Deep decarbonization pathways in CHINA

Fei Teng

Jun Xie

Qiang Liu

Xin Su

Xu Deng

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Lessons from the EU-funded research project IMAGINE

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Introduction

This work takes place in a context where:

- *in 2015, China submitted its Intended Nationally Determined Contributions (INDC) committing to peak CO2 emissions around 2030, to lower CO2 emissions per unit of GDP by 60% to 65% from the 2005 level, to increase the share of non-fossil fuels in primary energy consumption to around 20%, to increase the forest stock volume by around 4.5 billion cubic meters on the 2005 level, and to take adaptation actions to enhance mechanisms and capacities for effectively defending against climate change risks.*
- *in 2021, China submitted updated NDC commitments and Long Term Low Greenhouse Gas Emission Development Strategy (LT-LEDS/LTS) to achieve carbon neutrality before 2060 and peak CO2 emissions before 2030, to lower CO2 emissions per unit of GDP by over 65% by 2030 from the 2005 level, to increase the share of non-fossil fuels in primary energy consumption to around 25% by 2030, to increase the forest stock volume by 6 billion cubic meters from the 2005 level by 2030, and to bring its total installed capacity of wind and solar power to over 1.2 billion kilowatts by 2030.*
- *Several national and international estimate that the "carbon neutrality" objective covers all GHGs and not only CO2 emissions as for the peaking objective (as claimed by Xie Zhenhua from the Tsinghua University, and the Climate Action Tracker). As China's non-CO2 emissions account for about 2 GtCO2eq, this difference can make up to 0,1°C of global warming by 2100.*

In this context and under the EU-funded research project IMAGINE, we defined a set of three development pathways :

- **The REF scenario / the Current Policy Scenario (CPS) :** this scenario represents the current policies in place and ongoing transformational trends which do not enable to reach the carbon neutrality before 2060.
- **The CO2 Net-Zero scenario (DDS CO2):** this scenario illustrates the transformations needed to reach net-zero CO2 emissions before 2060. For non-CO2 emissions, it follows the same current policy pathways as the REF.
- **The GHG Net-Zero scenario (DDS GHG):** this scenario illustrates the transformations needed to reach net-zero GHG emissions before 2060.

Rationales and research questions

1) What are the additional transformations required to reach net-zero CO2 emission before 2060?

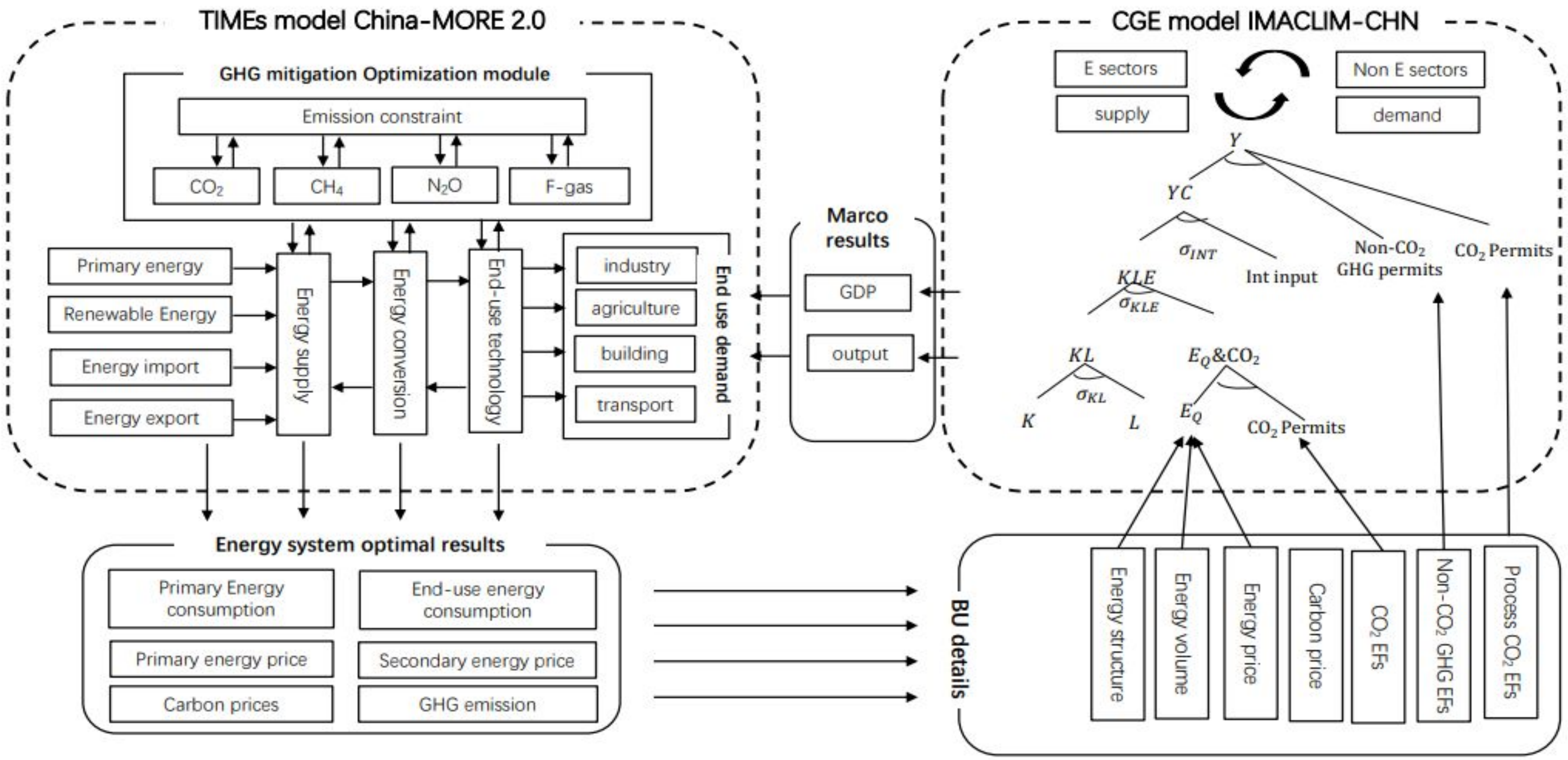
2) What are the additional transformations required to reach net-zero GHG emission before 2060?

- The comparison of REF with DDS CO2 will inform us on the additional transformations required to reach net-zero CO2 and development objectives before 2060.
- The comparison of DDS CO2 with DDS GHG will inform us on the additional effort in terms of transformations to reach net-zero GHG and not-CO2 only by 2060.

Other key country-specific questions aim to be informed by this work:

- What are the main emitting sectors and what sectors should be particularly address if we include all greenhouse gas emissions in the carbon neutrality target?
- How could this work support the revision of national development and climate policies and future UNFCCC's commitments?
- What key global and sectoral transformations must be considered to enable national Paris-compatible pathways?
- What are the key international enablers and cooperation needs for these sectoral transformations?

Modelling architecture & improvements



Here are the key academic publications and references on the modelling structure :

- *Wenying Chen (2005). The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling. Energy Policy 33 885–896*
- *Su, X., Ghersi Frédéric, Fei, T., Le Treut Gaëlle, & Meicong, L. (2022). The economic impact of a deep decarbonisation pathway for china: A hybrid model analysis through bottom-up and top-down linking. Mitigation and Adaptation Strategies for Global Change, 27(1) doi:https://doi.org/10.1007/s11027-021-09979-w*
- *·Yang, X, and F Teng. "Air Quality Benefit of China's Mitigation Target to Peak Its Emission by 2030." CLIMATE POLICY 18, no. 1 (2018): 99–110. https://doi.org/10.1080/14693062.2016.1244762.*

- CHINA-MORE model coupled with IMACLIM: China-MORE model is a bottom-up model, where CO2, N2O, CH4, F-gases emissions and mitigate technologies are detailly modeled. We complemented the technology model China-MORE by coupling it with a multi-sectoral IMACLIM model to analyze the long-term impacts of carbon neutrality targets on China's economic development.

- It is a hybrid energy/economy dataset on 2017 into China-MORE and built the interaction module passing the margin price and energy flow in China-MORE into IMACLIM-China and passing the macroeconomic results in IMACLIM-China to China-MORE adjusting the end-use energy demand.

- There is no forest sub-model in our modeling framework, therefore assume a 1 GtCO2 carbon sink from LULUCF sector in China based on literature survey (e.g. Xu et al, 2023 PNAS).

Part 1

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National overview of the deep decarbonization pathways

Nowadays, power, energy-intensive and light industries are the most emitting sectors in China

The power sector, energy-intensive and light industries are the most emitting sectors nowadays in China, considering GHG emissions.

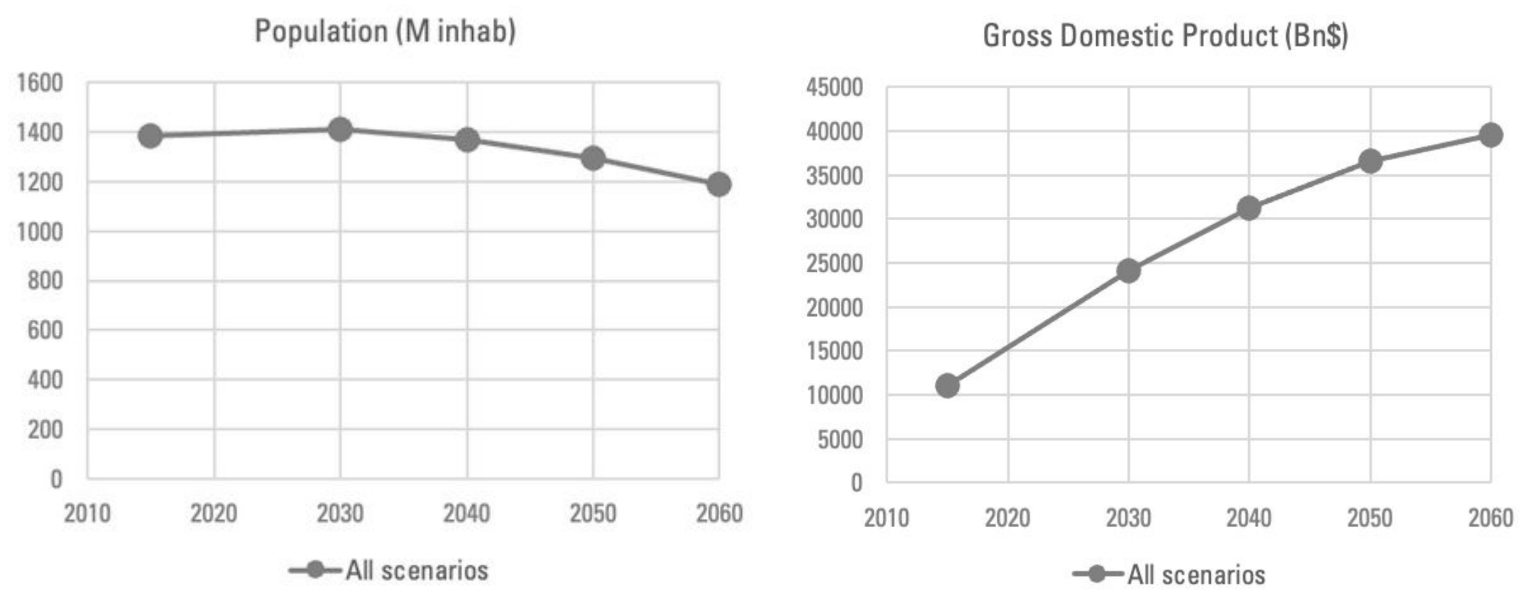
- The power sector is the most emitting sector (GHG & CO2) in China due to the high reliance on coal-power plants. See slide 23 for the power generation and slide 24 for extractive activities.
- For the energy-intensive industries: this is due to both coal combustion and processed emission from the iron & steel productions (see slide 18 for energy-intensive activities).
- For light industries: this is due to both coal combustion and processed emissions from manufacturing and non-ferrous metals (see slide 19 for light industries activities).

Figure 1. Main indicators for 2015

Indicator	Value in 2015
GHG emissions (MtCO2)	10679
CO2 emissions (MtCO2eq)	8603
CO2 emissions per capita (MtCO2/cap)	6
Non-CO2 emissions (MtCO2eq)	2076
Final energy consumption per capita (GJ/cap)	58
Population (Million)	1383
GDP (billion $ 2010)	11060
Most emitting sectors (GHG)	power, energy-intensive and light industries
Most emitting sectors due to combustion (CO2)	power, energy-intensive and light industries

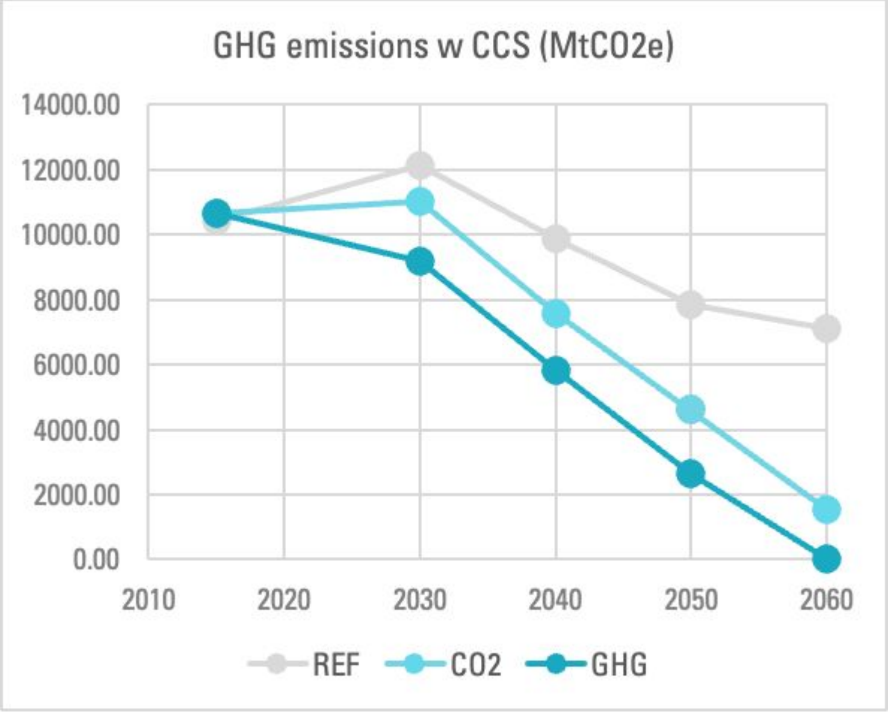
Reaching net-zero GHG emissions by 2060 is feasible, while ensuring socio-economic development

Figure 1. Socio-economic indicators (population, GDP per capita)



- The Chinese population is expected to peak around 2030 and decrease to 1.1 billion inhabitants by 2070, with a reducing active population.
- The GDP per capita will continue to grow, with a growth rate that decelerates after 2030 due to a contracting population and pronounced demographic ageing.
  - The consumption of agricultural and food products will decline as the population declines. The consumption in the construction sector will also decline as the per capita housing area gradually becomes saturated.
  - The role of services will rise steadily, reaching 72% and 80% of total non-energy consumption in 2035 and 2060 respectively.

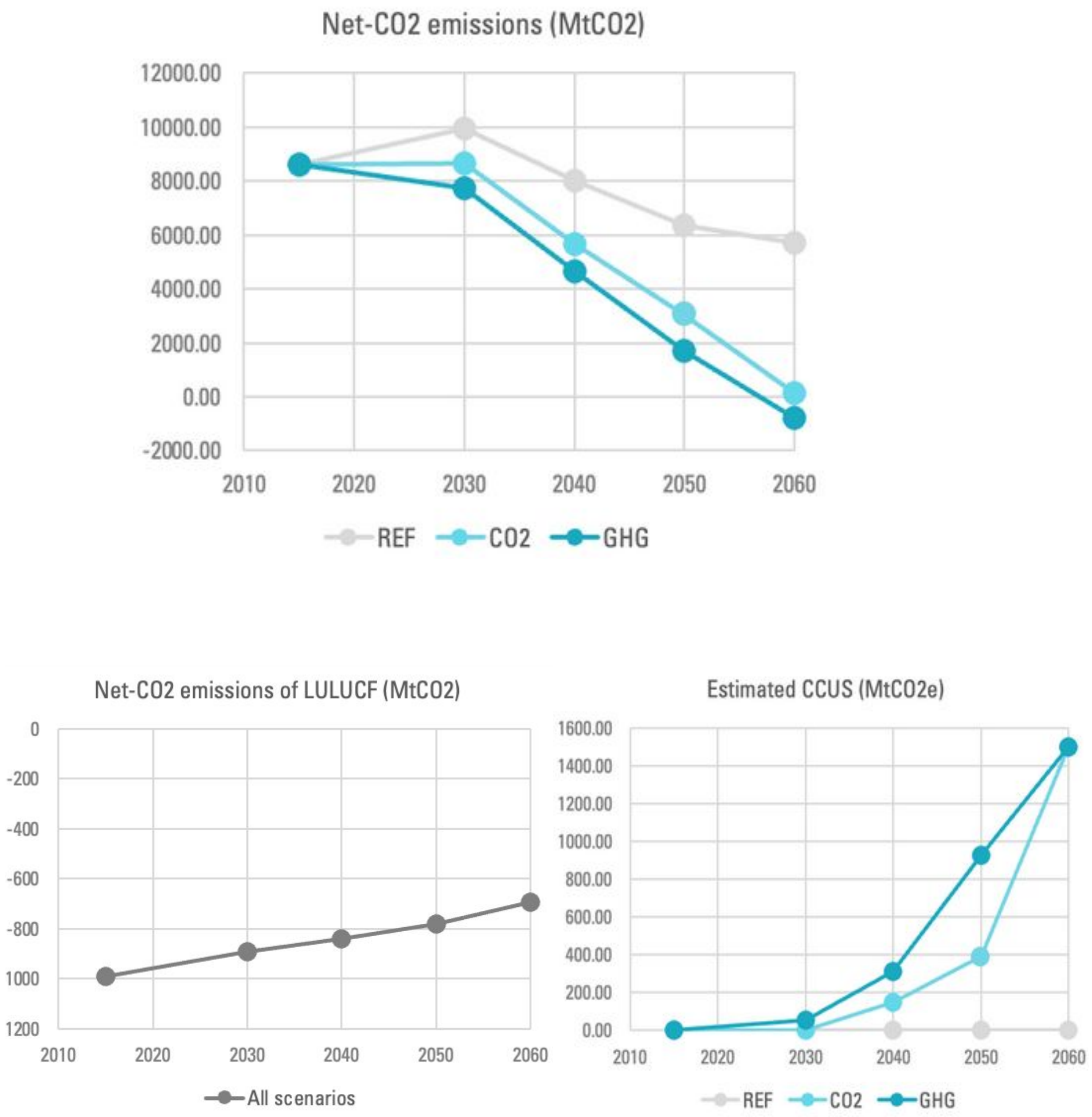
Figure 2. National net GHG emissions



- All scenarios peak GHG emissions around 2030 but have very different emission level in 2030 ranging from 8.5 to 12 GtCO2eq.
- Current policies as assessed by the REF scenario doesn't allow to reach the carbon neutrality targets by 2060.
- Compared to the DDS CO2 scenario, reaching GHG neutrality by 2060 requires an additional effort of 1,1 GtCO2eq.
- The DDS GHG scenario, based on a least-cost optimization pathway, requires a more important emission reduction before 2030 compared to DDS CO2 and follow the same decarbonization pace after 2030 towards 2060.

Total net-CO2 emissions represent about 81% of all net-GHG emissions in 2015 and could be reduced by 42% by 2040 towards net-zero by 2060

Figure 3. National net-CO2 emissions.



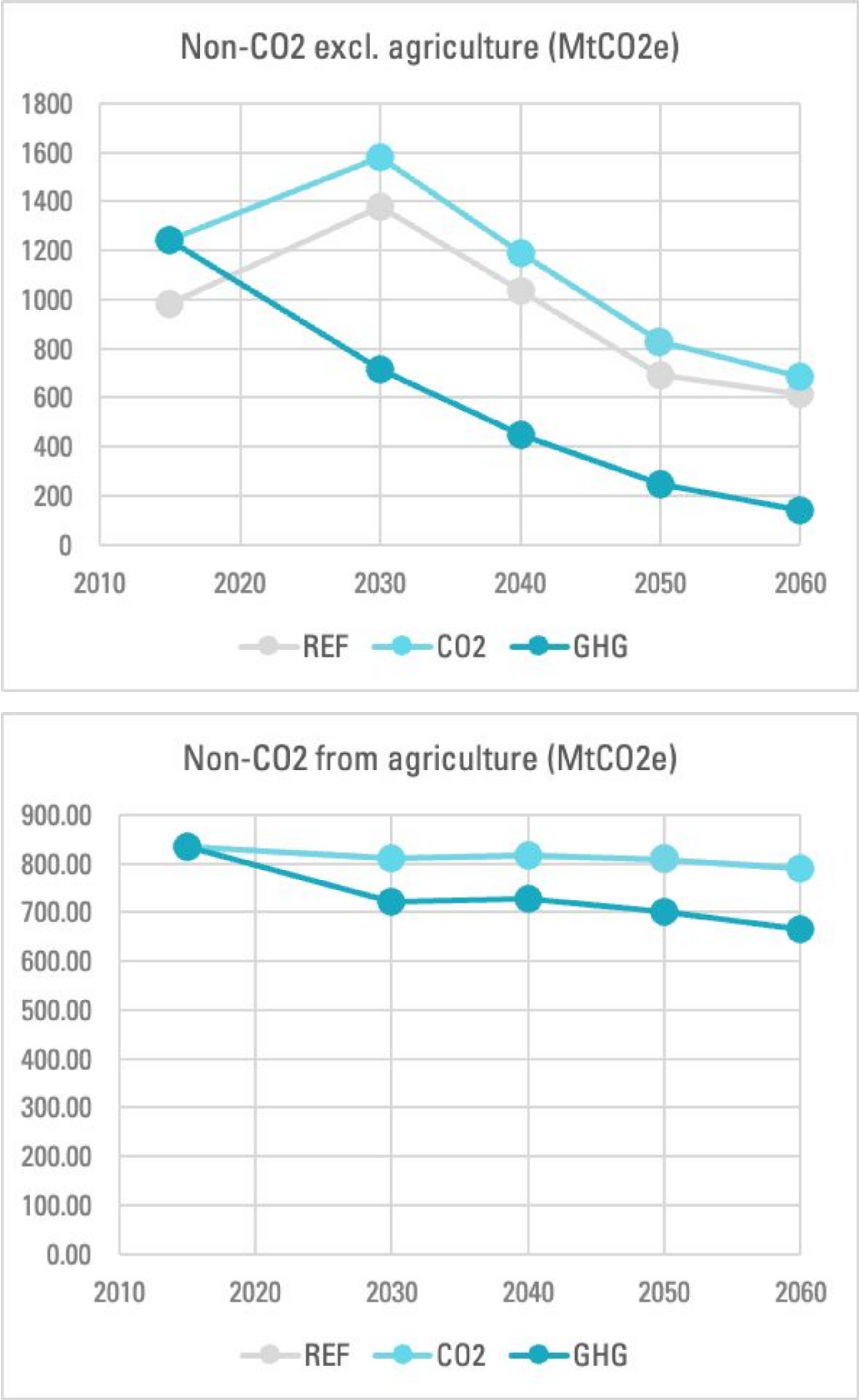
- 89% of the CO2 emissions (excluding LULUCF) are from fuel combustion and are mainly driven by the explosion of the energy demand and the current reliance on fossil fuels. Industrial processes represent 10% of the CO2 emissions. Waste emissions represent 0,4%.

- DDS GHG will reach net-zero CO2 before DDS CO2 in around 2055. Both scenarios reduce emissions at a similar pace, but the DDS GHG follow a similar emission trajectory after 2030, with the main difference being that the DDS GHG scenario reduces emissions more between 2020-2030. In both scenarios, CO2 emission reductions comes from efficiency improvement, fuel switch, electrification and CCS. CCS technology is deployed in cement industry, in the power supply from biomass. It is expected to capture and store from 3 to 35 Mt of CO2 in 2030 in the DDS CO2 and GHG scenario and 1,5t by 2060. CCS with biomass (BECCS) in the power sector makes up to 86% of the CCS capacities by 2070 in the DDS GHG scenario.

- LULUCF emissions are negative and absorb around 1/8 of China's annual CO2 emissions in 2020. The sink capacity reduces over time from -1000MtCO2 in 2020 to - 600Mt CO2 in 2070, following an identical trajectory in all scenarios. This is mainly due to aging structure of forest which reduces capacity to absorb carbon.

Total non-CO2 emissions represent 19% of all GHG emissions and could be reduced by 62% by 2060

Figure 4. National non-CO2 emissions.



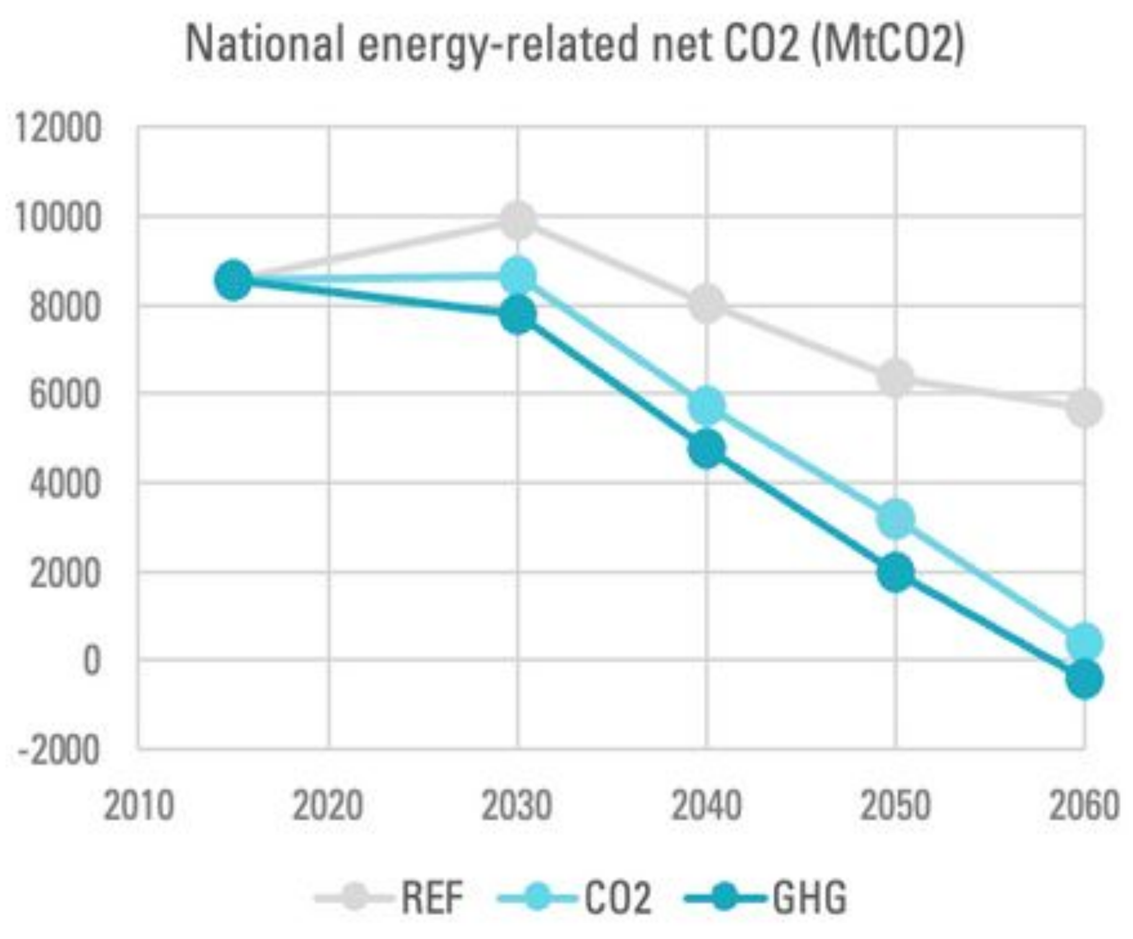
- The main non-CO2 emission sources in 2020 are in agriculture (46%), energy (41%), waste (9%) and industry (4%). The DDS CO2 scenario does not intend to reach GHG neutrality by 2060, and therefore this scenario does not seek to mitigate non-CO2 emissions. The DDS GHG scenario targets non-CO2 emissions with multiple mitigation strategies.

- Agriculture emits the largest share of non-CO2 emissions, and non-CO2 decrease by 4% in the REF & DDS CO2 scenarios, and the DDS GHG by 16%. The DDS GHG introduces additional transformations from 2020 in rice cultivation and livestock feeding to start a structural change which could save about 100-125MtCO2eq each year from 2030, comparing to the DDS CO2 scenario where these actions are not present.

- For the other sectors, non-CO2 emissions are reduced significantly, especially between 2020-2030. The REF and DDS CO2 scenarios reduce non-CO2 excl. agriculture by 26% 2020-2060, and the DDS GHG by 62%. The main drivers of this reduction is the drastic reduction of coal mining , which is a source of methane.

Total energy-related CO2 emissions represent 89% of all GHG emissions and could be reduced by 41% by 2040 toward net-zero by 2060 (1/3)

Figure 5. National energy-related CO2 emissions



- Around 89% of the GHG emissions comes from energy-related CO2 emissions. The level of emissions is decreasing in all scenarios and getting closer to zero in both DDS.

- Under the REF, China's current policies lead to energy efficiency gains and changes in the fuel supply in diminishing the use of coal and coke as solid energy sources towards 2030. However, while population continue to increase and GDP has the strongest rate, this is insufficient to cut emissions by 2030. But this will change after 2030, with a decrease of energy-related emissions until 2070.

- In the deep decarbonization scenarios (DDS):
  - The recent improvement in the end-use energy mix is mainly due to the development of further large-scale intensification in the industrial sector, with energy-efficient large-scale industrial technologies gradually replacing small, fragmented and inefficient production capacity.
  - Improvements in energy efficiency have led to an increase in the production of industrial products while the consumption of solid fuels has declined rather than increased. However, as electricity is several times more expensive than coal energy, there is a lack of willingness to further replace electricity in all sectors after energy-efficient technologies have been rolled out.

Total energy-related CO2 emissions (2/3): Reducing energy-related CO2 emissions requires systemic and technological changes to improve energy efficiency and reduce the fuel carbon content

Figure 6 . Energy consumption (GJ/capita)

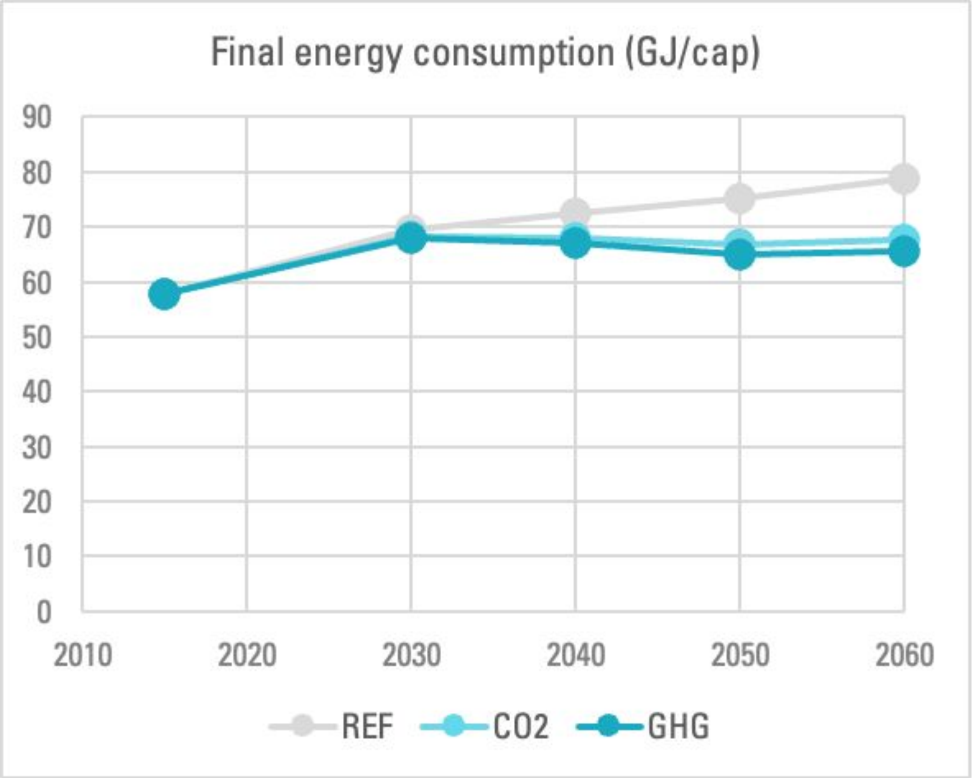


Figure 7. Energy consumption (MJ/$)

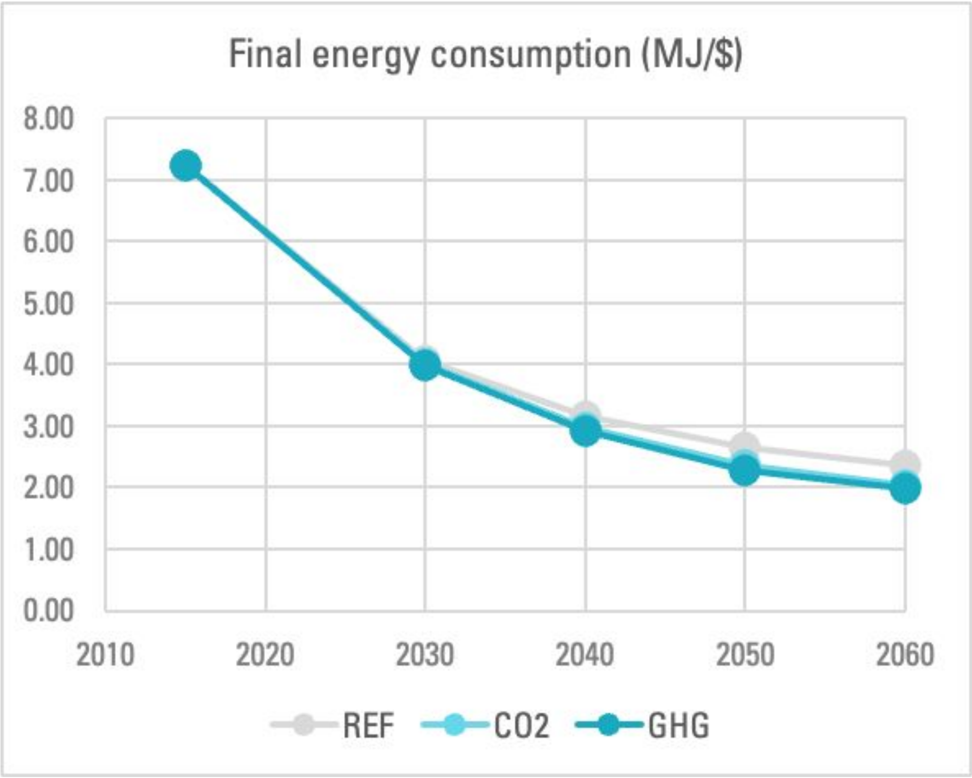
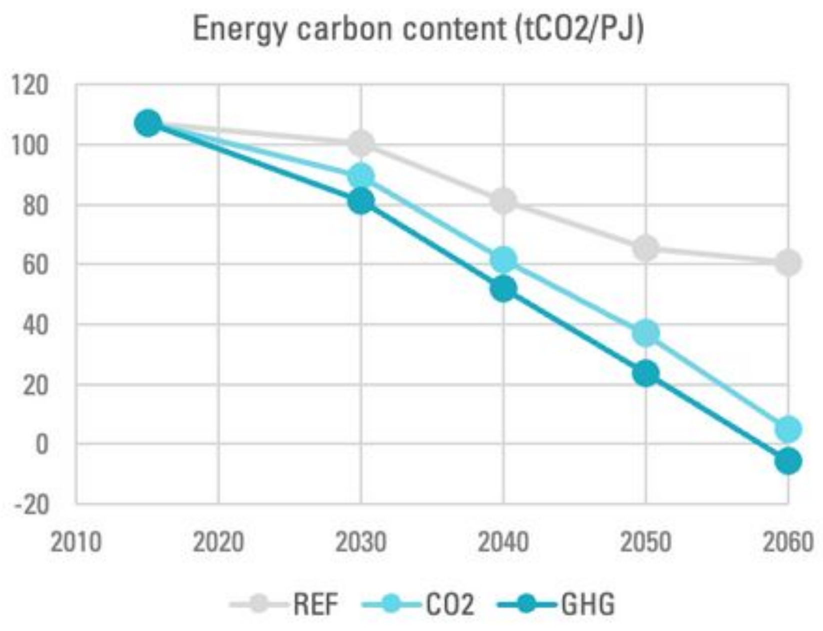


Figure 8. Energy carbon content (tCO2/PJ)



- The energy consumption per capita is increasing in both scenarios by 2070. In the DDS, it is reaches in 2070 similar levels to 2030 : 70PJ/cap.

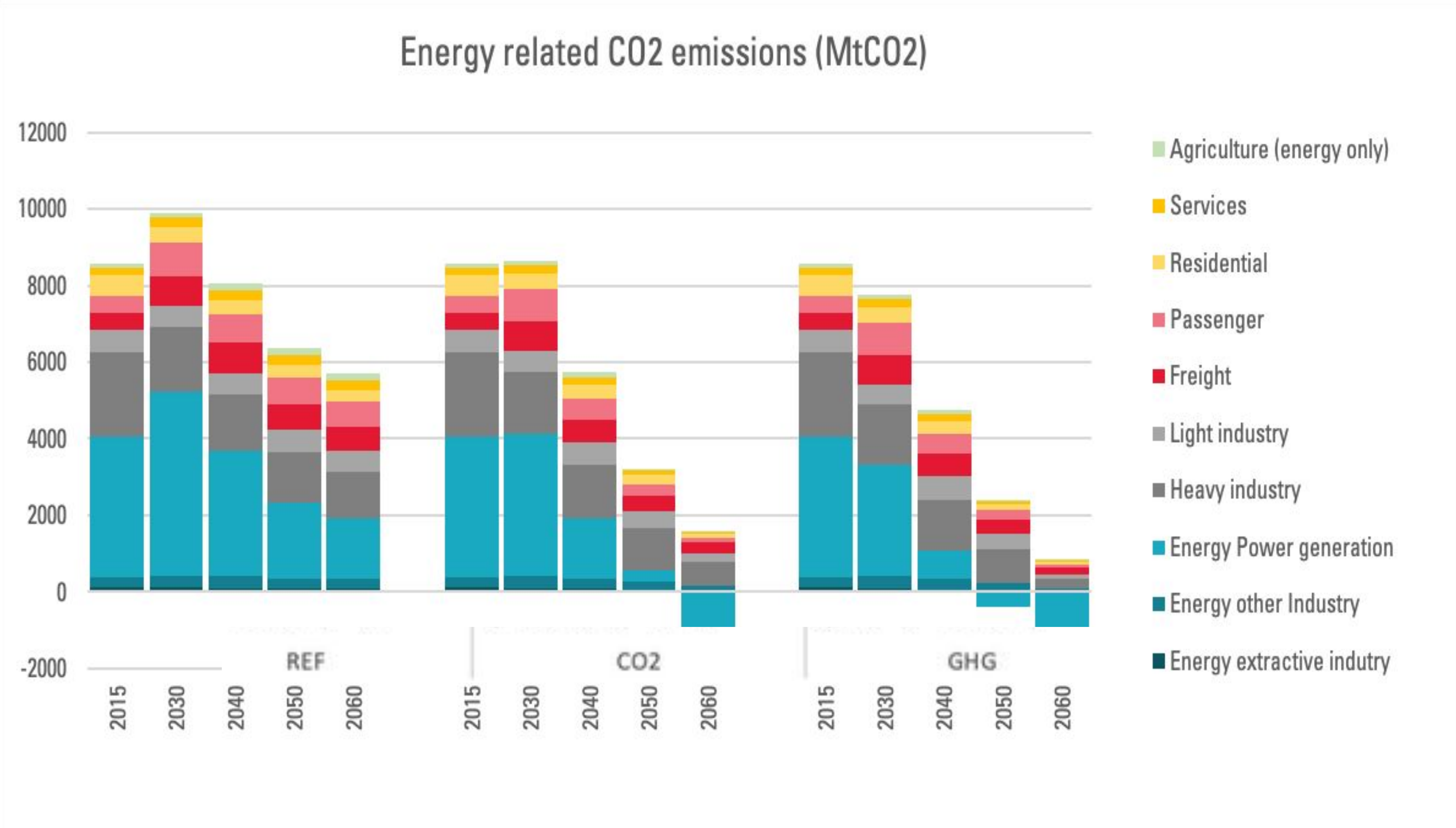
- Energy intensity strongly decreases until 1,8 MJ/$ unit in 2070 in the DDS GHG.
- The DDS CO2 & GHG follow similar trends, reaching lower levels than the CPS in 2060 by 17%. This is because energy demand decreases in the DDS CO2 and GHG, reaching in 2070 lower levels than in 2022; while the GDP continues to grow.

- The shift towards zero-emission fuels and CCS capacities will enable a decrease in the carbon content of fuels.

- Carbon content decreases by 19% in 2030 in the DDS GHG in comparison to the CPS, and then by 88% in 2070.

Total energy-related CO2 emissions (3/3): The key energy-related sectors for deep decarbonization are the power sector and the energy-intensive industries

Figure 9. Energy related CO2 emissions



- From now until 2030, the energy-consumption sectors with the highest emissions are the power sector and energy-intensive industries, and a majority of mitigation efforts must be concentrated in these sectors to reach the NDC objectives.
- When comparing the DDS CO2 and DDS GHG in 2030, we see that emissions cuts also needs to address the power sector and energy-intensive industries. To reach GHG neutrality and not only C02 neutrality, but the same sectors are also targeted, with deeper cuts than in the DDS CO2 scenario.
- When comparing the CPS and the DDS CO2 & GHG in 2060, we see that emissions cuts comes from the same main emitting sectors, and also from transport, both passenger and freight. A broader range of sectors needs to cut their emissions for China to reach neutrality in 2060.

Part 2

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Sectoral deep decarbonization pathways in the DDS GHG scenario

Part 2.1

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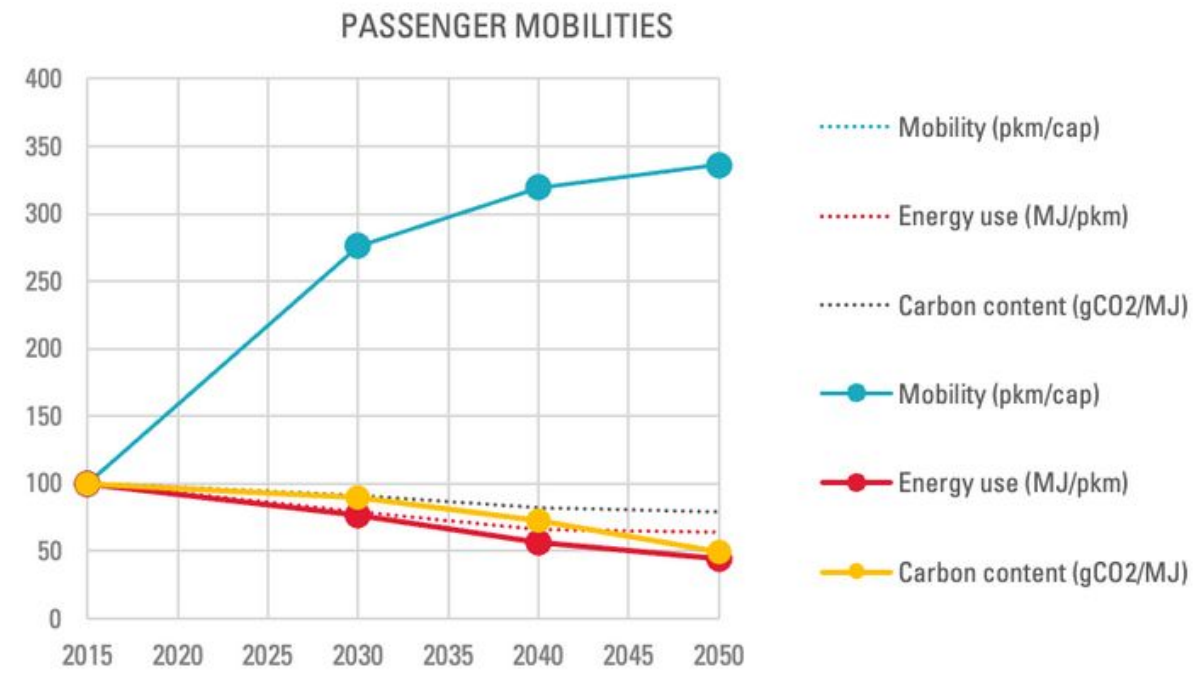
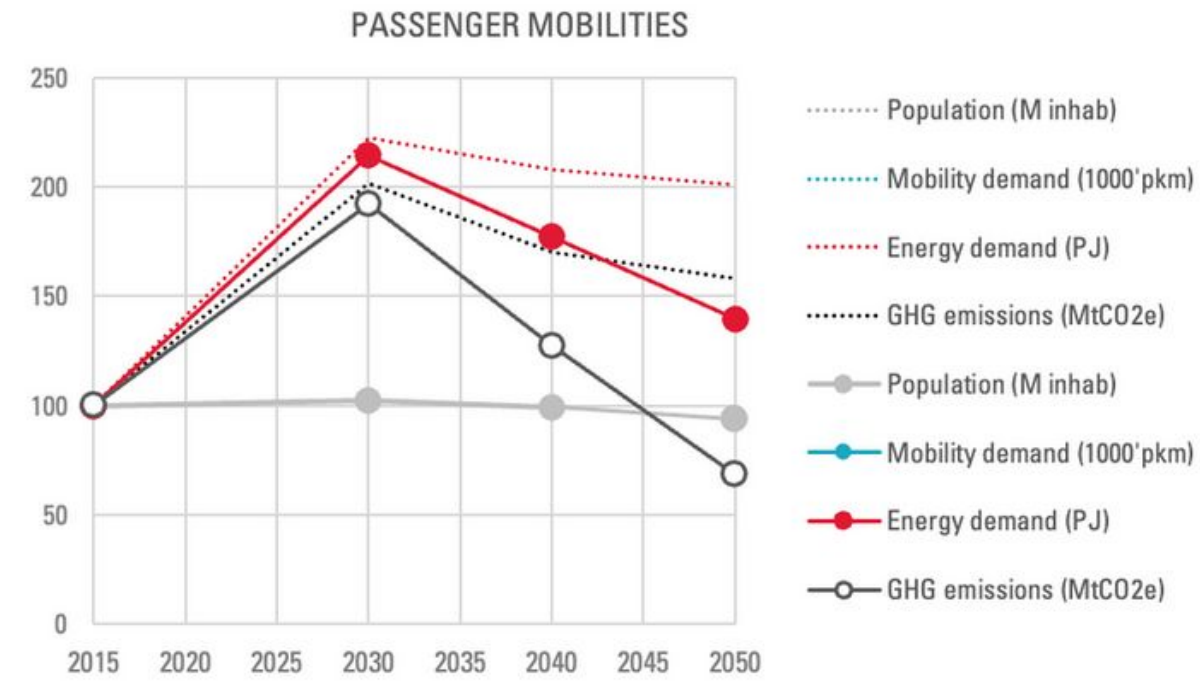
Transition of energy-related emission sectors: Transport, Buildings, non-energy producing Industries

Developing Paris-compatible PASSENGER MOBILITIES

Figure 10. Sectoral emission drivers and main aggregates (Index, 2015 base year)





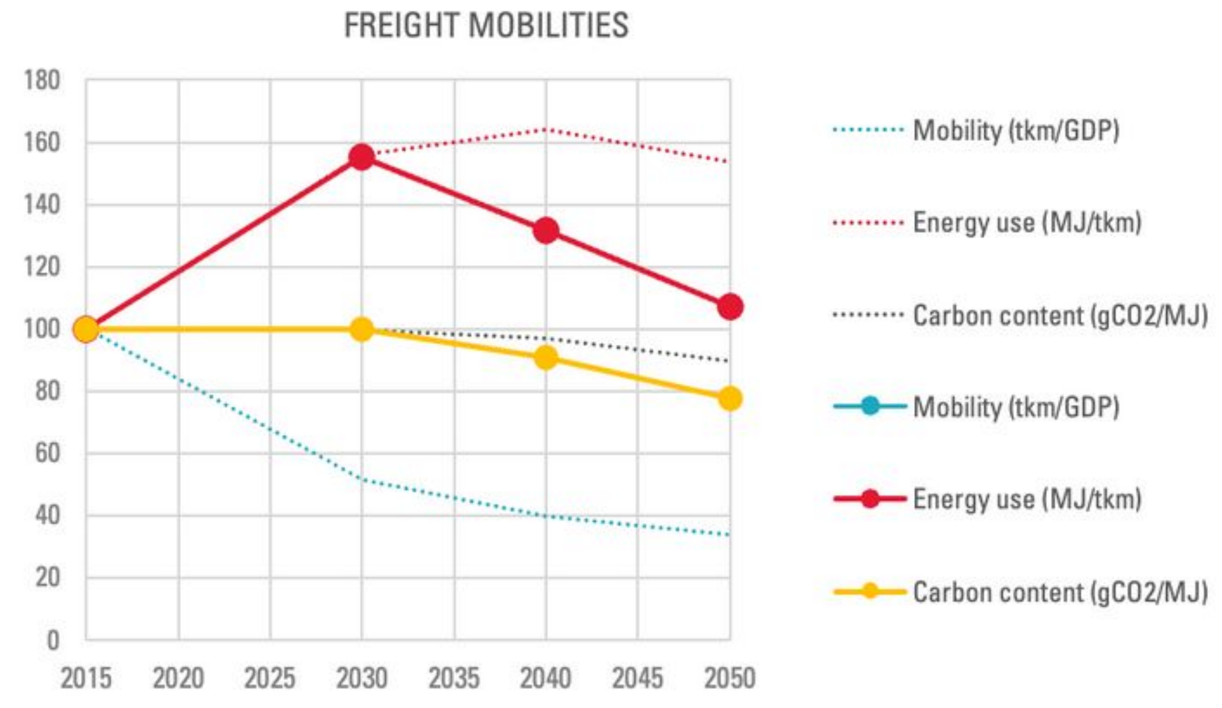
- The motorized mobility demand is expected to increase rapidly by 2.5 times in all scenarios from 2015, as people's income level increases, stabilizing and reaching up to 23 058 pkm per capita by 2070. The decarbonization strategy does not account yet for any measures to moderate mobility demand or structurally change the modal structure, however the current policies in place are expected to foster a stronger development of road-based mobility than train and air mobility. Therefore, the decarbonization strategy mostly focuses on measures to reduce energy consumption of vehicles and shift to electro-fuels.

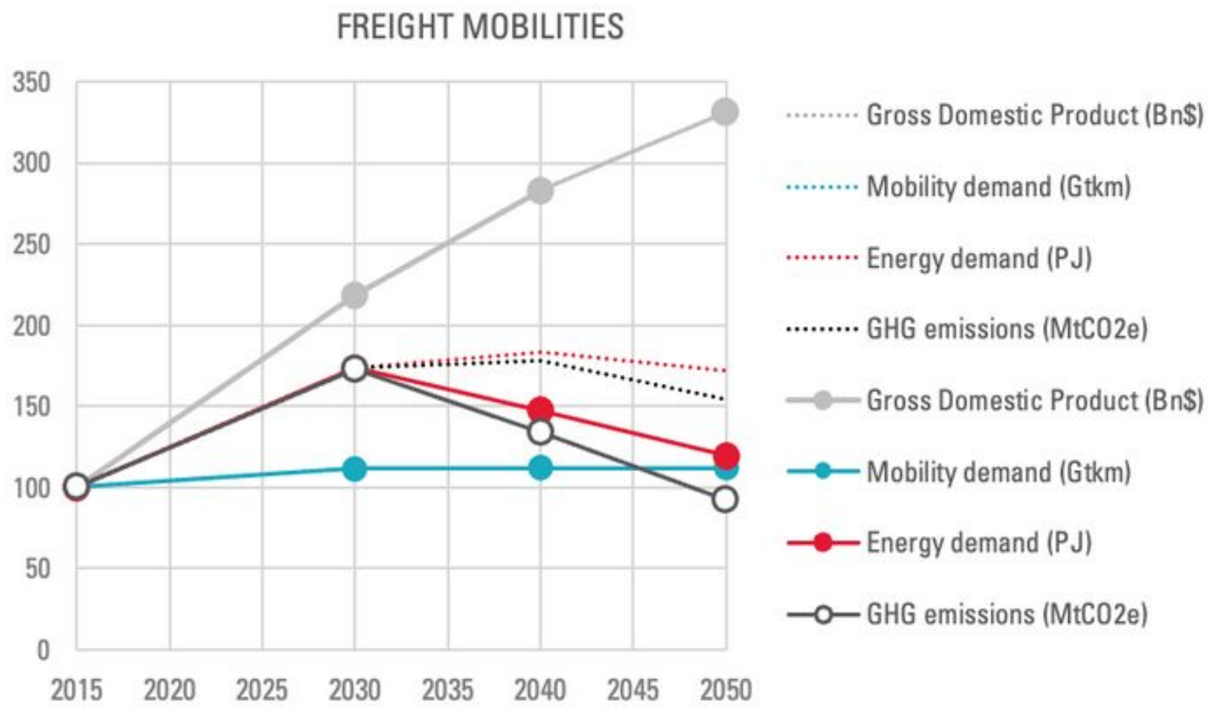
- The main decarbonization drivers is the shift away from fossil fuel to use direct electricity or electro-fuels. The share of non-fossil fuel energies increase from 2% in 2015 up to 93% by 2070. This is mainly due to a 100% shift of the road vehicles to battery-electric vehicles and an 80% share of SAF in aviation fuels. The remaining emissions comes from non-SAF air mobility. This technological change mostly explains the energy consumption reduction, while private mobility (car+2W) share continue to increase and represent about 50% of total mobility in 2070.

- Combined these transformations enable to moderate passenger transport energy consumption, peaking around 2030 and to cut emissions by 40% over the period 2010-2050, while the current policies would lead to a doubling of emissions by 2050.

Developing Paris-compatible FREIGHT MOBILITIES

Figure 11. Sectoral emission drivers and main aggregates (Index, 2015 base year)



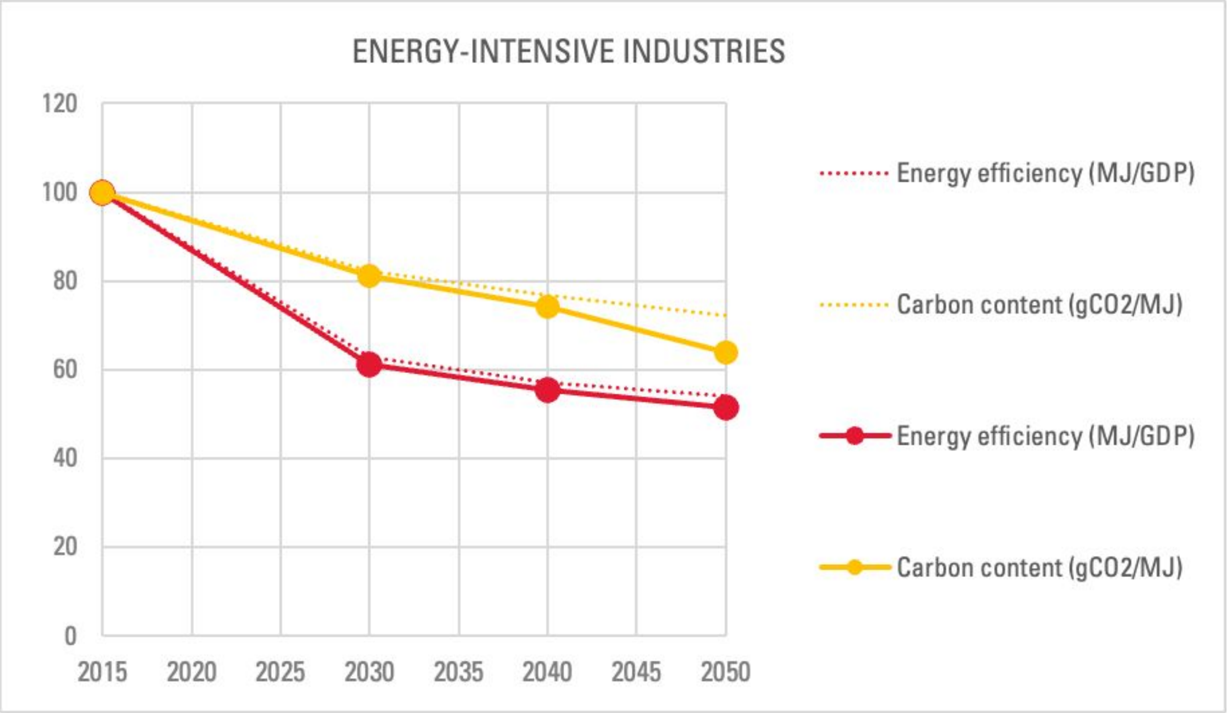


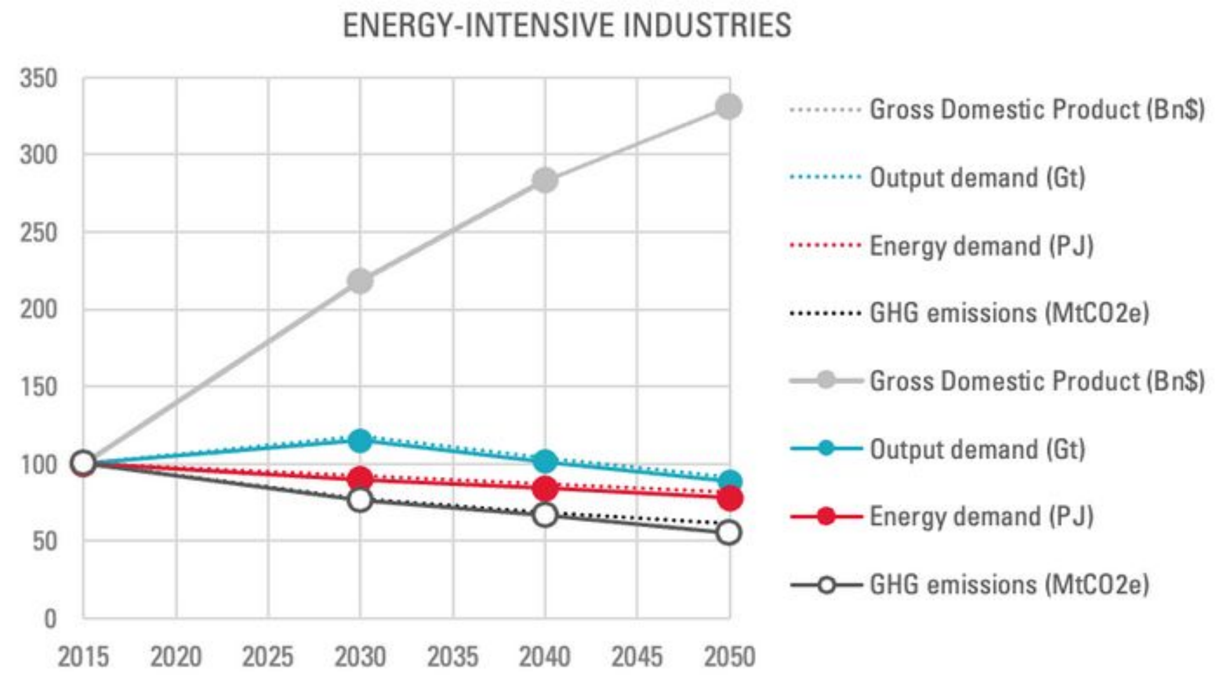
- The transition of the economy towards a more service-oriented and higher added value economy is similar in all scenarios and makes the freight intensity to GDP reduces by 75% and the total goods mobility stabilises around ca. 16 600 Gtkm from 2030 onwards. The decarbonization strategy does not account yet for any measures to moderate mobility demand, transform the supply chain structure and distances or change the modal structure.

- The main decarbonization drivers is the shift away from thermal engines and related fossil fuels which improve the energy efficiency in the sector and reduces the carbon content of fuels down to 13gCO2/MJ. The share of non-fossil fuel energies increase from 1.5% in 2015 up to 83% by 2070. This is mainly due to a 100% shift of light road vehicles to battery-electric vehicles and a 90% shift of heavy road vehicles to fuel cell electric trucks. In addition, a critical logistics service for China's freight decarbonization is the inland waterways and coastal transport representing ca. 60% of goods mobility, which will require a high development of electro-fuels.

Developing Paris-compatible ENERGY-INTENSIVE INDUSTRIES

Figure 12. Sectoral emission drivers and main aggregates (Index, 2015 base year)





- In the future, as China's infrastructure gradually improves, urbanization is completed and per capita living space becomes saturated, the development of the construction industry has slowed down, and the production of cement building materials has begun to gradually decline. Cement production in 2060 will decline by 48% compared to 2015. The transformation of the construction industry will lead to a rapid decline in steel demand, but there is still a large potential for growth in steel demand related to equipment manufacturing. The combined effect will be a slow decline in Chinese steel demand, with a 16% decline by 2060 compared to 2015.

- The decarbonization strategies rely essentially on a drastic shift in fuel content. The carbon content of fuels drops to 60g CO_2/MJ by 2070. The DDS GHG reaches a lower level of carbon content than the DDS CO_2 by 2070.

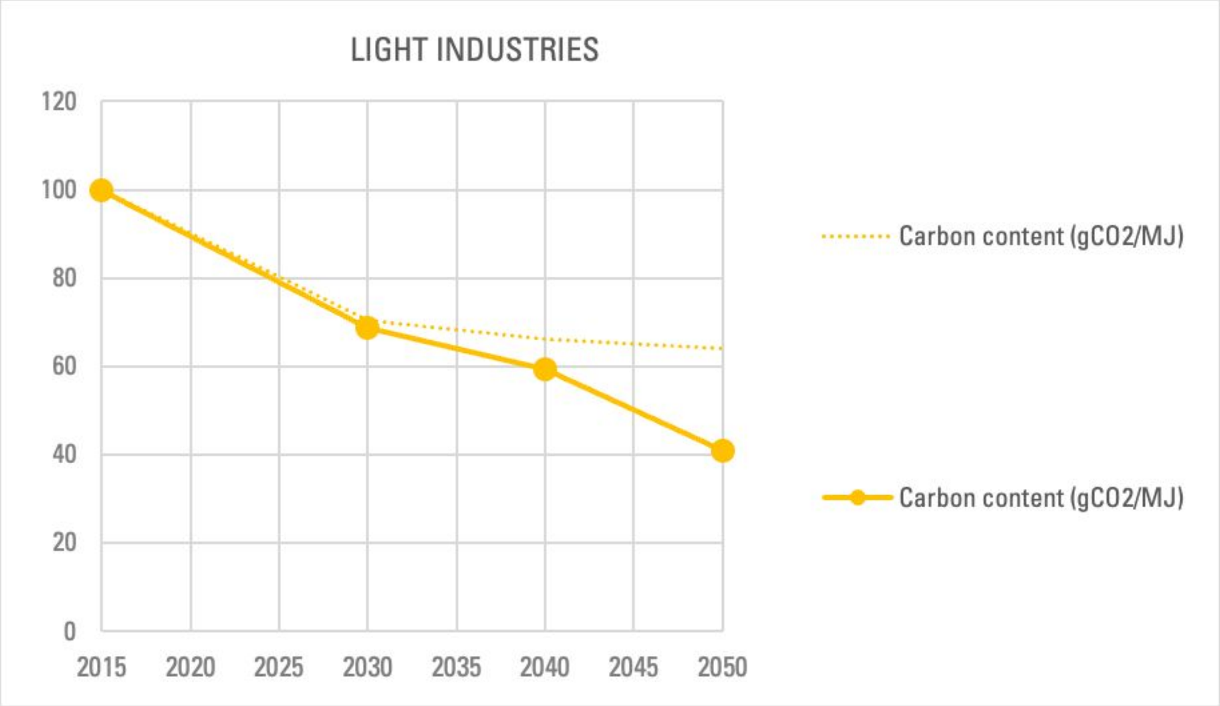
The main drivers are :

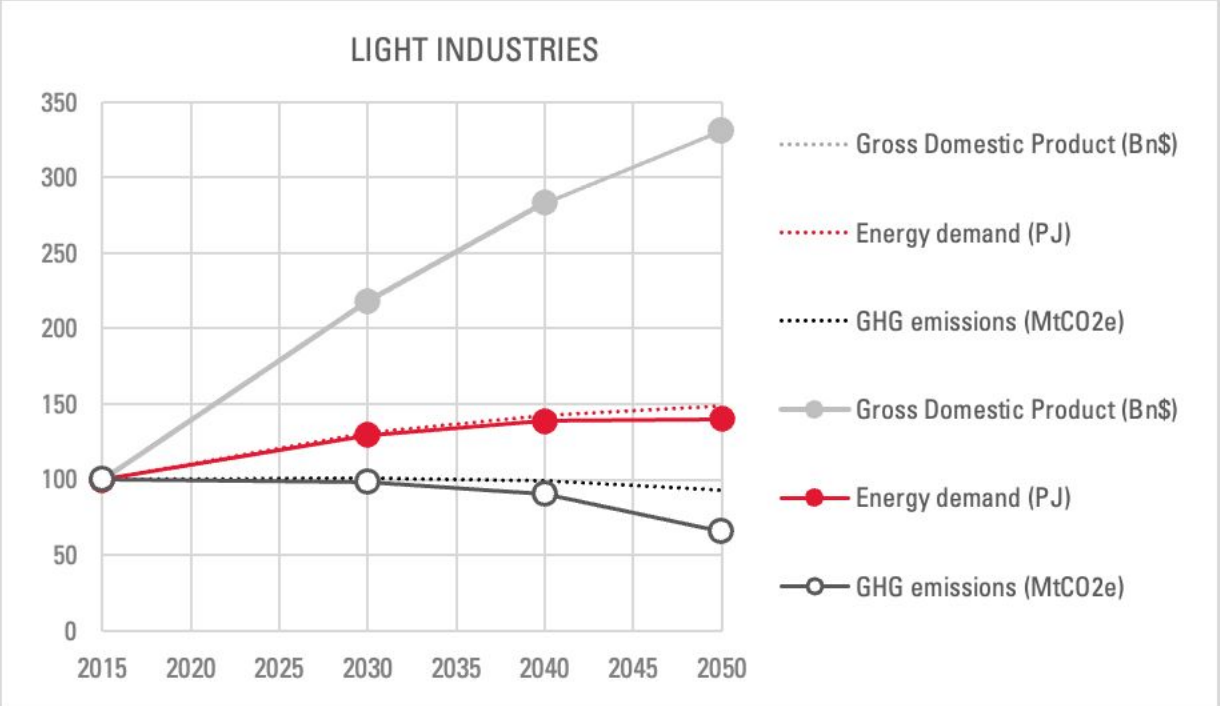
- the energy-intensive industries demand intensity :
- the deeper electrification notably of the iron & steel and cement productions & the development of CCS capacities for cement only.

- The key additional policies to compared to the REF should focus on the deeper electrification and accompany the decrease of production.

Developing Paris-compatible LIGHT INDUSTRIES

Figure 13. Sectoral emission drivers and main aggregates (Index, 2015 base year)





- Main light industries are mining industry (except fossil fuel extraction), non-metal material industries (except cement), construction, and others.
- The decarbonization strategies rely essentially on a drastic shift in fuel content. The carbon content of fuels drops to 5g CO_2/MJ by 2070. The DDS GHG reaches a lower level of emissions than the DDS CO_2 by 2070, notably due to the reduction for machinery and transport equipment and other LI.

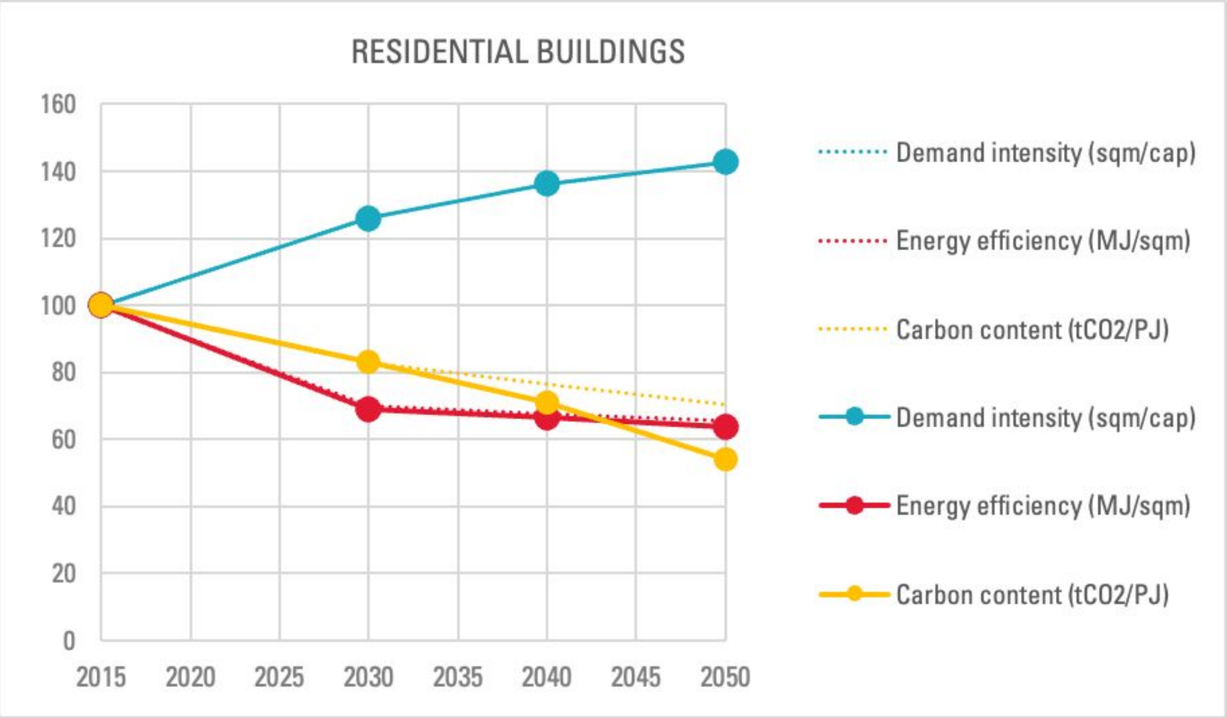
What are the main drivers of the changes explaining:

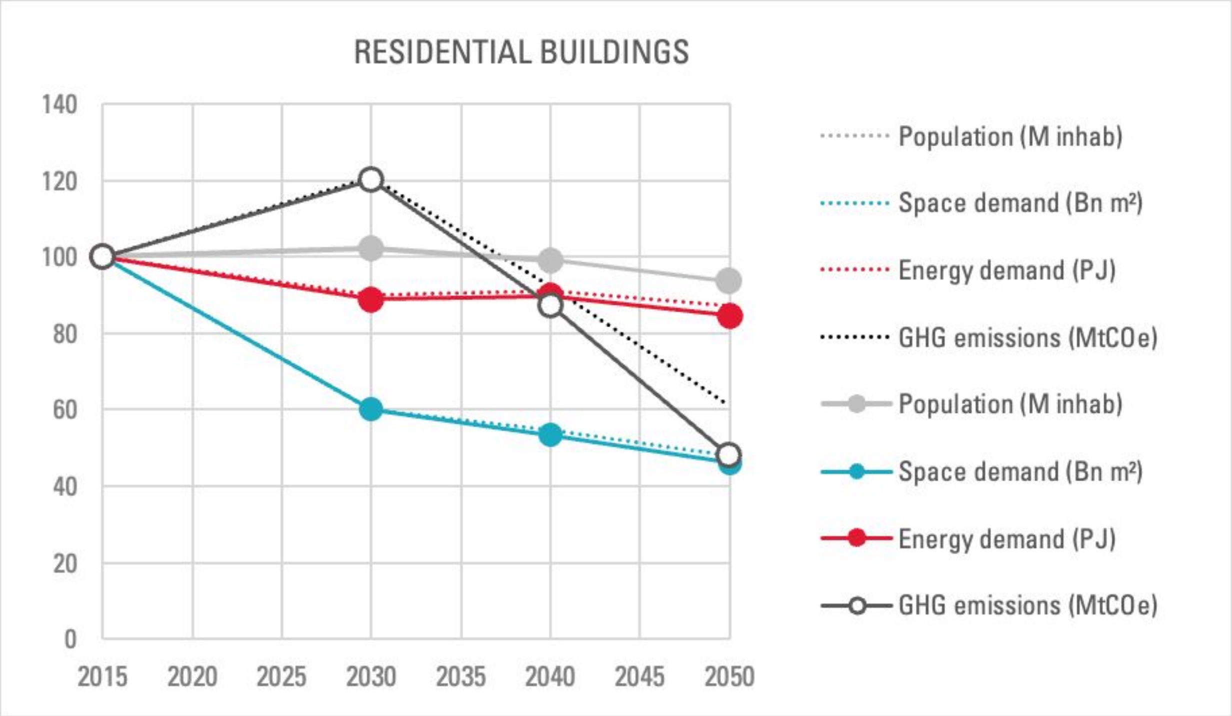
- The fuel carbon content (gCO_2/MJ): no more coal uses and decrease of gas uses, for an increase of power uses in all light industries.
- the deployment of modern and more energy-efficient systems.

- The key additional policies to compared to the REF should focus on the electrification of the light industries usages and the development of energy-efficient systems.

Developing Paris-compatible RESIDENTIAL BUILDINGS

Figure 14. Sectoral emission drivers and main aggregates (Index, 2015 base year)





- According to the REF, space heating and cooking are the main emission sources and will make up to 98**%** of the sector's emission by 2070. The GHG decarbonization strategy rely therefore on a reduction of both carbon content and energy consumption. The carbon content of fuels drops until 9g CO2/MJ by 2070. Both DDS scenarios reach the same level of carbon content and energy efficiency in 2070, however, the DDS GHG shows deeper reductions after 2040.

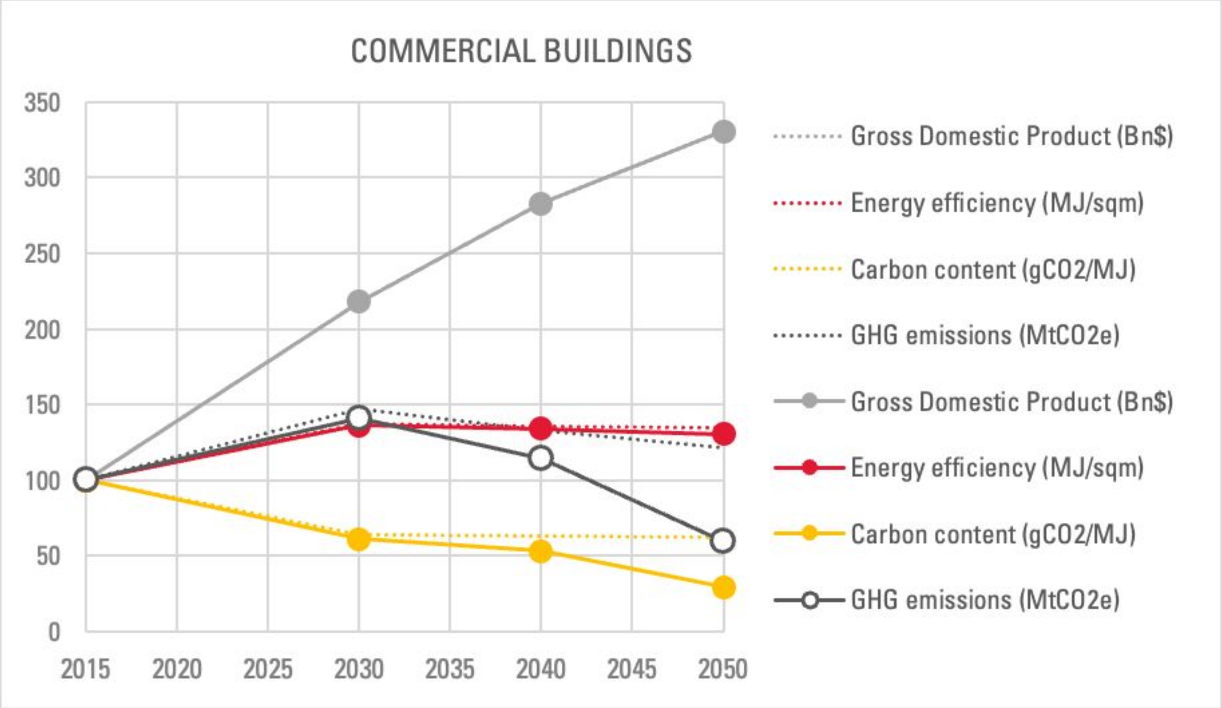
The main drivers are :

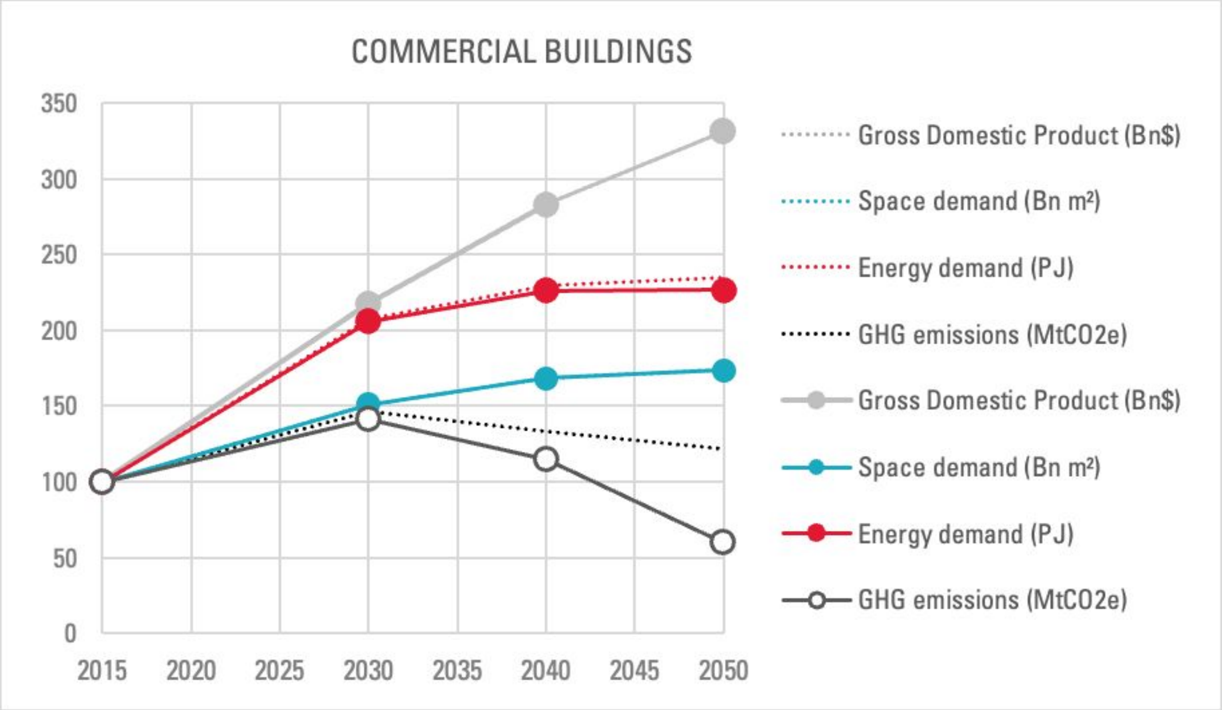
- the increase of residential building demand intensity : the standard of living of China's residents steadily improves, and the per capita floor space also continues to rise in both rural areas and cities.
- the decarbonization of carbon content in residential usages, notably with a strong electrification. In parallel, coal and biogas combustion stops, and a gas use slowly decreases.
- the deployment of modern and more energy-efficient systems notably in surface heating, the most emitting residential usage.

- The key additional policies to compared to the REF should focus on the deployment of energy-efficient systems for the main emitting residential usages: space heating and cooking.

Developing Paris-compatible COMMERCIAL BUILDINGS

Figure 15. Sectoral emission drivers and main aggregates (Index, 2015 base year)





- The standard of living of China's residents steadily improves, and the per capita floor space also continues to rise in both rural areas and cities (sqm/cap). According to the REF, space heating and water heating are the main emission sources and will make up to 100% of the sector's emission by 2070. The decarbonization strategies rely essentially on a drastic shift of fuel supply for the sector, such as for residentials. The carbon content of fuels drops until 2 gCO2/MJ by 2060. Both DDS scenarios reach the same level of carbon content and energy efficiency in 2070, however, the DDS GHG shows deeper reductions after 2040.

The main drivers are :

- the decarbonization of carbon content in residential usages : there is a strong electrification, There is also a stop of coal combustion and a small decrease of gas use.
- the deployment of modern and more energy-efficient systems notably in surface heating, the most emitting residential usage.

- The key additional policies to compared to the REF should focus on the electrification of commercial usages and the deployment of energy-efficient systems for the main emitting commercial usages: space heating and water heating.

Part 2.2

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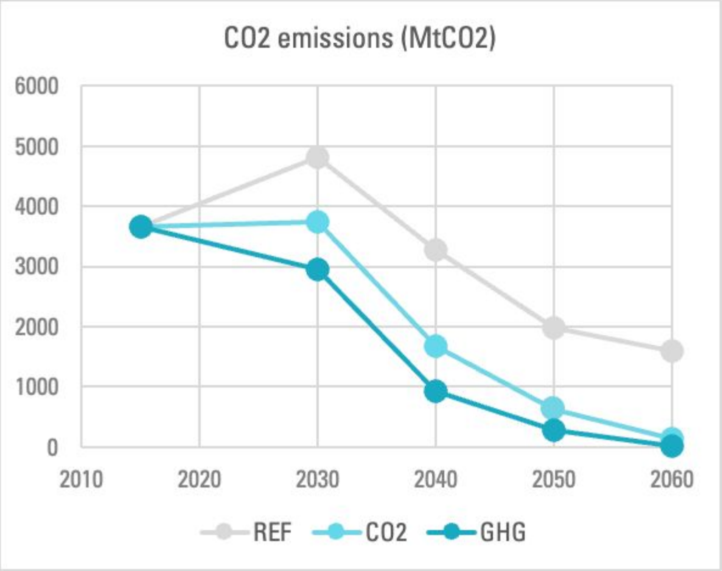
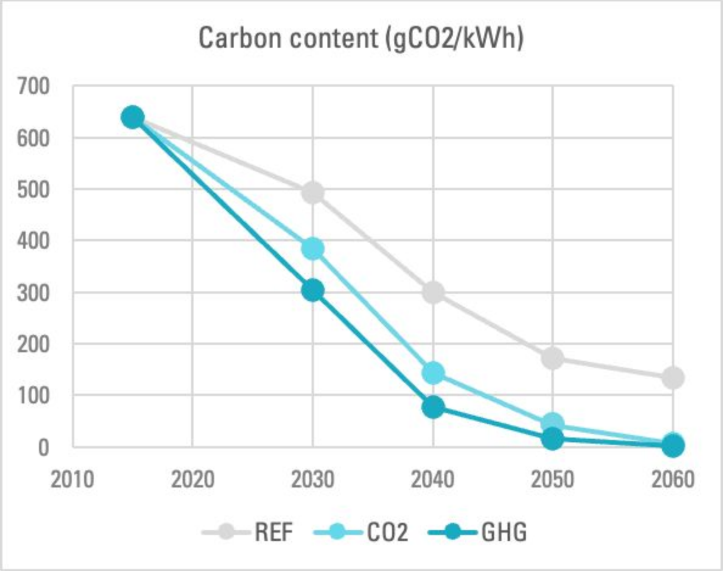
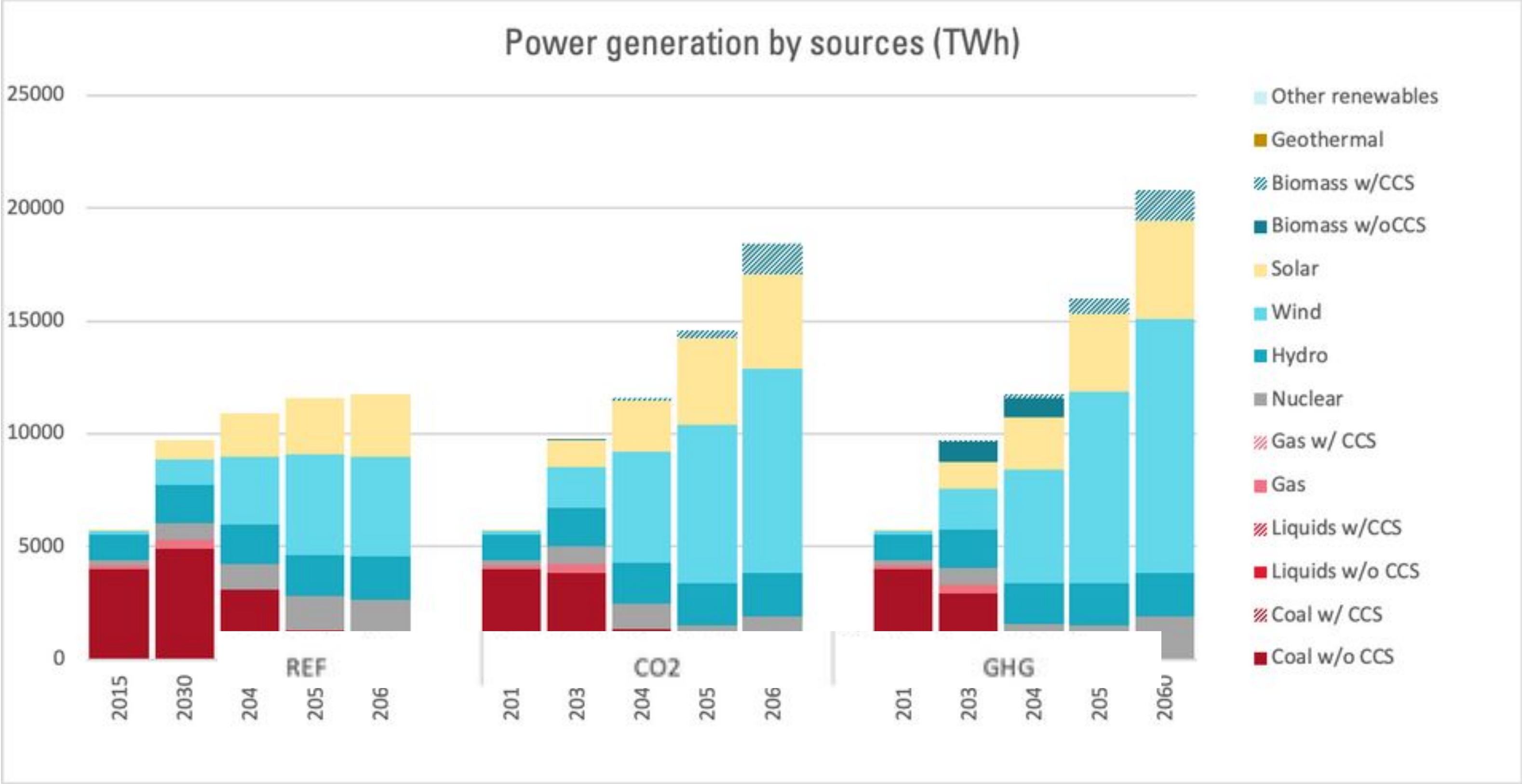
Transition of energy-related emission sectors:
Power generation, Extractive energy industries, Other energy production

Decarbonizing POWER GENERATION

Figure 16. Power generation by sources (Top, in TWh) and production emissions / electricity carbon content (Bottom, in MtCO2 & gCO2/kWh) .







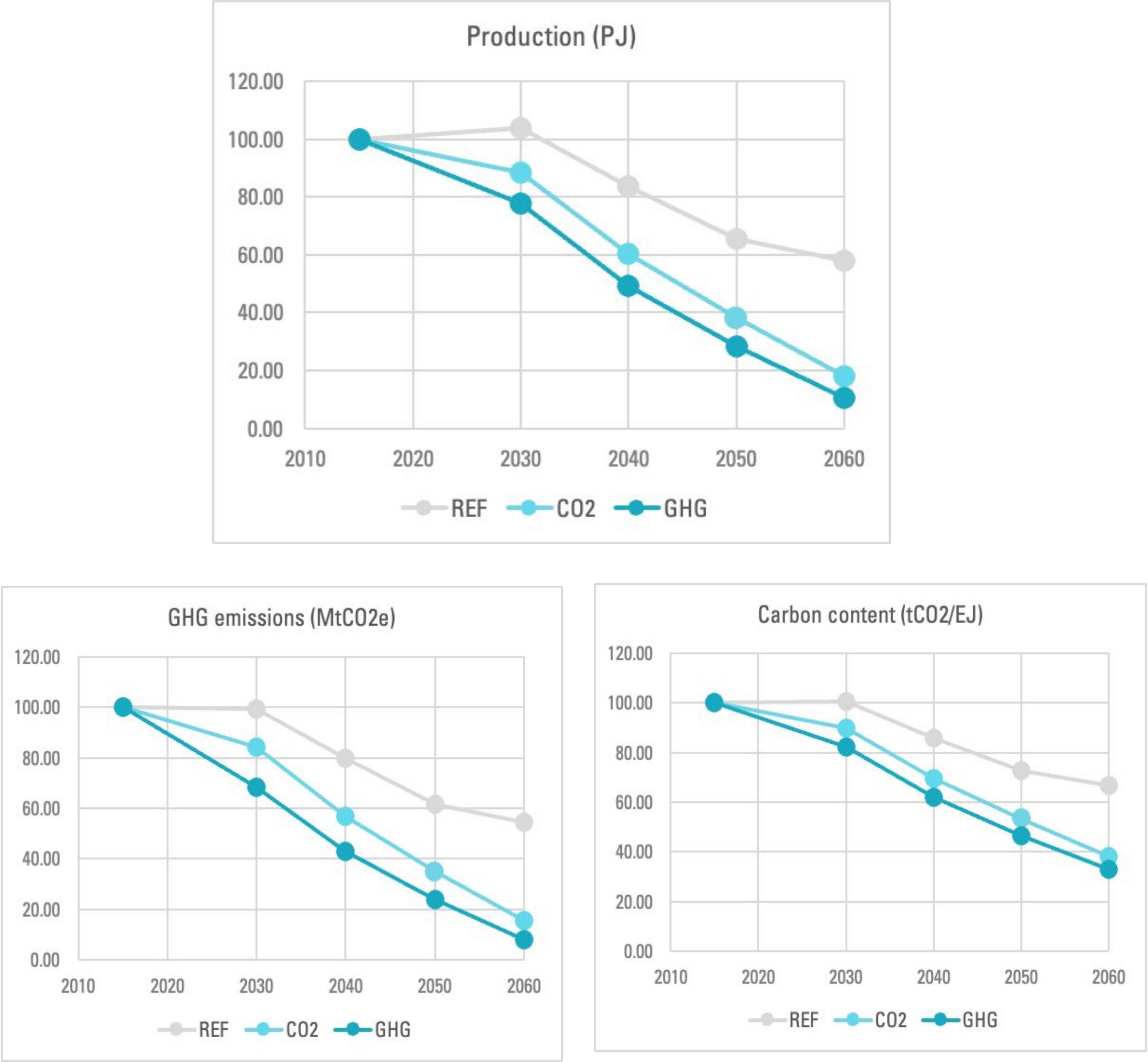
- Higher electrification rates lead to higher electricity demand in the GHG neutral scenario. By 2060, electricity demand in the GHG neutral scenario is 12% higher than in the CO2 neutral scenario, reaching 20,802 TWh. Main power sources will be wind and solar.

- Compared to the CO2 neutral scenario, the GHG neutral scenario shows a significantly accelerated phase-out of coal power, with the share of coal power declining to around 20% by 2030, and coal power largely phased out by 2040, with the share of power generation declining to 3%. The accelerated phase-out of coal power and the rapid growth of volatile renewable energy sources such as wind power increase the need for flexibility in peaking, bringing forward the large-scale deployment of biomass power generation technology to 2030.

- The key additional policies to compared to the REF should focus on the development of renewables & CCS capacities for biomass.

Decarbonizing EXTRACTIVE ENERGY INDUSTRIES

Figure 17. Coal, Oil and Gas production (Top, in PJ) and production emissions / carbon content (Bottom, in MtCO2e & MtCO2/MJ) .

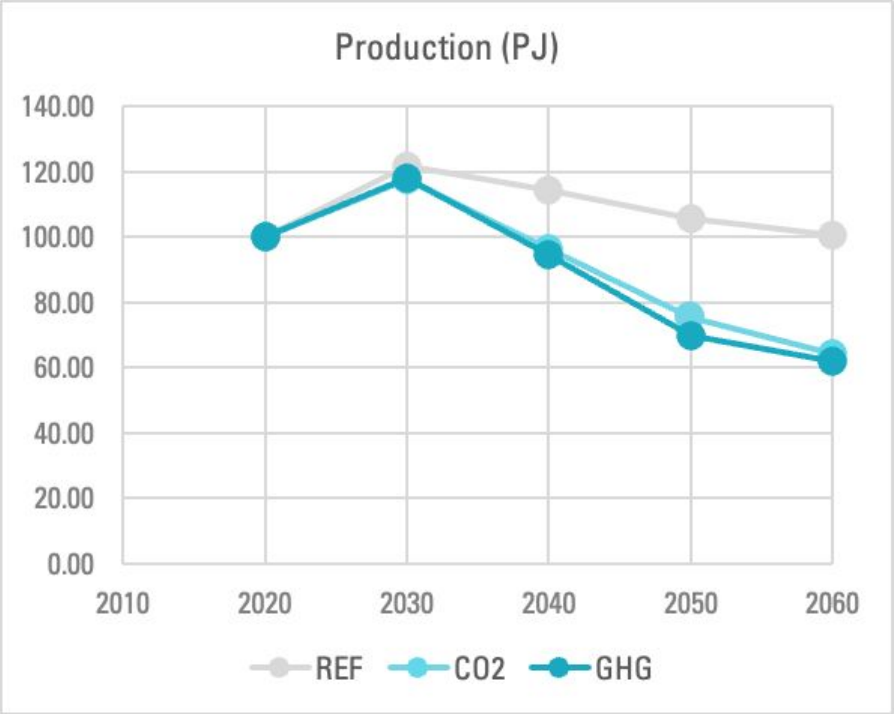


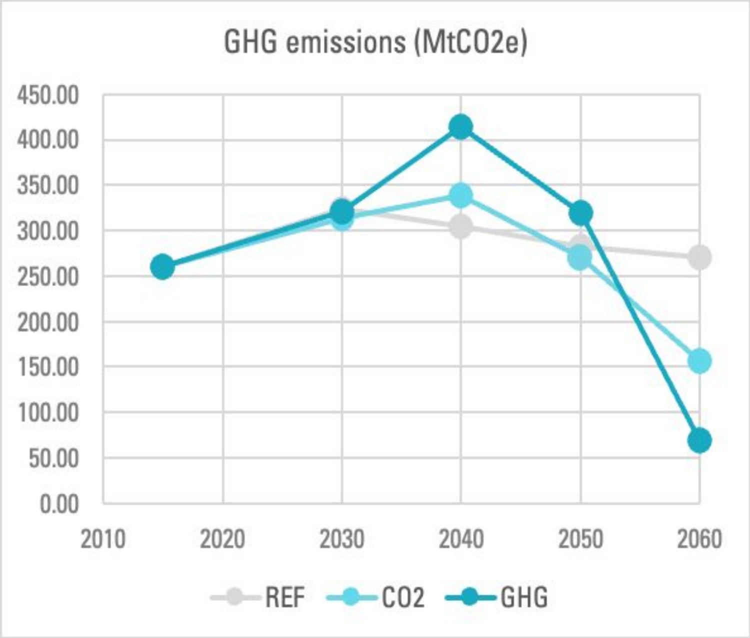
- Regarding extractive production in the GHG, coal production decreases drastically to stop by 2060. Gas and oil production continue steadily, they represent nowadays 30% of the extractive industries emissions. Emissions from extractive energy industries decrease in all scenarios and get 65% lower in the GHG in comparison to the REF in 2040.

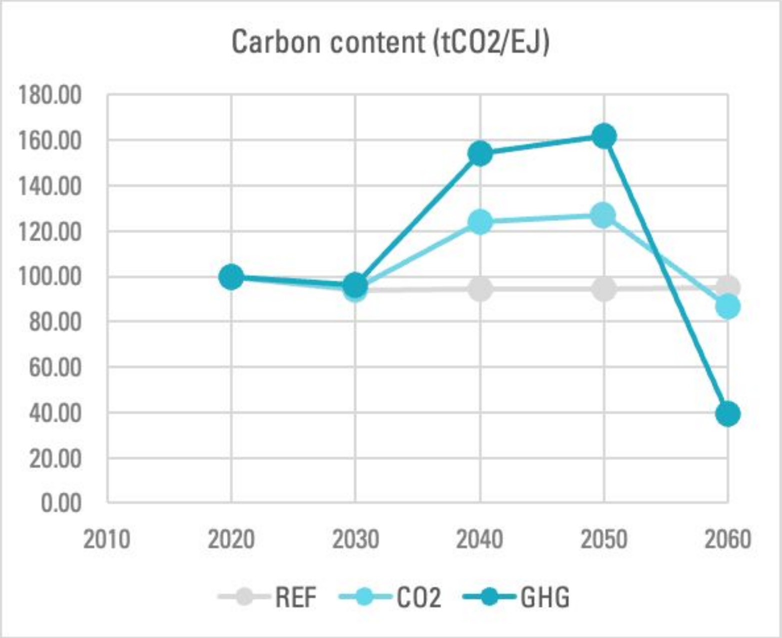
- Imports of all extractive industries decreases in the GHG. Exports of natural gas continues steadily, representing 7% (EJ) of the national production in 2070.

Decarbonizing OTHER ENERGY PRODUCTION INDUSTRIES

Figure 18. All other final fuel production* (Top, in PJ) and production emissions / carbon content of energy produced (Bottom, in MtCO2e & MtCO2e/MJ)







*All other solid, liquid, gaseous final fuel production activities (e.g. refineries, H2 generation, ...)

- Other energy production industries accounts here for the liquid from crude oil production (63% EJ and 45% of the total emissions in 2022) and the coke oven/gas oven (37% EJ and 55% of the total emissions) starting now, and for H2 generation starting in 2030.
- In the GHG, emissions are higher than the REF by 35% in 2040 and then decrease on a longer term, to reach 61 MtCO2. Coke oven/gas coke production strongly decreases to stabilize at 1,29 EJ by 2060. H2 production starts in 2030 and represents in 2070 almost 50%EJ of the total energy production.

Conclusions

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Key lessons for national & international climate and development decision processes

Lesson 1 - Key areas or sectors which require additional transformations

To move from CO2 neutrality to GHG neutrality:

- More ambitious action are required to mitigate non-CO2 GHG emissions in all sectors including energy, agriculture and waste treatment.
- Early deployment of CCS and CDR technologies (e.g. BECCS) are required to ensure in-time deployment of carbon sequestration and negative emissions technologies in hard-to-abate sectors.
- Earlier electrification in industry sectors is also critical to enable the shift from carbon neutrality to GHG neutrality.

Lesson 2 - Key short-term national policy packages and priorities to implement them

To move from CO_2 neutrality to GHG neutrality:

- Expansion of national ETS to more energy intensive sectors.
- Development of CCER market (offset market) to incentivize reduction in non-CO_2 emissions.
- Improved regulation and emission standard on methane, N_2O and F-gases.

Lesson 3 - Key international conditions to implement them

- A global GHG market to support additional ambition;
- An open and fair global trade regime on green technologies to ensure least cost production of mitigation technologies;
- A stable political signal to send clear long-term guidance to investor for investing in transition;
- A balance financing between transition finance and green finance.

Annex 1 : DECARBONIZATION PATHWAY FOR CHINA - values

CHN	2015	2030	2040	2050	2060	2070
Total GHG emissions (MtCO2e)	10679	9173	5813	2655	11	-250
Total CO2 emissions (MtCO2)	8603	7734	4636	1707	-794	-1030
Total energy-related CO2 emissions (MtCO2)	8565	7833	5070	2782	832	535
Total final energy consumption (PJ)	79921	95869	91753	83814	78216	76023
Total Pop (Million)	1383	1413	1371	1293	1191	1082
Total GDP (Billion USD (2015))	11060	24111	31313	36593	39583	41454