – 2000 m), but warming trends below 3000 m are not statistically significant. In Europe, remote sensing observations (since 1979) indicate that sea surface temperatures (SST) in the North Atlantic Ocean and in the Baltic Sea have respectively increased by 0.21°C and 0.40°C per decade. Increased SST influence the global oceanic circulation by modifying the density of water masses and therefore by altering the efficiency of the deep convection in high latitudes and the mixing between surface and deep-water masses. Moreover, higher SSTs can lead to a greater amount of water vapour in the atmosphere which has a direct influence on the weather patterns. As an example, the European climate in western Europe is strongly dependent on mass and energy exchanges between the atmosphere and the North Atlantic Ocean.

The ocean is likely to continue to warm throughout the 21st century. Projected ocean warming varies considerably across forcing scenarios. Globally averaged projected surface warming ranges from about 1 °C for RCP2.6 to more than 3 °C for RCP8.5 during the 21st century, and at a depth of 1 000 m ranges from 0.5 °C for RCP2.6 to 1.5 °C for RCP8.5.

3.5.2 Change in chemical properties

As GHG emissions increase, the dissolution of carbon in the ocean is more and more important leading to an acidification of ~30% which has affected ~95% of the near surface ocean. Since the 1980s, the pH value has declined at a rate of 0.02-0.03 units per decade.

Moreover, warmer oceans cause deoxygenation, because oxygen is less soluble in warmer water, and because of stratification (i.e. less mixing between surface and deep waters) which inhibits the production of oxygen from photosynthesis. The likely range of oxygen loss is estimated at 0.5-3.3% between 1970 and 2010 from the surface to 1000 m (IPCC, 2019).

3.5.3 Changes in the oceanic circulation

The Atlantic Meridional overturning circulation (AMOC) is an important component of the Earth's system as it is partly responsible (along with the atmosphere) of the heat transport from the tropics to the high latitude areas through a northward flow of warm and salty waters in the upper layer of the North Atlantic Ocean. Along its northward path, water cools down and becomes denser due to evaporation. In high latitude areas, cold and dense water sink down to the deep Atlantic Ocean and a southward flow takes place feeding the bottom layers of the different oceanic basins before coming back to the surface. The Gulf stream, which originates in the Gulf of Mexico is a branch of the AMOC. It follows the Florida coasts,

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crosses the Atlantic and reaches the western European coasts. As a result, it has a great influence on the North Atlantic weather patterns and on the western European climate. Global warming combined with freshwater inputs from ice melting have the potential to reduce water density and thus, the strength of the AMOC, resulting in a cooling of western European areas.

However, despite considerable improvements in observations of the large-scale oceanic circulation, and thus of the AMOC since 2004, a long-term decline of the AMOC has not yet been detected because the record is not yet long enough (IPCC, 2019). However, reductions of 16 and 30% have been reported at 26°N for the 2008-2017 and 2009-2010 periods respectively (Smeed et al., 2018) and indirect measurements indicate that the AMOC has started to decline since the mid-20th century (Caesar et al., 2018) and is now at its weakest level (Caesar et al., 2021). There is also large spread in the 21st century projections of the AMOC among the CMIP5 models, but taking the model ensemble results in a decline of 11 ± 14% and 32 ± 14% for the RCP2.6 and RCP8.5 scenarios (IPCC, 2019). However, these results do not take into account the freshwater input from Greenland melting which is expected to amplify the decline of the AMOC (Rahmstorf et al., 2015). Accounting for this additional source of fresh water Bakker et al. (2016) estimate that the decline could be amplified by 5-10% by 2100 under the RCP8.5 scenario and could lead to a complete collapse by 2200-2300.

3.5.4 Sea-level rise

Changes in global mean sea-level results from changes in the volume of the oceans and oceanic basins as well as changes in the mass of water contained in the oceans. On time scales ranging from a few years to a few decades, variations in the mean sea level result from the increase of the ocean volume due to thermal expansion and from variations in the mass of water due to exchanges with continental reservoirs, such as rivers, lakes and inland seas, snowpack, ground water, but also mountain glaciers and polar ice sheets. While sea-level rise was primarily due to thermal expansion throughout the 20th century, the contribution from ice sheets and glaciers has now become the dominant contribution. Altimetry observations provide estimates of the rate of sea level rise of 3.1 ± 0.3 mm/yr between 1993 and 2017 (WCRP Global Sea Level Budget Group, 2018) for a total sea level rise of 0.19 ± 0.02 m (IPCC, 2013).

Global mean sea level rise (Fig. 8) is projected to increase in the future between 0.29-0.59 m for the RCP2.6 scenario and between 0.61-1.10 m for the RCP8.5 scenario (IPCC, 2013). However, the ice-sheet contribution still represents a major source of uncertainty because process-based models still lack realistic representations of physical mechanisms controlling the future ice shelf loss which could increase in Antarctica. As a result, higher sea-level rise estimates cannot be ruled out and a few studies and expert assessments indicate that the rise in sea level could be as high as 1.5-2.5 m by 2100 and 2.5-5.4 m by 2300 (Jevrejeva et al., 2014, IPCC, 2019).

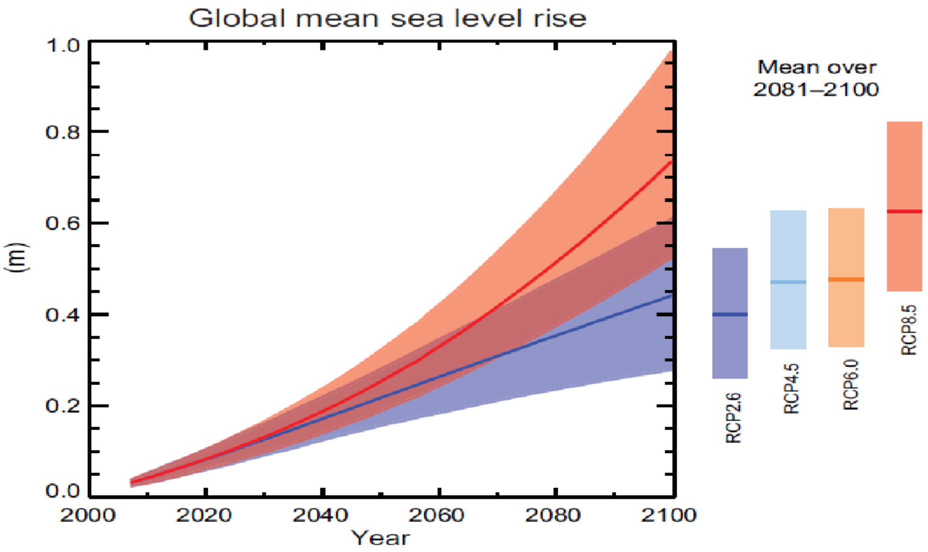

Figure 8: *Projections of sea level rise over the 21st century for the RCP2.6 and RCP8.5 scenarios (relative to 1986-2005) obtained from an ensemble of CMIP5 models. The assessed likely range (i.e. probability > 66%) is indicated by the shaded band. The vertical coloured bars indicate the assessed likely range of the mean for all the RCP scenarios for the period 2081-2100 and the median value is given as a horizontal bar (Source : IPCC, 2013).*

The rise in sea-level varies regionally as a result of variations in ocean circulation, winds and atmospheric pressure, vertical land movements, and human interventions (e.g. dams, irrigation, urbanization, deforestation and water extraction from aquifers).

The global mean sea level has increased along most of the European coastlines and it will likely continue throughout the 21st century with regional deviations from the global average with exceptions in Scandinavia due to the post-glacial rebound following the disappearance of the Fennoscandian ice sheet during the last deglaciation and the subsequent land rise. Future sea-level rise will favour coastal flooding and coastal erosion. Unless appropriate adaptation measures are taken, this will have major consequences on ecosystems, water resources, infrastructures and settlements, and human lives.

4. Impacts on the environment and ecosystems

4.1 Marine ecosystems

Changes in both the physical and chemical properties of the ocean alter the marine productivity and thus have substantial impacts on the health of marine ecosystems and the provision of seafood to society, such as through fisheries.

First, ocean acidification exerts a strong threat for coral reefs, by reducing the concentration of carbonate ions and therefore the material that corals need to build their skeleton. As coral reefs host numerous organisms, this negatively impacts the entire ecosystem.

Second, deoxygenation affects the metabolism of species by limiting the biological activity. In recent decades, oxygen-depleted areas have rapidly expanded leading to the so-called dead zones from which the organisms leave or in which they die. An outstanding example is the Baltic Sea in which the expansion of dead zones has experienced a 10-fold increase since 1900, but oxygen-depleted areas have also been observed in other European seas in recent decades.

Third, the increased stratification limits the transfer of nutrients to the surface lit-layer and thus limits the growth of phytoplankton. Ocean warming also contributes to modify the geographical range of habitat of marine organisms from phytoplankton to marine mammals. A northward expansion of warm water species and a northward retreat of cold-water species have been observed. As outlined in the IPCC Special Report on Ocean and Cryosphere (IPCC, 2019), this may change the community composition, alter the interactions between organisms and modify the structure of the ecosystem.

Finally, agricultural fertilizers such as N2O exert a strong negative influence on the marine environment. Indeed, excessive nutrients favour the deoxygenation and lead to harmful algal blooms in estuaries and other coastal areas.

4.2 Coastal zones

European coastlines are expanded along more than 100,000 km with about 200 million people living in coastal areas, and host important economic activities, such as tourism, and various ecosystems. Therefore, a growing attention is being paid to the evolution of the littoral owing to the risks posed by climate change. Among the most important risks are coastal floods, saltwater intrusions, coastal erosion and submergence of low-lying areas. Under global warming, low-lying European areas (e.g. Belgium, Netherlands, Denmark, southern and western France…) could be permanently inundated in response to sea-level rise.

4.2.1 Coastal flooding

Coastal flooding results from a variety of causes including storm surges produced by wind storms and sea-level rise. When surges coincide with high tidal levels, extensive flooding may occur, threatening ecosystems, infrastructures and human lives. As an example, the coastal flooding which occurred in 1953 in the North Sea destroyed 40 000 buildings and caused 2000 deaths in Netherlands, Belgium and United Kingdom. This kind of flooding event occurs every hundred years on average, but could happen annually by the end of the 21st century, unless appropriate protection measures are taken. A recent study (Vousdakas et al. 2017) estimates that the North Sea is projected to face with the strongest increase in extreme sea level events (up to 1 m under the RCP8.5 scenario) followed by the Baltic Sea and the Atlantic coast, and 5 million of Europeans could be affected by coastal flooding. Moreover, flood damages could increase by 2 to 3 orders of magnitude in the absence of adaptation (IPCC, 2019).

4.2.2 Saltwater intrusions

Saltwater intrusions into aquifers are caused by sea level rise and overexploitation of groundwater resources. These intrusions have the potential to threaten water supply, agriculture and ecosystems in coastal regions.

4.2.3 Coastal areas

Coastal erosion is due to the imbalance between supply and export of sedimentary material to the coast. This results in the retreat of the coastline and threatens the sandy dunes which are a significant protection for the littoral and for the hosted flora and fauna species. It may also have huge economic impacts because of the loss of land areas, and hence, because of the loss of properties and infrastructures. Coastal erosion is produced by strong winds, storm surges and high tidal levels and is amplified by sea level rise. It is also exacerbated by human activities because the natural flow of sediments in river basins is obstructed by various infrastructures. Hence, highly urbanized coastal zones are more exposed to possible damages. Currently, almost one fifth of the European coastline is affected by costal erosion with retreats of 0.5 to 2 m/yr on average. Adaptation solutions consisting in building natural or artificial barriers are therefore urgently needed. In the absence of appropriate adaptation measures, recent studies estimate that the coastline retreat could reach 65 m in southern Europe and 100 m in northern Europe (Athanasiou et al., 2019) for a 4°C warming but could be reduced by 50% if the warming was limited to 3°C (Vousdoukas et al., 2020).

4.3 Freshwater systems

In addition to changes in rainfall patterns, changes in the hydrological cycle induced by climate change also affect river flows, and may also increase the severity and frequency of droughts or river flooding.

4.3.1 River flows

River flows are not only influenced by rainfall and runoff, but also by other human inferences such as land use or morphological changes or river regulation. In addition, there is a substantial interannual and decadal variability. It is therefore difficult to detect long-term trends. However, according to recent studies (Blöschl et al. 2019), observations suggest that river flows have i/ increased in northwestern Europe due to increased rainfall in autumn and winter, ii/ decreased in southern Europe due to decreased precipitation and increase evaporation, iii/ decreased in eastern European regions as a result of a decline in snow cover and an increased snow melting. These regional differences reflect the seasonal trend of precipitation patterns. The seasonality is projected to change across Europe. Summer flows are projected to decrease in most of Europe, while winter and spring flows are expected to increase due to the risk of heavy rainfall (Beniston et al. 2018). In snow-dominated regions, such as the Alps, Scandinavia and the Baltic countries, the peak flow will occur earlier in the year due to less snow mass and earlier snowmelt. In mountainous regions, this trend will be likely amplified in the course of the 21st century due to the glacier retreat.

4.3.2 River flood

River floods are caused by prolonged or heavy precipitation events, and they are the most important natural hazard in Europe in terms of economic losses. Direct economic impacts are related to damages to infrastructures (buildings, transports, roads) and agricultural areas. There are also indirect damages such as production losses due to damaging transports or energy infrastructures. Flooding also has negative effects on the environment and human health. Almost 1500 floods have been reported in Europe since 1980 and more than half have occurred since 2000, but their occurrence results from several factors (land-use changes, expansion of urban areas, heavy precipitation) and it is therefore difficult to quantify the importance of each factor. As global warming is intensifying the hydrological cycle, more frequent heavy precipitation events are expected even in regions where the mean precipitation decreases) and more frequent flooding events could occur.

4.3.3 Droughts

Droughts are associated with rainfall deficits (meteorological droughts) or low-level water in lakes and natural reservoirs (hydrological droughts). The latter can be caused by prolonged rainfall deficit and by soil moisture deficit due to above- average evapotranspiration in response to high temperatures and hot extremes. They may have detrimental consequences on plant growth and crop yields, animal and vegetal ecosystems, water resource management (irrigation, power plant cooling) and on the availability of freshwater used for drinking.

Since the second half of the 20th century, dry areas have expanded in Europe, and the frequency and severity of droughts have increased in the Mediterranean countries, Portugal and parts of central Europe. On the other hand, drought episodes have become less frequent in parts of northern and eastern Europe, but have become more severe in Scandinavia and southeastern Europe. In recent years (2006-2010), around 15% of the EU territory and 17% of the EU population have been affected by droughts occurring each year, mainly in Southern (Mediterranean basin and Portugal) and Central Europe, and more recent episodes (2003, 2010, 2015, 2018 and 2019) have mainly affected Central Europe, despite westward expansion in 2015 and 2019. At the global scale, simultaneous drying in Australia, Mexico and the Mediterranean region suggest that increasing frequency and severity of droughts can be attributed to climate change. However, at the regional scale, there is no clear evidence because the signal is masked by the natural interannual and decadal variability. Nevertheless, model simulations carried out within the framework of the EURO-CORDEX consortium projects that the frequency and duration of extreme meteorological droughts will significantly increase at the end of the 21st century with respect to the 1971-2000 reference period (Forzieri et al. 2014) in the Mediterranean region. In northern Europe, projections indicate that droughts will become less severe.

4.4 Terrestrial ecosystems

Climate change also has many impacts on terrestrial ecosystems. Firstly, it greatly affects biodiversity by modifying the phenology of plants (with longer growing seasons and earlier pollen seasons) and the life cycle of animals (e.g. earlier arrival of migrant birds, earlier onset of reproduction and longer breeding season of many thermophilic insects). These trends, primarily due to increased temperatures, are projected to persist in the future. Secondly, global warming modifies the geographical range of flora and fauna species. This may induce changes in the species composition and can cause in turn a change in their mutual interactions (e.g. Montoya and Raffaelli 2010). Migration of some species towards higher latitudes and/or higher elevations are observed (Chen et al., 2011), but local and regional extinctions also occur for other species. The species which are expected to be the most affected are small populations, those with restricted climatic envelopes (i.e. range of favourable climatic conditions), such as those living in high latitudes or high elevations (Engler et al. 2011) or those whose ability to migrate is limited by human-made barriers, such as land use change and deforestation or expanded urbanization (Pereira et al. 2012). As a result of habitat fragmentation acting against mobility, migration often lags the change in climate. This could lead to a progressive decline of biodiversity. In Europe, the northward and upward shift of many plants and animals is projected to continue throughout the 21st century. For example, a modelling study suggests that 20 to 60 % of Alpine plant species, depending on their living elevation and the climate scenario, could lose up to 80% of their suitable habitat (Engler et al. 2011), unless they take refuge in micro-climatic areas (Scherrer and Körner 2011).

Biodiversity and ecosystems provide important functions to human populations by sequestering carbon (see section 2), modulating the impacts of extreme events, maintaining soil moisture and air quality, acting as buffer for diseases, providing natural barriers against storm surges and flooding, and providing cultural services for recreation, mental and physical health. As an example, forests provide numerous ecosystem services by protecting soils from erosion, by regulating locally the climate through the evapotranspiration or globally by storing carbon. They are also important for biodiversity by providing habitats for numerous species, and for human societies by providing wood products or timber used for heating. They are also a source of food products and offer some services for tourism. However, forests are currently being threatened by several factors exacerbated by climate change, such as droughts, storms, atmospheric pollution, diseases and parasites. However, there are still many gaps in the knowledge of the impacts of human activities on forests. Recent studies suggest an upward shift of the tree line as well as a northward shift of boreal forests. Broadleaf trees are expected to expand throughout the 21st century, while the needleleaf cover is expected to decrease despite a northward expansion in northern Europe (EEA 2017). In southern Europe, forested areas are projected to decline.

Europe faces increased risks of forest fires. These are due to many factors such as temperatures, land use, droughts, vegetation composition, wind speed and human behaviour. The Mediterranean region remains the most affected area because of noticeable warming, increased wind speed and more intense and frequent droughts (Turco et al. 2018), while fires in boreal forests are rather due to summer droughts (Drobyshev et al. 2015, 2016). The number of forest fires in the Mediterranean region increased from 1980 to 2000 but decreased thereafter. However, since the year 2017, unprecedented wildfires have occurred in many regions of the world, especially in Australia, South America, California and Europe. In Europe, these fires often coincided with record droughts and heatwaves. Such events are expected to become a key risk in the next decades, especially in southern Europe. However, a growing attention is now given to adaptation measures to reduce fire risk and fire damages. These include prescribed burnings, use of agricultural fields as fire breaks, behavioural changes, enhanced fire suppression and prevention activities (Khabarov et al. 2014). These measures have proven to be successful and despite a large number of fires in the Iberian Peninsula, the

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2019 season was one of the best ever in terms of preventing accidents and loss of life, and there were also less devastating fires in Europe than those occurring in 2017 and 2018.

5. Impacts on human societies

Global warming and related changes in natural systems have a strong influence on human societies, including water resources and food supplies, economic issues, health and well-being, energy production, migration of people and potentially geopolitical conflicts (Gemenne et al. 2014). There is a broad range of studies investigating the different aspects of these impacts and the potential adaptation strategies, synthesized in reports such as those provided by the IPCC (IPCC, 2014) or the European Environment Agency (EEA, 2017). The objective of this report is not to present an exhaustive review of all potential impacts but rather to give an overview of key changes that are affecting or are likely to affect European populations in the course of the 21st century.

5.1 Human health

Climate change impacts human health through warming temperatures, changes in precipitation, extreme events, degradation of the air quality and rising sea-levels. These impacts may directly affect the health of human beings (e.g. heat-related mortality or deaths and injuries from flooding or storms). There are also indirect effects of climate change, such as those acting on vector-borne diseases, food security and water quality. The severity of these risks is expected to increase in the future and will vary depending on where people live and to what extent they are exposed to climate risk, their economic status and how they are sensitive to health risks. It will also depend on the ability of public health and safety systems to address these new threats.

5.1.1 Extreme events

Extreme hot temperatures are associated with increases in mortality and morbidity. Exposure to extreme heat can lead to heat stroke and dehydration, as well as cardiovascular, respiratory, and cerebrovascular disease. In recent decades, the number of heat waves has increased across Europe and caused tens of thousands of premature deaths. An outstanding example is the heat wave in summer 2003 which caused at least 70 000 premature deaths (Robine et al. 2008). The most vulnerable populations include outdoor workers, homeless and low-income people, elderly persons, young children and people suffering from chronic diseases. In addition, people living in northern latitudes are more exposed because they are less prepared. Moreover, heat-related effects are exacerbated in urban areas because of the urban heat island effect and adverse heat impacts are often more frequent in cities than in the rural surroundings.

Heat waves are often accompanied by a degradation of the air quality because they favour wildfires, the stagnation of fine particulate matter and other air pollutants, and the formation of ground-level ozone. Particulate matter from wildfire smoke can often be carried over very long distances by winds, affecting people who live far from the source of this air pollutant (Ghorani-Azam et al. 2016). Worsened air quality is at the origin of respiratory, pulmonary and

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cardiovascular diseases. Warmer temperatures also favour the presence of allergens and asthma triggers due to the longer growing season for some plants having highly allergenic pollen. As the number and frequency of heat extremes is likely to increase in the future an excess of mortality is expected unless proper adaptation measures are taken.

Extreme low temperatures during cold spells also affect human health but cold-related mortality is projected to decrease owing to better social, economic and housing conditions in many European countries. However, whether or not global warming will lead to a further decrease in cold-related mortality remains an open question.

Increases in the frequency or severity of other extreme weather events, such as extreme precipitation, flooding, and storms, threaten the health of people during and after the event, through drowning, injuries, reducing the availability of safe food and drinking water, exposure to chemical risks, and creating or worsening mental health impacts such as depression and post-traumatic stress disorder. In addition, emergency evacuations can be difficult owing to damaging roads and bridges and disrupting access to hospitals. In most European regions an increasing trend of heavy precipitation has been observed in recent decades increasing the risk of river and coastal flooding. According to the World Health Organization, flooding has killed more than 1 000 people and affected 3.4 million over the period 2000-2011. Without adaptation, the number of people potentially affected by flooding every year by 2085 could increase from 775 000 to 5.5 million depending on the emission scenario, the western Europe being the most affected.

5.1.2 Vector borne diseases

Changes in temperature and precipitation increases the geographic range of vector-borne diseases and can lead to illnesses occurring earlier in the year or can bring non-endemic illnesses in the European areas. However, there are other factors favouring vector-borne diseases such as land use, travelling and human behaviour, vector control and public health capacities.

Lyme Borreliosis, transmitted by ticks, is the most common vector-borne disease in Europe. Ticks can also transmit tick-borne encephalitis and the mean annual cases reported in Europe has increased by ~400% over the past 30 years, although this can be due to a more robust detection. Global warming has increased the risk of tick-borne diseases in Europe by allowing ticks to survive at higher altitudes. The Asian tiger mosquito transmitting viral diseases (dengue, chikungunya, Zika) has been first recorded in Europe (Italy) in the 1990s. Since then, it has expanded its geographical range in several European countries and several cases of chikungunya have been reported in France and Italy (Rezza et al. 2007, Venturi et al 2017), and dengue in France and Croatia. Although malaria has been eradicated in Europe since the 1950s, several sporadic cases of local transmissions occur each year. In the United Kingdom it is estimated that, with temperature increases, the risk of local malaria transmission could increase by 8–15% by 2050. In Portugal, the number of days suitable for survival or malaria vectors is projected to increase. Malaria is unlikely to re-establish itself in Europe thanks to health systems in place and adequately functioning, but it might be introduced sporadically due to global travel and trade.

5.1.3 Food security and water quality

Warmer temperatures also favour the growth of bacteria in food, such as salmonella, or the exposure to chemical contaminants stemming from human activities. In the oceans, seafood is also impacted by toxins produced by harmful algae. For example, higher sea surface temperatures will lead to higher mercury concentrations in seafood. Increases in extreme weather events, such as heavy precipitation, will introduce contaminants into the food chain through water runoff. Moreover, crop yield (see Section 5.2) are also projected to decrease in southern Europe. While higher atmospheric CO_2 concentrations can act as a "fertilizer" for some plants, they also lower the amount of proteins and essential minerals in crops such as wheat, rice, and potatoes, making these foods less nutritious.

5.2 Agriculture and livestock

The agricultural sector is directly dependent on several climatic factors such as temperature, water availability and the occurrence of extreme climatic events. Crop yields and livestock production are therefore strongly influenced by climate change. On the other hand, increased CO_2 emissions favour fertilization and acts therefore as a positive impact. It is generally accepted that the productivity of crops will be positively impacted in northern Europe due to increased temperatures leading to a lengthened growing season (more than 10 days since 1992) and to a shortening of the frost period. Conversely, southern and central Europe are negatively impacted as a result of warmer temperatures, the occurrence of more frequent hot extremes and a decrease in precipitation. Since 1995, the water deficit has increased in large parts of southern and eastern Europe. This impact is expected to be most acute in the future, which may lead to an expansion of the irrigation systems. However, this expansion may be constrained by projected reductions in water availability and increased demand from other sectors and for other uses.

The extent to which climate change affects crop yields depends on the crop and type, the ability of the soil to store moisture and the climatic conditions in the region. For example, in north-east Spain, grape yield has been declining due to water deficits since the 1960s. Yields of several rainfed crops (e.g. wheat in France) are levelling off or decreasing (e.g. potato, wheat, maize and barley in Italy and southern-central Europe) because of increased temperatures. On the contrary longer growing seasons have increased the yield of wheat, maize and sugar beet in parts of northern-central Europe and of the United Kingdom. As a result, climate change will induce a reallocation of agricultural practices between European countries.

Future crop yield projections are subject to great uncertainty due to uncertainties in socio-economic scenarios, in climate projections and in the magnitude of the CO_2 fertilization effect. However, there are clear indications of deteriorating agro-climatic conditions. Moreover, there is a risk of enhanced interannual variability in crop productivity and livestock production which constitutes a challenge for proper crop management and for adaptation strategies, but also for food security.

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5.3 Fisheries

The effects of climate change on marine ecosystems lead to a modification of the entire seafood chain, by changing the primary production which affects the growth and survival of animals, by leading to the migration of certain species to higher latitudes, and by modifying the interactions between the different organisms. These effects have important socio-economic consequences, particularly in countries where fishing is the main activity. In many regions, the composition of fishing catches has been radically transformed and fish stocks have been reduced. For example, tropical areas experience the strongest decline, and by 2050, this decline is projected to be of ~40%. On the other hand, in regions at higher latitudes, such as the North Atlantic and North Pacific, there is an increase in the range of some fish species.

These changes pose challenges. In order to continue sustainable fisheries, fishing methods must be adopted, but the changes in spatial distribution and abundance of fish stocks have already challenged the management of some important fisheries and their economic benefits. The fishing industry and governments have found it difficult to agree on how to manage changing fish stocks, especially if fish cross international borders or if catches have to be significantly reduced.

5.4 Energy

The energy sector is responsible directly or indirectly for the majority of anthropogenic greenhouse gas emissions. Both energy supply and energy demand are highly sensitive to changes in climate conditions. Temperature is one of the major drivers of energy demand in Europe, affecting summer cooling and winter heating for residential properties and business/industry. Heating and cooling are responsible for a large fraction of the European energy use and for the electricity demand. Over the recent decades, heating has decreased, mainly in north-western Europe, and cooling has increased, particularly in southern and central countries.

The increased frequency of extreme weather events, including heat waves, droughts and storms, poses additional challenges for energy systems. Increases in temperatures and the occurrence of droughts may limit the availability of cooling water for thermal power generation in summer. However, the impacts of climate change on energy production depend on the energy mix and the geographical location. In particular, impacts on renewable energy generation are subject to strong regional variations. Hydropower production may experience significant risks due to the retreat of glaciers and the subsequent decrease of water availability. On the contrary, conditions in Scandinavia are expected to improve because of more abundant precipitation. The efficiency of fossil-powered generators and nuclear plants is sensitive to a reduced availability of cooling water due to increased temperatures and potential droughts. In this regard, France is the country facing the highest risks due to the great number of nuclear plants deployed on the territory. On the other hand, limited impacts on solar energy are expected. There is no general agreement concerning the impacts on wind power generation. Some studies project a limited effect of climate change (Tobin et al., 2015, 2016)

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despite a decrease of wind potential over Mediterranean areas and an increase over northern Europe, while others report a decline of the capacity of 6.9% and 9.7% under the RCP8.5 scenario by 2050 and 2070 respectively, with the highest decline in eastern and western Sweden, and in Andalusia. Finally, energy infrastructures installed in coastal zones are also exposed to the risk of sea-level rise.

5.5 Human migrations

Environmental changes have always been a key driver for population movements, even since the first hominids several million years ago. Today, climatic variations linked to human activities can occur on very short time scales (a few years to a few decades). The risk of climatic migrations is particularly exacerbated for populations already weakened by environmental conditions that are less favourable to the development of agriculture than in temperate latitudes, and by the fact that land use strategies do not always take into account all environmental risks. For example, in Africa and other parts of the world, there is a high population density around coastal areas and the risk of rising sea level is ignored. The current population movements related to the changing environmental conditions can be rapid in response to the occurrence of extreme events, or more gradual, such as those related to sea level rise. They can also be temporary or permanent. There is currently no consensus on the number of people displaced by climate change. This is because many factors leading to displacement are often intertwined, such as economic, political, social and demographic factors (Marotzke et al. 2020). Most displacement occurs preferentially within the country of origin, usually from rural to urban areas, but it can be expected that more and more people from North Africa or Sub-Saharan Africa will arrive in Europe, especially as decreasing rainfall and increasing temperatures (Gemenne. 2011, Defrance et al. 2017) have a deleterious effect on agricultural production. In addition to the disruption of ecosystem services, rising temperatures could lead to heat stress by exceeding the thermoregulatory capacities of the human body (Mora et al. 2017). Finally, populations from deltaic regions, where agricultural activities are often concentrated, or those living in low-lying areas are also expected to be more and more affected because of sea level rise, which could exceed 1 m by the end of the century. Non-linear phenomena such as changes in the oceanic circulation or the melting of the polar ice sheets, with still uncertain consequences on the climate and the environment, must also be taken into account in the migration forecasts of the coming decades (Defrance et al. 2017).

Year after year, climate-related disasters are displacing more people than conflicts and violence, although the climate-related problems, such as dwindling access to water and food resources, are themselves also sources of armed conflicts.

Given the scale of the migration risk, political measures are needed to ensure the rights of displaced persons. But the implementation of these measures is made difficult by conflicting narratives in international negotiations. For example, some see migration as a way to reduce population pressure on certain natural resources and recommend that migration be facilitated and financed (Black et al. 2011). Others, on the contrary, present migration as a failure of adaptation and a humanitarian tragedy to be avoided at all costs (Anik and Simsek 2018).

Following an initiative by the Swiss and Norwegian governments (Nansen initiative) launched in 2012[8], a protection agenda containing innovative solutions has been established to uphold the rights of displaced people (Gemenne and Brücker 2015), a new international organization (the Platform on Disaster Displacement) was set up to ensure the implementation of these solutions.

6. Conclusion

In this report, we have provided key examples of how climate change due to human activities may impact our environment and thereby human societies. There is a wide range of other possible consequences that have not been addressed here including the new challenges facing the tourism industry owing to deteriorating climatic conditions in some regions, or the economic costs that will be induced by the damages to infrastructures. Moreover, exposure to natural disasters can result in mental health consequences such as anxiety, depression and post-traumatic stress disorders. Although, there are still uncertainties associated with the magnitude of the different climate-related impacts at the local and regional scales, most of them have now become a reality. Our future will therefore depend on our willingness to reduce our greenhouse gas emissions and on the future socio-economic pathways. The implementation of appropriate adaptation and mitigation measures by policy-makers to meet the commitments made in the Paris Agreement in 2015 is therefore urgently needed.

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[8] The Nansen Initiative is a was a consultative process intended to build consensus among states on on key principles and elements to protect people displaced across borders in the context of disasters caused by natural hazards, including those linked to climate change. Among other things, better disaster preparedness should prevent such forced displacements and better protect those affected This agenda has been adopted by 109 states in Geneva in October 2015.

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PART II

Methodologies for assessing the carbon footprint

How to evaluate greenhouse gas emissions from transport in Europe

Produced by Bruno LE HEN ORTEGA

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1. Introduction

This report is part of the 'Erasmus Goes Green' (EGG) first Intellectual Output (IO1). The objective of IO1 is the "assessment of the transport-related carbon footprint of the Erasmus+ programme". It constitutes the backdrop for the next EGG objectives and intellectual outputs.

A major step in IO1 is to investigate carbon emissions: what are they? how to measure them? what are their impact on the environment? The knowledge acquired through this step will give a framework for the carbon footprint estimation of the current Erasmus+ programme (2014-2021) and a forecast for the next programme (2021-2027).

This report is the result of this step of investigation. It focuses on methodologies for carbon footprints with an emphasis on transport-related emissions in Europe. It is divided into two parts. The first part presents global definitions, the major international protocols, and the general methodology for carbon footprints. The second part then focuses on the transport sector, including the detailed methodologies for different modes of transport and the transport carbon footprint in Europe.

2. General definitions and methodology

2.1 What is a carbon footprint?

2.1.1 Greenhouse gases

A **Greenhouse Gas** (GHG) is a gas in the atmosphere that absorbs infrared radiations emitted by Earth and re-emits them towards its surface. It contributes to the **greenhouse effect**, a natural phenomenon that warms the Earth's surface and the lower layers of the atmosphere. GHG emissions can be natural or anthropogenic (i.e. caused by human activity). The increase of anthropogenic GHG emissions during the industrial era (since 1750) is responsible for the greenhouse effect disturbance resulting in global warming and climate change.

International awareness of this issue led to the adoption of the **UNFCCC treaty (United Nations Framework Convention on Climate Change)** in 1992. Its main objective is the "*stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*" [UNFCCC 1992, Article 2]. The 197 signing parties meet annually during the Conference of Parties (COP), which led to the adoption of the **Kyoto Protocol** in 1997 [UNFCCC 1997]. It sets binding individual GHG reduction targets for industrialized countries and the European Union (EU) over a five-year period 2008-2012. A second commitment period 2013-2020 was adopted under the Doha Amendment.

A list of six anthropogenic GHGs is defined under the Kyoto Protocol:

- CO_2 – carbon dioxide
- CH_4 – methane
- N_2O – nitrous oxide
- $HFCs$ – hydrofluorocarbons

- $PFCs$ – perfluorocarbons
- SF_6 – sulfur hexafluoride

A seventh GHG has been added later in 2012 with the Doha Amendment:

- NF_3 – nitrogen trifluoride

$\boldsymbol{CO_2}$ has the largest contribution to global warming with 72% of all anthropogenic GHG emissions in 2010 [IPCC 2013]. Most of them are coming from fossil fuel combustion and land use change (such as deforestation).

$\boldsymbol{CH_4}$ has the second largest contribution with 20% of emissions in 2010 [IPCC 2013]. It comes from biogenic sources (agriculture, ruminant livestock, waste treatment, …) but also from fossil fuel extraction and use.

$\boldsymbol{N_2O}$ is the third largest contributor with 5% of emissions in 2010 [IPCC 2013], mainly coming from agriculture and the fertilization of soil sources.

The four other categories of GHGs are called **fluorinated gases**. Together, they represent 2.2% of emissions in 2010 [IPCC 2013]. They are man-made and used in many industrial processes like electronics industry (NF_3, $PFCs$, SF_6), aluminium production ($PFCs$), electricity transmission and distribution (SF_6) or as refrigerants ($HFCs$). Even if their emissions are lower than CO_2, they have considerably longer lifetimes in the atmosphere and higher global warming potentials[9], which make them sensible GHGs.

The Kyoto Protocol only requires the reporting of these 7 categories. However, to be more complete, the UNFCCC guidelines [UNFCCC 2013] as well as other international methodologies, recommend the separate reporting of other gases.

For example, **precursor gases,** which mainly consist of $\boldsymbol{CO}$ (carbon monoxide), $\boldsymbol{NMVOCs}$ (non-methane volatile organic compounds) and $\boldsymbol{NO_X}$ (nitrogen oxides), are not considered as direct GHGs, but their emissions can indirectly enhance the greenhouse effect. They can create secondary GHGs. For example, the interaction of precursor gases with solar radiation in the troposphere (<10 km of altitude) creates tropospheric ozone (O_3), a GHG that also contributes to air pollution. Precursor gases can also increase the impact of direct GHGs, for example by extending the lifetime of CH_4 in the atmosphere.

Other GHGs have also been identified by the **IPCC (Intergovernmental Panel on Climate Change)** but not yet adopted by the COP. For example, $PFPEs$ (perfluoropolyethers) and $HFEs$ (hydrofluoroethers) which can be used for the electronic industry or as refrigerants.

Therefore, precursor gases, $PFPEs$, $HFEs$ and similar gases are encouraged to be reported separately, but they are not mandatory under the Kyoto Protocol.

Finally, there are other categories of GHGs that are not considered relevant for GHG inventories.

Water vapor is also a GHG, and the largest natural contributor to the greenhouse effect (2 or 3 times greater than CO_2). However, its anthropogenic sources (evaporation from irrigation

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[9] See the definition of global warming potential page 6.

and power plant cooling systems) are considered negligible compared to the natural sources [IPCC 2013]. Therefore, water vapor is not regulated under the Kyoto Protocol.

Some GHGs such as $CFCs$ (chlorofluorocarbons) and $HCFCs$ (hydrochlorofluorocarbons) are also **Ozone Depleting Substances**. They are already regulated by the **Montreal Protocol**, a treaty previously adopted by all UN members in 1987. These gases are already being phased out and the Kyoto Protocol rather focuses on $HFCs$ which have been used to replace them. Therefore, $CFCs$ and $HCFCs$ are not covered by the Kyoto Protocol.

The anthropogenic emissions of GHGs are responsible for global warming. The UNFCCC and the Kyoto Protocol are adopted to mitigate climate change worldwide.

They define 7 categories of GHGs to be regulated (CO_2, CH_4, N_2O, $HFCs$, $PFCs$, SF_6, NF_3). CO_2 is the main responsible GHG for global warming.

Other gases are also encouraged to be reported separately (CO, $NMVOCs$, NO_X, $PFPEs$, $HFEs$, …) or are already regulated by the Montreal Protocol ($CFCs, HCFCs$).

2.1.2 Greenhouse gas inventory and carbon footprint

The first step for reporting GHG emissions is a **GHG inventory**. It evaluates all GHG emissions in a defined perimeter during a specific period of time (usually one year). It details every anthropogenic source of GHG emissions but also every **carbon sink** that remove GHGs from the atmosphere (usually from forestry). It can be applied at all levels i.e. to a nation, a territory, an organization, a project, a product or an individual. **Time series** are obtained by reiterating GHG inventories year after year.

A GHG inventory has several benefits. First, it allows to comply to mandatory GHG reporting programs, both for nations within UNFCCC and the Kyoto Protocol, and organizations within national or international legislation. It also allows states and organizations to participate in GHG markets and trading programs. It can also increase the environmental transparency of organizations towards the population and public actors. But more importantly, a GHG inventory is the first step before setting GHG reduction targets and policies. The identification of precise GHG sources allows to identify the reduction opportunities and allows to couple them with economical benefits. Finally, time series year after year allow to monitor the progress towards reduction targets and evaluate regulation policies.

A GHG inventory has also several limitations. It does not represent a complete environmental impact study. GHG emissions are only one source of environmental pollution among others (water and air pollution, raw material depletion, …). Therefore, a GHG inventory must be included in a more global environmental policy framework in order to avoid the transfer of pollution between different sources (for example reducing GHG emissions but increasing mineral depletion). Moreover, a GHG inventory can be difficult to implement. It can be costly and time-consuming to develop the process required to obtain very precise data. Therefore, a GHG inventory is never exhaustive nor without uncertainty. Instead, it is a compromise

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between technical/economical feasibility and sufficient precision to achieve the inventory objective.

The **carbon footprint** is obtained as a result of the GHG inventory by summing up the different GHG emissions together. A carbon footprint is expressed in terms of **equivalent CO_2 emissions ($CO_{2_{eq}}$)**. To do so, we need to compare the different GHGs with CO_2.

Every GHG can be characterized by its **Global Warming Potential (GWP)**. It represents the total energy added to the climate system by the emission of a given mass of GHG, relatively to CO_2, over a given period of time after the emission. The greater a GWP is, the greater the GHG impacts the climate compared to CO_2 over that time period. Usually, this time period is 100 years. Impacts that happen more than 100 years after the emission are not considered.

A GWP is normalized to CO_2 which allows to convert GHG emissions into CO_2 equivalent emissions. For example, the SF_6 100-year GWP is 23 500 [IPCC 2013]. It means that during 100 years after its emission in the atmosphere, one gram of SF_6 is equivalent to the emission of 23 500 grams of CO_2. Therefore, SF_6 is often considered as the most dangerous individual GHG, not to mention its lifetime of 3200 years in the atmosphere. At a global level however, there is less SF_6 emissions than CO_2. Indeed, SF_6 is responsible for less than 2.2% of the total anthropogenic CO_2 equivalent emissions in 2010, while CO_2 is responsible for 72% of them (see Figure 1).

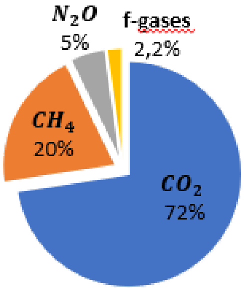

Figure 1 – Worldwide total GHG emissions in $CO_{2_{eq}}$ in 2010 [IPCC 2013]

GHG	$GWP_{100-year}$	Lifetime (years)
CO_2	1	several hundred of years
CH_4	28	12.4
N_2O	265	121

Table 1 – Usual properties of the three main anthropogenic GHGs reported in the fifth IPCC report [IPCC 2013]

A carbon footprint is expressed in $kgCO_{2_{eq}}$ (kilograms of equivalent carbon dioxide) or $tCO_{2_{eq}}$ (tons of equivalent carbon dioxide) and is obtained by multiplying each GHG emissions by its respective GWP:

$$Emissions_{CO_{2_{eq}}} = \sum_{GHG} Emissions_{GHG} \times GWP_{GHG}$$

It is worth mentioning that the GWP, while internationally accepted as the default metric for carbon footprint since the Kyoto Protocol, has some limitations. First of all, the choice of the GWP time period of 100 years is an arbitrary value judgment. Other usual values in literature are 20 years or 500 years. This choice can have a strong effect on the GWP values and can reflect different gases properties related to their lifetime in the atmosphere. The 20 year-GWP prioritizes gases with short lifetimes (CH_4 for example) while the 500 year-GWP prioritizes GHG with longer lifetimes (SF_6 for example). The preferred choice of 100 years, while harmonizing methodologies, is not based on any prevalent scientific argument [IPCC 2013]. Secondly, the GWP methodology induces large uncertainties in the result. For example, the IPCC estimates uncertainty on the 100-year GWP of CH_4 at ± 40% (for the 5%-95% uncertainty range) [IPCC 2013].

Other metrics are proposed, such as the Global Temperature change Potential (GTP) but it faces the same issues. The choice of one metric always contains implicit value judgements and large uncertainties.

A GHG inventory details every anthropogenic source of GHG emissions and carbon sinks. It can be applied to a nation, a territory, an organization, a project, a product or an individual.

The carbon footprint is obtained by adding all the GHG emissions which are converted to equivalent CO_2 emissions by using their 100-year GWP.

2.2 What are the existing international standards?

Several international standards and methodologies exist to ensure that GHG inventories around the world are coherent and comparable. They can be classified according to the item of the inventory (a nation, an organization, a product, …). In this section, we first present the most widely used standards for national inventories and then for organization inventories. They both consider human activities such as transport. Therefore, they are of interest in the EGG framework. Many other standards exist for the carbon footprint of a product, such as the PAS 2050 or the ISO 14067. However, they do not enter in the EGG framework and will not be detailed here.

All standards studied here are built in accordance with the Kyoto Protocol. They all consider the mandatory reporting of its 7 GHG categories (CO_2, CH_4, N_2O, $HFCs$, $PFCs$, SF_6, NF_3) and encourage the reporting of other gases. They also use the 100-year GWP methodology described above to obtain the global carbon footprint. Moreover, they all explicitly share the principles of “transparency”, “consistency”, “completeness” and “accuracy”. Their common objective is to improve these principles for GHG inventories.

2.2.1 National inventories: the UNFCCC and IPCC guidelines

All nations under the UNFCCC treaty are committed to *“develop, periodically update, publish and make available to the COP, national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the COP”* [UNFCCC 1992, Article 4, paragraph 1a].

All EU nations and the EU itself are parties of the UNFCCC and must report their GHG inventories along their GHG policies every year. The **UNFCCC reporting guidelines on annual inventories** define this reporting process [UNFCCC 2013]. Starting in 2000, developed nations must submit every 15th of April, a **National Inventory Report (NIR)** detailing the methodologies and the data used, and a **Common Reporting Format (CRF) tables** containing the emissions data.

However, the scientific methodology is not directly detailed in the UNFCCC guidelines. Instead, it refers to a second document, the **'2006 IPCC Guidelines for National Greenhouse Gas Inventories'** [IPCC 2006] developed by the IPCC Task Force on National Greenhouse Gas Inventories (IPCC-TFI). The 2006 IPCC guidelines have been refined later in 2019 [IPCC 2019]. However, this 2019 refinement did not affect methodologies for transport emissions.

For nations, the inventory perimeter is the national geographical territory. The reported GHG emissions are the ones physically emitted inside the territory. The 2006 IPCC guidelines use a **sectorial approach**, where national emissions are allocated into **five main sectors: 1-energy; 2-industrial processes and product use; 3-agriculture, forestry, and other land use; 4-waste; 5-other** (see Figure 2). These sectors are subdivided in categories and subcategories. This sectorial approach is specific to geographical territories.

The 'Transport' subcategory 1A3 is in the 'Energy' sector, under the 'Fuel combustion activities' category. It is divided in five subcategories according to the mode of transport: civil aviation, road transportation, railways, water-borne navigation and other transportation (see Figure 2 – green box).

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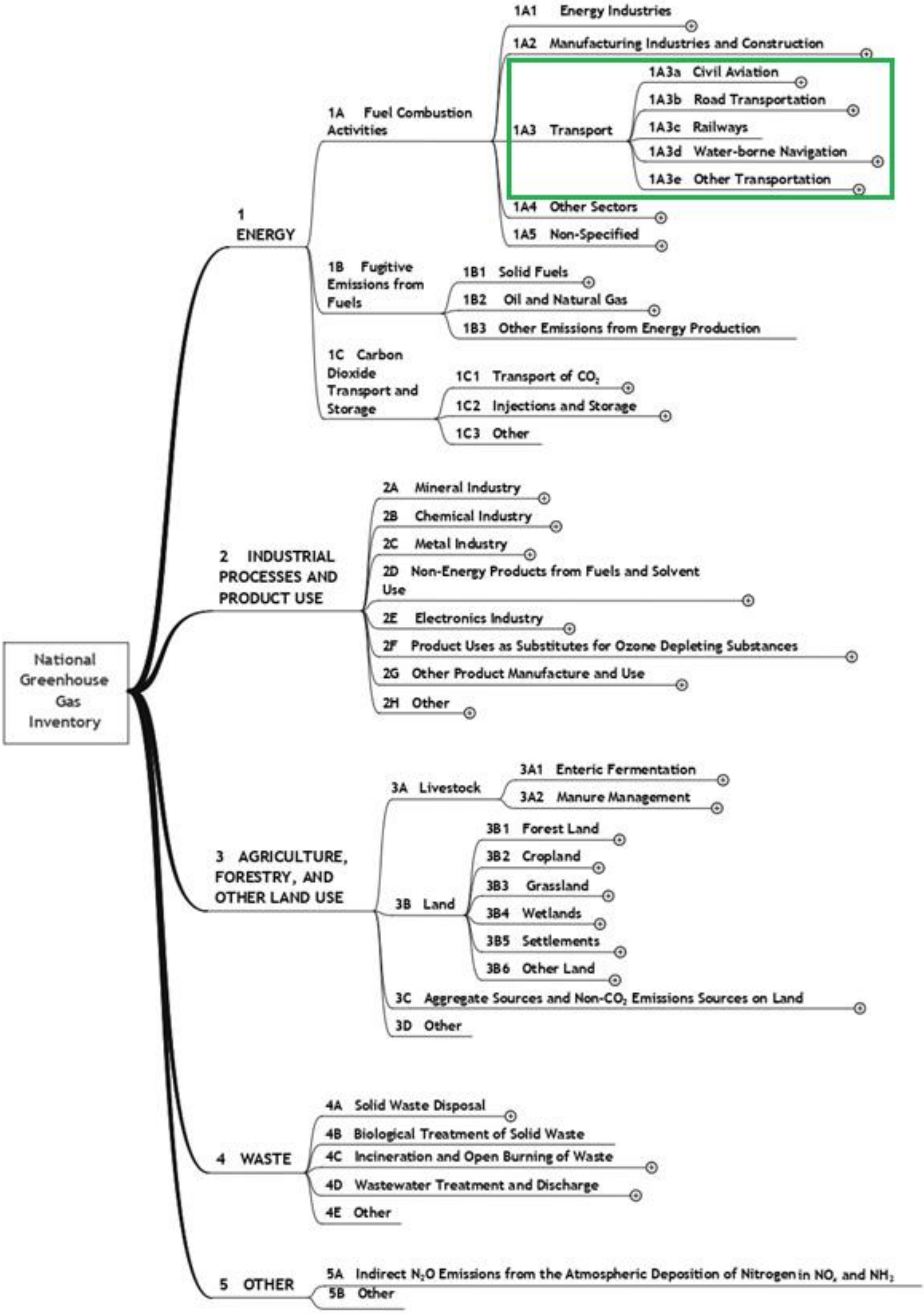

Figure 2 – Main categories of GHG emissions and removals defined in the 2006 IPCC Guidelines for National GHG Inventories [IPCC 2006]

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The 2006 IPCC guidelines provide detailed methodologies at a subcategory level for the estimation of GHG emissions. These methods are classified into three levels of detail, called **‘Tiers’**. A Tier 1 method is the default method while the Tier 3 is the most detailed method. Generally, Tier 1 methods rely on average data provided by the IPCC and are therefore applicable without many efforts. Higher tiers require more resources for calculation or data collection and can be more difficult to apply. The tiers methodologies will be presented with more detail in the next sections of this report.

The 2006 IPCC guidelines mainly focus on the seven GHGs to be reported. For precursor gases, it often refers to the **EMEP/EEA air pollutant emission inventory guidebook** [EMEP/EEA 2019] as a complement.

Air pollutants include the precursor gases CO, $NMVOCS$ and NO_X. Similarly to GHG emissions, they are an environmental issue covered by a UN convention (the Convention on Long-range Transboundary Air Pollution). At a European level, reporting guidelines are developed jointly by the **EMEP (European Monitoring and Evaluation Programme)** and the **EEA (European Energy Agency)**. The EMEP/EEA guidelines have been developed in accordance to the IPCC guidelines (same sectorial approach, use of tiers, …).

All developed nations under the UNFCCC treaty must report their GHG inventory, following UNFCCC guidelines. They publish every year a report (NIR) and emission data (CRF) tables.

The scientific methodology is detailed in the ‘2006 IPCC Guidelines for National Greenhouse Gas Inventories’. GHG emissions are divided in 5 sectors (energy, industrial processes, agriculture and land use, waste, other).

For each subcategory, methodologies are organized in tiers. Tier 1 are default methods and Tier 3 are detailed methods.

The EMEP/EEA guidelines are used as a complement for precursor gases.

2.2.2 Organization inventories: the GHG Protocol and ISO 14064 standards

We use the term ‘organization’ to designate companies but also other organizations with operations such as government agencies, non-governmental organizations, or universities. Organizations fall under national and international legislations on GHG reporting and regulation[10]. While legislations may vary in each country, they often share common general principles issued from internationally recognized standards. The most cited standards are the ISO 14064-1 and the GHG Protocol ‘Corporate Standard’.

ISO (International Organization for Standardization) is a worldwide non-governmental organization developing international standards for technologies and industries. It gathers 165 national standards organizations including all EU countries. The ISO 14060 family focuses on

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[10] EU organizations follow the directive No. 2003/87/CE on GHG emissions trading.

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GHG inventories and related reporting. It includes the **ISO 14064-1** [ISO 2018] on the development of GHG inventories specifically for organizations. A first version was published in 2006 and was revised in 2018. It is completed by the Technical Report ISO/TR 14069 [ISO 2013] which provides guidance in the application of the ISO 14064-1.

The **GHG Protocol** is a partnership between the World Resources Institute and the World Business Council for Sustainable Development – a coalition of 170 international companies. Since 1997, it has developed standards, tools, and formation on GHG inventories for public and private actors: seven different protocols have been published (for projects, for products, for cities, for policies, for public mitigation goals). Two of which are directly for organization inventories: the **'Corporate Standard'** [GHG Protocol, 2015], first published in 2001 and revised in 2015, and the **'Corporate Value Chain (Scope 3) Standard'** [GHG Protocol, 2011a]. A third document 'Technical Guidance for Calculating Scope 3 Emissions' [GHG Protocol, 2011b] completes them.

The inventory perimeter is more complex for an organization than for a country. Its operations are not defined by a geographical territory and can involve different actors or other organizations. The question of the responsibility of emissions is therefore of great importance. Instead of a sectorial approach, the ISO 14064-1 and the GHG Protocol use the concept of **direct/indirect emissions**. Direct emissions are emissions from GHG sources owned or controlled by the organization. Indirect emissions are emissions that are a consequence of the organization operations, but emitted by GHG sources not owned or controlled by the organization.

For example, a university uses electricity for its offices. The generation of this electricity emits GHG. These emissions are considered direct emissions for the electricity company and indirect emissions for the university. This concept allows to obtain a complete inventory across the whole value chain of the organization activities without double counting.

Following this concept, the GHG protocol allocates emissions into three different groups, also called "**Scopes**" (see Figure 3):

Scope 1 – Direct GHG emissions. For example, it can be emissions from an industrial process, or from the company vehicles.

Scope 2 – Indirect GHG emissions from purchased energy. They are indirect emissions from the production of electricity, steam or heating/cooling used by the organization. This category is apart from other indirect emissions because it represents the largest source of GHG emissions for many companies and a major possibility for GHG reduction. Scope 2 emissions are in the upstream value chain of the company.

Scope 3 – Other indirect GHG emissions. They are all the other indirect emissions. They can be in the upstream or downstream value chain. They are grouped in 15 sub-categories (see Figure 3 for details). These sub-categories include employee commuting and business travels, which are of interest for the EGG framework.

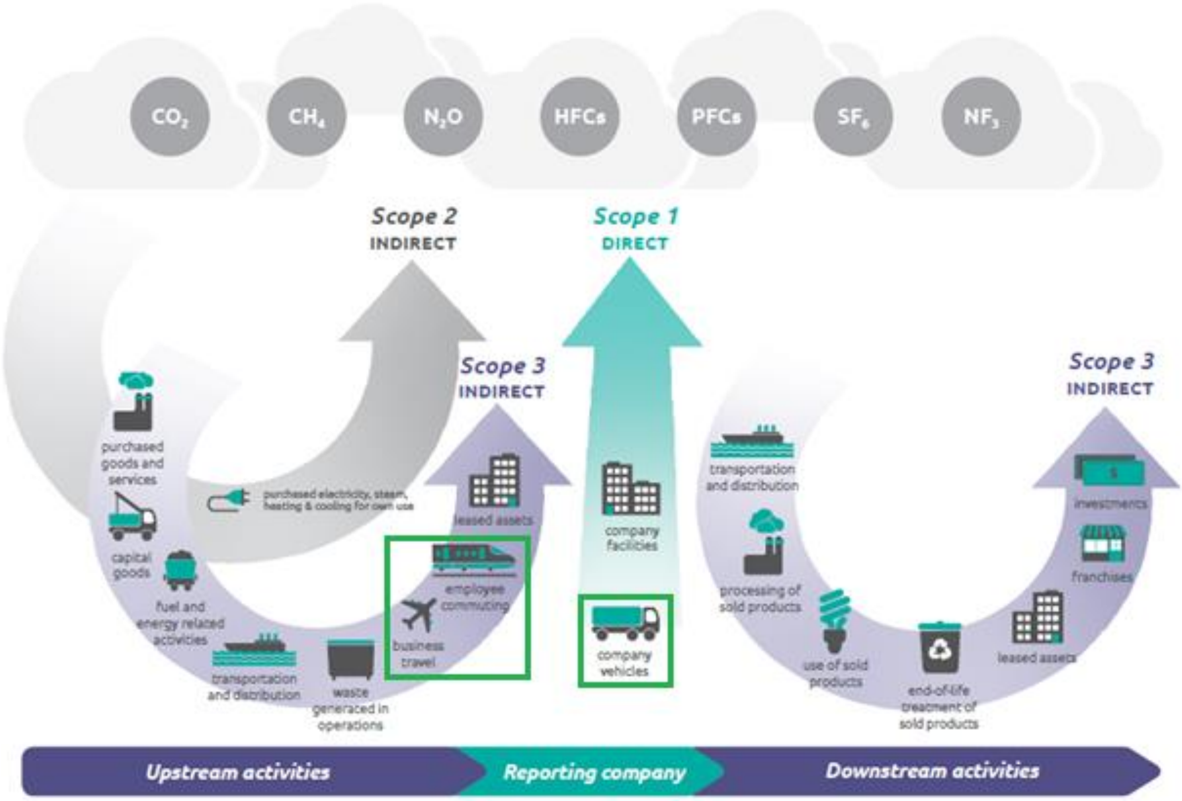

Figure 3 – Main categories of emissions and scopes from the GHG Protocol standards [GHG Protocol, 2011a]

The ISO 14064-1 has a more precise division of indirect emissions in five categories instead of two (imported energy, transportation, products used by the organization, use of products of the organization, and other sources). This difference in allocation categories does not affect the core methodologies and the two standards remain compatible. Indeed, the ISO 14064-1 and the two GHG Protocol standards have been developed in accordance with each other. Their content is compatible with only few differences. For example, the ISO 14064-1 is shorter and more concise. The GHG Protocol objectives are more inspirational in disseminating guidance for companies and therefore contains more context and practical cases.

The ISO 14064-1 and the GHG Protocol 'Corporate Standard' are the most used international standards for organizations. They are compatible with each other and use the same principle of direct/indirect emissions.

Direct emissions are from sources owned or controlled by the organization. Indirect emissions are a consequence of the organization activities. The GHG Protocol allocates emissions in three scopes: S1-direct emissions S2-indirect emissions from energy S3-other indirect emissions.

2.2.3 Comparing protocols: the case of indirect emissions

The national inventories (UNFCCC and IPCC) and organizational inventories (ISO and GHG Protocol) have different approaches to define their emission perimeter and responsibility. Nations use a sectorial approach and are only responsible for direct emissions inside the geographical territory. Organizations consider both direct and indirect emissions, without considering the location of the emission. This difference can lead to different result of carbon footprints.

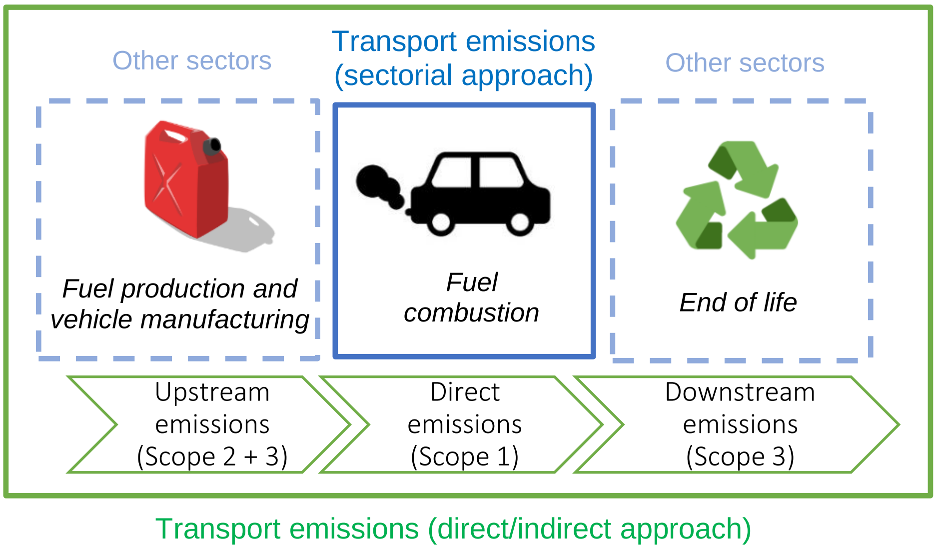

Figure 4 – Transport emissions from a vehicle owner using different perimeters approach

For the example of transport, let us consider a vehicle owner. Direct emissions correspond to the fuel combustion during the lifetime of the vehicle. Indirect emissions come from the fuel production (extraction, processing, transport), the vehicle manufacturing and the vehicle end of life (see Figure 4).

In the direct/indirect approach from organizational standards, the owner can decide to which level of detail he accounts for these indirect emissions (green box).

In the sectorial approach, only direct emissions from fuel combustion are allocated to the transport category[11] (blue box). Indirect emissions, if they are emitted inside the national territory, are allocated to other different categories such as ‘energy industry’, ‘manufacturing industry’ or ‘waste’.

This sectorial approach is necessary for national inventories to avoid double counting emissions between sectors. However, it is less transparent on the total value chain emissions. Therefore, to compare different modes of transportation and their total carbon emissions, the direct/indirect approach is preferred.

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[11] Exception for the fuel transportation, which is an indirect emission, but is considered in the transport sector.

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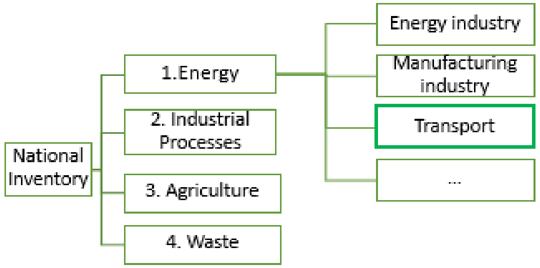
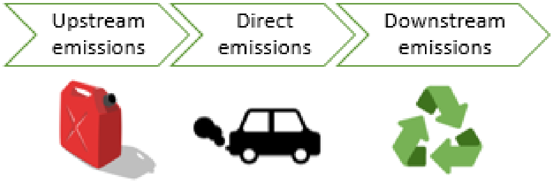
	Nations	Organizations	
Publisher	IPCC-TFI	ISO	GHG Protocol
Documents	2006 IPCC Guidelines for National Greenhouse Gas Inventories	ISO 14064-1	- Corporate Standard - Corporate Value Chain (Scope 3) Standard
Complementary documents	- 2019 Refinement to the 2006 IPCC Guidelines - EMEP/EEA air pollutant emission inventory guidebook 2019	ISO/TR 14069	Technical Guidance for Calculating Scope 3 Emissions
Perimeter approach	Sectorial approach 	Direct/indirect emissions 	
Advantages and inconvenients	⊕ detailed methodologies for each sector ⊖ no indirect emissions	⊕ indirect emissions and individual passenger responsibility ⊖ less detailed methodologies	

Table 2 – Comparison of major international protocols for GHG inventories

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A second difference is that national inventories only consider the global vehicle emissions, and do not consider individual passenger responsibility. The GHG Protocol and ISO standards are interesting to determine the individual share of emissions per passengers in the total transport emissions.

Finally, the IPCC guidelines provide much more detailed methodologies, with usually three tiers for each mode of transport. The organizational standards only provide a general methodology for all modes of transport without much detail and usually corresponding to Tier 1 or Tier 2 methodologies.

2.3 What is the general methodology?

The national inventories (UNFCCC and IPCC guidelines) and organizational inventories (ISO 14064-1 and GHG Protocol standards) share a common general methodology.

They share common steps for the conduct of a GHG inventory:

1- Definition of the inventory perimeter and the key categories
2- Select methodologies for each category
3- Collect the relevant data for each category
4- Estimate the GHG emissions and compile the inventory
5- Uncertainty analysis
6- Quality assessment and reporting

2.3.1 Step 1: Inventory perimeter and key categories

The first step is different for a nation or an organization, as described in the previous section.

For a nation, the perimeter is its geographical territory, and a sectorial approach is used.

For an organization, the perimeter definition is based on the direct/indirect emission approach. This is a very important step where the level of detail for indirect emissions is decided. Under the GHG Protocol standards, the reporting of Scope 1 and Scope 2 emissions are mandatory while Scope 3 emissions are only recommended, depending on whether they are key categories or not.

A **key category** is an important category under one of these criteria: high amount of emissions, increasing trend of emissions, high level of uncertainty. The standards provide methodologies to define and determine key categories according to the context. Usually, key categories are determined by simple comparison with previous or similar GHG inventories. Otherwise, simple methods called **screening methods** (usually Tier 1) are used to have an approximation of the importance of a category.

2.3.2 Step 2: Methodology selection

There are two main categories for GHG emissions estimation methods: direct measurement (using direct monitoring, mass balance or stoichiometry) or calculation. In practice, direct measurement can be costly and difficult to implement for all type of applications. Therefore, calculation methods will be used more often.

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The most common calculation approach is defined by the formula:

$$\boxed{Emissions = Activity\ Data \times Emission\ Factor}$$

It uses two types of data:

- **Activity Data (AD)** – a quantitative measure of an activity responsible for GHG emissions (or removal).
- **Emission Factors (EF)** – a factor quantifying the GHG emissions per unit of activity. It converts AD into GHG emissions.

For example, for a vehicle, the activity data can be the number of kilometers travelled or the number of liters of fuel consumed. The respective associated emission factors are expressed in $kgCO_{2_{eq}}/km$ or in $kgCO_{2_{eq}}/L$.

This equation is then adapted to the category specificities and refined in different tiers.

Usually, Tier 1 and Tier 2 methodologies use the same equation, but Tier 2 methods use more precise source of data. Therefore, the type of data used and their level of precision is of major importance. Tier 3 methodologies usually involve more complex models specific to the emission category. Methodologies specific for transport are detailed in the next section.

The standards provide **decision trees** to help nations and organizations chose the relevant tier methodology, depending on the available resources but also on the importance of the category. Due to their importance, key categories require more detailed methodologies (Tier 2 or Tier 3).

2.3.3 Step 3: Data collection

The data collection is a key step to obtain precise carbon footprints. It is also the most time-consuming step. Indeed, activity data is often obtained by national surveys for nation inventories, or surveys from suppliers for an organization. Creating a survey program from scratch is a laborious process. It is therefore recommended to check already existing data or programs before deciding to generate new data. In any case, this step always relies on sector specialists and requires expert judgment for methodological choices. This step must also be documented in detail with data sources and all assumptions to provide transparency on the GHG inventory.

Data (i.e. AD or EF) can be classified in two categories according to their sources:

- **Primary data** is obtained or derived from a direct measurement. For example, a primary AD can be an organization-specific measurement of its vehicle fleet travelled distances. Another example of primary EF can be obtained from the measurement of a fuel sample which is representative of the whole activity. In both cases, suitable survey and measurement methods, defined by specific standards, must be used.
- **Secondary data** is data obtained from other sources than primary data. Usually, it refers to published literature or databases such as industry-average or international-average data.

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Sometimes, data for a specific activity is not available or has some gaps. In these cases, alternative data can be created using data from another activity correlated to it. This data is called **proxy data**, or surrogate data. For example, if an EF for electricity production exists in Ukraine but not in Moldova, a company in Moldova can use the Ukraine EF as a proxy. Proxy data can be extrapolated, scaled up or customized to be more representative. Proxy data is also considered as a secondary data.

Finally, EF are classified depending on their level of detail. They can include direct but also indirect emissions. For fuel combustion activities:

- **Combustion EF** includes direct emissions from the fuel combustion only. For transport, it is also called **Tank-to-Wheel** EF.
- **Life cycle EF** includes direct fuel combustion emissions + indirect emissions from the fuel life cycle (fuel extraction, processing and transportation). It is also called **Well-to-Wheel** EF for transport.

  Moreover, for transport, the life cycle EF can also account for emissions from the vehicle and its infrastructures whole life cycle. In that case, it is called a full-scale Life Cycle Analysis EF. However, EFs with such level of detail are rarely available.

The choice for the EF level of detail depends on the choice of the inventory perimeter in the first step but also on the availability of such data.

There are many sources for EF data. The 2006 IPCC guidelines provide general international averaged combustion EF, used in Tier 1 methodologies. The IPCC-TFI also provides an online Emission Factor Database with more detailed EF[12].

The GHG Protocol provides a list of third-party EF databases[13]. It includes international but also national or sector databases. Noticeable examples are the GREET database from the U.S. EPA (Environmental Protection Agency) that includes full life cycle EF for different vehicles, the United Kingdom DEFRA (Department for Environment, Food and Rural Affairs) or the Base Carbone® from France ADEME (Agency for Environment and Energy Management). Each database has its own methodology to obtain EF, often compatible with the GHG Protocol. The GHG Protocol also developed tools for GHG inventories using these data sources, including a tool for transport activities[14].

Other global international averages for AD or EF can be obtained from international organizations publishing statistics such as the UN (United Nations), the IEA (International Energy Agency), the OECD (Organization for Economic Co-operation and Development) or the International Monetary Fund. At a European level, statistics can be found via Eurostat or the EEA (European Energy Agency). Nation level data can be found via National Statistics Agencies or in the annual NIR reports to the UNFCCC. Scientific literature from national laboratories and universities is also a relevant source of data.

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[12] Accessible on https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

[13] Accessible on https://ghgprotocol.org/life-cycle-databases

[14] Accessible on https://ghgprotocol.org/calculation-tools

2.3.4 Step 4: Estimating emissions

Once the methodology is chosen and the required data is collected, activity emissions are calculated for each GHG. They are converted into $CO_{2_{eq}}$ emissions using their 100-year GWP. GWP values are provided in the IPCC Assessment Reports. The last assessment report (AR5) was published in 2013 and some of its GWP values are given in Table 1. However, the UNFCCC guidelines use the previous report (AR4) values published in 2007, which are the latest values adopted by the COP. This difference of GWP values can lead to different results. Therefore, the choice of GWP values must be explicit for the transparency and comparability of the carbon footprints.

2.3.5 Step 5: Uncertainty evaluation

This step is essential for the transparency and comparability of inventories. When collecting data in step 3, data uncertainty should also be collected. If the data uncertainty is not available, general assumptions are provided in the standards to estimate it. Finally, classical methods for uncertainty evaluation (analytical approaches or Monte-Carlo approaches) are used to obtain the total carbon footprint uncertainty.

2.3.6 Step 6: Quality assessment and reporting

This step allows to ensure the principles of “transparency”, “consistency”, “completeness” and ”accuracy” by verifying the inventory process. The reporting should include, along with the results, all information (data used, hypothesis, methodologies, …) to allow a review of the full GHG inventory process.

A GHG inventory requires six steps: 1-perimeter definition, 2-methodology choice, 3-data collection, 4-emissions estimation, 5-uncertainty analysis, 6-quality assessment and reporting.

Usually, emissions are calculated from Activity Data (AD) and Emission Factors (EF). The collection of this data is of great importance for the inventory precision.

Data can be collected from direct specific sources (primary data) or from literature and existing databases (secondary data).

Emission factors can present different level of details to include direct and indirect emissions (combustion only = Tank-to-Wheel, combustion + fuel life cycle = Well-to-Wheel).

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3. Transport-specific carbon footprint and methodologies

3.1 What are the specific methodologies for transport?

Specific methodologies for transport can be found in:

- the 2006 IPCC Guidelines for National GHG Inventories (Volume 2 ‘Energy’ - Chapter 3 ‘Mobile combustion’) [IPCC 2006]
- the GHG Protocol ‘Technical Guidance for Calculating Scope 3 Emissions’ (categories 4-‘Upstream Transportation and Distribution’, 6-‘Business travel’ and 7-‘Employee commuting’) [GHG Protocol, 2011b]
- the EMEP/EEA air pollutant emission inventory guidebook 2019 [EMEP/EEA 2019]
- documentation from category-specific models and tools, mentioned below.

3.1.1 Generalities

Transport emissions come from different sources.

The fuel combustion produces direct emissions of CO_2, CH_4 and N_2O. It also emits the precursors CO, $NMVOCs$ and NO_X and other air pollutants such as SO_2 (sulphur dioxide) or PM (particulate matter).

Indirect emissions come from the vehicle life cycle and the fuel life cycle (fuel extraction, processing and transportation) including electricity generation for electric vehicles.

Other emissions, called fugitive emissions, can come from the use of mobile air conditioning (mostly $HFCs$).

a/ Emission Factors

As detailed in section 1.3.3, the national inventories only account for direct emissions. Therefore, the 2006 IPCC guidelines only present detailed transport methodologies for fuel combustion. To account for indirect emissions, the GHG Protocol uses the same methodologies, but replaces the combustion EF by a life cycle EF. **The choice of the EF is of great importance to define the perimeter of the study.** To compare different modes of passenger transportation, it is recommended to use at least Well-to-Wheel EF (direct emissions + fuel life cycle). More detailed EF (including the vehicle and infrastructures life cycles) are not always available.

To determine the share of individual passenger emissions, two possibilities appear in the GHG Protocol. For private vehicles such as cars or motorcycles, the total emissions are simply divided by the number of passengers. However, this data is not always available and can be replaced by statistics or survey average of the number of passengers.

For other modes of transportation (aviation, railway, buses, or maritime navigation), we use **EF expressed in $CO_{2_{eq}}$ per passenger**. These passenger-EF can be found in different databases. The methodologies to obtain these EFs are often based on passenger statistics (average number of passengers or passenger capacities). They can also be more detailed with EF per passenger depending on the seat category (first class, economic, …). To do so,

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a load factor is attributed to each seat category. This load factor includes the weight or volume of the passenger, its luggage and all the vehicle equipment necessary (seats for example). These load factors are different for each seat category and allow the emissions repartition between categories.

b/ Activity Data

Two main type of AD can be used for transport: **fuel consumption data** or **distance traveled data**.

Generally, the IPCC guidelines and the GHG Protocol recommend fuel-based data which is more precise. On the contrary, the exact distance travelled is not always measured or mentioned in official documents.

When fuel data is not available, distance data is used. However, when both type of data are available, a good practice is to verify that they are consistent with each other.

In the IPCC guidelines, it is supposed that the national fuel consumption is equal to the fuel sold inside the national territory. This assumption allows to simplify cases at borders, where the fuel is bought in one country and consumed in another country.

When fuel or distance data are not available, the GHG Protocol introduces a third possible method for organizations and individuals. They are based on the amount of money spent for a mode of transport and called **spend-based methods**. They require specific EF called EEIO (Environmentally-Extended Input Output) expressed in $kgCO_{2_{eq}}$ per money spent and obtained from economical industry models.

c/ Top-down / Bottom-up approaches

There are usually two approaches to estimate emissions.

Top-down approaches use aggregated data that represents all transport movements inside the study perimeter. For example, it can be the total amount of fuel used during the year by the company or inside the national territory. The total emissions are directly estimated from this aggregated data.

Bottom-up approaches use data from individual journeys. Emissions are estimated for each individual journey and then summed up. These approaches require data with a level of detail that is not always available for nations or organizations. Therefore, they are often considered as Tier 3 methodologies.

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For transport, direct GHG emissions come from fuel combustion (CO_2, CH_4, N_2O and precursors).

To account for indirect emissions, we use life-cycle EF (Well-to-Wheel).

To account for individual responsibility, we use specific EF per passenger, which can detail different seat categories (first class, economy, …).

Two main types of AD are used: fuel consumption data and distance data. The fuel data is preferred for more precision. A third AD is used in last resort for organizations, based on money spend on transport.

3.1.2 Methodologies by mode of transport

Transport emissions can be divided in different subcategories according to the mode of transportation. The IPCC guidelines define five subcategories:

- Civil aviation
- Road transportation
- Railways
- Water-borne navigation
- Other transportation

The ‘other transportation’ includes off-road mobile sources, such as ground activity in airports and harbors, agricultural tractors, snowmobiles but also chainsaws and forklifts.

Military transportation is not included in any of these subcategories, but in a separate category in the Energy sector.

International travel, also called international bunker, is composed of international aviation and international navigation. It is reported separately from the main inventory. Therefore, when studying UNFCCC national transport data, it should always be mentioned if international transport is included or not.

a/ Aviation

Aviation emissions mainly come from the combustion of jet fuel (jet kerosene or jet gasoline). Aviation gasoline is also used for small planes and helicopters, but it represents less than 1% of fuel consumption.

Aircraft emissions are composed of ~70% of CO_2 and ~30% of H_2O (water vapor). There is less than 1% of precursor gases and other emitted pollutants (mainly NO_X and CO) and even smaller amounts of N_2O and CH_4 emitted with modern engines.

The aircraft emissions occur at high altitudes, at the tropospheric limit (10 km of altitude). Their impact is therefore different than sources at the ground level. It is particularly true for precursors and water vapor, which are usually not mandatory for national reporting. The water vapor is responsible for the formation of vapor trails, also called **contrails**, in the atmosphere.

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This effect can be accounted by using an EF that includes the contrails and precursors, or by applying a correction factor to GHG emissions, called **radiative forcing factor** (usually between 1 and 2).

The operation of an aircraft can be divided in two phases: **'Landing/Take-Off (LTO) cycle'** and **'Cruise'**. LTO operations happen below ~900m and are responsible for 10% of fuel consumption. Cruise operations happen above ~900m and are responsible for 90% of fuel emissions (70% for CO emissions). However, for a given distance travelled, LTO use more fuel per distance than Cruise operations. Moreover, CH_4 emissions only occur during LTO cycles and are negligible during Cruise.

Activity data must be separated between domestic and international flights data.

The IPCC guidelines define three tiers for aviation:

Aviation - Tier 1

The emissions are estimated using fuel consumption data and average EF.

$$Emissions = Fuel\ consumption \times EF$$

For a nation, the activity data is the total fuel consumed in the territory. It can be obtained from national taxation authorities (top-down approach). It can also be obtained from surveys of company airlines or individual flight data (bottom-up approach).

For an organization or an individual, this data can be obtained from national averages or from the flight company if available.

Average EF are provided by the IPCC and based on fuel type and their carbon content. These international average data should be very similar to national data because the quality of jet fuel is very well defined internationally.

Aviation - Tier 2

This method is also based on fuel consumption but separates emissions from LTO cycles and Cruise operations.

$$Emissions = Emissions_{LTO} + \ Emissions_{Cruise}$$

$$Emissions_{LTO} = Number\ of\ LTO\ \times\ EF_{LTO}$$

$$Fuel\ consumption_{LTO} =\ Number\ of\ LTO \times Fuel\ consumption\ per\ LTO$$

$$Emissions_{Cruise} = (Fuel\ consumption\ -\ Fuel\ consumption_{LTO}) \times EF_{Cruise}$$

Activity data is obtained similarly as in Tier 1.

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Specific data is required for the two different phases. The LTO characteristics vary with different aircraft types. Therefore, data can also be detailed by aircraft type.

LTO EF are provided by the IPCC guidelines for each typical aircraft types. Cruise EF are the same as Tier 1 EF for all planes.

For a nation, the number of LTO corresponds to the total LTO cycles during the whole year in the territory, by aircraft types. For an organization or an individual, it corresponds to the number of LTO cycles from the individual journey.

Aviation - Tier 3

They are based on flight movement data: origin and destination, date, aircraft type, engine and trajectory data of individual flights (bottom-up approach).

For a nation, obtaining individual flights data is more difficult than aggregated national data. However, for individuals or organizations, origin/destination data are generally easily accessible.

There are two categories of Tier 3 methods:

- Tier 3A methodologies

  They only require the knowledge of the origin and the destination of individual flights. They are distance-based methods. Different Tier 3A methods exist. Usually, the distance is calculated as the shortest distance between two points. Different correction factors are added to consider deviations and vertical movements. Specific EF are used according to the travelled distance (short, middle and long haul for example). More precise models can also consider statistical data from the origin and destination airports such as aircraft types. Different Tier 3A methods can be found in the EMEP/EEA guidelines. The International Civil Aviation Organization also developed a specific tool based on their statistical data to evaluate the carbon footprint of individuals[15] [ICAO 2018].

- Tier 3B methodologies

  They use the full movement data available of individual flights. It consists of sophisticated computer models that evaluate each flight segment using aircraft aerodynamic and engine specific information. Two models are cited in the IPCC guidelines: the US Federal Aviation Administration SAGE (System for assessing Aviation's Global Emissions) and the **European Commission AERO2K**.

b/ Road transportation

Road vehicles are divided in four main categories, depending on national vehicle registries:

- Cars – primarily for the transport of persons (capacity < 12 persons).
- Motorcycles – not more than three wheels and weighting less than 680kg.

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[15] Accessible on https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx

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- Light duty trucks – primarily for transport of light-weight cargo (gross weight < 3500-3900 kg).
- Heavy duty trucks and buses (gross weight > 3500-3900 kg or capacity > 12 persons).

Vehicle categories can be refined depending on the fuel used and the type of engine technology. They can operate on many types of fuels: usually gasoline, diesel oil, Liquified Petroleum Gases or Liquefied Natural Gas. Other fuels can be issued from biomass such as biodiesels or biogasoline (bioethanol, biomethanol, …). Finally, electric vehicles can be fueled by electricity from a battery, or from hydrogen converted to electricity with a fuel cell. In both cases, electric vehicles do not emit GHGs during their operations and are only responsible for indirect emissions.

Vehicle categories can also be refined according to their age (<3 years, 3-8 years, >8 years) and their pollution control technology (three-way catalysts, oxidation catalysts, uncontrolled, …). The control technology can also be deduced according to the vehicle age and policies implementation years.

The main GHGs emitted from fuel combustion are CO_2, CH_4 and N_2O.

CO_2 emissions usually depend on the fuel type and its carbon content only. Therefore, fuel-based data is used for CO_2 emissions.

However, CH_4 and N_2O emissions do not only depend on the fuel type but also on the vehicle technology (especially pollution control technology) and the vehicle operations (type of road). Therefore, more precise data are necessary for these emissions: disaggregated fuel data by type of vehicles or distance-based data by type of vehicles (also called Vehicle Kilometers Travelled or VKT).

Different tiers methodologies are applied for the CO_2 emissions and the CH_4/N_2O emissions:

Road Transport - CO_2 - Tiers 1 and 2

The emissions are estimated using fuel-based data, disaggregated by type of fuel.

$$Emissions = \sum_{Fuel\ type} Fuel\ consumption \times EF$$

For nations, the fuel consumption data (equal to the fuel sold) is usually available from national taxation or energy authorities. However, uncertainty remains for transport fuel bought for non-road purposes.

For organizations or individuals, the fuel data can be obtained from the specific journey or from statistic averages. If not available, the distance data can be transformed to fuel data with fuel consumption per distance values.

The same formula applies for Tier 1 and Tier 2, but the EF differs.

For Tier 1, the EF is a default international average provided by the IPCC guidelines. It is based on the total carbon content of the fuel. However, the measured amount of carbon may be emitted not only as CO_2 but also as CH_4, CO, $NMVOC$ or particulate matter.

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For Tier 2, the EF is based on country-specific and year-specific averages. More precise EF can also be used. They can be adjusted to consider carbon not emitted as CO_2 for example.

For biofuels, the CO_2 emitted comes from carbon biomass combustion. For national inventories, these emissions are treated in the Agriculture and Land Use sectors. To avoid double counting, fuel data must be refined to obtain the share of biogenic carbon in fuel blends.

Additional CO_2 emissions can come from specific type of pollution control technologies which prevent NO_X emissions but instead emit more CO_2 (called urea-based catalysts). A specific formula to estimate these emissions is given in the IPCC guidelines.

Road Transport - CH_4 and N_2O - Tier 1

The emissions are estimated using fuel-based data, disaggregated by type of fuel.

$$Emissions = \sum_{Fuel\ type} Fuel\ consumption \times EF$$

It is the same method used for CO_2 Tier 1.

Road Transport - CH_4 and N_2O - Tier 2

The emissions are estimated using fuel-based data, disaggregated by fuel type, vehicle type and emission control technology.

$$Emissions = \sum_{\substack{Fuel \\ type}} \sum_{\substack{Vehicle \\ type}} \sum_{\substack{Emission \\ control \\ technology}} Fuel\ consumption \times EF$$

Vehicles are classified in the four categories mentioned above (cars, motorcycles, light duty trucks, heavy duty trucks and buses). The IPCC guidelines provide the EF for specific fuel, vehicle and emission control technology types.

Road Transport - CH_4 and N_2O - Tier 3

The emissions are estimated using the distance-based data (VKT), disaggregated by fuel type, vehicle type, emission control type and operating conditions. When VKT data is not available, fuel-based data are converted into distances by using fuel consumption per distance values.

$$Emissions = \sum_{\substack{Fuel \\ type}} \sum_{\substack{Vehicle \\ type}} \sum_{\substack{Emission \\ control \\ technology}} \sum_{\substack{Operating \\ conditions}} [Distance \times EF + Cold\ start\ emissions]$$

Operating conditions are mainly road types (rural, urban, highway, …) but can also include climate or other environmental factors. It might be difficult to obtain VKT data with such level of detail. Therefore, emission models can be used to obtain this data, such as the **COPERT model from EEA**.

Emissions are also divided between two operation phases. The thermally stabilized engine operations (hot) i.e. normal operations, and the warm-up phase (cold). When engines are cold, additional emissions occur, especially CH_4 emissions. These **cold start emissions** only apply for the initial fraction of the travel (approximately 3km – the average cold start duration being 180-240s). These emissions can be quantified in different ways. For example, they can be calculated from the number of starts per year derived from average trip length. The EEA COPERT model also provides cold start emissions with more precision.

c/ Railways

There are mainly three types of railway locomotives: diesel, electric or steam.

Electric locomotives do not generate direct combustion emissions. However, they are responsible for indirect emissions coming from electric generation. Steam locomotives are used in a very small proportion today, mainly for tourist attractions. Therefore, their contribution to GHG emissions is small. Methodologies for steam locomotives are similar to steam boilers but are not detailed here. Therefore, only diesel locomotives methodologies are presented in the IPCC guidelines.

Globally, the methodologies are similar to road transportation, with a separation between CO_2 and CH_4/N_2O emissions. CO_2 methods only consider the fuel type and its carbon content. CH_4 and N_2O emissions are based on fuel type but also on locomotive types (railcars, shunting or yard locomotives, line haul locomotives) and their operation (type of travel, weight load, …).

Railways - CO_2 - Tiers 1 and 2 + CH_4 and N_2O - Tier 1

The emissions are computed using fuel-based data, disaggregated by type of fuel:

$$Emissions = \sum_{Fuel\ type} Fuel\ consumption \times EF$$

The same formula is used for CO_2 Tier 1 and Tier 2, but the EF differs. For Tier 1, the EF is a default international average provided by the IPCC guidelines. For Tier 2, we use country specific EFs.

The same method is used for CH_4/N_2O Tier 1.

Railways - CH_4 and N_2O - Tier 2

The emissions are computed using the basic equation with fuel-based data, disaggregated by fuel type and locomotive type:

$$Emissions = \sum_{\substack{Fuel\\ type}} \sum_{\substack{Locomotive\\ type}} Fuel\ consumption \times EF$$

The IPCC guidelines provide the EFs for specific fuel and engine types.

Railways - CH_4 and N_2O – Example of Tier 3

Tier 3 methods are more detailed models, based on distance or fuel consumption, with more details on the typical travels (freight, intercity, regional, …) or the load weight. Several modelling tools are available (RAILI, COST 319, or the U.S. EPA NONROAD). A model example is given in the IPCC guidelines, based on the U.S. EPA methodology.

$$Emissions = \sum_{\substack{Fuel\\type}} \sum_{\substack{Locomotive\\type}} \sum_{\substack{Journey\\type}} Locomotives \times Hours \ \times Power \times Load\ factor \times EF$$

Where $Locomotives$ is the number of locomotives, $Hours$ is the annual hours of use, $Power$ is the average rated power of the locomotive in kW and $Load\ factor$ the typical load weight factor (between 0 and 1). The EF is expressed in $CO_{2_{eq}}/kWh$.

d/ Water navigation

Water navigation includes all types of ships, from recreational ships to ocean cargo ships, including hovercraft and hydrofoils. Usually, they are driven by diesel engines, and occasionally by steam or gas turbines.

Activity data must be separated between domestic and international data.

Globally, the methodologies are similar to road transportation, but with only two tiers. Different tiers can be applied for CO_2 or CH_4/N_2O emissions independently.

Water navigation - Tier 1

The emissions are estimated using fuel-based data, disaggregated by type of fuel:

$$Emissions = \sum_{Fuel\ type} Fuel\ consumption \times EF$$

The EFs can be international averages or country-specific averages.

Water navigation - Tier 2

The emissions are estimated with fuel-based data, disaggregated by fuel type and ship type:

$$Emissions = \sum_{\substack{Fuel\\type}} \sum_{\substack{Ship\\type}} Fuel\ consumption \times EF$$

The EFs are country-specific averages but can also be more detailed to account for, as an example, the type of engine. Other detailed methodologies can also be used based on individual ship movement data (when data is available). For example, the EMEP/EEA presents a detailed methodology based on ship type, engine type and movement data.

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Methodologies from the 2006 IPCC guidelines are described for each mode of transport: aviation, road transport, railways and water-navigation. International transport is reported separately from the main results.

Aviation can add a radiative forcing factor for non-CO_2 emissions at high altitudes (contrails and precursors).

Other modes distinguish CO_2 emissions (depending on the fuel type only) and CH_4 / N_2O emissions (depending on the fuel type and the vehicle technology and operation).

Tier 1:

Generally, the Tier 1 method is based on global fuel consumption data with EF by fuel type. Tier 1 EF are international averages provided by the IPCC.

Tier 2:

Tier 2 are also based on fuel consumption, but they use more precise data by type of technology and EF from national averages.

Tier 3:

Finally, Tier 3 methods are more complex models. They require more detailed data from individual journeys. Examples of existing models are given (European Commission AERO2K for aviation, EEA COPERT model for road transport, EMEP/EEA methods, …).

3.2 What is the carbon footprint of transport?

3.2.1 In the world

The UNFCCC collects the national GHG inventories of its different parties. However, following the principle of *"common but differentiated responsibilities and respective capabilities"* [UNFCCC 1992, Article 3], developed countries are supposed to lead the way on climate change mitigation. Therefore, the reporting requirements apply differently depending on the country situation.

Annex I parties mainly consist of industrialized countries, members of the OECD, and follow the IPCC guidelines described above [IPCC 2019]. They report every year a full time series of their national inventories. However, different tier methodologies can be used in different countries for the same sector.

Non-Annex I parties (which includes China and less-developed countries) have a separate reporting process. Their inventory is less frequent and can present some gaps due to less robust statistical data infrastructure.

Therefore, it is often complicated to obtain up-to-date and homogenized data of worldwide total $CO_{2_{eq}}$ emissions.

To compensate for this shortcoming, the European Commission **JRC (Joint Research Center)** developed the **Emissions Database for Global Atmospheric Research (EDGAR)**. It applies a consistent bottom-up methodology for all countries, based on the IPCC sectorial guidelines and global statistics (mainly from the International Energy Agency). The results are used for the IPCC assessment reports. It studies the different GHGs but also air pollutants,

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gas by gas. However, the reported results are not aggregated in $CO_{2_{eq}}$. To give an order of magnitude on trends of emissions, results from EDGAR last report on CO_2 emissions only are presented in Table 3 [JRC 2020].

Worldwide, CO_2 emissions represent a total amount of 38 Gt in 2019 [JRC 2020]. They have increased by 68% since 1990 (see Table 3).

All sector emissions have increased. In particular, the transport sector has increased by 78% and represents approximatively 8.2 Gt in 2019. It is the third most emitting sector, behind power industry and industrial combustion (see Figure 5).

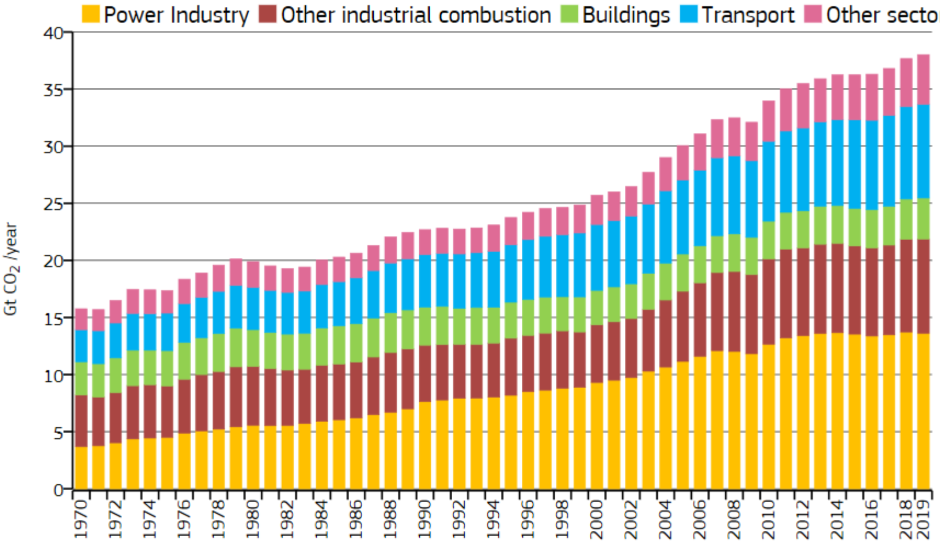
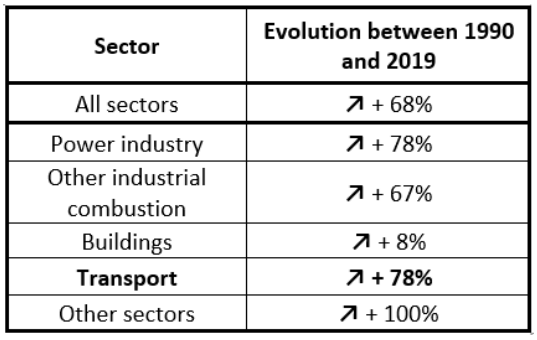


Figure 5 – Worlwide CO_2 emissions by sectors since 1970 [JRC 2020]



Sector	Evolution between 1990 and 2019
All sectors	↗ + 68%
Power industry	↗ + 78%
Other industrial combustion	↗ + 67%
Buildings	↗ + 8%
Transport	**↗ + 78%**
Other sectors	↗ + 100%

Table 3 – Evolution of worldwide CO_2 emissions by sectors since 1990 [JRC 2020].

The top six emitters of CO_2 in 2019 account for 67% of world emissions (China 30.3%, USA 13.4%, EU27+UK 8.7%, India 6.8%, Russia 4.7% and Japan 3.0 %). The EU has slowly reduced its emissions in the last decade, followed by USA (see Figure 6). Meanwhile, China has become the largest emitter and India emissions continue to increase [JRC 2020].

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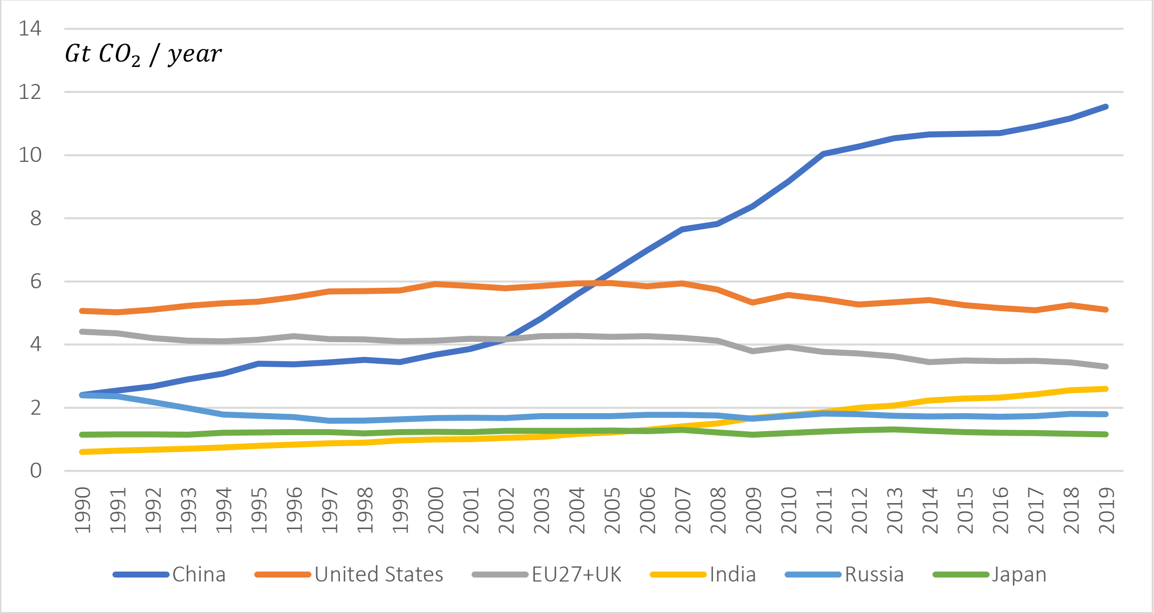

Figure 6 – Evolution of fossil CO_2 emissions of the major emitting economies since 1990. Data from [JRC 2020].

3.2.2 In the European Union

All 27 members of the EU and the EU itself are Annex I parties to the UNFCCC and the Kyoto Protocol. Therefore, every EU country must submit every year its individual national GHG inventory to the UNFCCC. All individual reports and data are publicly available on the UNFCCC website[16]. The most recent data is from 2020 but it involves annual emissions from 2018.

To submit an EU global GHG inventory to the UNFCCC, EU members must also report their emissions to the EU[17]. The organism in charge of compiling the national reports and data is the European Environment Agency (EEA). The latest available aggregated data is accessible on the EEA website[18] [EEA 2020b]. They also provide a summary of the methodologies used by each country for each sector.

Figures presented below are obtained from the EEA dataset [EEA 2020b] for the 27 members only (EU-27). The reference base year is 1990. Figures also include international transport, which is generally excluded when following IPCC guidelines. Finally, carbon sinks are not considered here to simplify the figures.

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[16] Accessible on https://unfccc.int/ghg-inventories-annex-i-parties/2020

[17] Under the Monitoring Mechanism Regulation (EU regulation 523/2013) since 2013, replaced by the Governance Mechanism (regulation EU 1999/2018) starting in 2021 to account for the Paris Agreement

[18] Accessible on https://www.eea.europa.eu/themes/climate/eu-greenhouse-gas-inventory

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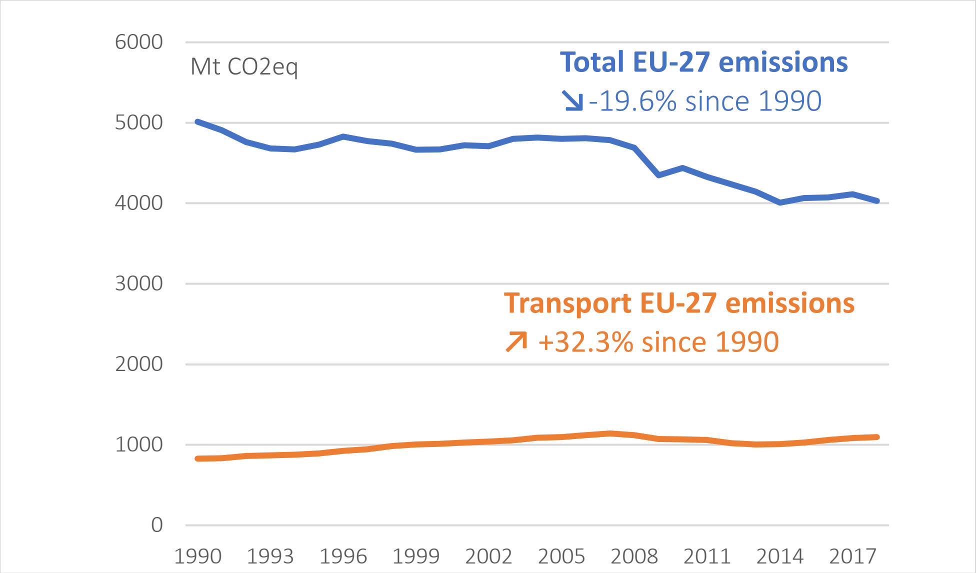

Figure 7 – Evolution of total and transport GHG emissions in $CO_{2_{eq}}$ in the EU-27 since 1990 (including international transport and excluding carbon sinks). Data from [EEA 2020b].

Between 1990 and 2018, the EU-27 decreased its global GHG emissions by 19.6% (see Figure 7). In 2018, they represent 4032 $MtCO_{2_{eq}}$. The top 5 emitter countries are responsible for 65% of all emissions (Germany 22%, France 12%, Italy 11%, Poland 10%, Spain 9%) [EEA 2020b].

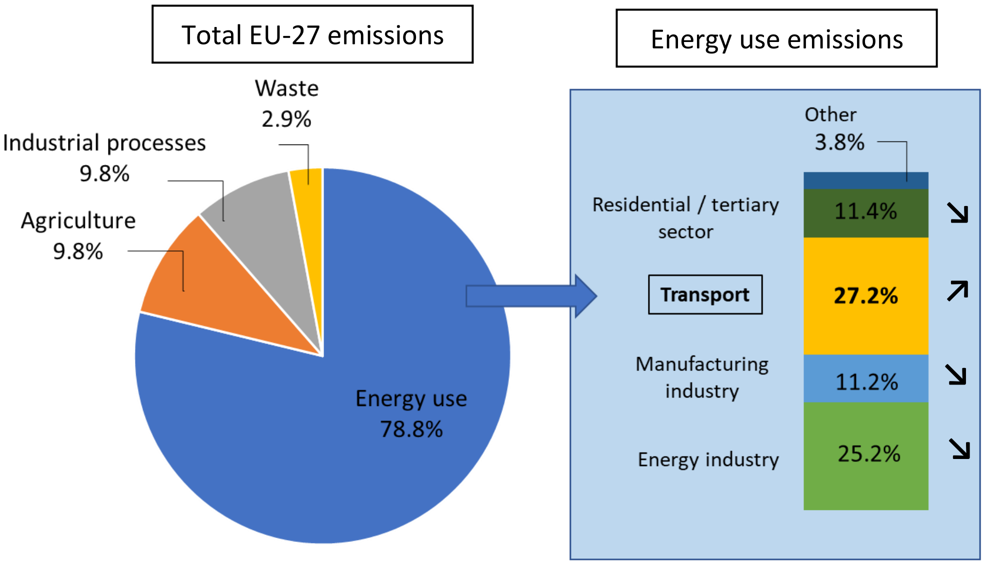

Figure 8 - Repartition of total GHG emissions in $CO_{2_{eq}}$ in the EU-27 in 2018 using a sectorial approach (including international transport and excluding carbon sinks). Data from [EEA 2020b].

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During the same period, the transport emissions increased by 32.3%. The peak of transport emissions was reached in 2007, followed by a decrease over the 2008-2013 period. Since 2013, transport emissions have increased again to reach 1096 $MtCO_{2_{eq}}$ in 2018 [EEA 2020b].

Transport is the only key sector whose emissions have not decreased over the 1990-2018 period (with the other exception of refrigerants and air conditioning) [EEA 2020a].

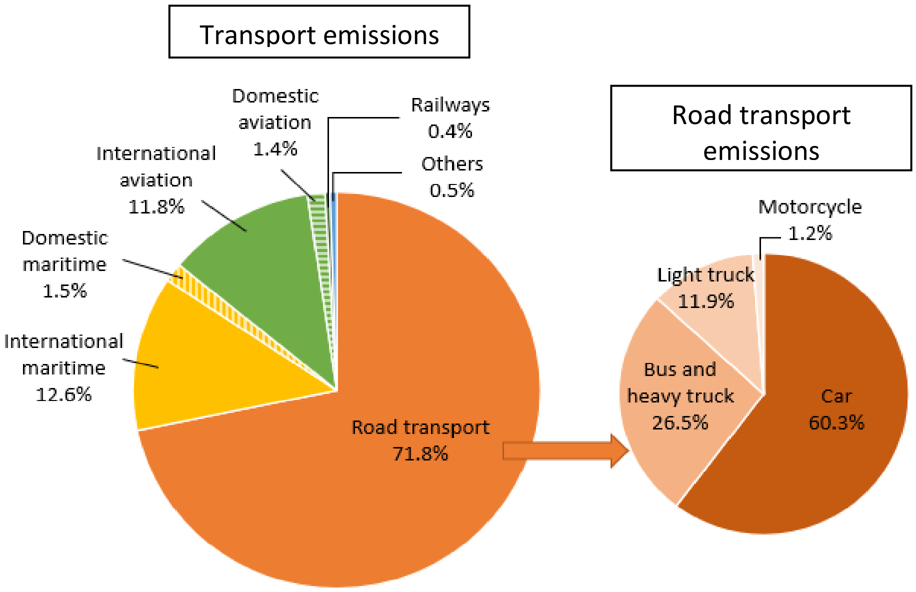

Figure 9 - Repartition of transport GHG emissions in $CO_{2_{eq}}$ *in the EU-27 in 2018 (including international transport). Data from [EEA 2020b].*

In 2018, EU-27 emissions are dominated by energy use emissions, stemming mainly from the transport sector with 27.2% of all GHG emissions (see Figure 8).

Road transportation is the main contributor and is responsible for 71.8% of transport emissions. Its emissions are mainly due to the use of private cars (see Figure 9). International navigation and aviation then represent 24% of the transport emissions. Domestic navigation and aviation both represent less than 2%, and railway less than 1%.

All categories of transport have increased their emissions since 1990, except railways (-66%) and domestic navigation (-26%). International aviation emissions have increased by 141% between 1990 and 2018 [EEA 2020b].

However, these results do not include indirect emissions. Therefore, they cannot be used to compare the total impact between different modes of transport. For example, railways heavily rely on electric propulsion but electricity generation emissions are not considered in the transport category (they are in the energy industry category).

To compare the modes of transport, a separate report ordered by the EEA presents results including Well-to-Wheel emissions (direct emissions + indirect emissions from fuel life cycle) [Fraunhofer ISI 2020]. Results are given in $\mathrm{gCO_{2_{eq}}}$ per pkm (passenger kilometer) which gives the emissions to move one passenger over one kilometer. For passenger cars, the average car occupancy used is 1.6.

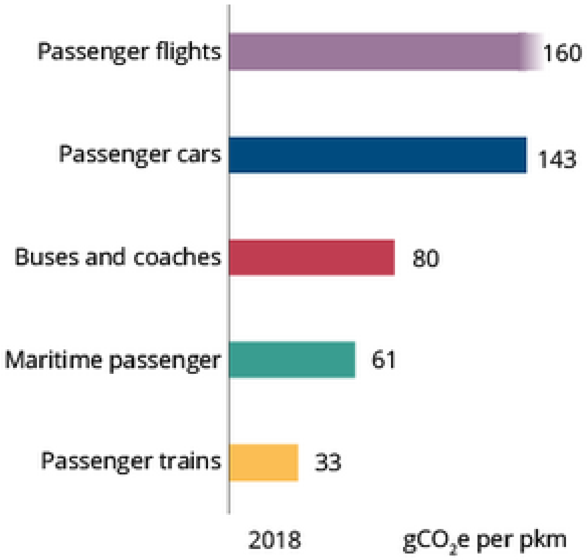

Figure 10 – Average Well-to-Wheel GHG emissions by mode of passenger transport in 2018, EU-27 [Fraunhofer ISI 2020]

For a passenger, airplane is the mode of transport that emits the most, closely followed by cars. The train is by far the least emitting one (~5 times less than an airplane).

For railways, indirect emissions represent more than 80% of the total emissions, heavily dominated by electricity generation. For cars and buses, indirect emissions represent ~20% of total emissions, and ~10% for airplanes. Electricity generation only represents 0.08% of car emissions in 2018 [Fraunhofer ISI 2020].

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<u>In the world</u>

It is difficult to obtain worldwide homogenized total $\mathrm{CO}_{2_{\mathrm{eq}}}$ GHG emissions. CO_2 emissions only give an order of magnitude on emission trends.

CO_2 emissions are rising from all sectors in the world. Transport is one of the most emitting sectors.

EU is the third world emitter, but its emissions have slowly decreased over the last decade. The emissions from China and developing countries have strongly increased over the same period.

<u>In the European Union (EU-27)</u>

The EEA compiles national inventories to report to the UNFCCC.

Total emissions have decreased by 20% while transport emissions have increased by 32% since 1990. Transport is also the first emission sector with 27% of all emissions. All key sectors are decreasing except transport.

Transport emissions mainly come from road transport (72%) and international travel (24%). Road transport is dominated by car emissions. However, indirect emissions are not accounted in these results.

A separate report compares Well-to-Wheel emissions per km for one passenger for different modes of transport. Airplanes and cars are the modes that emit the most while the train is the least emitting one.

4. Conclusion

What are the GHG emissions of transport?

Seven categories of greenhouse gases are defined internationally for carbon footprints. Three of them are predominant for transport emissions (CO_2, CH_4, N_2O).

Transport emissions are either from direct fuel combustion (Tank-to-Wheel), or from indirect emissions. These indirect emissions can include the fuel life cycle, including electricity generation for electric vehicles (Well-to-Tank). They can also include the vehicle and its infrastructures life cycle, but this level of detail is difficult to obtain.

Other gases, mainly precursor gases, are also encouraged to be reported, but separately. An exception is made for air travel where water vapor (responsible for contrails) and precursors emitted at high altitude can be accounted with a radiative forcing factor.

How to measure them?

Several international standards have been described. The IPCC guidelines for national inventories allowed us to explain the EU GHG inventory results. It also provided detailed methodologies for each mode of transport but only accounting for direct emissions. The organizational protocols (GHG Protocol and ISO 14064-1) allowed us to consider indirect emissions and the individual passenger share of emissions, more adapted for the EGG framework. The 6 steps to achieve a GHG inventory have been detailed.

The study perimeter defines to which level of detail indirect emissions are considered.

The choice of the methodology can go from the simple equation ($Emissions = AD \times EF$) to more complex models (AERO2K, COPERT).

When available, fuel AD should be preferred to distance AD.

Different sources and databases for EF have been mentioned[19]. The choice of the EF should consider indirect emissions and passenger share of emissions. They should also be country-specific if possible (data available on national NIR reports to the UNFCCC).

The 100-year GWP values for $CO_{2_{eq}}$ emissions are taken from the IPCC assessment reports.

Finally, the reporting of results should indicate uncertainties but also all hypothesis, data sources and the choice of GWP values to be transparent and comparable.

What is their impact?

In the world, transport is one of the most emitting sectors and its emissions are strongly increasing. In the EU, it is the most emitting sector and the only sector with increasing emissions, which make it a priority for environmental policies. These emissions are mainly from road transport and international travel.

At a passenger level, plane and cars are the most impactful modes of transport. Railways are the least emitting mode because they rely heavily on electric propulsion and the decarbonation of electricity generation in the EU. Therefore, the choice of train transportation should be prioritized in the EU.

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PART III

The European Green Deal

Low emission targets in the EGD

Produced by Eda AYAYDIN

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1. Introduction

It's time to convince people to do more than just turn off the water when brushing teeth and it's time to convince states to do more than just warn about the seriousness of greenhouse gas emissions. Climate is changing rapidly. This is caused by human activities; therefore, the solutions targeting to limit the impacts of climate change belong to humans. The European Union has already started to lead the fight against climate change. One of the biggest concerns of the EU is to reduce greenhouse gas emissions in order to achieve a sustainable and efficient economy. The European Union wants to be the first and leading organization in tackling climate change by setting alliances with the purpose of decreasing emissions. We will try to understand to what extent the policies and measures adopted by the EU are efficient to achieve the target of being a role-model in the fight against climate change by analysing the European Green Deal and its roadmap.

2. The Green Deal in brief

The short-term emission plan targets a 55 % reduction of gas emissions by 2030 and the long-term target of the European Commission is zero emission net by 2050. The president of the European Commission Ursula Von der Leyen is ready to adopt new policies to achieve the targets and the Commission has already adopted some new measures such as the European Green Deal.

Source : https://op.europa.eu/en/publication-detail/-/publication/ed23f3b1-8375-11ea-bf12-01aa75ed71a1/language-en/format-PDF/source-177259382

The Green Deal aims to regulate the economy in a low carbon-based sustainable manner. The targets of the Green Deal will be reached through reducing the green-house gases by new policies. According to these, all European countries must take responsibility including the

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coal-based economies such as Poland and the Czech Republic which have to do their best by determining ambitious and feasible goals. The Green Deal requires huge efforts in order to reach the target that is a more prosperous Europe with an environmentally efficient economy and social order.

The European Green Deal shall be carried out in three steps:

1. Climate Target Plan to reach 55 % reduction in greenhouse gases by 2030
2. Climate Law in order to reach zero emissions by 2050
3. Climate Pact to involve EU citizens into this action.

2.1 Climate Target Plan

The European Commission submitted a plan in September 2020 to deal with climate change. This plan was accepted in December 2020. The heads of state and governments of the European Union agreed to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. By approving this, the Council of the European Union put this new objective in the European Climate Law and put it into force. [20] Reaching this target is not easy as far as political and economical issues are concerned. Politically, countries whose economy is dependent on coal do not explicitly support this transition since some of them are developing countries and this transition seems to challenge their economic power. Countries having immense industrial activities are not completely keen because of the difficulties and challenges of changing an economic and industrial model.

There is no doubt that the Green Deal is an expensive investment for the future. The plan of reduction of greenhouse gases costs 147 billion euros to the EU and the target of 55 % reduction by 2030 will cost 82 more billion euros. However, according to the estimates of the European Commission, this investment will pay back, and Europe will no longer be under the threat of environmental risks. In addition, according to EU calculations, current sea level rise has already a heavy cost and this cost will increase to 145 billion euros by 2050 and 650 billion euros by 2080.[21] By taking into consideration the possible economic challenges of applying Green Deal policies, the commission has already planned an aid package called “Just Transition Mechanism''. This financial aid will be provided to the countries who are experiencing difficulties in the process of green transition.

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[20] European Commission, EU Climate Target Plan 2030, Brussels, September 2020, (https://ec.europa.eu/commission/presscorner/detail/en/fs_20_1609) Accessed in January 2021.

[21] Politico, “What is the Green Deal?”, *Politico*, 20 October 2020, (https://www.politico.eu/article/what-is-the-green-deal/), Accessed in January 2020.

2.2 Climate Law

European Climate Law is an ambitious action proposed by the European Commission in March 2020. The European Commission aims to achieve zero net emission by 2050. The Climate Law aims at providing a sustainable society, an environmentally risk-free atmosphere to businesses and a resource efficient economy.[22]

2.3 Climate Pact

At the individual level, the European Commission initiated a project called European Climate Pact that involves citizens and organizations into the climate action project. The aim of the pact is to share knowledge, to create a social consciousness on climate change and to develop solutions to fight against climate change.[23] According to this project, volunteers "Climate diplomats" of the European Union can take a role in this process by awakening consciousness on challenges related to climate.

3. Energy and Emission

3.1 Energy Target

The most important factor of the greenhouse gas emissions in Europe is the use of fossil fuel while a quarter of emissions derive from transportation in Europe.[24] The dependence on fossil fuel is high and the use of renewable energy for transportation is in the lowest stage . One of the important aims is the transition to a clean energy-based transportation system. On the other hand, the use of bio-based natural products in agriculture is very important for reducing emissions. According to the director of the International Energy Agency (IEA), Fatih Birol, the energy transition dominates the IEA's agenda for 2021[25]. He underlines the role of renewable energy, electrification and hydrogen. Dr. Birol highlights the importance of the oil and gas companies for the cooperation against climate change. Having huge financial abilities and cutting-edge technology, oil and gas companies are important collaborators in the fight against climate change to achieve a decrease in greenhouse gas emissions.

3.2 Emissions Trading System and effort sharing

According to the new proposal for a Regulation of the European Commission, the EU member states have to draw their national plans on energy and climate change in line with the EU regulations and the Paris Agreement in order to achieve the reduction in greenhouse gas

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[22] European Commission, *The European Climate Law*, Brussels, March, 2020, (https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/factsheet_ctp_en.pdf) Accessed in January 2021.

[23] European Commission, *The European Climate Pact*, Brussels, December 2020, (https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/pact/202012_factsheet_pact_en.pdf) Accessed in January 2021.

[24] European Commission, "A European Strategy for Low-Emission Mobility", Brussels, 20 July 2016.

[25] "IEA key priorities and special projects for 2021", https://www.iea.org/events/iea-key-priorities-and-special-projects-for-2021?utm_content=buffer494b6&utm_medium=social&utm_source=twitter-ieabirol&utm_campaign=buffer

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emissions. Reducing Greenhouse gases emissions is one of the main responses to climate change but the scope of the ETS unfortunately does not include agriculture, transportation, building and waste. This is why, under the EU governance, all members of the EU as sovereign states need to determine their own ambitious objectives to achieve the short-term targets of the 2030 agenda.

The EU Emissions Trading System is at the cornerstone of these targets. It is a long and complicated method that has been applied since 2005. In a nutshell, it is a cap-and-trade system that caps the greenhouse gas emissions of facilities such as power stations and industrial plants as well as aircrafts. Companies can buy allowances for emission according to these caps and they can trade these allowances.

As a complementary mechanism to EU ETS, the Effort sharing legislation sets binding greenhouse gas emissions targets for the period 2021-2030. This mechanism covers the sectors which the ETS does not cover such as transportation, agriculture, buildings and waste. This mechanism is the alternative to not pricing the emissions in the EU. However, climate economists are worried about the “waterbed effect”: any effort of a government on one sector which will be covered by ETS will not impact the total emissions since the emissions from this particular sector may rise in other countries.

4. To what extent might the European Green Deal be successful?

In 2019, greenhouse gas emisions decreased by 3,7 % compared to their 2018 level while the GDP grew. But according to the EU ETS data, while the emissions of power plants decreased by 15% and industries by 2 %, the emissions in aviation grew by 1% in the European Economic Area.[26] Therefore, the average 9,1 % annual decrease shows us the efficiency of the EU Emissions Trade System. The EU ETS is responsible for the reduction of emissions at installations (power plants and industrial plants) and aviation, so the numbers don’t include transportation, agriculture, buildings and waste. Therefore, policies leading to decreases in these sectors are very efficient s when taking into consideration the fact that transportation and agriculture emit at serious levels.

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[26] European Commission, « EU greenhouse gas emissions fell in 2019 to the lowest level in three decades”, Press Release, Brussels, 30 November 2020, (https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2182) Accessed in January 2020.

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4.1 Will Europe become a leader in this field?

The environmental problems we are facing today are global and the European Union cannot continue to reduce emissions alone. However, its efforts are important in terms of supplying economic and scientific support as well as political image which will force other institutions to react too. Acting together will be for sure more efficient in order to convince the states and private actors. That is why the European Union is eager to build alliances.[27]

The EU does all these efforts in line with the Paris Climate Agreement, all the targets are coherent with the agreement. The European Union aims to be a leader in terms of raising awareness on climate change. However, the EU cannot achieve the legally binding targets at national level without cooperation. Climate change doesn't recognize borders, it is not a regional problem, therefore the EU needs a global help in its efforts. For example, Norway and Iceland are not members of the European Union, but they are in the EU ETS initiative and they are also parties to the 2030 target. The EU wants to extend its cooperation with other regions beyond Europe, NGOs, IGOs and states to be more efficient.

The European Green Deal is one of the rare initiatives which aims to change the mode of production. Until now, generally, the climate initiatives' target was to change consumption behaviours. It is a well-known fact that changing the mode of production is more difficult than the mode of consumption since the addressees are automatically the states. It is more difficult and time consuming to try to deal with states than making up-down changes for people. Therefore, the Green Deal is very essential at this point, maybe it is not easy to realize the targets, but it is a very supportive regional mechanism for the global Paris Agreement.

4.2 Some bad scenarios

Bad scenarios are economic damages on the EU budget and carbon transmissions from out of the EU towards the EU. If the companies move their installation from the EU to other countries because of the emission restrictions, this would for sure affect the economy. However, carbon dioxide knows no borders. On the other hand, products made of carbon would return to the EU by trade. The result might not be very satisfactory, because, if this kind of production with high emissions continues, the global emission level cannot decrease in these circumstances. Therefore, these results may disappoint not only the EU and the companies who adopted the EU's Green Deal policies, but also the states who signed the Paris agreement. In order to avoid this kind of a threat, the European Commission designed a "carbon border adjustment mechanism". Thanks to the high carbon import prices, they can adjust the use of carbon and reduce the risk of carbon leakage.[28]

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[27] European Commission, *The European Green Deal*, Brussels, 11 December 2019. (https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf) Accessed in January 2021.

[28] European Commission, Inception Impact Assessment on "Carbon Border Adjustment Mechanism", 04 March 2020, Brussels, (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12228-Carbon-Border-Adjustment-Mechanism), Accessed in January 2020.

4.3 What do scientists think ?

“Turning an urgent challenge into a unique opportunity” is the motto of the Green deal. Is this true? According to the Director of the Potsdam Institute for Climate Impact Research, Ottmar Edenhofer, there is a lot of ambiguity, especially in the carbon prices. According to him, the 55 % is an aspirational goal and the goal of zero emissions by 2050 cannot be achieved[29]. On the other side, Jacob Werksman, Principal Adviser to Directorate General for Climate Action in the European Commission, thinks that the Green Deal is very ambitious by targeting the low-carbon and a climate-resilient economy which is an investment for the next generations.[30] There are pessimistic and optimistic approaches to the Green Deal, but Ursula Von Der Leyen took a very big step against climate change.

5. Conclusion

The endeavours of the European Commission to reduce the greenhouse gas emissions in tackling climate change cannot be ignored. The biggest challenge is to convince the economic and political stakeholders. Nevertheless, the European Commission seems very determined in this project and is leading the way in the fight against climate change. decision makers involved in the Green Deal project deem that they borrowed money from people to invest for the future of the next generations. Indeed, it is necessary to remember the costs of environmental risks such as the sea level rise. For example, in the United States, wildfires or sea level rises caused by climate change will cost nearly $ 100 billion in 2020.[31] Therefore, the measures taken by the European Union are very relevant steps for the short and the long term.

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