Renewable pathways to climate-neutral Japan

Reaching zero emissions by 2050
in the Japanese energy system

EXECUTIVE SUMMARY

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STUDY
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Key messages of the study

1. **Net zero emissions can be achieved in Japan at reasonable costs based on renewables deployment and electrification.** An interim target of at least 40% renewables in power generation is required in 2030 to transition towards a 100% objective in 2050. Electrification of heat, transport and industry, as well as various flexibility options (such as grid reinforcement, storage and demand-side flexibility) will facilitate the integration of renewables, while bringing down emissions to net zero in 2050.
2. **A three-step roadmap is needed to achieve climate neutrality by 2050.** The first step consists of a 45% reduction in greenhouse gas emissions by 2030 (relative to 2010). Second, emissions must decline by at least 90% by 2045 (relative to 2010). Finally, green synthetic fuels eliminate residual emissions, mostly from high-temperature heat generation in industry.
3. **Hydrogen will be used sparingly, even if it is imported, as direct electrification is more efficient and less expensive.** Direct electrification should therefore be prioritized wherever possible in transportation, space heating and low and mid-temperature heat in industry. Domestic production of green hydrogen will also put considerable pressure on the power system.
4. **Nuclear power is not necessary to achieve the long-term decarbonization target at lower cost.** Renewables will outcompete nuclear new build and lifetime extension projects already by 2025, leading to a gradual phase-out of nuclear power plants at the end of their technical lifetime if not stopped earlier.
5. **Japan has to kick-start enhanced climate action as soon as possible and increase its interim sectoral targets to reach 45% lower GHG emissions and at least 40% renewables in power generation by 2030.** The upcoming discussions on the 6th Strategic Energy Plan and concrete regulatory measures, such as an effective carbon pricing mechanism, will be crucial to determine how Japan goes about achieving those interim 2030 targets and climate neutrality by 2050.

Executive summary

Five years after the adoption of the Paris agreement,[1] 2020 saw many countries committing to a climate neutrality target by 2050, including Japan, the European Union, the UK, South Korea and lately the USA. China has also committed to making its economy climate-neutral by 2060. The Japanese pledge is a fantastic opportunity to fundamentally transform the country's energy system over the next thirty years and overcome its current dependence on fossil fuels.[2] With this new pledge, Japan significantly accelerates its climate commitment, increasing its previous national targets from an 80% greenhouse gas (GHG) emissions reduction[3] to a completely decarbonised society by 2050. This transformation is needed quickly, and it will be crucial to determine a pathway towards net zero emissions that sets ambitious yet achievable interim goals for 2030 and beyond. The development of the 6th Strategic Energy Plan offers an important opportunity to review those interim targets.

2020 was a turbulent year. The COVID-19 pandemic has very much challenged the international community. In Japan, public spending was increased by 70% to $1.6 trillion (¥175 trillion) in 2020 to respond to the crisis. The increase amounts to about 13% of annual GDP, showing strong efforts can be made when necessary. In order to accelerate the transformation of the Japanese energy system towards climate neutrality, public and private investments, including those made as stimulus spending, should target climate mitigation measures through a large-scale investment program within the framework of a Japanese Green Growth strategy.

Several technology options exist to decarbonize the energy system. At the international level, several countries such as Germany are adopting renewables-based decarbonization strategies. In Japan, however, the experts and policy discussions are still largely open regarding the long-term role of renewables, nuclear and CCS technologies, as well as the use of synthetic fuels such as hydrogen.

This study, conducted by Renewable Energy Institute (REI) and Agora Energiewende with the support of LUT University, describes pathways that Japan can take to achieve climate neutrality by 2050 based on renewables in the most cost-effective way. The study covers all energy-related greenhouse gas emissions (GHG), as well as some emissions from industry processes based on fossil fuels (such as steel making). In total 88% of all current GHG emissions are covered, including energy conversion (38%),

[1] It set "to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels".
[2] Japan currently imports 88% of its primary energy mostly in the form of fossil fuels. Data from Ministry of Economy, Trade and Industry – Agency for Natural Resources and Energy, "Energy White paper 2020".
[3] No base year provided

transport (17%), buildings (10%) and industry (23%).[4,5] The evolution of final energy demand was estimated based on three framing assumptions: population decline (-20% between 2017 and 2050 according to governmental projections), current levels of industrial output will be maintained, and moderate energy efficiency improvements. The sectors were modelled in 3 categories of energy use: power, heat and transport, and all their GHG emissions are accounted for. The cost-optimized modelling was conducted in five-year steps with an hourly resolution to ensure the supply-demand balance at each hour between the nine interconnected grid regions in Japan.[6] Stakeholder meetings were organized with the main stakeholders in the debate in Japan in order to validate the assumptions and discuss the preliminary results.

I. Japanese emissions today slightly below 1990 levels

Energy policies to reduce energy consumption – whether because of supply security, air pollution, resource scarcity, or geopolitical dependence – have been around for a very long time in Japan. Climate considerations are a more recent development.[7] In the Kyoto protocol, Japan committed to a 6% reduction of GHG emissions by 2012 relative to 1990 levels.

As can be seen in Figure 1, GHG emissions increased in the 1990s, peaking in 2013 at 1 408 Mt CO_2eq. Emissions rose mainly due to a gradual increase in energy consumption in the commercial and industrial sectors; furthermore, fossil fuel temporarily replaced nuclear power after the Fukushima accident in 2011. In particular, nuclear power dropped from 25% before the accident to 6% afterwards, with the gap being closed mostly by gas, but also with some additional coal and oil power generation. Japan decided not to participate in the second commitment period (2013 to 2020) of the Kyoto protocol.

By 2018, overall emissions had decreased by 12% compared to 2013, which is about 2.5% below 1990 levels. Most of the emissions reductions since 1990 were achieved in the industry sector (-21% before allocation of the emissions from the energy conversion sector) through energy efficiency of processes and the replacement of a large share of its oil consumption (by gas and electricity). However, this decrease was partly compensated by an increase in emissions in the energy conversion sector linked to rising industrial demand. In electricity generation, the deployment of renewables has partially compensated for the increase of CO_2 emissions due to the reduction of nuclear power. Since 2010, new policies have been introduced to support the installation of renewable energy, with particular emphasis on the rapid expansion of PV (62 GW installed at the end of 2019). As a result, renewables represented 9.3% of primary energy supply in 2019 and 18% of power generation, explaining most of the emissions reduction since 2013. Emissions in the building sector decreased by 10% between 1990 and 2018, while no changes were made in the transport sector.

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[4] Non-energy-related emissions from industrial processes, agriculture and waste were not taken into account in this study. In the industrial sector, non-energetic emissions such as limestone from cement or the chemical industry were not included, while process emissions for steelmaking (reduction of iron ore) were accounted as energy-related emissions (even though oxidoreduction is not strictly speaking a combustion reaction). In total, the non-energy-related emissions in Japan amounted to about 153 MtCO_2eq in 2018 (12% of total GHG emissions). Important efforts will be required to reduce those emissions, but since they are more difficult to abate, some remaining emissions are expected by 2050. Those remaining emissions will need to be offset by carbon sinks to reach climate neutrality in the overall Japanese economy, notably through CCS in the industry, direct air capture (DAC) as well as land use, land-use change and forestry (LULUCF). The emissions from international bunkers (aviation and maritime transport) are excluded from the national emissions as in the United Nations Framework Convention on Climate Change (UNFCCC) approach and are excluded from this study.

[5] Figures according to Greenhouse Gas Inventory Office of Japan (GIO), National Greenhouse Gas Inventory of Japan 2020

[6] The isolated EPCO region of Okinawa was not considered in this study.

[7] After the UN Framework Convention on Climate Change was adopted at the environmental summit in Rio de Janeiro in 1992, binding emissions reduction targets were set by the 1997 Kyoto Protocol.

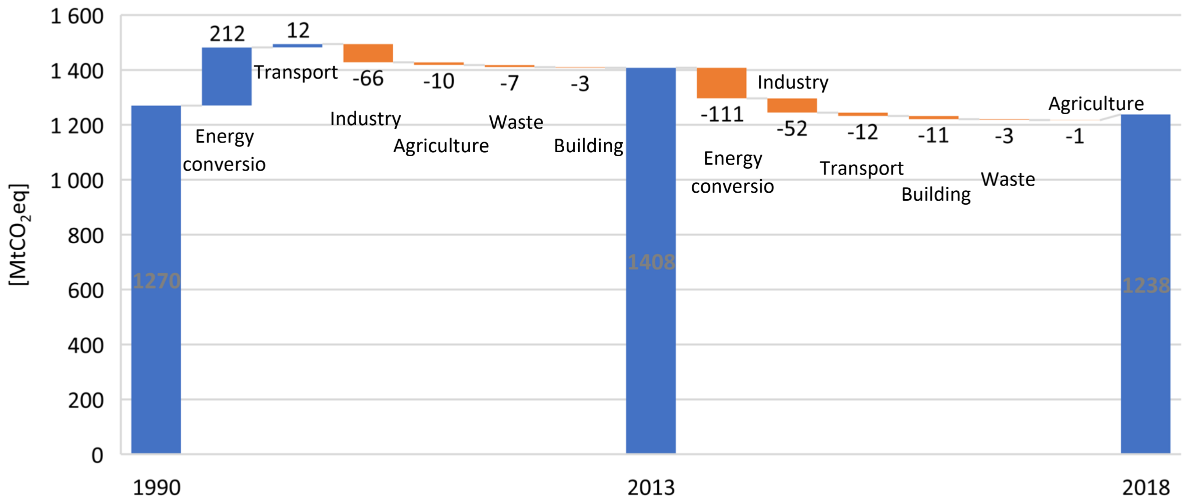

Figure 1: Reduction of GHG emissions since 1990 (in Mt CO_2eq, before allocation of emissions from the energy conversion sector into demand sectors). Source: own presentation from National Greenhouse Gas Inventory of Japan, Greenhouse Gas Inventory Office of Japan (GIO)

The Strategic Energy Plan has set Japanese mid- to long-term energy targets since 2003. With the current plan (5th and latest plan from 2018), Japan aims at reducing its GHG emissions by 26% by 2030 relative to 2013. This nationally determined contribution (NDC) has been criticized as not being sufficiently ambitious and not compatible with the Paris agreement. And indeed, some sectoral targets are partly already achieved, in particular in the industry sector, which already reached its indicative reduction target (-6.5% CO_2 emissions relative to 2013) in 2016, 14 years ahead of time.

In order to reach climate neutrality by 2050, the interim targets set in the Strategic Energy Plan will need to be increased in order to put Japan on a path towards climate neutrality as quickly as possible. The elaboration of the 6th Strategic Energy Plan provides a major opportunity for enhancing interim GHG reduction targets and clarifying the question of the long-term energy mix in Japan. In order to contribute to this debate, this study proposes a robust and cost-effective techno-economic pathway based on renewables for climate neutrality by 2050.

II. Three steps towards climate neutrality in Japan by 2050 (in the energy-related sectors)

As can be seen in Figure 2, the decarbonization pathway proposed in this study follows a three-stage process:

1. By 2030: GHG emissions decrease by 45% (relative to 2010)
2. By 2045: GHG emissions decrease by 90% (relative to 2010)
3. By 2050: zero GHG through an increased use of green synthetic fuels in the last step of the transition to eliminate residual emissions, mostly linked to high temperature heat generation in industry

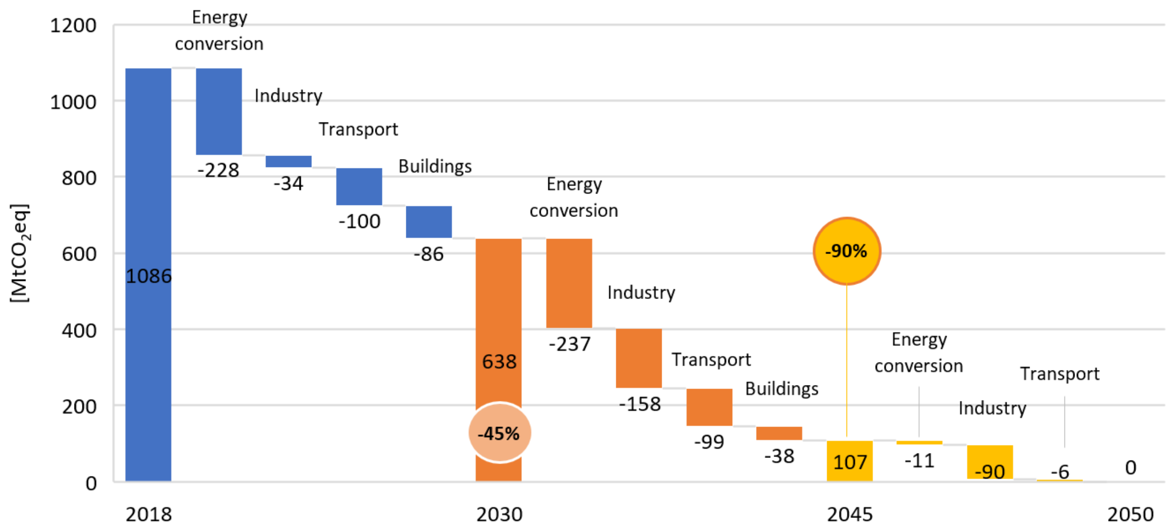

Figure 2: Pathway towards climate neutrality by 2050 in the energy consuming sectors (in Mt CO_2eq).

Step 1: Reduce GHG emissions by 45% by 2030 relative to 2010

In order to make climate neutrality possible by 2050, GHG emissions must be reduced drastically starting today. Actions taken in the 2020s will decide whether climate neutrality can be achieved by mid-century. To be in line with the 1.5-degree scenario for Japan, emissions should be reduced by 45% by 2030 relative to 2010. This goal represents a very significant strengthening of the current reduction target of -26%.

The energy conversion sector has the greatest GHG reduction potential (-230 Mt CO_2eq by 2030 below the latest available emissions data from 2018), followed by the transport (-100 Mt CO_2eq by 2030) and building sectors (-86 Mt CO_2eq by 2030). Industry could contribute with a reduction of 34 Mt CO_2eq.

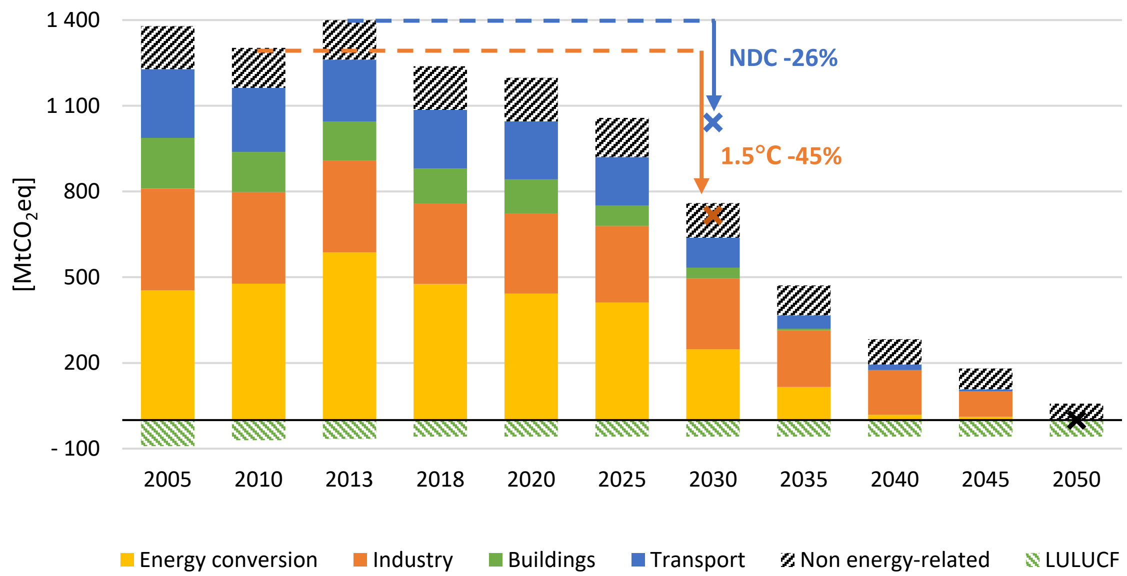

Figure 3: Base Policy Scenario with imports – evolution of energy-related GHG emissions per sector and current climate targets (in Mt CO_2eq).

The cornerstone of the strategy lies in the transformation of the **energy conversion sector**. An accelerated coal phase-out in power generation by 2030 and the increased expansion of renewables in power generation (to at least 40% of power generation) will provide the lion's share of emissions reductions. To assess the feasibility of replacing all nuclear generation by renewables at this time horizon, this scenario contains no additional nuclear restart and a nuclear phase-out by 2030. Growing electrification in all sectors will slightly increase electricity consumption between 2020 and 2030 (+5%, corresponding to 48 additional TWh). To cover the demand, the installed capacity of PV more than doubles (144 GW in 2030), while wind capacity sees a six-fold increase (25 GW in 2030) so that renewable power generation reaches about 400 TWh (against 185 TWh in 2019). The required annual net newly installed capacity is then 8.4 GW of PV, 1.5 GW of onshore wind, and 0.7 GW of offshore wind between 2021 and 2030. In comparison, 8.5 GW of PV and 0.2 GW of onshore wind were installed yearly on average between 2014 and 2019.

Prosumers[8] play an important role even in this first stage of the transition. Due to relatively high retail electricity prices, prosumer PV is highly competitive in densely populated areas such as Tokyo, leading to a quick capacity growth of decentralized PV in the 2020s. From 23 GW of installed PV for prosumers in 2020, it more than doubles in 10 years, reaching 70 GW by 2030. This amount represents half of the total installed PV capacity and helps reduce the area footprint of the RE-based energy system.

Reducing emissions in the **industrial sector** will require further energy efficiency improvements and the electrification of low and medium temperature heat first. For high temperature heat applications that are difficult to electrify directly, substituting fossil fuels with green hydrogen will start to be relevant in 2030. New processes in the basic materials industry, in particular steel, will further contribute to emission reductions. The steel industry in particular could be a pioneer in this regard by replacing old blast furnaces with direct reduction systems fueled mainly by hydrogen and smaller proportions of natural gas in the interim. Sustainable solutions for carbon as a reduction agent exist by mid-century, such as the use of biomethane, synthetic methane and biochar. Although these technologies will mostly be deployed after 2030, it will be important when making reinvestment decisions in the 2020s to avoid stranded assets that would be climate-incompatible in the long run. In addition, investment decisions in recycling routes (in order to increase the use of secondary raw materials) and the import routes for hydrogen should be tackled well before 2030 so that these solutions can exploit their full potential after 2030.

In the **building sector**, people mostly keep their heating behaviors in the scenario. Efficient heat pumps quickly expand as they become cheaper than conventional devices, so that electricity covers the demand. Old buildings are replaced by new builds complying with ambitious energy efficiency standards or receive energy efficient retrofits. The energy efficiency gains compensate for a possible rebound effect,[9] so that final heat consumption in 2030 is 7% below current levels (same as today in terms of consumption per capita level).

In the **transport sector**, there is a slight change in current trends. Mobility habits do not transform, but people use slightly more public transport, cycle and walk more. Direct electrification is expected to develop with the adoption of battery-electric and plug-in hybrid vehicles in all road transport segments (light, medium and heavy-duty vehicles including buses), as well as rail transport assumed to be fully electrified. In 2030, 12.5 million electric vehicles will be on the roads (against about 1 million

[8] In this study, prosumers are residential, commercial and industrial entities installing PV systems on their rooftop, with or without lithium-ion batteries. See section 2.1 for more details.

[9] The "rebound effect" is the well-known phenomenon that improving energy efficiency may save less energy than expected due to an increase in consumption, such as by increasing the average heating temperature.

today). This trend in electrification and efficiency will keep increasing for all technologies, leading to a decline in final energy demand for transport by 37%.

Keeping coal power generation in the system longer than 2030 will not only keep GHG emissions higher for a longer time, but also make the transition more difficult in the later steps, as it delays the deployment of renewables by about 5 years.[10] In such a delayed scenario, only half as much PV and onshore wind capacities would be built in 2021-2030, which would need to be compensated for in the years after 2030 when direct and indirect electrification would intensify. In this scenario, keeping some existing nuclear power plants in the system after 2030 could support a smoother coal phase-out, with less gas capacities used in 2030, while a faster renewables ramp or stronger effort on energy efficiency would be another option. However, the nuclear option does not change the long-term picture: nuclear new builds and lifetime extension projects are likely to be more expensive than renewables as soon as 2025. A slower electrification rate in the transport and building sectors would also keep emissions higher for a longer time; increasing the need for synthetic fuels in those sectors would not tap the full cost-effective potential of direct electrification.

Step 2: Reduce GHG emissions by 90% in 2045 relative to 2010

Large efforts are needed in this second step of the transition to prolong the emissions reductions achieved in the first step, while the emissions will get more difficult and costly to abate if not planned properly. By 2045, coal, oil and fossil gas consumption in the energy conversion, transport, building sectors will need to be reduced drastically, as well as in all the segments of the industrial sector that allow it at reasonable cost. Electrification will continue across all sectors, directly where possible and indirectly using sustainable hydrogen and other synthetic fuels. Hydrogen will also be increasingly used as a raw material in the industrial sector. Efficiency improvements remain important to help reduce emissions in all economic sectors. By 2045, electrification and defossilization added with a decrease in final energy consumption (due to efficiency gains and population decline) will lead to a decline in primary energy demand by 51% (from 2020). This step will require proper planning early on for the necessary technologies to be available at the lowest possible cost.

The **energy conversion sector** will remain a key sector to decarbonize. Electrification and increased hydrogen production will raise power consumption by 30% mostly for heat production (industry and building sectors), reaching about 1 300 TWh by 2045. Renewables will continue to expand to reach a share of 98% in the power mix at this time horizon. To cover the demand, PV will be installed massively, as being the cheapest local source, and almost reaches the technical capacity limit of 524 GW assumed in this study (utility-scale installations use1.3% of total available land area assumed in this study). 73 GW of onshore wind will be installed, a large share of it in the windy eastern regions (62% of installed capacities in Hokkaido and Tohoku). Wind power will be mostly exported to other more densely populated and industrialized regions, implying a significant increase in grid interconnections between regions. Also, 44 GW of offshore wind capacities are installed by 2045, which will be built close to load centers in the central part of the country. The net annual installed capacity between 2031 and 2045 is then 25 GW of PV, 3.9 GW of onshore wind, and 2.5 GW of offshore wind. Imports of renewable power from Russia and Korea/China could reduce the need for local renewable generation and add some flexibility to the system, though the benefit will remain marginal as market prices in Japan will remain low. Also, decentralized solutions closer to the consumption centers are a favorable option, especially PV with storage, to avoid costly and restrictive grid expansion.

[10] A rather conservative CO_2 price of 2 519 ¥/tCO_2 (about 23 US$/t$CO_2$) was assumed in 2030 in this sensitivity analysis (compared to 265 ¥/tCO_2, 2.4 US$/t$CO_2$ in 2020). The lower the CO_2 price, the stronger the effect will be, coal power generation remaining competitive in the market.

The **industrial sector** achieves the largest emissions reduction during this period (-158 Mt CO_2eq), by continuing to electrify low and medium temperature heat and using synthetic hydrogen and methane in high temperature industrial processes after 2035 to gradually replace fossil fuels. The use of biomass in Japan will be very limited due to very restricted resource availability for sustainable biomass.[11]

The **building sector** is the first sector to completely decarbonize: thanks to the continued efforts made already in the 2020s, demand will be electrified by 2040 with heat pumps and direct electric heating systems that are the most cost-efficient solution for low temperature heat needs (such as heating, cooling and hot water). Old buildings will further receive energy efficient retrofits and new dwellings will comply with strict energy efficiency standards.

The **transport sector** sees limited change in mobility trends. Electrification continues, especially in road transport with close to 45 million electric vehicles by 2045. Where direct electrification is difficult, indirect electrification will be needed through electricity-based decarbonized synthetic fuels such as green hydrogen, synthetic methane, and mostly Fischer-Tropsch (FT) fuels, particularly for maritime transport and aviation. Demand for sustainable e-fuels in transport kicks in from 2035 onwards, mostly FT fuels that will be imported due to their very high cost if locally produced (total consumption 83 TWh by 2045, more than three-quarters of which is imported).

Step 3: Increased use of green synthetic fuels in the last step to eliminate residual emissions, mostly in industry

The emissions still emitted in 2045 are the hardest to abate, typically in the industrial sector but also in the transport sector (aviation and maritime transport). Abating those emissions will drive further the demand for e-fuels, specifically synthetic hydrogen and methane. In 2050, heat demand for high temperature industrial processes is supplied by e-fuels, while medium temperature industrial heat demand is covered by industrial scale heat pumps, direct electric heating, and very limited sustainable biomass. Hydrogen will play a very limited role in the transport sector, which will mostly use FT fuels (more than three quarters of which – 89 TWh – will be imported).

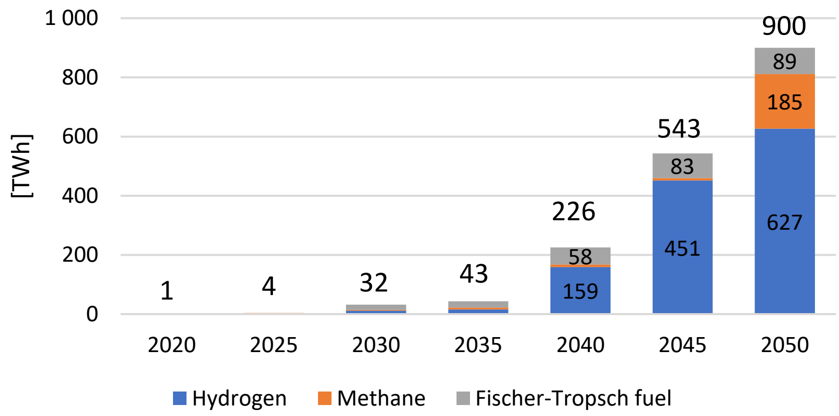

Figure 4: Base Policy Scenario with imports – evolution of synthetic fuel consumption from 2020 to 2050.

[11] Sustainable biomass includes residues from agriculture and forestry, construction wood wastes, biowastes, sludge and municipal wastes, excluding recyclable fractions like plastics, paper, cardboard. The assumptions on resources potential are based on data from the Food and Agriculture Organization of the United Nations (for agriculture and forestry residues) and from the World Bank (for waste potential).

A significant amount of sustainable hydrogen and methane will thus be needed to supply mostly the industry (600 TWh of hydrogen and 185 TWh of methane in 2050, up from 420 TWh of hydrogen and 8 TWh of methane in 2045). Green hydrogen produced domestically is expected to reach 3 TWh in 2030 (~77 000 t in high heating value), up to 68 TWh in 2040 (~2 Mt) and 353 TWh in 2050 (9 Mt), while about the same amount will be imported after 2035. By 2050, 30% of all generated power will go into hydrogen production (430 TWh).

Most of the renewable power to supply the electrolyzers will come from onshore wind power produced in the eastern regions (68% of installed onshore wind capacities are in Hokkaido and Tohoku) and transported to the regions where electrolyzers will be built, namely in Tokyo and the other central regions. 73 GW_{el} of electrolyzers will be needed by 2050 to produce 350 TWh of hydrogen. Such a strategy would require a substantial grid deployment program to directly connect the Hokkaido and Tokyo regions electrically (17 GW of direct grid connection between the two regions in 2050). Offshore wind will be of secondary importance because of its higher costs, but it could play a more important role if costs declined.

Importing about half of the necessary sustainable e-fuels limits both the pressure on resource availability in Japan and on total system costs, in particular for heat generation. Even in the scenario where Japan imports power and most of its synthetic fuels, the energy system mix would have 68% local resources (against only 12% today). This transformation strategy would therefore enhance significantly the country’s energy security.

Direct Air Capture (DAC) units are used to a very limited extent to produce synthetic fuels, not for CCS purposes. Conventional power plants fitted with CCS have high relative cost and hence play a negligible role in reducing energy-related emissions. The energy sector thus reaches carbon neutrality solely by means of defossilization and emission abatement. This study does not consider non-energy related emissions, which are considered difficult to decarbonize (non-energetic industrial process emissions, agriculture, waste); here, DAC and CCS could come into play.

This renewable decarbonized energy system can be built in Japan by 2050 at a reasonable cost, with total system costs about 30% lower in 2050 than in 2020. Currently, Japan spends about 17 trillion ¥ (154 b$) yearly in fossil fuel imports,[12] representing the largest share of the national energy system costs and 22% of imports in value. According to the model, annual system costs decline significantly from around 24.7 trillion ¥ (225 b$) in 2020 to about 17.4 trillion ¥ (159 b$) in 2050 after a slight increase in 2030. This spending represents about 3% of the current GDP in 2050. Instead of being spent on energy imports, the money goes predominantly into the national economy; only 4.5 trillion ¥ (41 b$) goes into synthetic fuel import in 2050. Capital investments in power and heat generation, energy storage, transmission grids and fuel synthesis technologies throughout the transition reach 3.6 trillion ¥ (33 b$) per year, representing about 2.5% of current gross investment levels.[13] However, these investments are not evenly spread over the transition period: the later the transition, the later the investments have to be made at once, which makes the transition less realizable. Renewables remain a favored technology due to a significant cost decrease, especially in the next 10 years. New nuclear power plants, except the two units under construction (Ohma and Shimane), are not installed in the scenarios due to high costs.[14]

[12] Data for 2019 from Japan foreign trade council Inc, Foreign Trade 2020, 31.03.2020.
[13] Gross fixed capital formation (GFCF) for 2019 estimated at 146 017 b¥ by the OECD (https://data.oecd.org/gdp/investment-gfcf.htm).
[14] The possibility of a life-time extension of nuclear (up to 60 years of technical lifetime) was not taken into account in this study. Other studies (REI 2020, Agora 2020) show that retrofitting nuclear power plants could be more expensive than renewable projects as soon as 2025.

III. Three pillars of the transition to climate neutrality

Pillar 1: Energy efficiency and the reduction of energy demand

The population decline projected in Japan (-20%) was assumed to reduce final energy consumption steadily from 2020 to 2050. In terms of primary energy, electrification and defossilization reduce demand by 34% due to efficiency improvements: on the supply side, 19% thanks to renewables-based electrification; and 15% on the demand side, mostly due to the electrification of the transport sector and increased motor efficiency. Overall, primary energy demand declines by 54% during the transition from 4 600 TWh in 2020 (16 700 PJ) to about 2 100 TWh (7 700 PJ) in 2050.

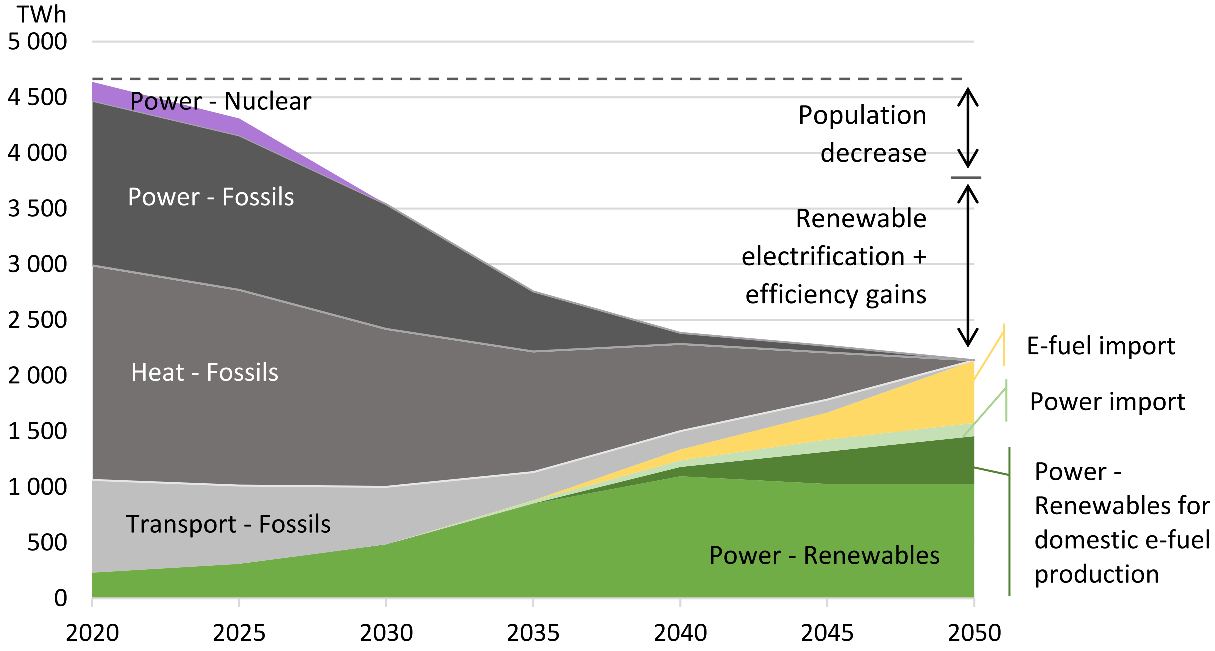

Figure 5: Base Policy Scenario with imports – evolution of primary energy demand from 2020 to 2050.

In the building sector, the increasing use of heat pumps to generate space heating and hot water will reduce fuel consumption through the use of ambient heat. Efficient heat pumps and appliances also need to replace older, less efficient devices. In the energy conversion sector, the deployment of renewable electricity increases the efficiency of power generation by replacing thermal power plants that have high conversion losses. In 2050, most electricity will be generated by wind and PV, which have no conversion losses (the secondary energy carrier, electricity, is primary energy). Only about 1.5% of power generation will be based on combustion fuels, two-thirds of which will be biomethane from waste and residues and one-third hydrogen.

In the transport sector, more efficient electric vehicles will increasingly replace combustion engine vehicles. And in the industrial sector, the broader use of more efficient technologies, notably electric furnaces, will further reduce primary energy demand. In addition, especially in the basic materials industry, the development of the circular economy will make good use of secondary materials, which entail much less energy than producing primary material does – though this aspect was not analyzed in this study.

Final demand reduction was assumed to be moderate, mostly following the trend in population decline. In all sectors, demand could decline more quickly if proactive measures were taken already today.

Pillar 2: Defossilization, renewable power generation and electrification

The importance of electricity and especially renewable power will grow during the transition. In many applications, especially in transport, space heating, cooling and hot water, the use of electricity proves to be the most efficient solution, especially compared with combustion engines and boilers. Wherever possible, direct electrification must be pursued in transport, space heating and industrial processes as the most efficient use of primary energy. Indirect electrification through the use of sustainable synthetic fuels will remain more expensive and should be reserved to cases where direct electrification is not feasible. Without electrification and defossilization of the power, heat and transport sectors, the Japanese energy system's primary energy demand (PED) would be 74% higher in 2050.

Power demand increases significantly by 2050 mostly due to the production of e-fuels, although their use is limited to the necessary minimum and about 50% is imported. In a scenario with about 50% imported e-fuels, electricity demand increases by 50% (Figure 6). This increase would reach up to +115% if all the synthetic fuels were produced domestically.

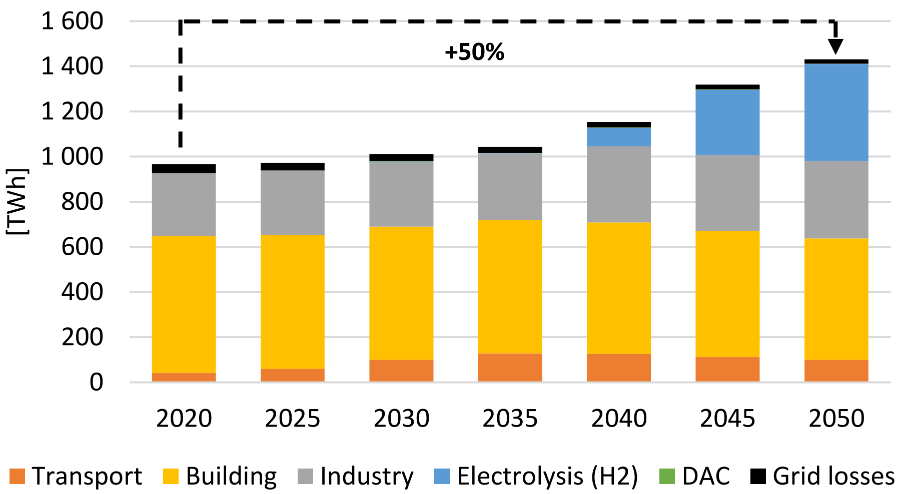

Figure 6: Base Policy Scenario with imports – evolution of gross power consumption from 2020 to 2050.

In order to achieve climate neutrality, this demand has to be met as soon as possible by sustainable power. Coal power is phased out by 2030 while oil-fired power plants are put on cold reserve; by 2050 gas-based generation switches to e-fuels. Demand is covered increasingly by renewables during the transition to reach 100% by 2050. Only about 1.5% of power generation will be based on combustion fuels replacing fossil fuels, mainly biomethane and green hydrogen. Generation from renewable sources more than doubles from 185 TWh in 2019 to 400 TWh in 2030, and from there more than triples to 1 350 TWh in 2050.

PV becomes the main source of power as its cost is expected to decline substantially in Japan, reaching on average 3.9 ¥/kWh (35 $/MWh) in 2050. By 2030, installed PV capacity more than doubles (144 GW), and the maximum technical potential set in this study is reached by 2050 in all the modelled scenarios (524 GW). By 2050, a little over one third of installed capacity is held by prosumers, who play a significant role in minimizing the cost of grid reinforcement. Onshore and offshore wind are installed less (88 GW and 63 GW, respectively, in 2050) but contribute significantly to total power generation (given their higher capacity factor). On average, the annually installed capacity required is about 8.4 GW of PV, 1.5 GW of onshore wind, and 0.7 GW of offshore wind between 2021 and 2030, and of 20 GW of PV, 3.7 GW of onshore wind, and 2.8 GW of offshore wind between 2031 and 2050. As a comparison, 2015 was the most successful year for PV installations in Japan with almost 11 GW installed compared to 6.5 GW in 2018.[15]

PV combined with short-term storage covers most local power demand, whereas wind energy is largely transported from the eastern regions to the central ones, which are more densely populated and more concentrated in industrial demand. New grid connections are then also needed, doubling from the currently available 40 GW. A new direct connection from Hokkaido to the densely populated Tokyo area is profitable.[16]

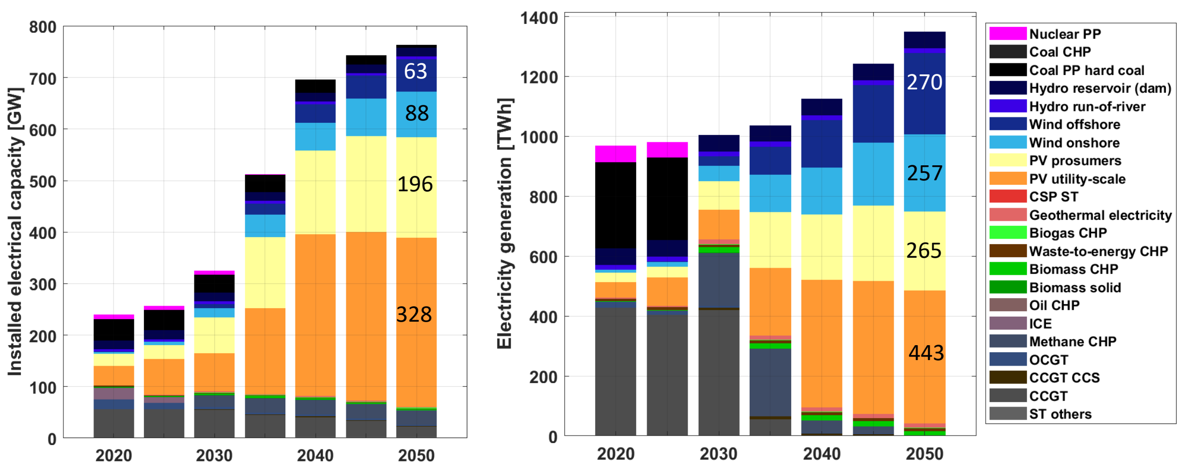

Figure 7: Base Policy Scenario with imports – evolution of power generation capacity (left) and generation (right) from 2020 to 2050.

To integrate those high levels of renewables and keep the system balanced at all times, the electricity system will have to become significantly more flexible – through more battery storage, the deployment of heat pumps, electrolyzers and electric vehicles (notably with smart charging and vehicle-to-grid or V2G technologies), and through more electricity trading between regions. The spatial and temporal distribution of generation will balance variable generation and enable the efficient use of renewable electricity, while the remaining conventional gas power plants fill in gaps.[17] The short-term balancing of electricity demand and supply will take place primarily through short-term storage (battery storage, smart charging and vehicle-to-grid technologies), load management and electricity trading. Seasonal variations in electricity supply will be primarily balanced through the generation and reconversion of synthetic methane (power-to-gas and gas-to-power) made with wind power from the northern regions, although this option will not be required much thanks to the flexibility offered by the import of synthetic fuels.

In 2050, the overall system capacity exceeds 750 GW (including VRE and flexible generation), and flexible demand adjusts to the generation profile of variable renewables. Since massive flexible

[15] https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019
[16] In 2020, the grids are used according to existing net transfer capacity (NTC) limits (about 50%), but later the NTC limits are considered to be relaxed to a grid utilization capacity factor (CF) of 80%. Even if the NTC is kept at 50% until 2050, the impact of the necessary additional grids on LCOE remains at about 4% of total LCOE.
[17] Those gas power plants are switched to run on green hydrogen or synthetic methane in 2050.

demand exists, the peak load will vary from about 84 GW during hours of low renewable power production, mostly in summer at night ("dark doldrums") to about 490 GW in winter at midday, when PV and wind feed-in are high. Flexible demand (storage, V2G charging, power-to-mobility, power-to-heat, power-to-fuels) is activated during those high PV and wind feed-in times, pushing up the maximal load and resulting in a rather low curtailment level of renewables (1.1% of total power generation). Inflexible demand can be met by flexible energy sources available in sufficient amounts such as hydro dams, pumped-hydro storage, gas turbines and gas CHP running on biogas and e-fuels, biomass power plants and CHP, battery storage, as well as some wind capacity generating during every hour.

Pillar 3: Hydrogen and sustainable synthetic fuels

The complete defossilization of transport and industrial processes requires substantial volumes of green synthetic fuels to substitute fossil fuels in hard-to-abate segments such as high temperature heat in industry, heavy-duty vehicle goods transport, maritime transport and aviation. Synthetic methane and most hydrogen is used in the industrial sector, while Fischer–Tropsch (FT) fuels are used in the transport sector. The slower the electrification of the transport sector, the more FT fuels are required during the transition. In the modelled scenarios, hydrogen represents about 65-75% of all synthetic fuels; the industry sector consumes about 80-90% of those synthetic fuels.

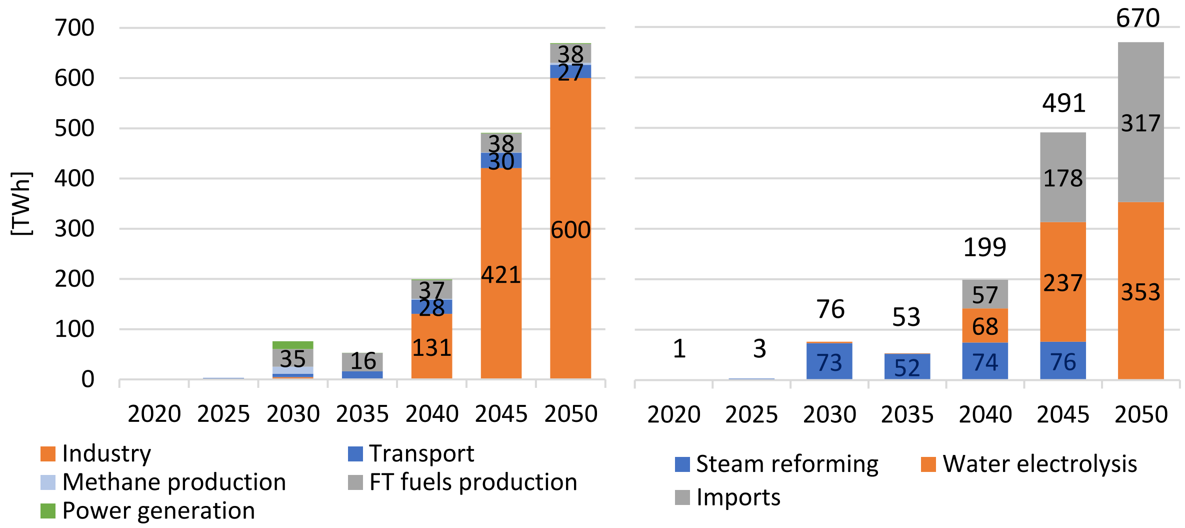

Figure 8: Base Policy Scenario with imports – evolution of hydrogen demand (left) and supply (right) from 2020 to 2050.

As electricity-based energy carriers, synthetic fuels are more expensive than electricity and can compete with fossil fuels only if carbon prices reach very high levels of about 36 000-60 000 ¥/tCO_2eq (330-550 $/t$CO_2$eq). Even if the use of hydrogen is limited to the most hard-to-abate sectors, hydrogen demand rises to about 670 TWh by 2050 in all the scenarios, amounting to about 17 Mt of hydrogen.[18] 600 TWh of hydrogen is used in the industrial sector, 37 TWh to produce e-fuels for the transport sector, especially aviation and maritime transport. Some more is needed to produce synthetic methane for use as fuel in gas turbines.

[18] As a result of the cost-optimization, hydrogen is consumed in sectors where less expensive direct electrification is not an option. Given the sectorial perimeters set for the modelling, the real total demand for hydrogen could be subject to decreasing factors (for example, material recycling is not included in this study) and increasing factors (the chemical sector is not included in this study).

The current hydrogen strategy in Japan foresees a demand of 5 to 10 Mt "in the future", mostly to be used in power plants. This study shows that hydrogen will need to be used very sparingly as it will not be available massively; its use in power plants will be limited (to about 42 kt in 2050); direct electrification should be prioritized wherever possible. Ways to reduce the need for synthetic fuels will need to be explored, such as material circularity.

Synthetic fuels will certainly need to be imported to reduce pressure on the Japanese energy system. Indeed, 3.5 TWh of power is needed to produce 2.8 TWh of hydrogen in 2030, which translates to 430 TWh of electricity by 2050 for the domestic production of 350 TWh of hydrogen. It is possible for Japan to produce almost all its synthetic fuel demand domestically.[19] However, this volume of domestic synfuel would require about 190 GW more wind generation capacity (compared to a scenario with about 50% imported synthetic fuels) and 100 GW more grid interconnection between wind farms (mostly in the north) and load centers[20]; low-cost PV is assumed to have reached its space limitations. Such a scenario would put a strain on land availability and increase the cost of heat production in Japan. The cost increase will also vary according to trends in the cost of electrolysis in Japan, which in turn will depend on how proactively the local electrolyzer industry is developed there and on how quickly low-cost electrolyzers are imported.

IV. Recommendations

- Climate neutrality based on renewables is technically and economically possible in Japan. Investments should be part of a comprehensive program to boost economic growth and move the economy towards climate neutrality, as part of the Japanese Green Growth strategy.
- Japan has to kick-start enhanced climate action as soon as possible. Its 2030 target must be increased to reach a 45% GHG emissions reduction (relative to 2010) and targeted actions adopted in all sectors of the economy. The renewable energy target in power generation should be increased to at least 40% of the power mix by 2030, accompanied by a comprehensive policy package to drive investments in renewables. Electrification needs to be accelerated, notably through the deployment of heat pumps and electric vehicles (EVs). Market access of those technologies must be guaranteed through better regulation and incentives, such as for the deployment of EV charging infrastructure. Improvements in energy efficiency must be supported with ambitious building standards and stringer regulation for vehicles. A realistic coal phase-out plan by 2030 should be defined. The current hydrogen strategy should be refined to focus the use of hydrogen on sectors where CO_2 emissions are most difficult to abate and where direct electrification is not an alternative. The development of green hydrogen infrastructures (domestic and imported) should be concretized.
- In order to accelerate the green transition in the energy, industrial, transport and building sectors, Japan will need a mix of instruments that combines market-based incentives, targeted support mechanisms and regulatory policies. Energy taxes, levies and duties will have to be reformed and carbon pricing increased, as existing price structures tend to promote oil, coal and gas and impede the use of renewable electricity. The upcoming discussions on the 6th Strategic Energy Plan will be crucial to this end.

[19] Only a small amount of FT fuels can still be imported in this scenario, leading to about 3% of primary energy demand imported to Japan in 2050, compared to 90% today.
[20] The model considers it more cost-effective to transport electricity close to where synthetic fuels are needed and to produce them there, rather than installing the electrolyzers close to power generation sources and transporting, say, green hydrogen or methane in converted gas grids.

- Government action starting now will determine how Japan goes about achieving climate neutrality by 2050 and a 45% reduction in GHG emissions by 2030. Intelligent policy instruments will be needed to make the Japanese economy sustainable and resilient. This transformation will need to ensure that structural changes are as fair and inclusive as possible.

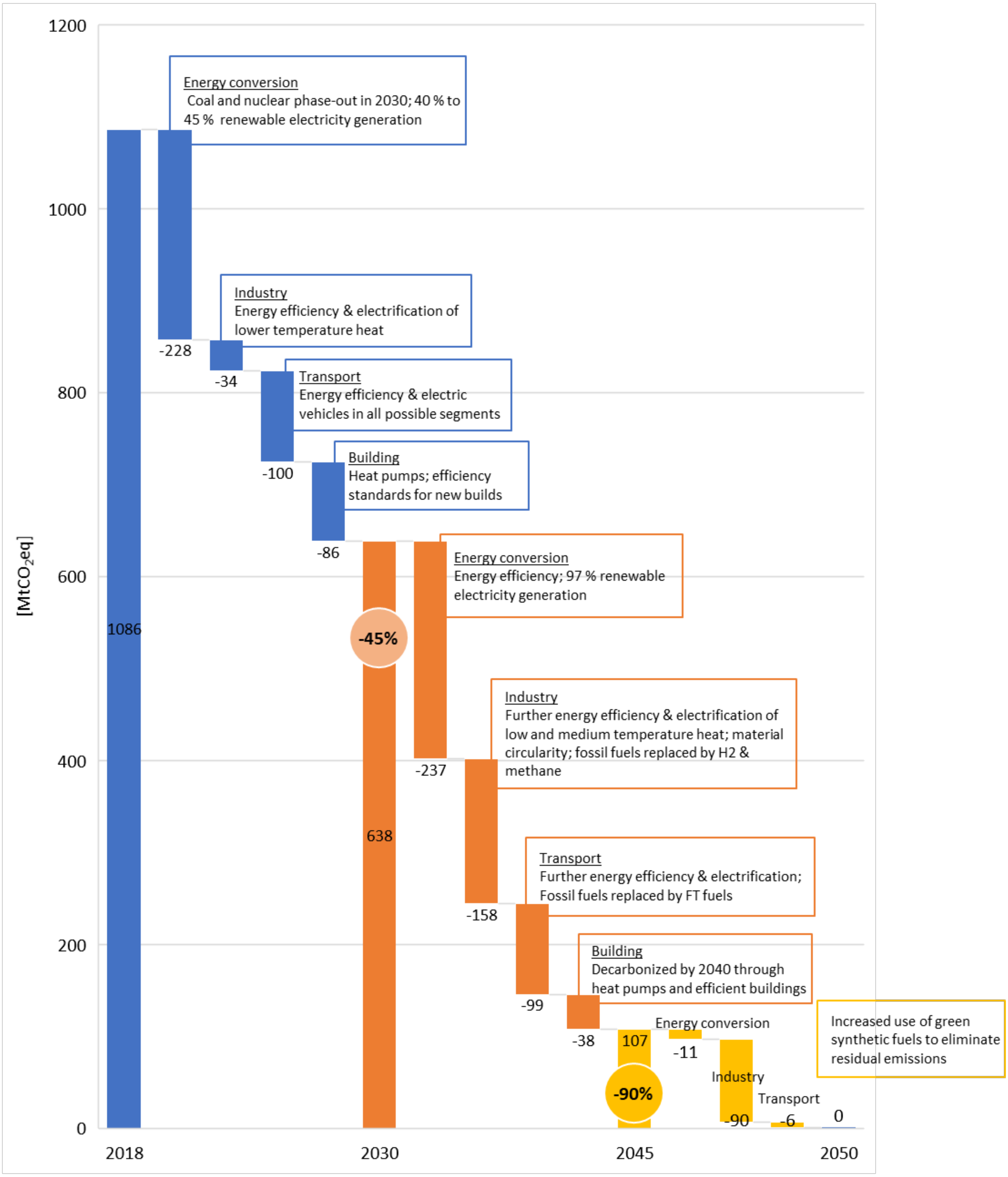

Figure 9: Three steps towards climate neutrality in the BPS imports scenario (GHG emissions in $MtCO_2eq$)

		2020	2030	2050	2030/2020 % change	2050/2020 % change
Energy-related GHG emissions (Mt CO_2eq)						
	Total	**1 045**	**638**	**-**	**-39%**	**-100%**
	Energy conversion	443	248	-	-44%	-100%
	Industry	281	247	-	-12%	-100%
	Buildings	119	38	-	-68%	-100%
	Transport	203	105	-	-48%	-100%
Primary energy consumption (PJ)	**Total**	**16 694**	**12 742**	**7 698**	**-24%**	**-54%**
	Coal	4 843	1 073	-	-78%	-100%
	Oil	3 001	1 604	-	-47%	-100%
	Gas	7 406	8 320	-	12%	-100%
	Nuclear	611	-	-	-100%	-100%
	Renewables	833	1 745	7 698	+109%	+824%
Electricity						
	Gross electricity consumption (TWh_{el})	962	1 009	1 430	+5%	+49%
	Gross electricity generation (TWh_{el})	970	1 021	1 351	+5%	+39%
	Renewable share in generation (%)	18	39	100	+113%	+453%
	Onshore wind capacity (GW)	4	18	88	+361%	+2 168%
	Offshore wind capacity (GW)	0	7	63	+12 155%	+105 048%
	Solar PV capacity (GW)	61	144	524	+134%	+752%
	Number of electric vehicles (M)	1	12	44	+908%	+3 480%
	Heat pumps (GW_{th})	46	89	142	+92%	+207%
Synthetic fuels demand (TWh_{th})	**Total**	**1**	**106**	**947**	**+7 507%**	**+67 906%**
	Hydrogen (TWh_{th})	1	76	670	+5 360%	+48 034%
	Share of import	-	-	*47%*		
	SNG (TWh_{th})	-	12	188		
	Share of import	-	-	*94%*		
	FT (TWh_{th})	-	18	89		
	Share of import	-	-	*78%*		
	Domestic electrolyzer capacity (GW_{el})	-	1	73		
	Power input for green H2 production (share of power generation) (%)	-	*0.3%*	*32%*		
	Population in Japan (M)	125	117	100		
	CO_2 price (JPY/t_{CO2})	289	5 496	18 000		

Figure 10: Base Policy Scenario with imports at a glance

How do we accomplish the clean-energy transition?

Agora Energiewende develops scientifically based and politically feasible approaches for ensuring successful energy transition in Germany, Europe and worldwide. We see ourselves as a think-tank and policy laboratory, centered around dialogue with energy policy stakeholders. Together with participants from public policy, civil society, business and academia, we develop a common understanding of energy transitions, its challenges and courses of action.

Renewable Energy Institute was established in the aftermath of Fukushima Nuclear Accident, in August 2011, to establish renewable energy based society in Japan and other countries. REI conducts scientific studies on renewable energy policies, advocates the policy makers and introduces global knowledges of renewables to the public.

Agora Energiewende and Renewable Energy Institute initiated in 2016 a partner ship with the goal to transfer expertise and deepen information exchanges about the ongoing energy transition in Germany and Japan.

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