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Whatever It Takes to Reach Net Zero Emissions Around 2050 and Limit Global Warming to 1.5C: The Cases of United States, China, European Union and Japan

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Whatever It Takes to Reach Net Zero Emissions Around 2050 and Limit Global Warming to 1.5C: The Cases of United States, China, European Union and Japan

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Abstract

This paper analyzes the most recent NDCs as well as public political commitments of the US, China, the EU and Japan (56% of the world GHG emissions) to meet the goal of reaching the 2050 net zero emissions target necessary to limit global warming to the 1.5C. This analysis is made against the background of the transition pathways defined by the REMIND-MAgPIE 2.1-4.2 integrated assessment model for an orderly transition to reach that target. The commitments of US, China, the EU and Japan are not in line with the requirements to limit global warming. Only the EU seems to have an adequate, sufficiently detailed and legally binding strategy to fulfil that pledge. This finding is in line with the recent United Nations Report concluding that even with enhanced 2030 targets and the additional public statements, the world is on track for a temperature increase between 1.8-2.4C this century even assuming that every country puts in place effective policies that will fully achieve its set targets. In all four regions of the world and particularly in 2025-2030, the orderly transition to net zero around 2050 demands the highest investments in renewable energies for electricity, CCUS and energy efficiency. China, the most critical to reach global carbon neutrality, is by far the most highly dependent on CCUS and, more generally, on CDR technologies to reach the 2050 net zero target due to an energy mix dominated by fossil fuels.

JEL Codes: F64, L38, O44, Q55

Key Words: Environment, international public goods, environmental economics-technological innovation

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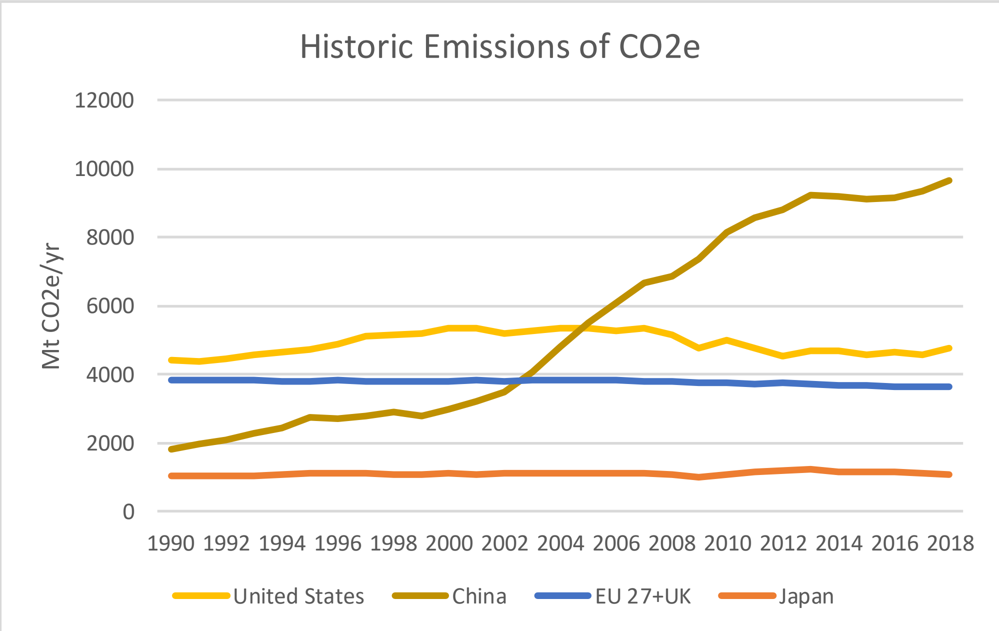
1- Introduction

In 2021, the United Nations estimates that 151 countries, including the European Union (EU), have now committed to the 2050 net zero CO2 pledge.[2] Almost 90% of global emissions and over 90% of global GDP is now covered by mid-century net zero or carbon neutrality commitments, rising from just 30% of global GDP at the end of 2019.[3] The United States (US), China, European Union plus UK (EU28) and Japan accounted for approximately 56% of Green House Gas Emissions (GHG measured by MtCO2e)[4] as of 2018 (Figure 1) with relevant differences in the per capita GHG and the carbon intensity per GDP among regions (Table 1).[5] These four regions represented approximately 55% of the world GDP in 2018.[6]

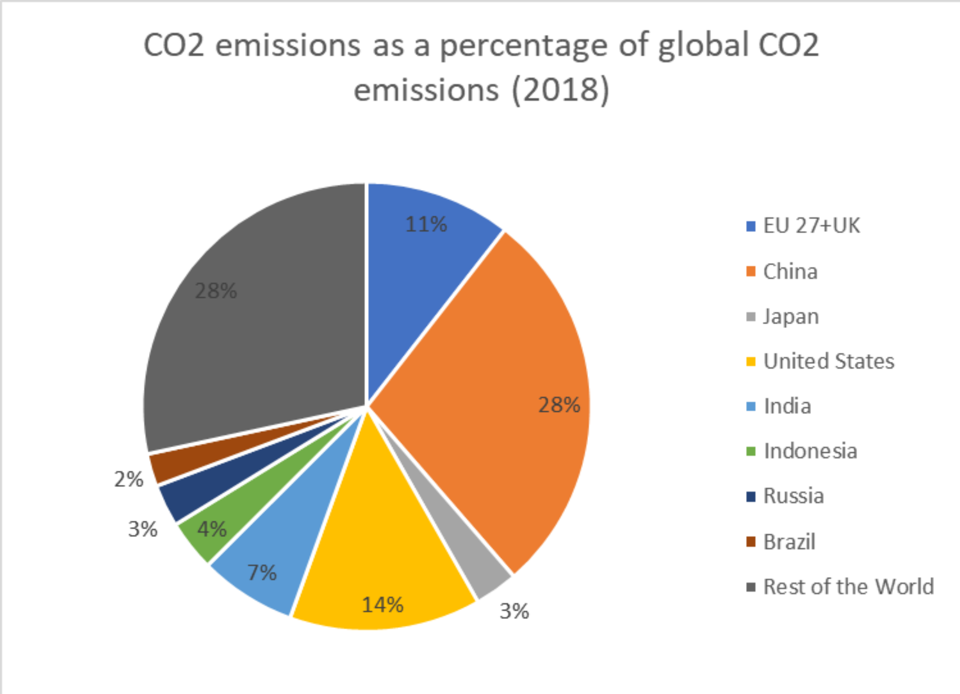
Figure 1: Historical emissions (1990-2018) and share of emissions (Mts CO2e, 2018): China, US, EU28 and Japan

Panel A



[2] Climate Ambition Alliance: Net zero 2050 (https://climateaction.unfccc.int/Initiatives?id=95 accessed 11/11/2021).
[3] COP26 World Leaders Summit-Presidency Summary 3/11/21 (https://ukcop26.org/cop26-world-leaders-summit-presidency-summary/ accessed 23/11/2021).
[4] The sum of CO2 and non CO2 GHG is represented as CO2e (CO2 equivalent). The main non CO2 GHG include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and the so-called F-gases (hydrofluorocarbons and perfluorocarbons).
[5] https://www.climatewatchdata.org/ghg-emissions?end_year=2018&start_year=1990 accessed 20/09/2021.
[6] IMF, World Economic Outlook April 2021, nominal GDP current prices 2017 PPP international USD.

Panel B



Source: Climate Data Watch (CAITS)

Table 1: Tons CO2e (2018) excluding Land Use, Land Use Change and Forestry (LULUCF)

Country	***CO2e / capita***	***CO2e / million USD GDP***
US	20.69	328.47
China	9.62	964.39
Japan	9.80	250.26
EU (27)	8.47	236,96
UK	7.03	163,25

Source: Climate Data Watch (CAITS)

The Intergovernmental Panel on Climate Change (IPCC, 2021) concludes that global temperatures will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 2C will be exceeded during the 21st century unless deep reductions in CO2 and other greenhouse gas emissions occur in the coming decades. The current climate change crisis is an example of ‘the tragedy of the commons’ on a global scale. The ‘tragedy of the commons’ refers to the situation when individuals, acting rationally in their own self-interest, nonetheless act irrationally as a collective group by irreparably depleting a resource that is owned in common (O´Gorman, 2010).

The objectives of this paper are twofold. First, analyze and compare the 2050 Net zero emission strategies of the world´s major economies: US, China, EU and Japan.

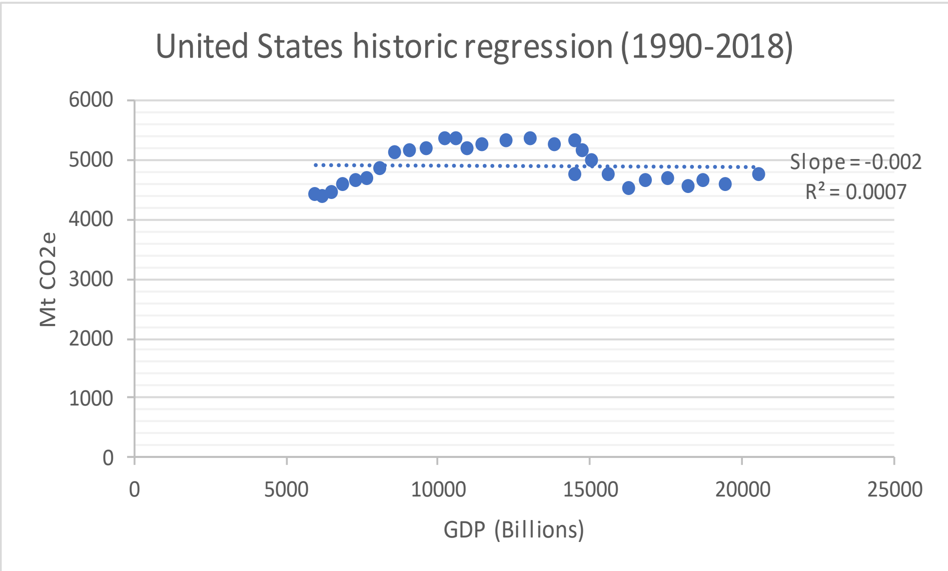
Implementation of net zero policies varies significantly across major economies as well as their starting points. The institutional backing, emissions reduction targets and paths vary widely. Second, we assess the transition pathways using integrated assessment models (IAMs) and, more precisely, the REMIND-MAgPIE 2.1-4.2 and analyze the assumptions behind an orderly transition scenario to net zero emissions around 2050.[7] We present this scenario as a climate transition risk scenario characterized by high policy ambition and immediate policy reaction. This implies, for example, the smooth reduction in emissions, smooth capital and job-reallocation, gradual changes in energy prices etc.

2- The Net zero emissions commitments of China, US, EU and Japan: Emissions reduction goals are converging although strategies differ

Each of these regions comes from a different starting point due to their different economic structures and policy choices in the past. In the recent historical period only, the EU28 has managed to raise nominal GDP while reducing absolute CO2 emissions. In China, US and Japan this has not been the case, with both emissions and GDP rising (China and Japan) or barely decreasing (US) over the period. (Figure 2).

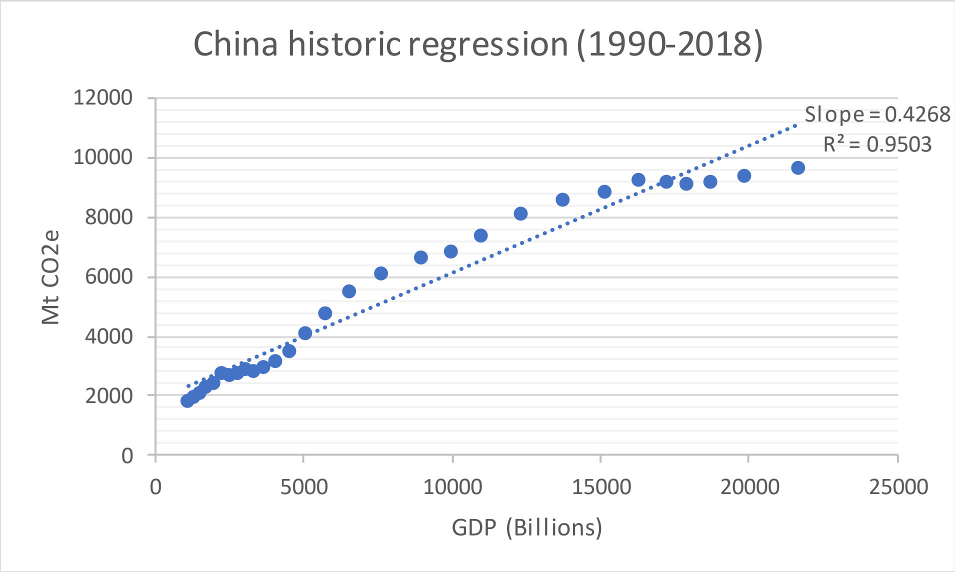
Figure 2: Historical correlations between nominal GDP (current prices PPP international USD) and CO2e emissions (1990-2018)

Panel A: US

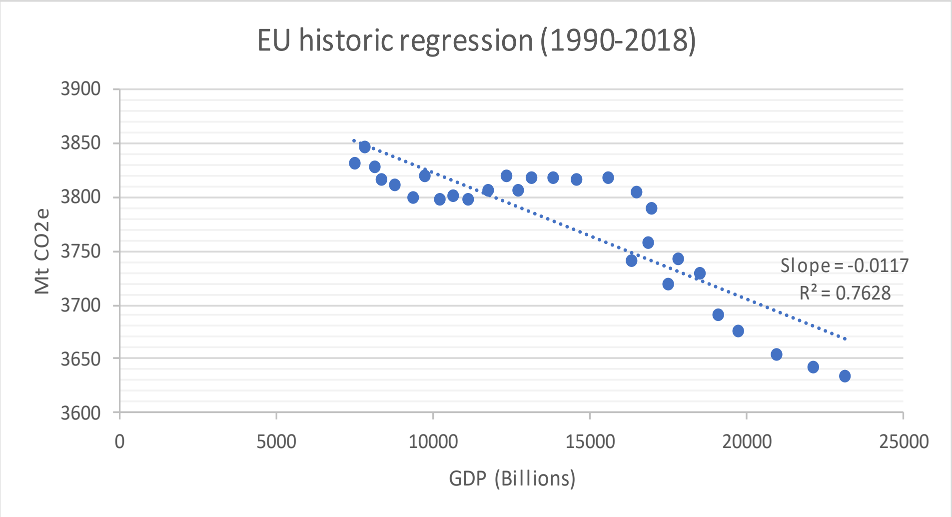


[7] This climate model has been developed by an academic consortium from the Potsdam Institute for Climate Impact Research (PIK), International Institute for Applied Systems Analysis (IIASA), University of Maryland (UMD), Climate Analytics (CA) and the Swiss Federal Institute of Technology in Zurich (ETHZ) (NGFS, Climate Scenarios Database, 2021). I use this particular model because allows for the comparability among US, China, EU(28) and Japan.

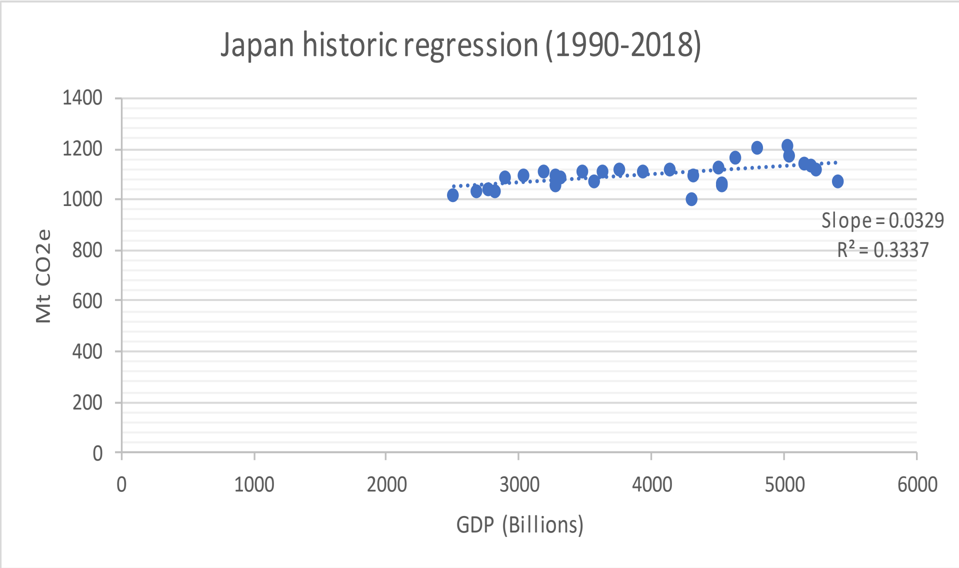
Panel B: China



Panel C: EU28



Panel D: Japan



Source: CAIT, IMF WEO April 2021 and author´s analysis

As signatories of the UN Paris Agreement of December 2015,[8] these countries are legally bound by this international treaty to regularly set national targets (Nationally Determined Contributions –NDC-) to meet the goal of limiting global warming to well below 2 C, preferably to 1.5 C, compared to preindustrial levels (Nieto, 2020). The 197 signatories of the Glasgow Climate Pact agreed at COP26 in November 2021 recognize that the 1.5C goal should be the norm, as the 2C has been shown to be significantly more harmful and riskier.[9] Among the consequences: increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, and proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover and permafrost. To reach the 1.5C goal, countries aim to achieve a climate neutral world by mid-century. GHG emissions that cannot be eliminated by this point would have to be balanced by removing an equivalent amount of CO2.[10] This would prevent further CO2 accumulating in the atmosphere, where it persists for hundreds of years. This phenomenon gives rise to the concept of a "Carbon budget" – the remaining amount of CO2 that can be emitted into the atmosphere until reaching the atmospheric concentration threshold which scientists predict (with certain probability) would lead to mean global warming of more than 1.5 degrees (Knutti and Rogelj, 2015).[11]

[8] See https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement accessed 20/09/2021.

[9] IPCC, AR6 Climate Change 2021: The Physical Science Basis (https://www.ipcc.ch/report/ar6/wg1/ accessed 19/11/2021).

[10] UN metric for transfers of emissions of different gases to a common scale (CO2e): Global Warming Potential over 100 years GWP-100.

[11] For a detailed analysis of the conceptual strengths of "carbon budgets" see van Vuuren et al 2016.

In the global GHG emission pathways for limiting increases of temperature to 1.5C presented by the IPCC (2019), "net zero" CO2 emissions are reached around 2050 (between 2046 and 2055), when global average temperature is expected to stabilize. However, "net zero" GHG emissions that require larger amounts of removals, would only be reached sometime between 2061 and 2084 when average global temperatures are expected to peak and decline (Rogelj et al., 2018). This path of temperature reduction is subject to high uncertainty for a number of reasons that include, among others, the metric precision of gases and the proportion of GHG reduction versus removals (UK Climate Change Committee, 2015).

Definitions matter when interpreting net zero targets (Rogelj et al, 2021) in terms of:

- scope of emissions (CO2 and non-CO2 GHGs);
- target year and intermediate targets to reach "net zero" with the possibility of emission budgets covering each year, and;
- strategy based on reduction and/or removal/offset of emissions that permanently cancel existing emissions.

Significant differences in net-zero emissions approaches exist across China, the US, the EU and Japan in terms of their policy actions, including recent commitments to achieve an orderly transition (Table 2). This makes comparisons difficult. China focuses on reducing the carbon intensity of its economic activity. The 14th Five-Year Plan (2021-25) puts emphasis on transforming the power system towards renewables and away from coal-fired power generation as well as on the development of low carbon technologies (e.g. green hydrogen, oxygen blast furnace in the steel production) and permanent emissions´ removal technologies (CCUS for cement and coal). In the recent past, the strategy was based on supply restrictions such as capacity reduction in steel, coal, aluminum (2016 -2018). As yet, carbon pricing does not play an important role. though China launched a national Emission Trading System (ETS) in 2021.[12] This ETS only covers electric power still heavily reliant on coal.[13] It has been announced that it will expand to aviation, petrochemical engineering, paper making, construction, non-ferrous metals and chemical engineering.

The EU and Japan focus on emissions´ reduction and both impose limits on emissions´ removals either via natural sinks (EU) or CCUS (Japan). In the EU, the strategy relies heavily on carbon pricing and environmental regulation, while carbon pricing does not play a significant role in Japan. Moreover, the EU not only has the most ambitious policies but also it also is the only region where those are enshrined in an EU Law. Japan, China, the US and Japan face greater implementation risk given their generally less ambitious policies with less detailed implementation framework (e.g. lack of annual carbon budgets).[14]

[12] Previously, there were seven pilot local markets that were launched in 2013.

[13] Allowances are currently given out for free, although the authorities have previously indicated that it will introduce allowance auctions in the future (Goldman Sachs: Equity Research, 24 June 2021).

[14] The 2021 UN Climate Change Conference (COP26) main goals were to encourage parties to come forward with ambitious NDCs that establish their emission reduction targets for 2030, discuss adaptation measures, increase climate finance and finalize the Paris Rulebook (the detailed rules that make the 2015 Paris Agreement operational). Among other things, parties were to agree on the details of the so-called Art.6 that lays down rules for international carbon markets, enabling parties to trade

Table 2: Emissions´ reduction strategies: US, China, EU, Japan

Country	***Scope***	***Target Year***		***Objective***	***Main Strategy***[15]	***Key Policy Instruments***
		Final	*Intermediate*			
US	GHG (CO2e)	**2030**	26-28 % below 2005 levels in 2025 (no budgets covering each year)	50-52 % below 2005 *(5.35 Gt recent peak)* levels in 2030	Emissions reduction Emissions removal (CCUS)	-Federal programs including a scheme that would pay utility companies to increase their renewable energy supplies -Private investment in innovation and deployment of carbon pollution-free technology and infrastructure. Tax credits for private investment in innovation (e.g. electric vehicles) and deployment of carbon pollution-free technology and infrastructure (CCUS) - Sector regulations on emission standards *(Build Back Better Reconciliation Bill)*
China	Carbon intensity — CO2 per unit of GDP	**Before 2060**	Peak before 2030 "3060 Target" (no budgets covering each year. Local governments are setting their own carbon targets)	**Net zero** *(President Xi Jinping speech at UN General Assembly, 2020)*	Emissions reduction -to cut carbon intensity by more than 65% from 2005 (*5.49 Gt*) levels by 2030, -increase the share of non-fossil fuels in energy consumption to 25 % by 2030 -cut energy consumption / unit of GDP by 13.5% and CO2	-Public and private investment in renewable sources of energy and technology -Carbon pricing (ETS with intensity based caps instead of absolute emissions cap) *(14th Five-Year Plan (2021-25)* - Potentially more constraints in output in steel, aluminum

emission reductions. Broadly speaking, progress was made in this regard as the first step was agreed: Creating an oversight body, which will meet twice a year to work on the details of how the market should function. In addition, parties were seeking to establish a common time frame for their NDCs. At the COP26, it was agreed ratcheting up of national emissions reduction pledges every five years. Against this background, the EU Council called upon all Parties to present also long-term low GHG emissions development strategies towards reaching net zero emissions by 2050 and it notes that much more global ambition is needed if we are to arrive with commitments that, in aggregate, keep the 1.5 °C objective within reach, in line with the Paris Agreement. However, the agreements of COP26 fell short of reaching this objective.

[15] In order to indicate the effort of emissions reduction, strategies use the year the emissions peaked as a reference year.

					emissions / GDP by 18% - Total installed capacity of wind and solar to reach more than 1,200GW Emissions removal (CCUS-coal, cement- ; aforestation)	and cement in selected regions, and the risk of suspension of new capacity additions in aluminum as in the recent past *(Goldman Sachs, 24 June, 2021)*
EU	GHG (CO2e)	**2050**	At least 55% reduction vs. 1990 *(3.29 Gt recent peak)* levels by 2030 Climate Law includes measures to keep track of progress including making its legislative proposal for the Union 2040 climate target	**Net zero** GHG (*Climate Law, 2021*)	Emissions reduction At least 55% reduction vs. 1990 *(3.29 Gt recent peak)* levels by 2030 Limits to the net removals- natural sinks- (225 MtCO2 eq)	-Carbon pricing is key (ETS, Taxes and subsidies) - Environmental regulation
Japan	GHG (CO2e)	**2050**	At least 46% reduction in 2030 vs. 2013 (*1.21 Gt recent peak*) Committed to meet the goal of cutting to 50 %	**Net zero** *(Prime Minister´s speech, 2021)*	Emissions reduction Emissions removal Natural sinks and CCUS maximum usage	-Public funding for innovation and tax credits for private investment -Environmental regulation and standards - Existing nuclear infrastructure

Source: Nationally Determined Contribution (NDC), Reducing Greenhouse Gases (https://www4.unfccc.int/sites/ndcstaging/Pages/LatestSubmissions.aspx), China´s Achievements, New Goals and New Measures for Nationally Determined Contributions (November, 2021) (https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%E2%80%99s%20Achievements,%20New%20Goals%20and%20New%20Measures%20for%20Nationally%20Determined%20Contributions.pdf). China: Nation to set obligatory carbon goals (http://english.www.gov.cn/statecouncil/ministries/202010/29/content_WS5f9a019dc6d0f7257693e947.html), Goldman Sachs, 16 April 2021, Japan: PM Suga announced "Carbon Neutrality by 2050" goal at the national Diet https://japan.kantei.go.jp/99_suga/statement/202010/_00006.html; METI unveiled "Green Growth Strategy" (https://www.meti.go.jp/english/press/2020/pdf/1225_001a.pdf). EU Climate Law https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119&from=EN. At COP26, all countries committed to revisit and strengthen their NDC 2030 targets in 2022. Author´s analysis

3. Whatever it takes to reach Net zero around 2050 and limit global warming to 1.5C: Climate orderly transition scenario

Government policies are just one of the main transmission channels to achieve an orderly change to a carbon-neutral economy. Other channels are consumer preferences; technological changes and carbon pricing. Consumer preferences are often steered by the other two. Although EU consumers are particularly sensitive to tackle climate change, the EU´s innovation in key technologies has lagged compared to the US and China (Moody's, 2021 p.10). An important exception is in renewable energy equipment manufacturing, where the EU has become a global leader.

Climate scenarios represent likely paths of GHG concentrations and various adaptation and mitigation strategies associated with them over the long run (IPCC, 2000). These scenarios are meant to be optimal (i.e., cost effective) transitions given a set of policy and technology assumptions. Scenarios are not forecasts and they are subject to a high degree of uncertainty partly due to their very long term horizon. These scenarios are used to inform decision-making under uncertainty, sketching out possible pathways to reach desired outcomes (e.g. identify optimal sets of policy tools or technological mixes that align with a specific CO2 emission reduction path/target).

This subsection explores the orderly climate transition scenario that limits global warming to 1.5C through stringent climate policies and innovation, reaching global net zero CO2 emissions around 2050. Some jurisdictions such as the US, EU28 and Japan reach Net zero for all GHGs, hence net zero CO2 before 2050. Such orderly transition would imply immediate policy action; fast technological change; at least medium levels of Carbon Capture and Storage (CCUS) and other forms of Carbon Dioxide Removal (CDR), as well as low regional carbon price variation. Figure 4 Panel A shows the CO2 emission reduction paths of the US, China, EU28 and Japan to reach Net zero around 2050 as per the REMIND-MAgPIE 2.1-4.2 model (NGFS, 2021).[16] Panel B shows the same reduction path but with a historical perspective from 1990. Indeed, the REMIND-MAgPIE 2.1-4.2 model choses particular structural and parametric assumptions in the representation of the mitigation to Net zero around 2050. Estimates are subject to considerable uncertainty and it is for this reason that the comparison of the same scenario narrative within different models allows for an estimation of the order of magnitude that the uncertainties regarding future potentials entail. However, the rational to use the REMIND-MAgPIE integrated assessment model is based on the comparability among these particular countries (Leimbach et al, 2010).

In the case of China, an orderly climate transition scenario towards Net zero around 2050 would imply a reduction path of the CO2 emissions that is particularly pronounced from 2021 to 2030 (Figure 3). Figure 3 shows the historical reduction and the required

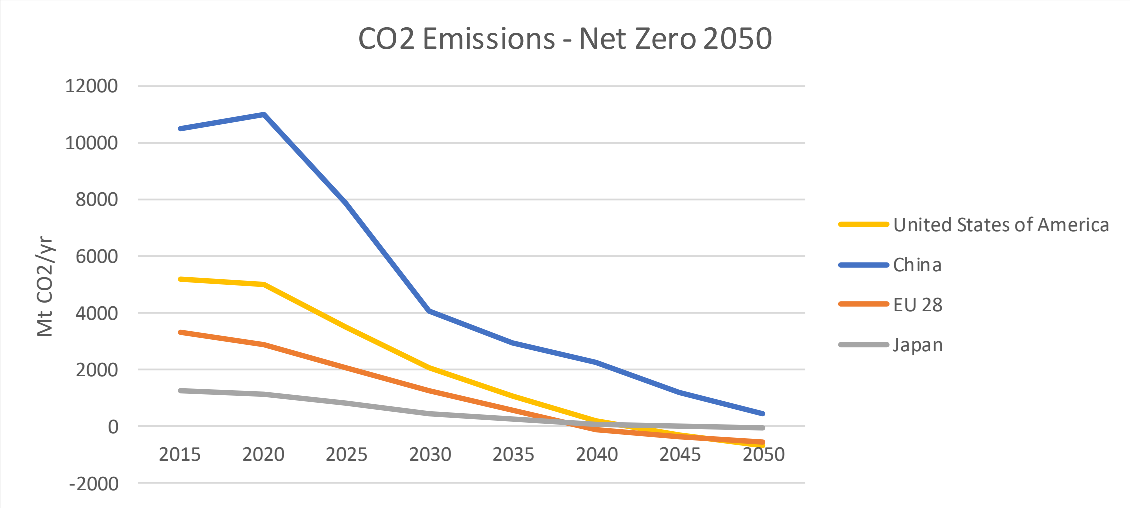
[16] I use the REMIND-MAgPIE 2.1-4.2 integrated assessment model. REMIND: (Regionalized model of investment and development) is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows analyzing technology options and policy proposals for climate mitigation, and models regional energy investments and interregional trade in goods, energy carriers and emissions allowances. MAgPIE: (Model of Agricultural Production and its Impact on the Environment) is a global land use allocation model. MAgPIE derives future projections of spatial land use patterns, yields and regional costs of agricultural production. The coupling approach between REMIND and MAgPIE is designed to derive scenarios with equilibrated bioenergy and emissions markets. In equilibrium, bio-energy demand patterns computed by REMIND are fulfilled in MAgPIE at the same bioenergy and emissions prices that the demand patterns were based on.

The model characteristics are as follows: REMIND is a General Equilibrium Model (closed economy) used for all sectors but agriculture, with intertemporal (perfect foresight) and welfare maximization. This allows the model to fully anticipate changes occurring over this century (e.g. increasing costs of exhaustible resources, declining costs of solar and wind technologies, increasing carbon prices) and also allows for an endogenous change in consumption, GDP and demand for energy in response to climate policies. MAgPIE is a Partial Equilibrium Model use for the agricultural sector, with recursive dynamic (myopic) and cost minimization. REMIND-MAgPIE considers technological change as exogenous except for solar, wind and batteries, which are endogenous.

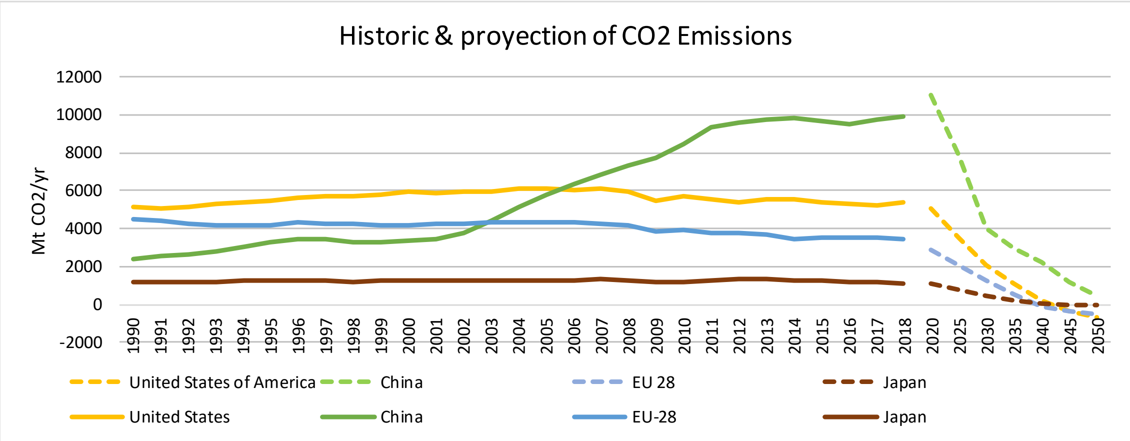
reduction of CO2 as per the REMIND-MAgPIE in order to reach net zero emissions around 2050 for the US, China, EU28 and Japan. Indeed, China would need to tackle the sharpest reduction.

Figure 3: CO2 emission reduction paths in the Net zero around 2050 scenario

Panel A: Reduction path (Mts CO2/yr from energy, industrial processes and land-use) (2015 -2050)



Panel B: Historical emissions path (Mt CO2) (1990-2018) *and estimated reduction path (Mts CO2) (2020-2050) to reach Net zero around 2050*

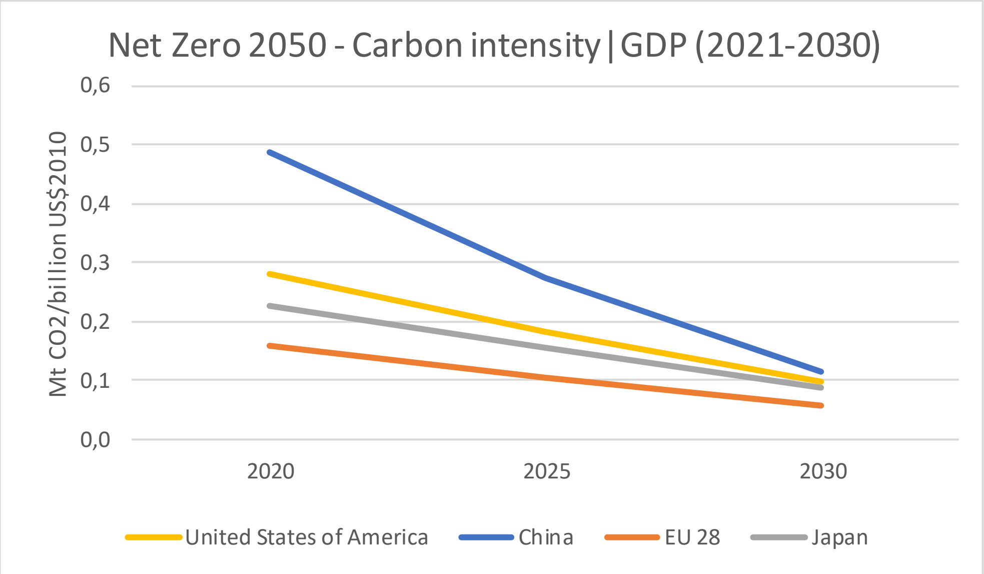


Source: CO2 Emissions Oxford Martin School, GCDL Oxford University (1990-2018). Projections in dotted lines REMIND-MAgPIE (2020-2050) (https://data.ene.iiasa.ac.at/ngfs/#/downloads). Emission paths are based on assumptions regarding GDP and population growth assumed as a baseline to continue in line with current trends (NGFS, 2021)

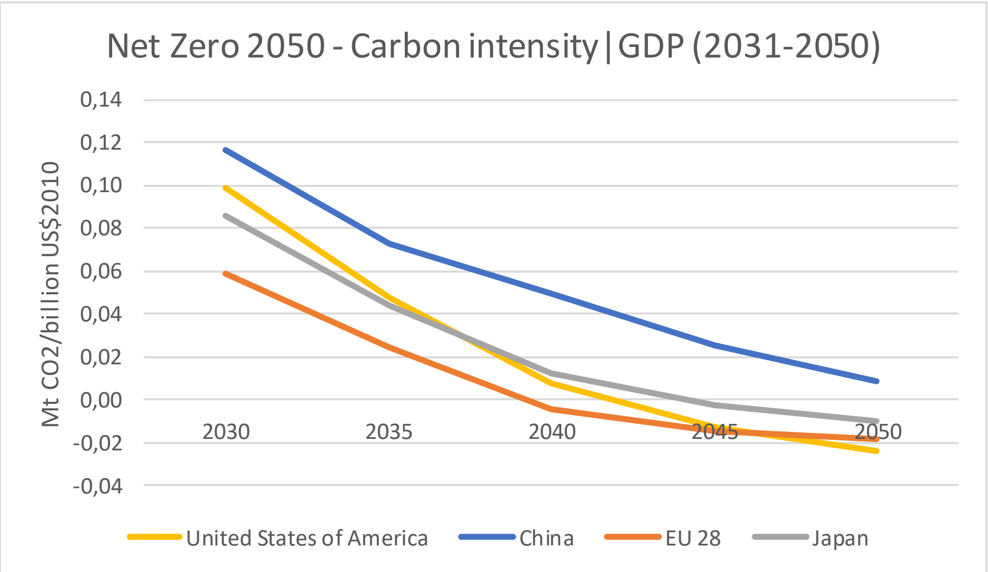
The most recent government commitments foresee reaching peak carbon intensity in terms of GDP just before 2030. In China, an orderly transition demands a reduction path of carbon intensity that should start well before 2030 and it needs to be intense (approximately 78% from 2020 to 2030) (Figure 4 Panel A).

Figure 4: Carbon intensity (*Mts CO2/ Bill USD (2010)*) reduction path (2021-2050)

Panel A: 2020-2030



Panel B: 2030 – 2050



Source: REMIND-MAgPIE (2020-2050) (https://data.ene.iiasa.ac.at/ngfs/#/downloads). Exchange rate movements over the past 10 years can have an impact over the shape of these curves

In the US, the CO2 emission reduction effort consistent with Net zero around 2050 is close to 66% from 2015 to 2030 and above the level of ambition of the national authorities for the same period. In Japan, the abatement effort would need to be close to 64% of CO2 emissions, much higher than the minimum of 46% CO2e announced by the authorities between 2013 and 2030 (Figure 3 Panel A). The EU has committed to a reduction of 55% of CO2 emissions from 1990 to 2030. An orderly transition scenario demands a reduction of CO2 of approximately 57% (including the UK) in the next decade (2021 to 2030) as envisaged in the REMIND-MAgPIE model (Panel A).[17] The EU "Fit for 55" proposed measures seem broadly better aligned with the abatement path envisaged in the REMIND-MAgPIE model, although they are not enforceable as yet.

Negative emissions are required in an orderly scenario that limits global warming to 1.5C for three purposes: to offset residual hard to abate emissions (i.e. bioenergy with CCS –BECCS- in the power sector); to remove historical emissions from the atmosphere; and to lessen atmospheric CO2 if emission reductions are not delivered soon enough. However, the world is far off from the trajectory toward sufficient negative emissions and this is explained by the constraints in CDR technologies like biomass with CCS (IPCC, 2019). [18]

3.1 The assumptions behind the orderly transition to Net zero around 2050 scenario

This orderly scenario assumes that optimal carbon prices in line with the long-term targets are implemented immediately after 2020. In Integrated Assessment Models in general, and the REMIND-MAgPIE in particular, shadow emissions prices are a proxy for government policy intensity (emissions prices are defined as the marginal abatement cost of an incremental ton of greenhouse gas emissions for a given short term policy – immediate or delayed). The carbon price is the main policy instrument and it is an endogenous variable (adjusted to meet the net zero target via iterations), which denotes the economy-wide carbon price. The general equilibrium model REMIND-MAgPIE recycles the revenues from carbon pricing via the general budget of each region.

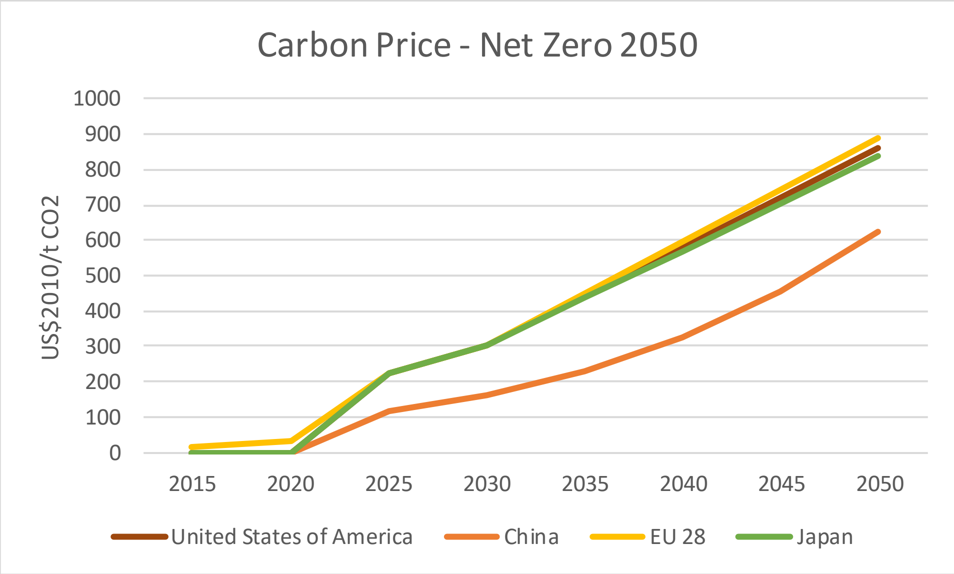
Figure 5 shows the shadow emissions prices consistent with the net zero 2050 scenario. The shadow emissions prices or total abatement costs will increase with increasing policy ambition (i.e. reaching net zero sooner) and technology costs in each particular region.

The EU 28 shows the largest price increases. In comparison with the EU "Fit for 55" strategy, it should be highlighted that the latter relies heavily on carbon pricing (ETS, taxes) and stringent environmental regulation. At the time of writing, neither the US nor Japan have announced the launching of nationwide ETSs. In China, allowances are currently given for free in the recently launched country-wide ETS, although authorities have indicated that it will introduce allowance options in the future (Goldman Sachs, June 2021).

As per the REMIND-MAgPIE model assumed overall level of policy coordination across regions of the world, the orderly scenario features some form of regional differentiation (e.g. carbon pricing, technological availability), however, it assumes high policy coordination across sectors within each region.

[17] Note that, the EU28 also includes de UK although it was not a member of the EU since 2020.
[18] Note that this is very contested, the extent to which negative emissions actually can be observed.

Figure 5: CO2 prices (USD2010)



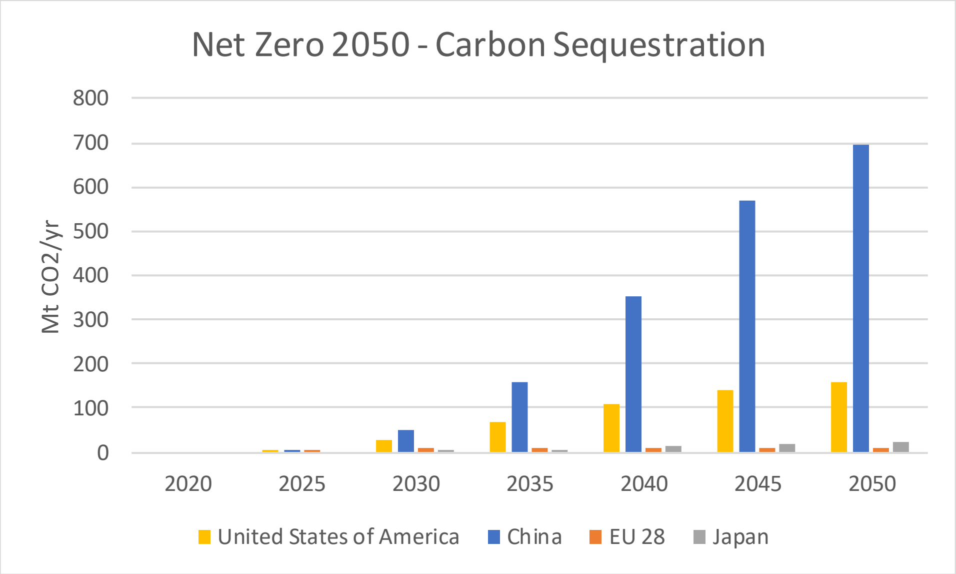
Source: REMIND-MAgPIE (https://data.ene.iiasa.ac.at/ngfs/#/downloads)

Regarding technology availability, a general consensus in the literature (Riahi et al., 2013) with structured comparison of technological sensitivities is that the assumptions on availability of carbon dioxide removal such as CCUS (Koelbl et al., 2014) have a particularly profound impact on mitigation trajectories, as higher availability enables a more gradual phase-out of the use of fossil fuel across various sectors. The net zero around 2050 orderly scenario assumes medium availability of CDR.[19] Also, the literature has explored the sensitivity of results to a range of technological assumptions regarding renewables, end-use efficiency, nuclear and several land-use related options (Creutzig et al., 2017, Grubler et al., 2018). REMIND-MAgPIE considers technological change as exogenous except for solar, wind and batteries, which are endogenous. The capital costs for renewable energy technologies are endogenously determined as a result of learning dynamics. Figure 6 (Panel A and B) shows the assumptions regarding CCUS and CDR via afforestation expressed in MtCO2 removed per year in the net zero around 2050 scenario for the four regions of the world in this study.

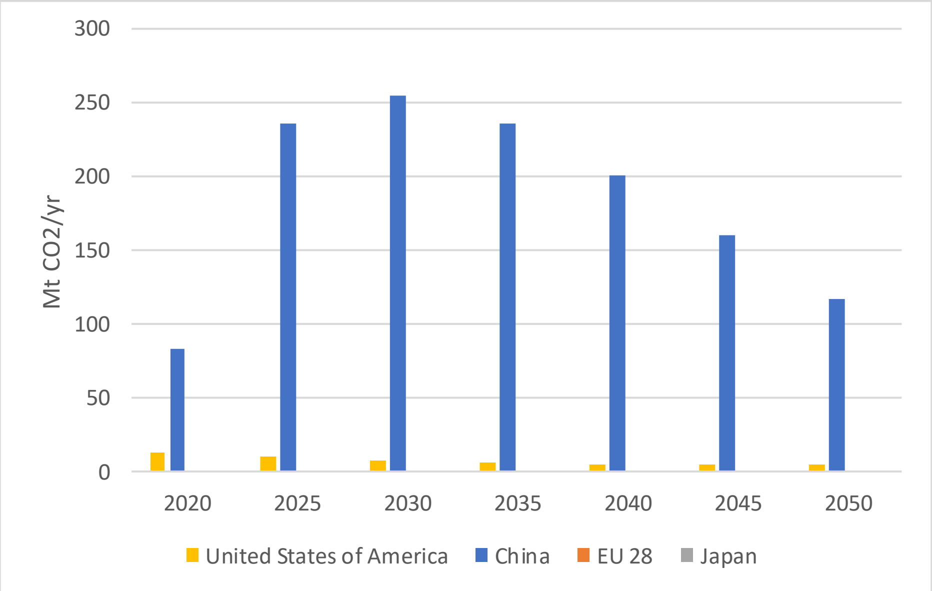
[19] Combining liquid fossil fuel burning technologies with CCUS can reduce CO_2 emissions significantly while deploying Carbon Dioxide Removal (CDR) technologies can compensate emissions from hard-to-abate sectors (e.g. cement, steel) by removing CO2 from the atmosphere and locking it into storages (e.g. afforestation, geological reservoirs). Current technologies have varying degree of maturity (e.g. degree of permanent removal) and face several hurdles (e.g. public acceptance) so their deployment at scale remains subject to uncertainties.

Figure 6: CCUS and CDR (*MtCO2/yr)*

Panel A: CCUS (MtCO2/yr)



Panel B: CDR (MtCO2/yr): Afforestation



Source: REMIND-MAgPIE (https://data.ene.iiasa.ac.at/ngfs/#/downloads)

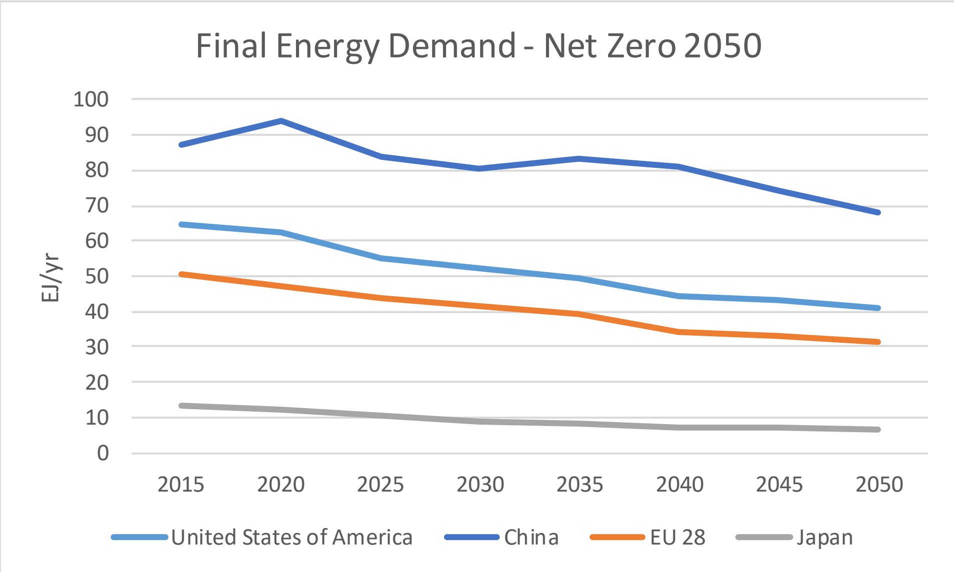
In all four regions, CCUS technology should become an increasingly important tool to remove CO2 permanently from 2030. In China and the US, political commitments to rely on these technologies for emissions´ removal seem broadly consistent with this scenario. As a matter of fact, in the COP26, China and the US found a way to cooperate around the development of CCUS technologies in addition to regulatory standards and electrification policies. [20]

[20] US-China Joint Glasgow Declaration on Enhancing Climate Action in the 2020s' (https://www.state.gov/u-s-china-joint-glasgow-declaration-on-enhancing-climate-action-in-the-2020s/ accessed 19/11/2021).

While afforestation, which does not secure permanent removal, reduces its importance progressively in the cases of China and the US in their orderly transition to net zero around 2050. For the EU28 and Japan, the model assumes no CO2 removal via afforestation. The EU Climate Law limits CO2 removal to 225 MtCO2e via natural sinks above the assumptions of the climate model to reach the emissions objective in 2050.

The Net zero around 2050 implies continued economic growth but with a decrease in energy demand thanks to improvements in energy efficiency and changes in consumer behavior. From 2020 to 2050, the lowest reduction of energy demand in percentage is in China as per the REMIND-MAgPIE model (Figure 7).[21]

Figure 7: Final Energy Demand *(EJ/yr)*



Source: REMIND-MAgPIE (https://data.ene.iiasa.ac.at/ngfs/#/downloads)

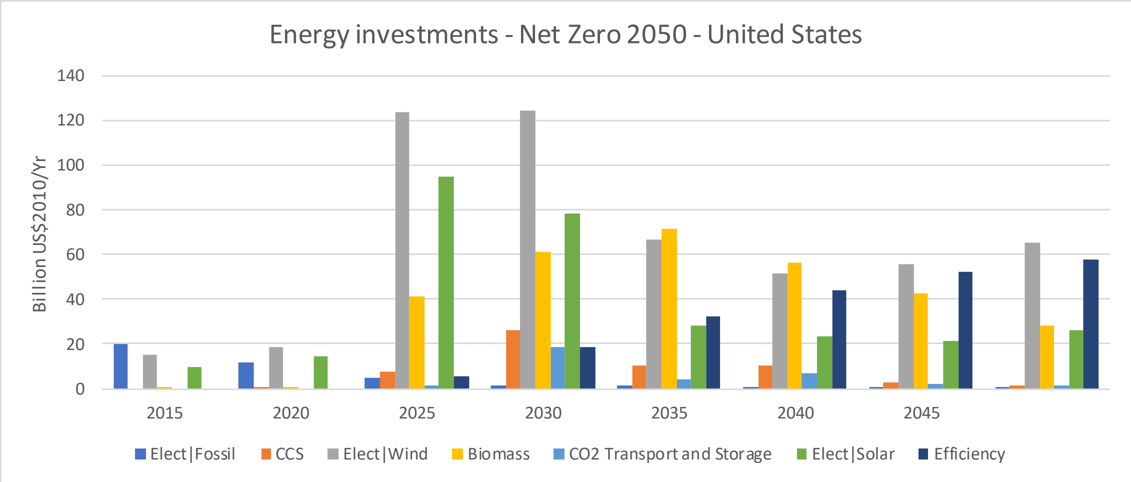
Investment in energy efficiency needs to increase significantly from 2025 to 2050, particularly towards the end of the period in the four regions of the world as per the REMIND-Mag-PIE model (Figure 8) in order to meet the net zero around 2050 scenario in an orderly fashion. Investment in renewables (wind and solar) needs to increase particularly in the 2025 -2030 period in this scenario, with wind energy receiving the largest energy investment in all four regions. Also, investment in biomass need to increase from 2025 in all four regions. Investment in CCUS has a sizeable impact on the mitigation trajectories, as higher availability allows a more gradual phase-out of fossil fuels, which still be recipient sectors of investment. CCUS and CDR choices in general, other than afforestation, are often subject to constraints (e.g. technology ramp up). Based on evolving scientific insights on these constraints, and on limited experience with these options in recent years, which further constrain the near-term ramp-up, CCUS and CDR investments peak in 2030. In terms of percentage of GDP,

[21] The reduction is an average for the five-year period.

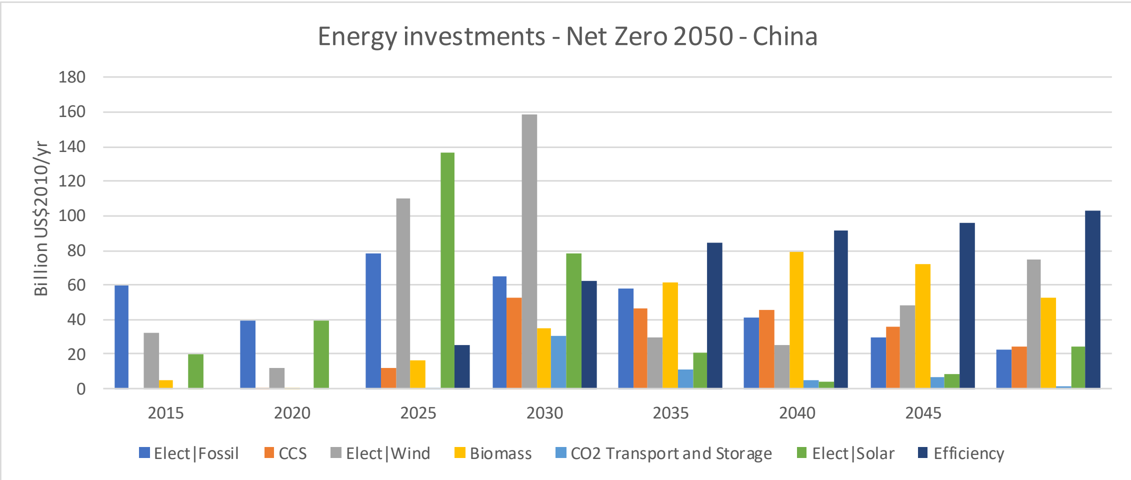
the accumulated investment on renewables and CCUS ranges between approximately 5% (EU28) and 7% (US) in the model over five years from 2025 to 2030.

Figure 8: Energy investments, five-year annual average (Bill USD2010/yr)

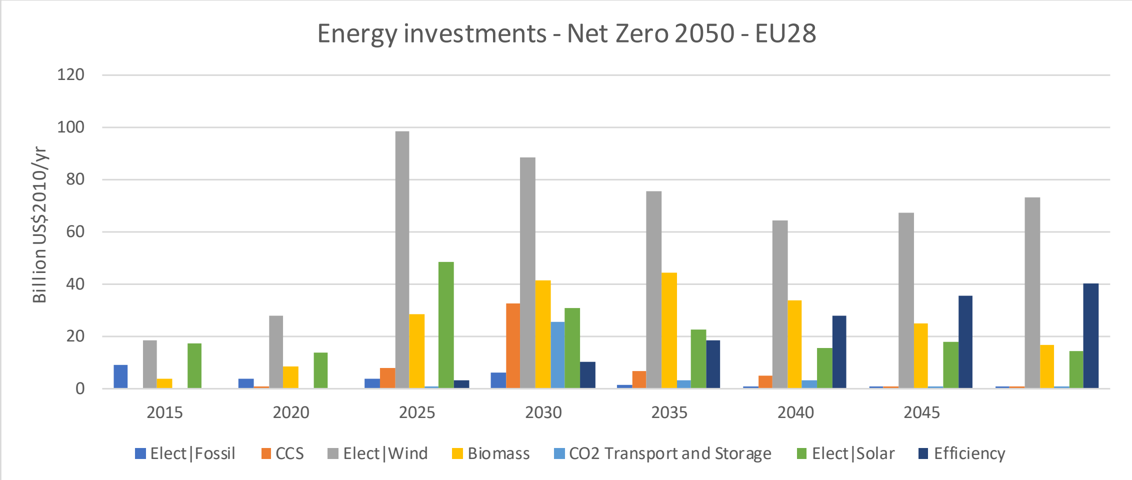
Panel A: US



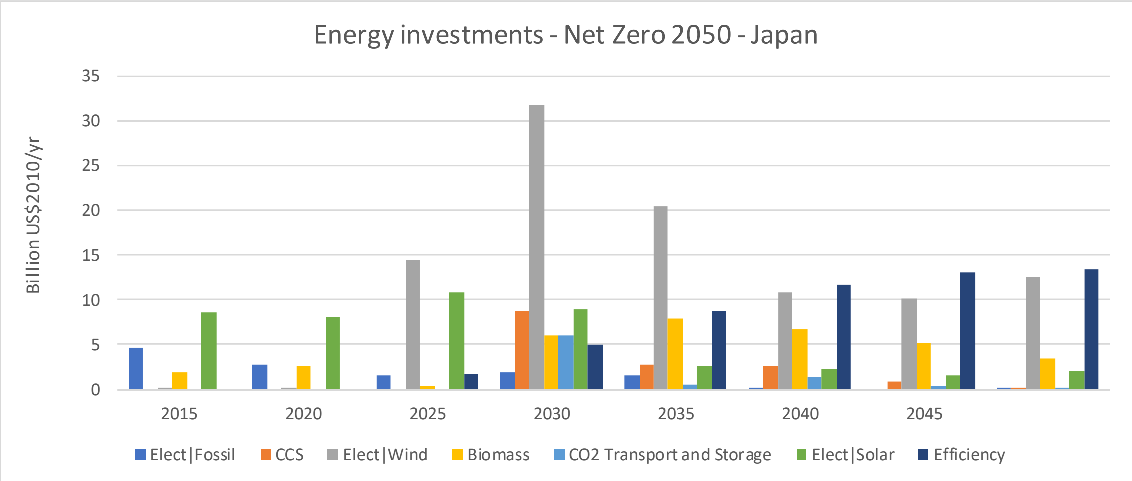
Panel B: China



Panel C: EU28



Panel D: Japan



Source: REMIND-MAgPIE (https://data.ene.iiasa.ac.at/ngfs/#/downloads). The data represent average annual investment for each 5-year time period

In order to reach the net zero emissions around 2050 in an orderly manner, the necessary accumulated investments in renewable sources of energy; biomass as well as CCUS estimated by the model are in total approximately twice the investment required to meet the national commitments stated in their NDC as of June 2021 (Table 3).

Table 3: Accumulated Investment (renewables, biomass and CCUS) Billion USD (2010) for 2020-2050

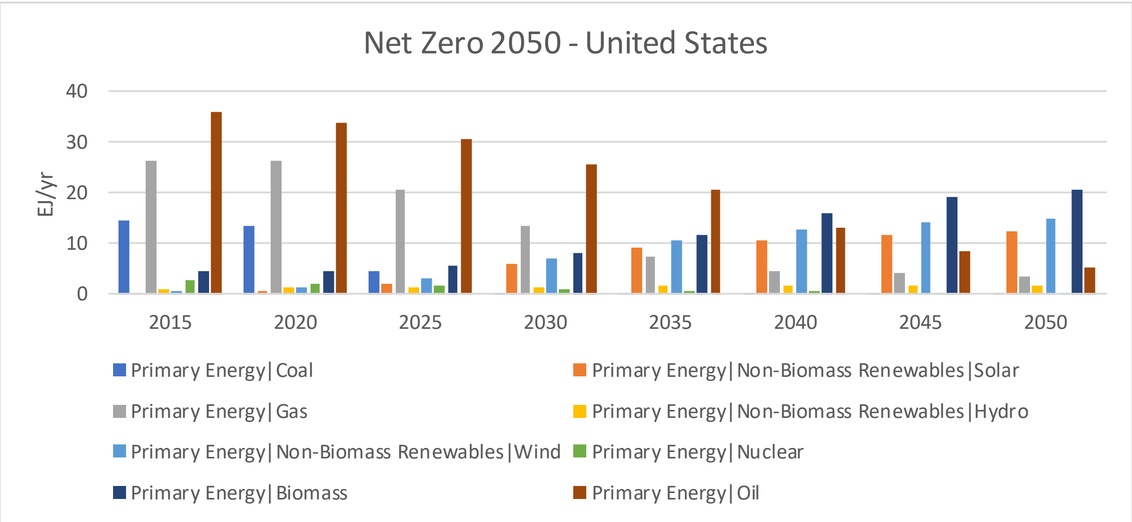
	US	China	EU28	Japan	*Total*
Net Zero 2050	5559,9	6233,1	4312,6	889,4	*16994,9*
NDC	2538,8	2756,3	3311,9	342,3	*8949,3*

Source: REMIND-MAgPIE (https://data.ene.iiasa.ac.at/ngfs/#/downloads). NDC as of June 2021. The data represents total accumulated 2020-2050. Exchange rate movements over the past 10 years can impact these values.

As a result of these investments that combine CDR technologies (including CCUS) with very low emissions sources of energy (i.e. renewables) as well as improvements in the efficient use of energy, the energy mix changes over time, showing the speed with which fossil fuels are phased out, and with which solar, wind, etc., are phased in. Both the speed as well as the type of energy substitute changes by region over time (Figure 9). In the US (Panel A), the orderly transition to net zero around 2050 would require an important reduction of the dependency on oil and gas (2020-2035), while the renewable sources of energy (wind, solar and particularly biomass) would become most important from 2040 to 2050. China (Panel B) is the most reliant on fossil fuels and it would need to quickly reduce its dependence on coal (2020-2025)[22] that would be partially substituted by oil and gas. At the same time, renewable sources of energy need to increase their importance. From 2020 to 2030, the increase in the renewable sources of energy (biomass, hydropower, wind and solar) needs to be approximately 89 percent. The government has committed to an increase of a 25 percent today. In the 2025-2030 period, China´s total installed capacity of wind and solar (GW) would need to be more than double of the total committed by the authorities to meet their 2060 net zero objective. Hence, the urgency to ramp up CCUS technologies. In the EU28 (Panel C), the dependency reduction of oil (2020-2035) is substituted by renewable energy sources particularly biomass and wind (2035-2050). Japan (Panel D) needs to quickly reduce its dependence on coal (2020-2035) and scale up renewable sources of energy (biomass and wind) from 2025. Nuclear is assumed to play the largest role in the energy mix among the four regions.

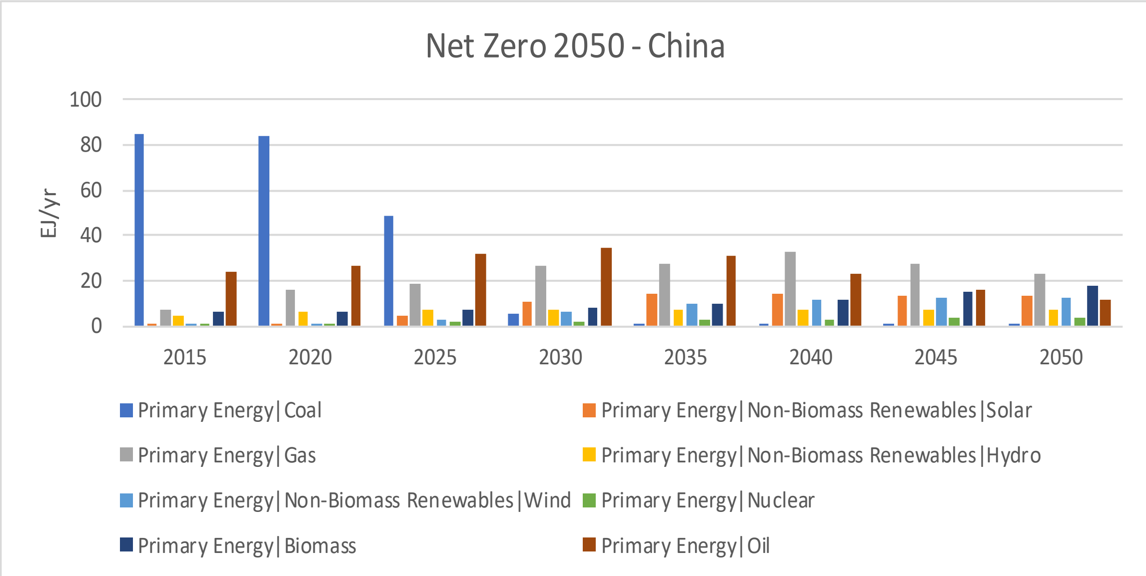
Figure 9: Energy Mix *(EJ/yr)*

Panel A: US

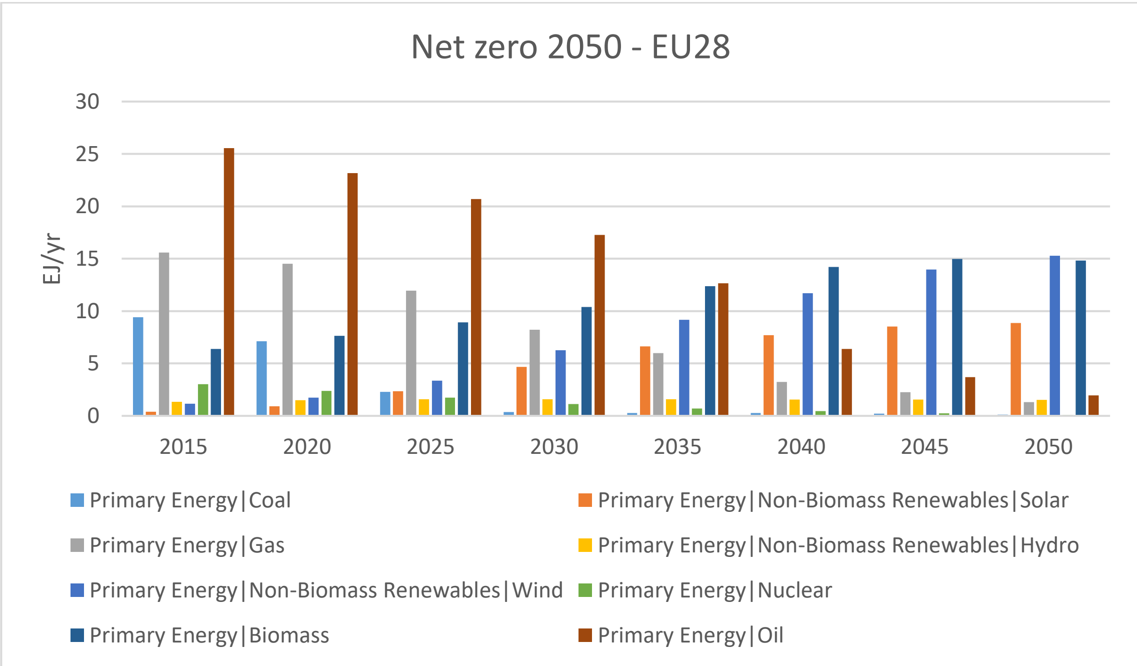


[22] At the COP26, China weakened the pact on the 'phase out' of coal, limiting its commitment to 'phase down.´

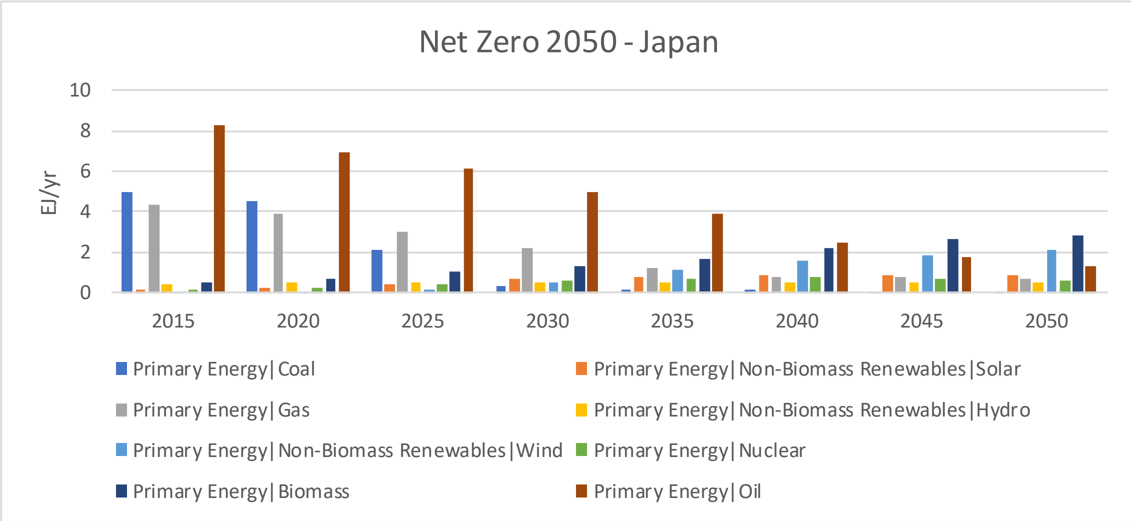
Panel B: China



Panel C: The EU28



Panel D: Japan



Source: REMIND-MAgPIE (https://data.ene.iiasa.ac.at/ngfs/#/downloads)

4. Conclusions

The signatories of the UN Paris Agreement of December 2015 are legally bound to regularly set national targets to meet the goal of limiting global warming to well below 2 C, preferably to 1.5 C. In November 2021, the signatories of the Glasgow Climate Pact agreed at COP26 recognize that the 1.5C goal should be the norm, as the 2C has been shown to be significantly more harmful and riskier.

This paper analyzes the most recent NDCs as well as public political commitments of the US, China, the EU and Japan to meet that goal in light of the transition pathways defined by the REMIND-MAgPIE 2.1-4.2 for an orderly transition scenario to net zero emissions around 2050. The most important conclusions of this paper are as follows:

- Nationally Determined Contributions (NDCs) of US, China, the EU and Japan (56% of the world GHG emissions) are not in line with the requirements to reach net zero emissions around 2050.[23] Only the EU seems to have an adequate, sufficiently detailed and legally binding strategy to fulfil that pledge. This finding is in line with the recent United Nations Report concluding that even with enhanced 2030 targets and the additional statements (not part of the NDCs under the Paris Agreement), the world is on track for a temperature increase between 1.8-2.4C this century even assuming that every country puts in place effective policies that will fully achieve its set targets.[24]

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[23] According to the NDC Synthesis Report released by the UN on 17 September 2021, about 86 revised NDCs were submitted by a group of 113 parties accounting for about 49% of global GHG emissions. Under the updated NDCs, GHG emissions are projected to be reduced by 12% in 2030 compared to 2010, still insufficient in comparison with the 45% emissions reduction needed by 2030 to limit temperature to 1.5°C (https://unfccc.int/documents/306848 accessed 19/10/2021).

[24] This is an "optimistic or best case scenario" Emissions Gap Report 2021, UNEP, 26 October, 2021 (https://www.unep.org/resources/emissions-gap-report-2021 accessed 15 November, 2021). Note that

- The EU would need to support the highest marginal abatement costs of CO2 to reach Net zero around 2050, while China would bear the lowest. Comparing the model output with the EU strategy, the latter places a special emphasis on carbon pricing:[25] a common regional price for large emitters although with sectoral differences (ETS) as well as taxation (fuels) including subsidies for renewable energies, hydrogen, advance biofuels and biogases. However, the EU puts less emphasis on the technological developments.

- In all four regions of the world and particularly in 2025-2030, the orderly transition to net zero around 2050 demands the highest investments in renewable energies for electricity, CCUS and energy efficiency. In absolute terms, the largest investment would need to be in wind. Japan would need the largest increase of investment in wind as compared to the other regions over that period.

- The necessary accumulated investments in renewable sources of energy for electricity (wind and solar), biomass as well as CCUS estimated by the model are in terms of percentage of GDP in a range between approximately 5% (EU28) and 7% (US) in the 2025 – 2030 period, when investments need the largest increase.

- China, the most critical to reach global carbon neutrality, is by far the most highly dependent on CCUS and, more generally, on CDR technologies to reach the net zero around 2050 due to an energy mix dominated by fossil fuels (2020-2050). The US follows at a distance due to an energy mix that is largely dependent on oil (2020-2035). Such technologies play an insignificant role in the EU.

- In the 2025-2030 period, China´s total installed capacity of wind and solar (GW) would need to be more than double of the total committed by the authorities to meet their 2060 net zero objective. Moreover, it would need to further increase after 2030.

In sum, NDCs need to increase ambition and countries secure their effective execution if the objective of limiting the temperature to 1.5C as agreed at Glasgow Climate Pact (COP26) is to be reached.

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[25] The COP 26 did represent a game-changer with the adoption of rules governing the international trade in emissions reduction units.

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