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Setting the Trajectories of the Japan 2050 Low Carbon Navigator: Complexities and Uniqueness of the Nuclear Energy Sector

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ABSTRACT

The 2011 earthquake and subsequent accident at the Fukushima Daiichi nuclear power plant compelled the policymakers in Japan to rethink the country's previously-adopted energy policy which was based on nuclear power as the mainstay of Japan's energy supply. At the same time, Japan's commitment to reduce its greenhouse gas (GHG) emissions by 80 per cent below the 1990s levels by 2050 is faced with challenges, since a decreased dependence on nuclear power has already increased Japan's use of fossil fuels for power generation at least in the short term. Against this backdrop, the choices Japan faces now include, among others, whether to focus more on cutting its energy demand or relying more on decarbonising on the supply side, how to generate electricity, and what types of technologies to use. How Japan addresses these concerns are critical for the country's social, economic and environmental dimensions of sustainability. There is a growing interest in simplified tools that can provide an easy-to-understand chart to help understand the energy and emission options that are available for Japan. The Japan 2050 Low Carbon Navigator (Low Carbon Navigator) is such a quantitative tool which can support the policymaking process by engaging a wider audience in the energy and emissions debate. It is a user-friendly tool which lets the users to develop their own pathways combinations to achieve emissions reduction and ensure energy security, and see the impact using real scientific data. With uncertainties surrounding the future of Japan's nuclear sector, a number of complex, unprecedented issues needed to be taken into account for developing the trajectories and making the assumptions within the Low Carbon Navigator model. These assumptions and trajectories under the nuclear sector are very different from the ones in the other energy supply sector. The purpose of this paper is to explain in details how the assumptions and trajectories under the nuclear sector have been developed and incorporated within the whole Low Carbon Navigator model. The paper is divided into several sections. Section 2 provides a review of the evolution of nuclear energy sector in Japan. Along with a brief history of the development of the Japanese nuclear sector, this section also covers the current challenges facing the country, and governmental policy changes that came forth as a consequence of the Fukushima accident. Section 3 focuses on the assumptions and trajectory setting of the nuclear sector in the Japan 2050 Low Carbon Navigator. It discusses the issues that have been taken into consideration in making the assumptions, relevant data sources, and explains the calculation procedures for this sector in the Low Carbon Navigator model. This section also provides several demonstration pathways generated by simulations under the Low Carbon Navigator. These examples demonstrate the impact of the nuclear sector in Japan's future energy and emissions pathways. Section 4 concludes the paper with some explanation on what the Low Carbon Navigator can do, and what its limitations are.

Keywords: Japan 2050 Low Carbon Navigator, nuclear energy, energy and emissions

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1. Introduction

Japan is at a crossroads in choosing its future energy and emissions reduction policies. The 2011 earthquake and subsequent accident at the Fukushima Daiichi nuclear power plant compelled the policymakers to rethink the country's previously-adopted energy policy which was based on nuclear power as the mainstay of Japan's energy supply (Hiranuma, 2014). Ensuring Japan's future energy security thus has become a major policy issue. At the same time, Japan's commitment to reduce its greenhouse gas (GHG) emissions by 80 per cent below the 1990s levels by 2050 (MOE, 2012) is faced with challenges, since a decreased dependence on nuclear power has already increased Japan's use of fossil fuels for power generation at least in the short term. In July 2015, Japan submitted its proposed post-2020 climate actions—the Intended Nationally Determined Contributions (INDC)—to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), where the country pledged a 26 per cent reduction of GHG emissions compared to 2013 levels (equivalent to 25.4 per cent reductions from 2005 levels) (Government of Japan, 2015). Against this backdrop, the choices Japan faces now include, among others, whether to focus more on cutting its energy demand or relying more on decarbonising on the supply side, how to generate electricity, and what types of technologies to use.

How Japan addresses these concerns are critical for the country's social, economic and environmental dimensions of sustainability. There is a growing interest in simplified tools that can provide an easy-to-understand chart to help understand the energy and emission options that are available for Japan, and to communicate on how Japan's policies related to energy and climate change can impact on the country's economic growth, environmental protection as well as safety. The Japan 2050 Low Carbon Navigator (Low Carbon Navigator) is such a quantitative tool which can support the policymaking process by engaging a wider audience in the energy and emissions debate.

The Low Carbon Navigator builds upon the UK 2050 Pathways Calculator (2050 Calculator), an innovative energy and emissions pathways simulation tool developed by the UK Department of Energy and Climate Change (DECC) in 2010. The 2050 Calculator is a user-friendly tool which lets the users to develop their own pathways combinations to achieve emissions reduction and ensure energy security, and see the impact using real scientific data. This simple but powerful tool has been able to bring the complex energy and emission-related issues to policymakers as well as experts and general public for dialogues and education purposes. In Japan, the Institute for Global Environmental Strategies (IGES) and the National Institute for Environmental Studies (NIES) jointly started working on developing the Japanese version of the 2050 Calculator in 2013 with technical support from the UK DECC and the British Embassy Tokyo. The prototype of the Japanese version, known as Japan 2050 Low Carbon Navigator, was launched for the general public in July 2014[3].

[3] Two versions of the Low Carbon Navigator have been developed. An Excel version (Zhou *et al*., 2014) provides a complete picture of the model including data and underlying assumptions, and is useful for expert audience (the model can be downloaded from http://www.2050-low-carbon-navi.jp/web/en/). A more simplified Web Tool (Shirakawa *et al*., 2014) is for policy makers and general audience, and can be accessed at http://www.en-2050-low-carbon-navi.jp/. For a detailed overview of the Low Carbon Navigator including the methodology and discussions of all the covered sectors, please see Moinuddin *et al*. (2015), which can be accessed at http://pub.iges.or.jp/modules/envirolib/view.php?docid=5395.

The Low Carbon Navigator provides a platform for engaging in dialogues on the challenges and opportunities of the future energy system and the responses to climate change. This transparent and handy tool can help answer the key questions of how Japan's energy system may evolve over the next few decades and how it will affect the country's GHG emissions, energy security and import dependence, electricity systems, energy development and related costs. It uses a scenario-based approach to explore potential pathways and to illustrate the likely outcomes under these scenarios. The assumptions under different scenarios are clear, simple and easy-to-understand. All the supply and demand sectors of the Japanese economy have been considered. Instead of combining the sectors together, the Low Carbon Navigator takes a sector-by-sector approach. The trajectories are set in the direction of least to maximum effort of Japan toward developing a low carbon society. While the pathways options for the demand side sectors take into consideration the possible decrease or increase in demand over time thanks to behavioural changes, efficiency improvements of appliances as well as macroeconomic aspects such as industrial activities and demographic changes, the supply side sectors have been developed to reflect Japan's potential in each sector toward providing cleaner energy. For example, in case of renewable energy, the Low Carbon Navigator takes into consideration the country's renewables potentials and then sets up the pathways to show varying levels of renewable energy generation capacity under least to maximum efforts in exploiting these sectors.

However, while identifying the potential trajectories for the nuclear energy sector, the above approach appeared to be too naïve given the context of Japan after 2011 earthquake and tsunami and the ensuing Fukushima nuclear power plant accident. A lot of public debates is taking place for and against nuclear power in Japan and even beyond. Following the nuclear accident, safety concerns prompted the Japanese government to temporarily cease the operations of most of the nuclear plants until newly-developed safety procedures have been completed. By September 2013, all the nuclear plants stopped operations under this initiative, and as of April 2015, none of the plants resumed operations. This is a massive shock for the country's energy supply, as the nuclear sector accounted for over a quarter of the total power generation in Japan until the 2011 nuclear accident. Consequently Japan's dependence on imported fossil fuels has increased dramatically, which also raised concerns over the country's commitment to reduce emissions.

Because of these concerns and uncertainties relating to Japan's nuclear sector, we felt that the Low Carbon Navigator should reflect the challenges facing this sector. Levers under other energy supply sectors focus mostly on generation capacity potential, but this approach would not capture the complexities of the country's nuclear sector at the moment. The trajectories and levers under this sector therefore were developed in a way so that the users can provide their opinion on restarting the existing nuclear plants as well as building new ones.

The purpose of this paper is to explain in details how assumptions and the trajectories under the nuclear sector have been developed and incorporated within the whole Low Carbon Navigator model. The paper is divided into several sections. Section 2 provides a review of the evolution of nuclear energy sector in Japan. Along with a brief history of the development of the Japanese nuclear sector, this section also covers the current challenges facing the country, and governmental policy developments after the Fukushima accident. Section 3 focuses on the assumptions and trajectory setting of the nuclear sector in the Japan 2050 Low Carbon Navigator. It discusses the issues that have been taken into consideration in making the assumptions, relevant data sources, and explains the calculation procedures for this sector in the Low Carbon Navigator model. This section also provides several demonstration pathways generated by simulations under the Low Carbon Navigator. These examples demonstrate the impact of the nuclear sector in Japan's future energy and emissions pathways. Section 4 concludes the paper.

2. Development of the Nuclear Sector in Japan

Japan has a decades-long history of nuclear energy, dating back to the 1950s. At that time, Japan initiated an ambitious plan for recovering the war-torn economy. In the early 1950s, more than two-thirds of Japan's power generation depended on hydro, followed by coal (about one-third) and a small portion on oil (Omoto, 2012). With industrial activities expected to gear up, ensuring energy security soon became a major issue of the government. The government intended to diversify its energy supply, and avoid environmental issues typically associated with fossil fuel sources (Omoto, 2012). To support the economic recovery programme with adequate supply of energy, the Japanese authorities promptly turned to nuclear energy (Nelson, 2011). Accordingly, in 1954, the government appropriated a significant amount of funds (230 million Japanese yen) for nuclear energy research and development (WNA, 2015).

From the very beginning, Japan has maintained that its nuclear energy development must focus strictly for peaceful purposes. In 1955, the country adopted the Atomic Energy Basic Act, which clearly stipulated that Japan's nuclear sector will be developed only for the welfare of human kind and for raising national living standards (Government of Japan, 1955). The following year, as a preparation for joining the global initiative of creating the International Atomic Energy Agency (IAEA), Japan established associated national organs such as the Atomic Energy Commission, Science and Technology Agency, Japan Atomic Energy Research Institute (JAERI), and the Atomic Fuel Corporation (Omoto, 2012). The same year, the Atomic Energy Commission developed the country's first long-term plan for research and development and utilisation of nuclear power, which focused on domestic capacity building following initial experience from imported nuclear power plants.

2.1 Decades of Nuclear Energy Deployment

In the initial stage, Japan had to rely on external expertise to build nuclear power plants. The Japan Power Demonstration Reactor (JPDR) developed the county's first reactor in 1963, which had a gross electricity capacity of 13 MW (IAEA, 2015a). The 166 megawatt (MW) Tokai 1 plant, the country's first commercial reactor, was built with British-designed Magnox technology. After five years of construction works, the first grid connection from this gas cooled reactor (GCR) plant was established in end 1965 (IAEA, 2015a). Tokai 1 plant's operations continued until 1998. Other early days plants include 357 MW Tsuruga 1 (grid connection in 1969), 340 MW Mihama 1 (grid connection in 1970) and the tsunami-affected 460 MW Fukushima-Daiichi 1 (grid connection in 1970) (IAEA, 2015a). Although initially Japan depended on British technology, it soon turned to the United States. For example, the Fukushima-Daiichi 1 plant used a boiling water reactor from General Electric (Maize, 2011). For a short period of time, Japan would typically purchase the plant designs from US companies and develop the plants together with Japanese companies (WNA, 2015).

Construction of nuclear power plants in Japan paced up from the 1970s, with pronounced intention of diversifying energy supply, and avoiding detrimental environmental effects associated with fossil fuels (Omoto, 2012). The country put significant efforts for developing domestic nuclear technology and by the late 1970s Japan developed its own domestic capacity to construct nuclear power facilities using light water reactors (WNA, 2015).

While ensuring energy supply security was a major motivation behind Japan's turn to nuclear power, another impetus came from the rapid economic growth of 1960s and subsequent concerns over increased environmental pollution from the use of fossil fuels (Oguma, 2012). Additionally, encouraging the diversification of power sources by promoting nuclear power (along with natural gas) got further justification from the government mainly because of the two oil crises in the 1970s (Government of Japan, 2010). Massive efforts put by the Japanese industry saw rapid and continuous deployment of nuclear power plants in Japan in the subsequent decades. Figure 1 shows decade-wise capacity addition and construction of power plants from 1961 to present. Fastest installations took place during the decades of 1970s, 1980s and 1990s. As many as 50 new plants came into operation during these three decades, which added more than 44 gigawatt (GW) to

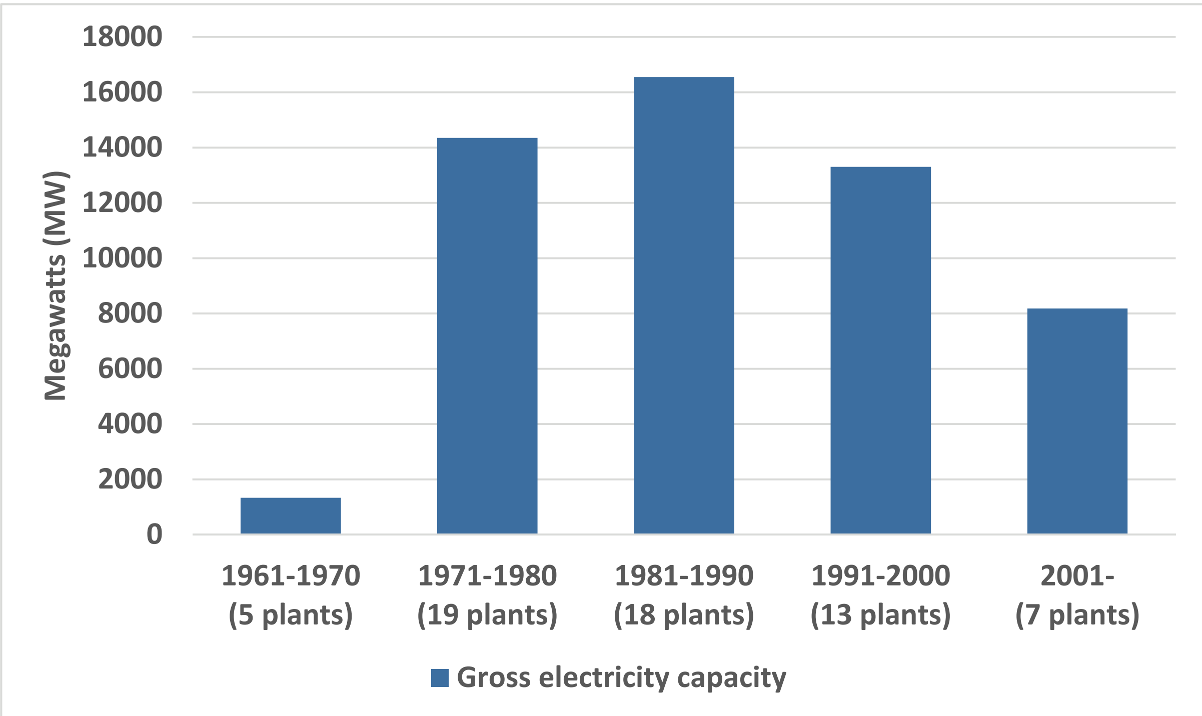

Fig. 1. Deployment of nuclear installations in Japan, 1961 to present

Note: Deployment data includes operational as well as shut down (long-term and permanent) and under construction installations.

Source: Authors' compilation based on data from PRIS database (IAEA, 2015a)

Japan's power generation capacity. Among these reactors, Hamaoka-5, a boiling water reactor that came into effect in 2004 and still in operation, has the highest gross electricity generation capacity of 1.38 GW (IAEA, 2015a). The pace of the rapid development of nuclear units slowed down since the late 1990s, due to the shrinking of the Japanese economy as well as the increase in construction costs and an accident that took place at the Tokaimura plant in 1999 (Oguma, 2012).

Apart from the early reliance on imported technology, most of these nuclear installations were done using domestic technology. Kajima Corporation, a leading Japanese engineering and architecture company established in 1840, constructed more than 60 per cent of the nuclear power units in Japan (Kajima, 2010).

It would be worth noting that Japan's nuclear power development faced opposition domestically from the very early stage. This was not surprising given that the memories of Hiroshima and Nagasaki were still fresh in the minds of Japanese people. According to a 1956 survey by the United States Department of State, 39 per cent people in Japan at that time considered nuclear power to be harmful, against 22 per cent who considered it to be beneficial (Nelson, 2011). Nuclear issue has continued to be a sensitive one and reached its peak with the recent Fukushima accident.

Figure 2 shows the locations of nuclear facilities in Japan in 2010. The plants are scattered all over the country, and are located near

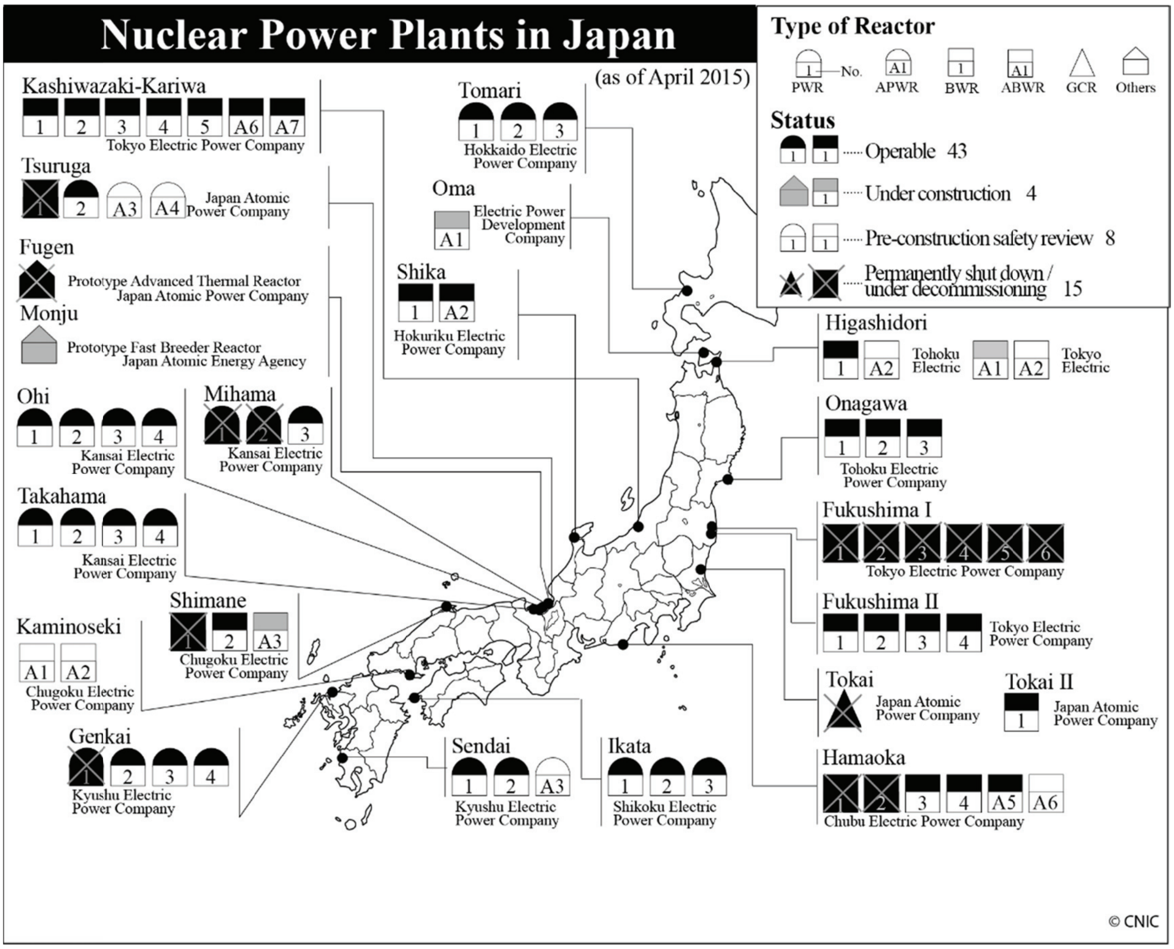

Fig. 2. Locations of nuclear power installations in Japan
Source: CNIC (2014)

depopulated coastal areas. This was a result of a study done by the Japanese government in 1960, which found that if the plants were developed in cities, the economic cost of dealing with the aftermath would be extremely high (Oguma, 2012).

The continuous deployment of nuclear installations for a prolonged period of time made Japan one of the most intensive users of nuclear energy. In fact, in terms of number of reactors as well as net electricity generation capacity, Japan is ranked at third in the world, after the United States and France (Figure 3).

2.2 Contributions to the Energy and Electricity Sector

Over the years, nuclear energy became a significant contributor to Japan's energy and electricity sector. Its share in the country's primary energy supply increased from negligible in the 1960s and early 1970s to nearly 12 per cent in 2010 before decreasing again in the aftermath of the 2011 nuclear accident (Figure 4). The increase in the share of nuclear energy, together with natural gas, also contributed to a decrease in Japan's dependence on oil.

Figure 5 shows nuclear power generation capacity of Japan from 1965 to 2012. As discussed earlier, the country has followed a policy of continuous deployment of nuclear installations for about five decades. As of 2012, installed electricity generation capacity (including auto-production) of all the plants in Japan is over 46 GW (EDMC, 2014). The figure shows that deployment rate slowed down since the late 1990s.

Corresponding to the increase in Japan's installed nuclear capacity, nuclear electricity generation also increased significantly. A comparative illustration of the change over time in nuclear electricity's share in total electricity generation against other sectors is given in Figure 6. While in 1970 nuclear electricity contributed

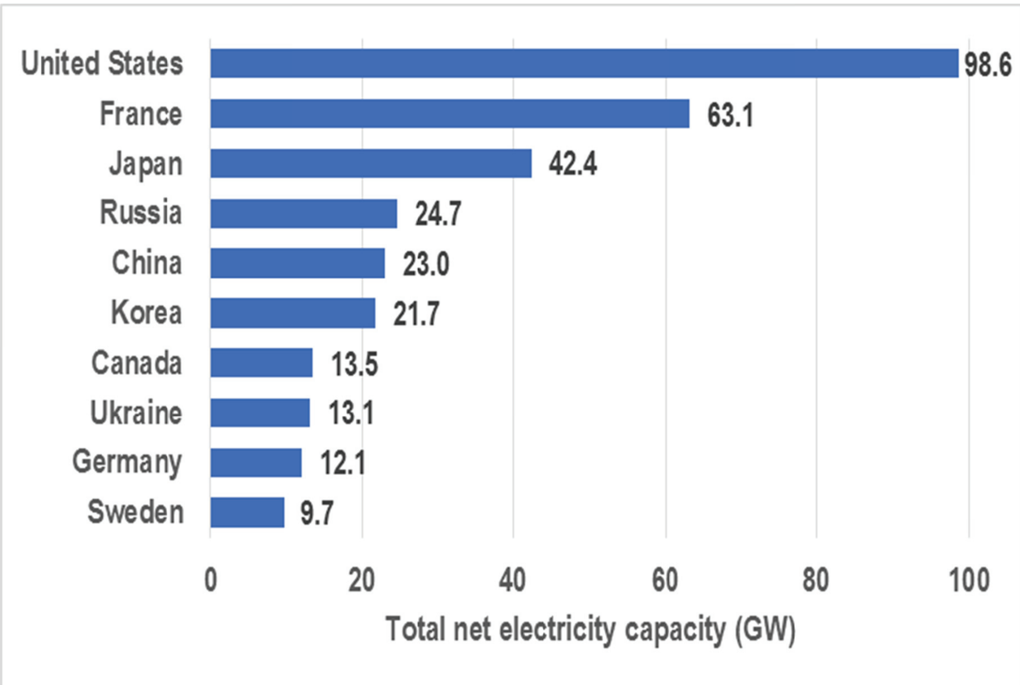

Fig. 3. Top ten countries in terms of net nuclear electricity capacity
Source: PRIS database (IAEA, 2015b)

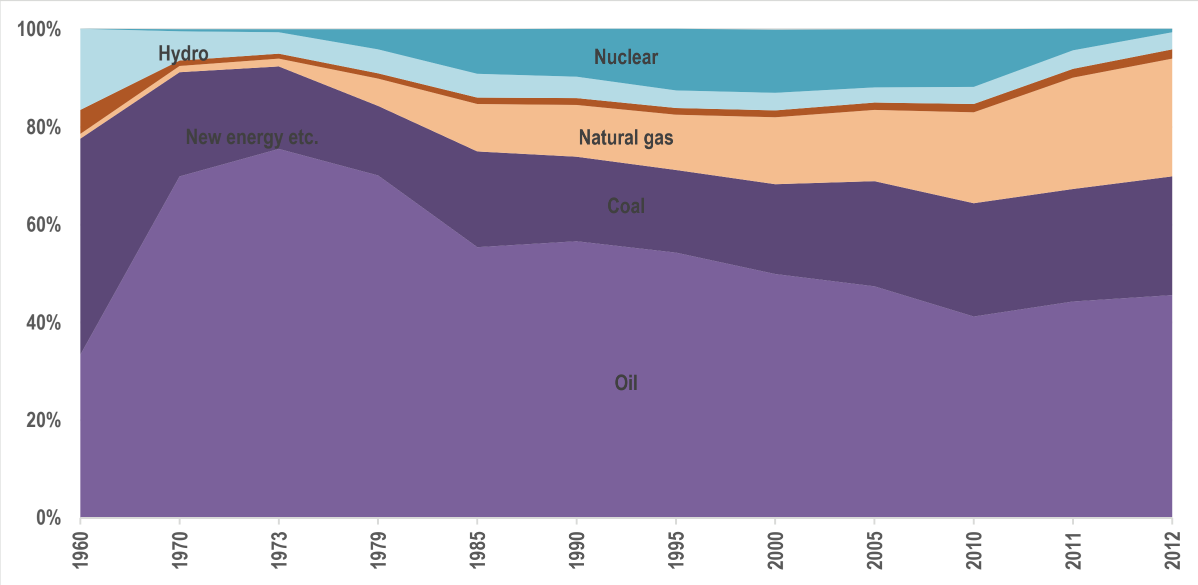

Fig. 4. Trends in total primary energy supply of Japan, 1960-2012
Source: Authors' compilation based on data from EDMC (2014)

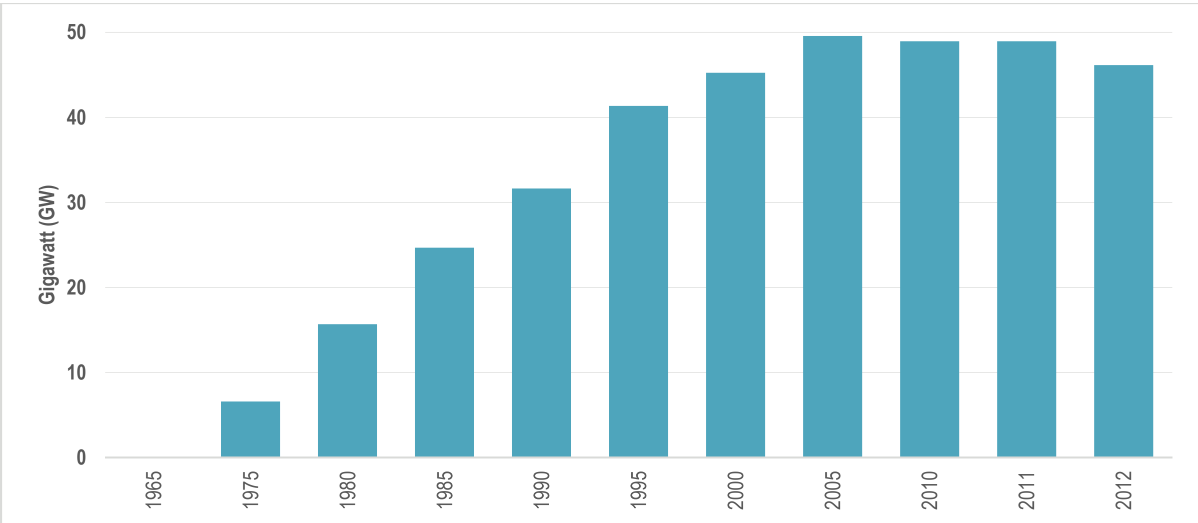

Fig. 5. Installed capacity of nuclear electricity generating plants
Note: Data includes capacity of electric utilities as well as auto-producers. Variations in the data (based on the sources) is observed (e.g., between data from PRIS database and EDMC, 2014).
Source: Based on data from EDMC (2014)

to only 1% of total electricity generation, by 1990 it increased to nearly a quarter, with moderate increase until 2010. In line with the increase of nuclear sector's share, the shares of both hydro and thermal sources decreased, although in absolute terms the contributions of these two sectors—particularly thermal—increased quite significantly. However, the most phenomenal increase occurred undoubtedly in nuclear sector's contribution, which increased around 63 times over the 40 years, from 4.5 TWh in 1970 to 288 TWh in 2010 (estimated from EDMC data).

The contributions from the nuclear sector supported the growing energy demand posed by the Japanese industrial sector throughout this period. In addition, as a cleaner source of

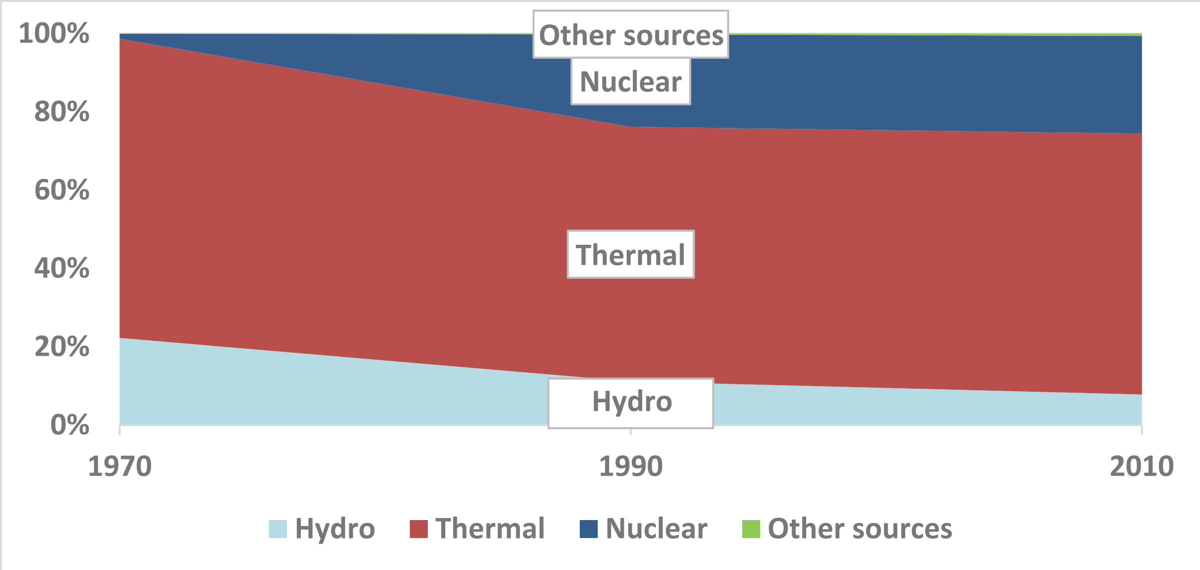

Fig. 6. Comparison of electricity generation from nuclear and other sources (1970, 1990 and 2010)
Source: Authors' compilation based on data from EDMC (2014)

energy, it also helped Japan curtail emissions that would otherwise have occurred from the use of conventional fossil fuels.

2.3 The Fukushima Nuclear Accident and Aftermath

Japan's pre-Fukushima energy policy aimed at further expansion of nuclear power in the future. Japan's 2010 Basic Energy Plan called for the construction of 14 new nuclear power plants between 2010 and 2030—in addition to the 54 reactors already existing (METI, 2010). This nuclear power expansion plan would have increased the installed capacity from 49 GWe in 2010 to 68 GWe in 2030, and the electricity generation from 288 TWh in 2010 to around 540 TWh, or nearly half of total centralized power generation (from "general electric utilities") in 2030 (METI, 2010).

However, Japan's nuclear power sector received a major blow when the 2011 earthquake and the subsequent Tsunami severely damaged the Fukushima Daiichi nuclear power plant. The disaster raised safety concerns of other nuclear plants in Japan, which prompted the government to enact stringent safety regulations and to initiate temporary shutdown of the existing plants for inspection. The last of the 48 reactors in Japan went offline by September 2013 (Chellaney, 2014), and as of April 2015, none of the reactors resumed operation. Consequently, for the first time in several decades, Japan is now generating power without any contribution from the nuclear sector. The gap has been filled up with imported fossil fuels (Figure 7), with implications for Japan's import dependence, as well as energy costs.

The whole situation has also complicated Japan's ambitious emissions reduction plans (25 per cent and 80 per cent reductions respectively by 2020 and 2050 against 1990 levels). The country's pre-Fukushima Basic Energy Plan 2010 emphasised nuclear power as the mainstay of the country's energy supply, and outlined a policy to achieve these reduction by expanding Japan's nuclear capacity and power generation (METI, 2010). This expansion plan, however, has become unrealistic in the wake of the nuclear disaster and the government is revising the country's policies to reduce its dependence on nuclear energy. For example, the *Innovative Strategy for Energy and the Environment 2012* calls for realizing "a society not dependent on nuclear power in earliest possible future" (Energy and Environment Council, 2012). In addition to that, public polls suggest that anti-nuclear public perception has gained its momentum (Chellaney, 2014). In April 2014, the government adopted an updated Strategic Energy Plan (the 4th Basic Energy Plan), which focuses on developing "multilayered and diversified flexible energy supply-demand structure" (METI, 2014). On the supply side, the 4th Basic Energy Plan aims at reducing Japan's overdependence on nuclear energy.

The new energy policies that Japan has adopted as well as their subsequent revisions are likely to have significant consequences for the country's emissions reduction efforts. This is particularly true in the context of the uncertainty surrounding the country's future nuclear power use and political instability (Kuramochi, 2014). While Japan's long term GHG reduction target remains the same, the 2020 target has been revised quite drastically. The new target, announced at the COP19 in Warsaw in 2013, is to reduce emissions by 3.8 per cent compared to 2005 levels by 2020 (MOE, 2013), while previously it was 25 per cent from the 1990 levels within the same period of time. The target, however, is tentative and subject to change in accordance with revisions in Japan's energy policy.

It is important to note that while uncertainties over the future of Japan's nuclear power use exist, none of the current policies mention anything about never restarting the plants that are temporarily shut down. The government has set out new set of safety standards for nuclear power plants, and restarting any of the shut down plants will be subject to meeting these stringent standards (Kuramochi, 2014). Resuming operations for a few reactors is already being considered (Chellaney, 2014).

3. Nuclear Sector in the Low Carbon Navigator: Assumptions and Trajectory Setting[4]

Before the Fukushima Daiichi nuclear accident in 2011, Japan was a leading producer of nuclear power in the world. With a capacity of 49 GW, the country produced around 288 TWh/y of electricity in 2010 which was delivered to the grid (IEA, 2013). However, in the aftermath of the 2011 Fukushima disaster, none of Japan's nuclear power stations are in operation as of April 2015. Some drastic changes in the country's nuclear power production were expected. Two major policy decisions will affect the future of Japan's nuclear energy. The first one is related to the restart policy of the existing nuclear power plants. The second issue concerns the impact of new-build policy on future capacity. These policies are likely to be decisive in Japan's future energy supply mix, and hence will have significant consequences for the country's energy security, self-sufficiency and import dependence, and emissions reduction efforts.

Against the changing landscape of Japan's energy sector in general and nuclear sector in particular, the Low Carbon Navigator development team felt that the nuclear energy supply trajectories should reflect the challenges that Japan faces now. Thus the ensuing levers under this sector need to incorporate options beyond mere generation capacity potential. We therefore took a unique

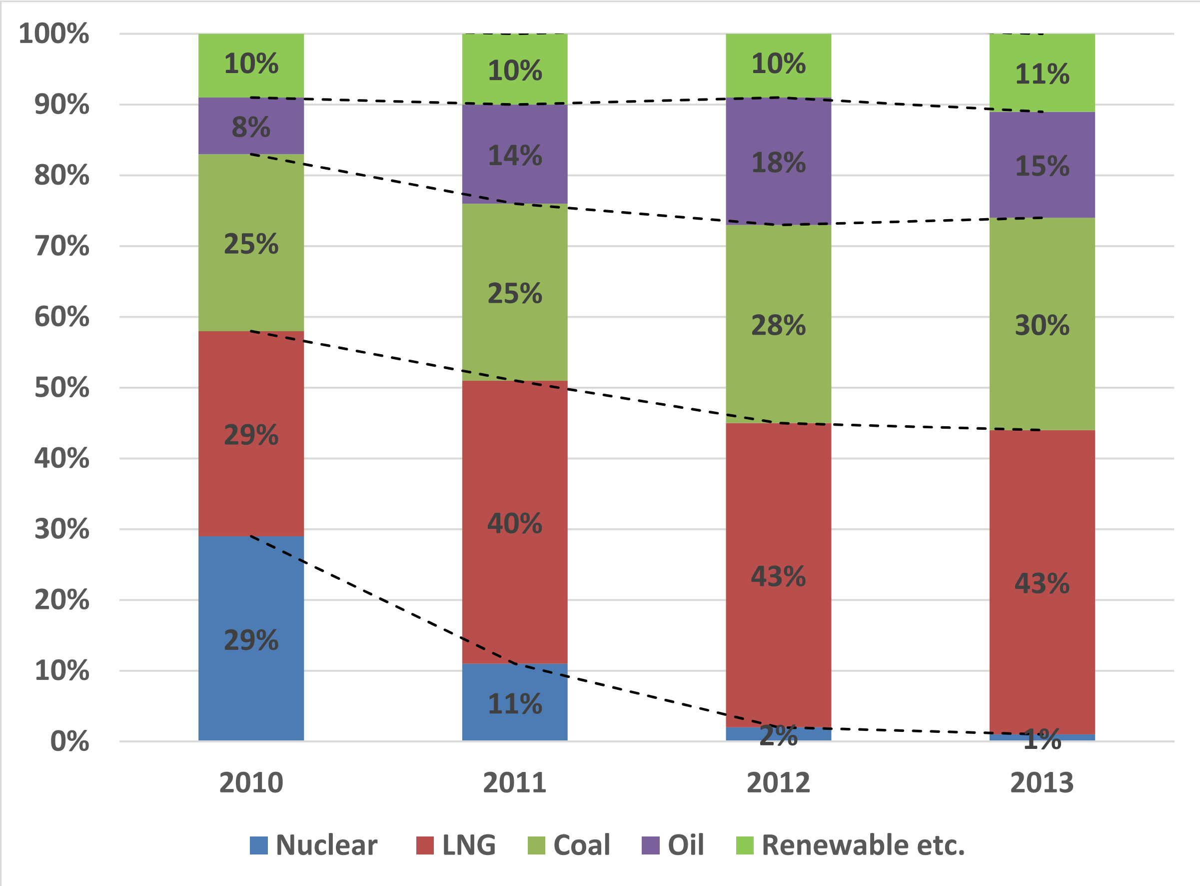

Fig. 7. Drastic change in Japan's electricity generation energy mix in recent years
Source: Compiled by METI Based on "Outline Of Electric Power Development in FY 2013" (cited in Fujino, 2014)

approach to allow the users to reflect their opinions through the Low Carbon Navigator's levers under the nuclear sector.

The trajectories have been set up on the basis of progressively higher efforts toward transition to a low-carbon society. For example, Trajectory A in the nuclear sector represents low efforts and continuation of existing capacity and technology, whereas Trajectory D represents great efforts leading toward increased use of advanced technology. Trajectory E in this sector represents the physical limit/technological potential. The trajectories under the nuclear sector as well as under other sectors in the Low Carbon Navigator have been developed through intensive literature review and consultation with relevant experts in Japan.

3.1 Impact of Restart Policy

The restart policy affects all the existing nuclear plants in operation before the Fukushima accident. For Fukushima Daiichi and Daini plants, it is clear that all the reactors will be decommissioned. However, for other plants (i.e. not in Fukushima) that were hit by the 2011 earthquake and currently under temporary shutdown, the question is whether they will resume operations in the future or whether they will be

[4] Discussions on trajectory setting under this section is based on Moinuddin *et al.* (2015).

decommissioned. For the plants which were not hit by the earthquake, the question is when they will resume operations. These are complex issues but are nevertheless important in formulating Japan's future nuclear energy pathways. Based on these, the Low Carbon Navigator has developed five trajectories. The users of the Low Carbon Navigator will be able to input their opinion by choosing their preferred restart policy and see its effect on Japan's energy and emissions future. The users can choose options among complete abandonment of nuclear capacity, limited restart or full restart. The options for restart policy also differentiate the plants according to plants' lifespan (40 years, 50 years, or 60 years). Currently, the lifetime of existing nuclear reactors is regulated to 40 years. The reactors may extend their lifetime by another 20 years only if they pass the special examination by Japan's Nuclear Regulation Authority. By combining the lifespan input with the other lever (i.e. new build policy) the users can reflect their views on phasing out nuclear power generation some time in the future. Five different trajectories are provided under this lever, which are explained below along with the illustration in Figure 8.

Trajectory A

Trajectory A assumes that Japan will shut down all of its nuclear power plants from 2010 onwards and they will never be restarted. In other words Japan will phase out its nuclear capacity completely and focus on other sources of energy.

Trajectory B

Trajectory B assumes that only half of the existing nuclear plants will be restarted. With no new-build rate, nuclear capacity will come down from 49 GW in 2010 to below 10 GW in 2030 and to zero by 2050.

Trajectory C

Trajectory C assumes a restart policy where Japan only allows all existing nuclear plants with

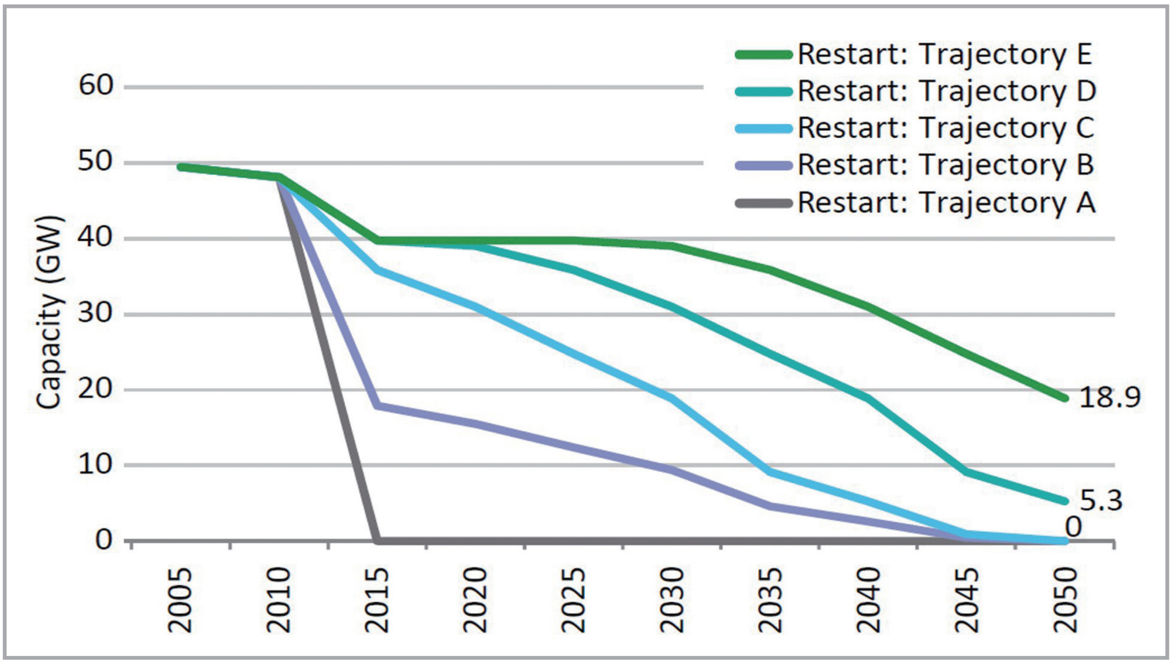

Fig. 8. Impact of restart policy on future capacity (no new build assumed)
Source: Developed by the Low Carbon Navigator team

a 40 year lifespan to operate. With the retirement of exhausted plants and no new-build, Japan's capacity will gradually decline, but at a slower pace than Trajectory B. By 2030, capacity will be around 19 GW and eventually zero by 2050.

Trajectory D

The assumption under Trajectory D is similar to Trajectory C, but here all plants with a 50 year lifespan are allowed to operate and no new plants are built. It will mean that despite the declining trend, Japan will still have limited, 5.3 GW (32 TWh/y electricity) nuclear capacity.

Trajectory E

The assumption under Trajectory E is similar to Trajectories C and D. The difference is that plants with a 60 year lifespan are allowed to operate, though no new plants are built. Thus, though capacity will decline, Japan will still have limited, 18.9 GW (111 TWh/y electricity) nuclear capacity in 2050 as plants with longer lifespan are allowed to operate.

The significance of this lever is huge. For example, as Japan has negligible renewable capacity at the moment, selecting Trajectory A (immediate shut down and never restart) and assuming no new-build policy will mean that the country will have to depend on conventional/fossil fuels at least until the renewables sector develops. This will lead toward increased emissions from the fuels sector. In addition, as Japan has very limited domestically available conventional energy resources, choosing Trajectory A will increase the country's energy import dependence and consequently reduce its energy self-sufficiency. The subsequent trajectories, which stipulates restarting plants with specified life-spans, allow Japan to maintain varying degrees of nuclear power generation. This will help control the use of fossil fuels to some extent and give time to develop the renewables sector.

3.2 Impact of New-Build Policy

Options under this lever affect plants that are under construction, and plants that may be built in the future. The users may choose among a varying degree of new build policy, ranging from no new build to very aggressive level of new build rate. It also provides the users to choose among several options for delaying the building of new plants. This lever interacts with the previous one on restart policy. For example. If a user chooses no restart at all in the first lever and no-new-build in the second lever, it will mean that the user prefers immediate abandonment of any nuclear capacity for Japan. The following five trajectories have been developed under this lever. Figure 9 provides an illustration of these trajectories.

Trajectory A

Trajectory A assumes that no new nuclear plants will be developed and existing plants will retire once their lifespan is over. Assuming a full restart policy with a 40 year lifespan for the plants, Japan's existing nuclear capacity will go down gradually to 19 GW in 2030 and eventually to zero by 2050.

Trajectory B

This trajectory assumes that two of the three plants currently under construction (Ohma No. 1, Shimane No. 3) will be allowed to develop, but with a 5-year delay. With a full restart policy (40 year lifespan), this trajectory will lead Japan's nuclear capacity to decrease to 2.8 GW in 2050, which will generate 16 TWh/y of electricity.

Trajectory C

In addition to Trajectory A, construction of TEPCO Higashidori No. 1 reactor will start operating with a 5-year delay. Furthermore, the operation of new-builds will take place from 2035 onwards, and Japan will achieve a 1GW/y build rate after 2040. With a full restart policy (40 year lifespan), Japan's nuclear capacity under this trajectory will be 16.6 GW (generating 105 TWh/y) in 2050.

Trajectory D

Trajectory D assumes a more aggressive new-build policy. The operation of new-builds will take place from 2035 with a new capacity installation rate of 1.5 GW/y from 2040 onwards. It will mean that with full restart policy (40 year lifespan) Japan's nuclear capacity will be 22.9 GW in 2050. The resulting generation will be 164 TWh/y.

Trajectory E

Trajectory E assumes the most aggressive new-build policy. The operation of new-builds will take place from 2035 with a new capacity installation rate of 2 GW/y from 2040 onwards. It will mean that with full restart policy (40 year lifespan) Japan's nuclear capacity will be 29.1 GW in 2050. The resulting generation will be 208 TWh/y. Thus, even with the most optimistic assumptions, nuclear power will only contribute to less than one-third of Japan's total electricity generation in 2050.

Together with the restart policy lever, the new-build policy lever helps the users to input their views on the extent of emphasis Japan should give on the nuclear sector. For example, even with a full restart policy, Japan will eventually phase out its nuclear capacity if a user selects no-new-build option (Trajectory A). This will mean that unless the country puts significant effort in developing the renewables sector, its dependence on fossil fuels will increase significantly, resulting in increased import dependence as well as higher level of emissions from the fuels. On the other hand, if a user chooses an aggressive new-build policy, for example, Trajectory D, then nuclear power will continue to be a major contributor in Japan's energy and electricity sector, and in controlling the country's GHG emissions as well as import dependence.

3.3 Data and Calculation Procedures[5]

All these trajectories have been developed after rigorous review of existing literature and then incorporating feedback from several expert review meetings. The trajectory assumptions interact with the fixed assumptions under this sector. Fixed assumptions are also based on existing literature and data, and include own-use requirements (as percentage of generated electricity), average transmission loss, thermal efficiency (based on gross calorific values), and legacy plant capacities (built prior to 2010). In addition to the trajectories and fixed assumptions, the Low Carbon Navigator also includes five load factor assumptions ranging from negative to aggressive.

3.4 Demonstration of Impact: Example Pathways

The Japan 2050 Low Carbon Navigator covers all the energy supply and demand sectors as well as society scenarios[6] which allow the users to create thousands of pathways for reducing emissions and ensuring energy security. The significance of each sector varies in these pathways in accordance with the user's choices. For a

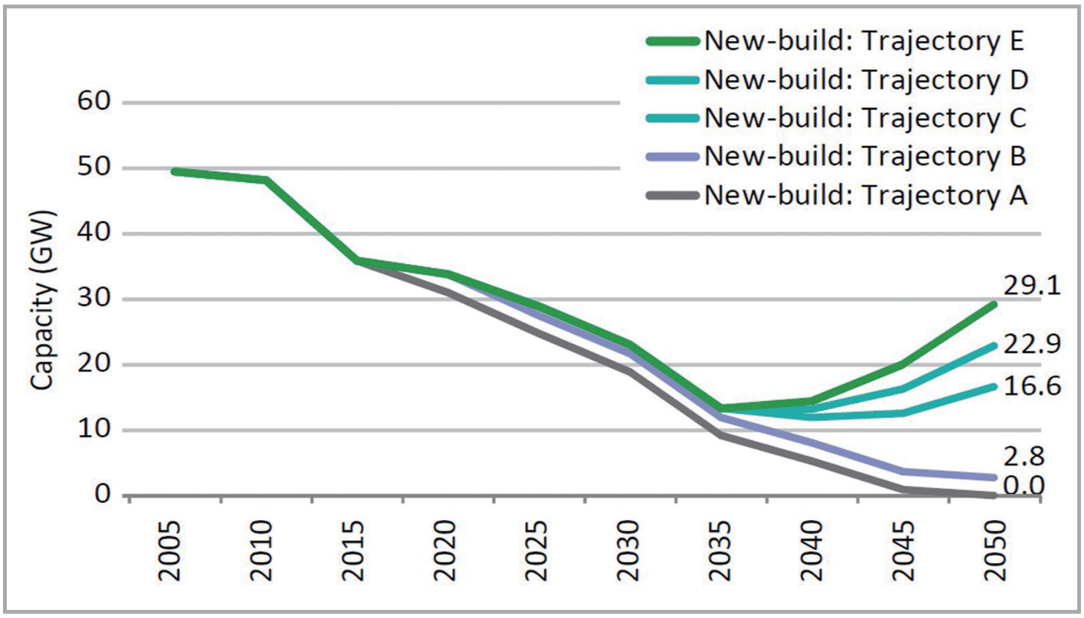

Fig. 9. Impact of new-build policy on future capacity (full restart with 40-year life assume)
Source: Source: Developed by the Low Carbon Navigator team

simplified demonstration purpose focusing on the nuclear sector under the Low Carbon Navigator, two different scenarios have been developed with varying degree of emphasis on Japan's reliance on nuclear power.

In the first scenario, Japan deprioritises its nuclear sector and puts more effort in developing its renewable energy sector. Under this renewable energy scenario, Japan does restart all of its existing nuclear reactors that have a 40-year lifespan, but abandons all the under-construction plants and does not build any new plants (Trajectory C for restart policy and Trajectory A for new-build policy). This will mean that once all the restarted plants' lifespan is expired, Japan will phase out its nuclear power generation. With these assumptions, Japan's nuclear capacity will be zero by 2050. On the other hand, all the levers under the renewable energy sectors will be set at Level 4, which is the maximum effort (but not physical limit/ technical potential) that Japan can put. Levers for conventional power generation as well as demand side scenarios are set at least-effort level (all at Level 1).

The second scenario is developed to reflect Japan's pre-Fukushima energy policy where nuclear sector is the mainstay of the country's energy supply (Trajectory D for both restart and new build policy). In this nuclear energy scenario, all the other supply side as well as demand side levers are kept at minimum level (Level 1). Society scenarios under both example scenarios are set at R&D for equal comparison. The results under these two scenarios are discussed below.

3.4.1 Power generation capacity and energy mix

[5] Since this paper focuses only on the nuclear sector in the Low Carbon Navigator, the explanation of the data/calculations procedures is limited to this sector. However, the results generated by the Low Carbon Navigator is a combination of the inputs under all the supply and demand sectors. For details about the overall data and calculation procedures, please refer to Zhou *et al*. (2014) and Moinuddin *et al*. (2015).

[6] The society scenarios allow the users to choose among five different but possible economy and society futures. For details, see Moinuddin *et al*. (2015).

Figure 10 and Figure 11 present Japan's power generation capacity and energy mix under the two example pathways. In the renewable energy scenario, Japan's nuclear power generation capacity comes down to zero by 2050. Consequently, this sector's share in electricity generation also goes down from 29 per cent in 2010 to none in 2050. On the other hand, vast expansion in renewables capacity (75 per cent of total capacity) leads to a massive increase in renewables' share in electricity

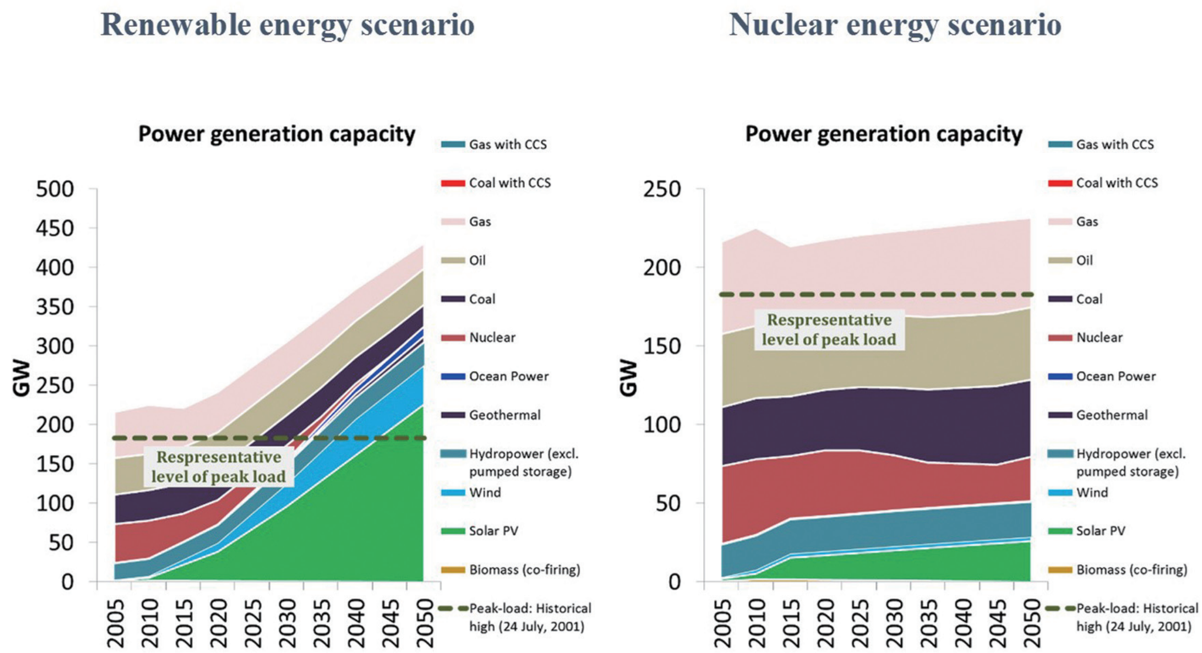

Fig. 10. Comparison of power generation capacity under the two example scenarios
Source: Authors' compilation from simulation results generated by the Low Carbon Navigator

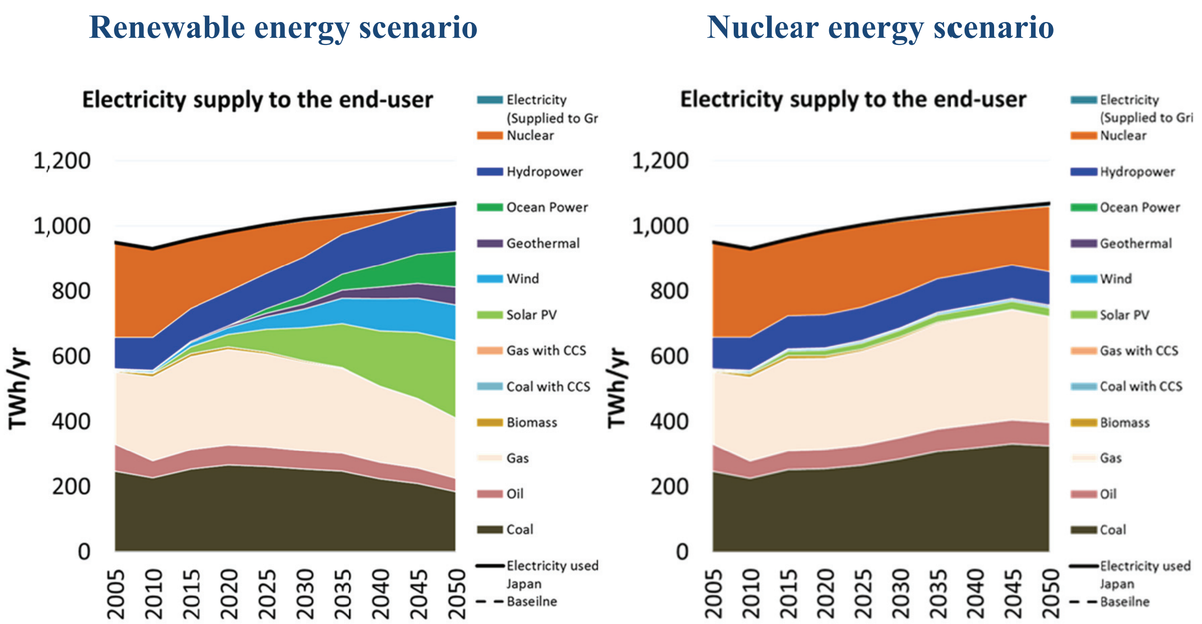

Fig. 11. Comparison of energy mix under the two example scenarios
Source: Authors' compilation from simulation results generated by the Low Carbon Navigator

generation, accounting for around 61 per cent in 2050 against 12 per cent in 2010. By default, the Low Carbon Navigator prioritises the use of renewable energy whenever the users' choices make the capacity available, with the rest filled up by conventional energy sources. Thus, the heavy expansion of renewables leads to great decrease (from 88 per cent in 2010 to below 39 per cent in 2050) in electricity generation from other sources such as coal, oil and gas. The shares of all the conventional energy sources show downward trend under this scenario.

Even in the nuclear energy scenario, the share of nuclear energy in Japan's electricity generation mix goes down from around 29 per cent in 2010 to around 19 per cent in 2050. Although plants with 50-year lifespan are allowed to restart to the full extent, many of these will retire by 2050. In addition, new builds under this scenario is allowed only after 2035. A combination of these two factors is the reason behind the decrease of Japan's nuclear capacity from 48 GW in 2010 to 28 GW in 2050. However, as this scenario assumes quite aggressive build rate of 1.5 GW/year from 2040 onwards, the capacity will increase greatly in the longer term beyond 2050. Overall shares (in terms of both capacity and energy mix) of other conventional energy sources as well as renewables will increase only marginally.

3.4.2 GHG emissions

Figure 12 shows the comparative illustration of emission reduction achievements under the two example scenarios. Despite heavy expansion of the use of renewables and reduction of the use of conventional energy sources, emission reduction under the renewables scenario is only around 30 per cent from 1990 levels. Thus Japan falls short of achieving its committed target of 80 per cent reduction (against 1990 levels) of GHG emissions.

The nuclear energy scenario does not produce a promising emission reduction picture either.

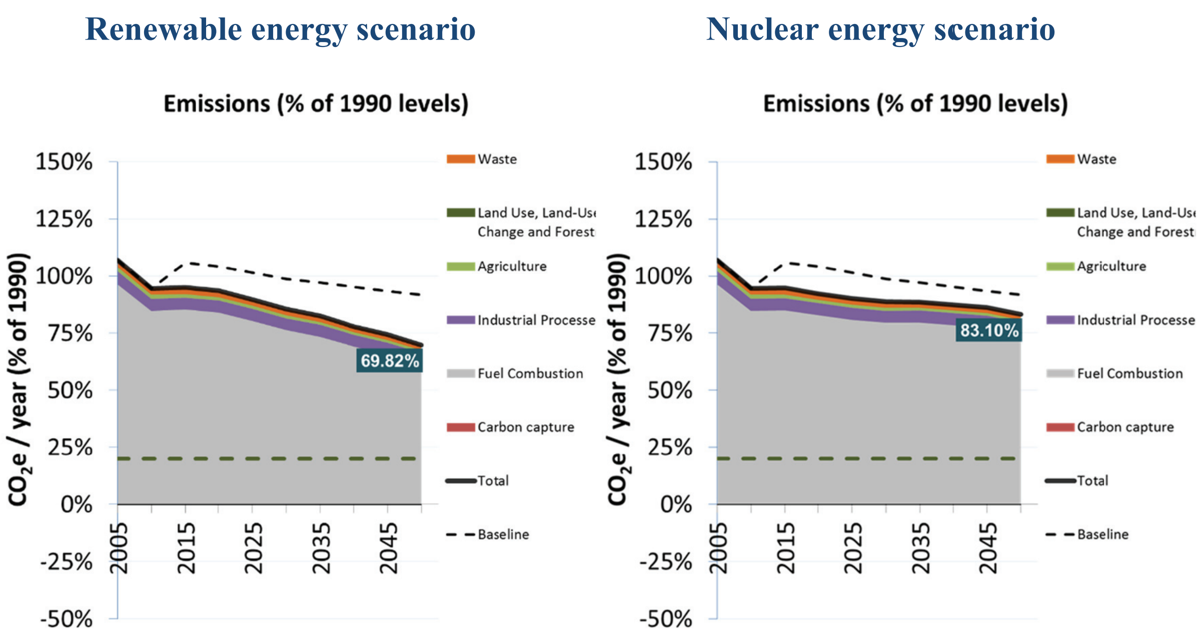

Fig. 12. Comparison of emissions reduction under the two scenarios

Note: The dotted lines on the lower side of the figures represent the 2050 target of 80 per cent reduction compared to 1990 level.

Source: Authors' compilation from simulation results generated by the Low Carbon Navigator

Under the nuclear energy scenario, the emissions reduction is only around 17 per cent compared to 1990 levels.

It is however, important to note that the assumptions under the two example scenarios focus only on supply side efforts, thereby keeping consumption patterns in the same level as in 2010 (i.e. all the levers in the demand side have been kept at Level 1 under both scenarios). It is evident from these two examples that relying solely on either nuclear or renewables without any change in the consumption pattern is unlikely to enable Japan achieve its emissions reduction targets. A combination of demand and supply side scenarios is therefore necessary. The significance of demand-side actions has already been stressed in several policy documents of Japan including the New Growth Strategy of 2010.

Given the above, another example scenario—"the great effort scenario"—is presented in Figure 13. In this scenario, Japan maximises its efforts to achieve a low carbon society by actions taken in both supply and demand side sectors. All the levers under this scenario are set at Trajectory D or Level 4. Society scenario is set at R&D. With both nuclear and renewables set at the highest level, their combined contribution to the supply mix for electricity generation is around 83 per cent in 2050, thus leaving only around 17 per cent to be filled up by other conventional fuels. More impressive contributions come from the demand side, where consumption pattern changes lead to a 45 per cent reduction in energy consumption in 2050 from the 2010 levels. These combined effects of the changes in the supply and demand sides contribute to a huge reduction of emissions by over 83 per cent compared to 1990 levels. The nuclear sector plays its part in this emissions reduction, but the contributions of renewables and consumption patter changes are also very significant, if not more important.

4. Conclusion

Realising a low carbon society will require clear direction and actions from the concerned authorities as well as participation of the country's citizens in the decision making process. An integrated approach is needed to build confidence to act, make long-term planning, be innovative, and gradually change behaviour. The Japan 2050 Low Carbon Navigator has been developed to

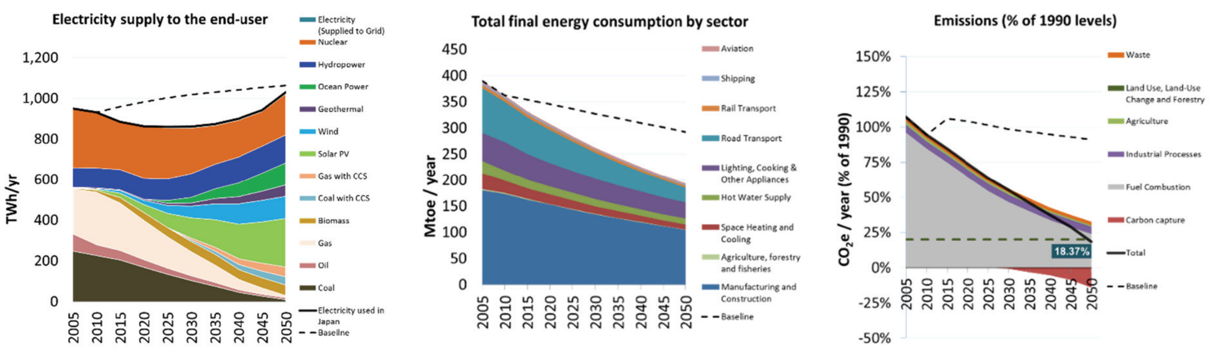

Fig. 13. Electricity supply mix, total final energy consumption and emissions reductions under the great effort scenario

Note: The dotted line at the lower side of the emissions figure represents the 2050 target of 80 per cent reduction compared to 1990 level.

Source: Authors' compilation from simulation results generated by the Low Carbon Navigator

demonstrate the scale of changes that are likely to be required for Japan to make the transition to a low carbon economy.

This paper focuses exclusively on how the nuclear power sector has been incorporated in the Low Carbon Navigator. With uncertainties surrounding the future of Japan's nuclear sector, a number of complex, unprecedented issues need to be taken into account for developing the trajectories and making the assumptions within the Low Carbon Navigator model. These assumptions and trajectories are very different from the ones in the other energy supply sectors. This paper has been prepared to explain these issues in details. The discussions of the assumptions/trajectories have been preceded by a brief discussion on Japan's nuclear power sector development, which is expected to give the audience the context of the challenges that were faced while making these assumptions and developing the trajectories. The demonstration pathways help the readers understand the significance of the nuclear sector in Japan's future energy and emissions pathways, and highlights that instead of taking policy actions in one single sector, a comprehensive approach covering both supply and demand side sectors may be required for realizing a low carbon economy.

For this, people need to understand the implications of the decisions that are made now. The Low Carbon Navigator provides a platform to facilitate such multi-stakeholder discussions and better understanding of the fundamentals of different energy mixes and mitigation options for Japan, to give wider public access and receive feedback simultaneously. The Low Carbon Navigator demonstrates the choices/trade-offs available to the country in its transition to a low carbon economy. However, it does not make predictions or projections for the future. In other words, while the Low Carbon Navigator is helpful in exploring a range of available pathways, none of these generated pathways should be prejudged as optimal.

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設定日本2050低碳領航器的軌跡：核能的複雜性與獨特性

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摘 要

日本於2011年發生地震與後續福島第一核電廠發生的核災，迫使日本政府重新思考過去採用以核能為主要能源供給的能源政策。同時，日本承諾到2050年將溫室氣體量較1990年降低80%的目標正面臨挑戰，原因在於為了降低對核能發電的依賴，已促使日本在短期間增加了化石燃料發電。在此情況下，日本目前需要面臨的選擇包括：是否要將重點放在削減能源需求或是在供給面倚重較多的低碳能源、應採用何種方式發電、以及應採用何種技術來發電。日本在這些問題上的考量對其國家的社會、經濟及環境的永續極其重要，因此若能有一項簡化的工具能提供易於瞭解的圖示，以協助了解日本在能源與碳排放方面有那些可行的選項將很有助益，而日本的2050低碳領航器即是如此。它是一項量化工具，在政策制定過程中，透過更廣泛的群眾參與能源和碳排放的討論，以協助決策支援。此工具易於使用，使用者可自行發展路徑的組合以達到減量目的及確保能源安全，並可從實際的科學數據中了解其結果帶來的衝擊。日本的核能未來充滿著不確定性，在利用低碳領航器模型發展低碳軌跡時，許多複雜的、前所未有的問題及假設均須納入考量，而這些針對核能的假設及軌跡與其他能源供給部門的差異極大。本文的目的在詳細解說如何發展核能部門的假設與軌跡，並將其整合入整個低碳領航器的模型中。本文分成數個章節，第二章提供日本核能部門的發展回顧，並簡述日本核能的發展歷史。此章同時包含目前日本面臨的挑戰，及福島核災後政府的政策發展。第三章著重在日本2050低碳領航器中核能的假設與軌跡設定。其中討論了做假設時須考量的問題、相關的資料來源、及解釋在低碳領航器模型中的計算過程。此章同時提供幾個經由低碳領航器模擬產生的示範路徑，這些範例展示了日本未來的能源與排放路徑中對核能的衝擊。第四章除作總結外，並對低碳領航器的功能及限制作些許的說明。

關鍵詞：日本2050低碳領航器、核能、能源與排放

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