Balancing Japan's Energy and Climate Goals: Exploring Post-Fukushima Energy Supply Options

Report of the Disaster Study Project conducted jointly by Economy and Environment Group (EE) and Climate Change Group (CC)

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Summary

This study assessed the implications of a long term phase-out of nuclear energy supply in Japan toward 2050 and its replacement with renewable energy, based on an assumption that technical issues related to intermittency are taken care of. This study performed two sets of energy scenario analyses using the TIMES Integrated Assessment Model (TIAM-WORLD), a technology-driven bottom-up energy model. The indicators used for the comparison are: (1) total energy supply system cost, (2) amount of fossil fuel imports, and (3) CO_2 emissions. The first analysis (Analysis I) assesses the implications of the preferred energy choices between renewable energy and fossil fuel, to compensate the nuclear power phase-out by 2050 in the absence of a mid- to long-term GHG emissions reduction target. The second analysis (Analysis II) investigates the future energy mix to achieve an 80% reduction in CO_2 emissions by 2050 compared to the 1990 level with and without a gradual phase-out of nuclear power.

The result of Analysis I indicates that the total final energy consumption drops from 310 million tons of oil equivalent (Mtoe) in 2009 to 210-220 Mtoe in 2050, depending on the scenario. The major reasons for such reduction are a steady decline in population, number of households and other demographic factors by 2050 and changes in economic structure via reduction in domestic industrial production. The renewable energy dependent scenario is estimated to be only 0.2% more expensive than the fossil fuel dependent scenario in terms of the discounted total energy system costs of each between 2005 and 2050. The incremental energy system cost for the renewable energy scenario is estimated to be around 0.04% of national GDP, while the renewable energy scenario contributes to a national wealth saving by lowering fossil fuel imports significantly to the point of almost complete offset of the total system cost increase.

Analysis II shows that final energy consumption drops to 200 Mtoe in 2050 under both scenarios of with and without a gradual phase-out of nuclear power, reflecting a more stringent CO_2 emissions reduction compared to Analysis I. Most of the final energy consumption shifts from primary fuel to decarbonised electricity added with carbon capture and storage (CCS) to achieve the 80% target without the use of nuclear power. In the nuclear phase-out scenario, wind and solar power plants are expected to be installed to the capacity limit of 80 GW and 176 GW respectively, by 2050. The CCS requirement is doubled in the nuclear phase-out scenario compared to the pre-Fukushima energy plan (i.e., nuclear-based) achieving the 80% CO_2 reduction target. The additional need for CCS is estimated to be around 170Mt/yr in 2050 over the pre-Fukushima energy plan, and the increase in annual total energy system cost for the nuclear phase-out scenario compared to the nuclear scenario is estimated to be on average around 0.13% of national GDP.

This study brings forth a set of policy measures that can be prioritised in Japan in order to ensure long term energy security while meeting the long-term CO_2 reduction target. The key messages of this study are: i) that transition from a fossil-fuel/nuclear dominated energy mix to a renewable energy dominated fuel mix is feasible from an economic point of view, and ii) Japan’s target of 80% CO_2 emission reduction by 2050 compared to the 1990 level is economically feasible provided certain conditions are met. Whether or not this target is met hinges on an escalated deployment of renewable energy, use of advanced technologies for conventional power generation and deployment of economically viable CCS technology. The study concludes with the opinion that Japan can be cautiously optimistic about achieving its long term emissions reduction target by 2050 if all the enabling policies are put into place in a timely manner.

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The base model and its reference case used in this study are developed and maintained by KanORS/KanLo (www.KanORS-EMR.org/DCM/TIAM_World). It is also recognized here the valuable contribution of Dr. Amit Kanudia in terms of setting the technical details of the model and its calibration.

We present this report before you with the confidence that we are successfully able to address one of the most important and policy relevant topics for Japan in the post-Fukushima period which will help contribute to the policy making towards low carbon development in Japan as well as in the Asian region.

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Abbreviations

bbl	Barrel = 117.3 litres
COP	Conference Of Parties of the United Nations Framework Convention on Climate Change
CSP	Concentrated Solar Power
EJ	Exajoule = 10^{18} joules
FIT	Feed-In Tariff
FY	Fiscal Year (in Japan, fiscal year begins on 1 April and ends on 31 March)
GHG	Greenhouse Gases
GW	Gigawatt = 10^{9} watt
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IEEJ	Institute of Energy Economics, Japan
IGCC	Integrated Gasification Combined Cycle power plant
IGES	Institute for Global Environmental Strategies
IPCC	Intergovernmental Panel on Climate Change
JPY	Japanese Yen
kW	Kilowatt = 10^{3} watt
kWh	Kilowatt-hour
LHV	Lower Heating Value
LULUCF	Land Use, Land Use Change and Forestry
Mbtu	Metric British thermal unit = $1.055*10^{3}$ joules
METI	Ministry of Economy, Trade and Industry, Japan
MoEJ	Ministry of the Environment, Japan
MW	Megawatt = 10^{6} watt
NEDO	New Energy and Industrial Technology Development Organization
NGCC	Natural Gas Combined Cycle power plant
NPO-REN	Nuclear Phase Out – Renewable energy promotion scenario
NPO-FF	Nuclear Phase Out – Fossil Fuel dependent scenario
NPO-LC	Nuclear Phase Out-Low Carbon scenario
NPU	National Policy Unit, the government of Japan
O&M	Operation and Maintenance
PC	Pulverized Coal power plant
PV	Photovoltaic
RPS	Renewable Standard Portfolio
REF	Pre-Fukushima Reference scenario
REF-LC	Reference-Low Carbon scenario
TOE	Ton of Oil Equivalent = $41.868*10^{9}$ joules
TWh	Terawatt-hour = 10^{12} kWh
UNFCCC	United Nations Framework Convention on Climate Change
USC	Ultra-SuperCritical
USD	U.S. dollars

1 Introduction

1.1 Background

As one of the largest primary energy consumers in the world Japan has relied heavily on nuclear power not only to meet a significant share of its electricity demand but also to minimise the cost of petroleum imports. Japan is endowed with only a negligible quantity of fossil fuel resources compared to how much it consumes. Despite the key role Japan played in developing renewable energy technology in the preceding decade[1] (Japan Renewable Energy Policy Platform, 2009, 2010), fossil fuels and nuclear energy have maintained their dominance, leaving the renewables sector on the sidelines.

This was so until the nuclear disaster at Fukushima, which has led to some inevitable changes in Japan's domestic energy policy framework towards a higher reliance on alternative supply sources. Allied with this deep shift in energy policy are concerns surrounding the availability, affordability and sustainability of transitioning to an alternative energy supply.

In order to comprehensively reformulate Japan's energy and environmental strategies, the government set up the inter-ministerial Energy and Environmental Council under the National Policy Unit in June 2011, which is tasked with developing an "Innovative Strategy for Energy and Environment" (hereafter, "Innovative Strategy") before summer 2012 (NPU, 2011a). The three core principles of the Innovative Strategy are:

1. Realisation of a new best mix of energy sources
   - Draw up a scenario of reduced dependence on nuclear energy
   - Utilise a clear and strategic schedule to avoid energy shortfalls and price rises
   - Conduct a thorough review of nuclear power policies and operate under a new framework
2. Realisation of new energy systems
   - Distributed energy system (as opposed to the current centralised energy system dominated by local monopoly-based power utilities)
   - Seek to make an international contribution as an advanced problem-solving nation
3. Formation of national consensus
   - Stimulate national discussions to overcome the confrontation between nuclear proponents and opponents
   - Verify objective data
   - Formulate innovative energy and environmental strategies while maintaining

[1] Japan's renewable energy market has remained frozen due to market policies for renewables not being sufficiently examined or implemented. Solar and wind power sectors reflected annual growth of more than 30% between 2000 and 2004, but slowed down due to discontinuation of subsidies.

dialogue with a broad range of national figures

Issues surrounding the feasibility and public acceptability of the continued reliance on nuclear power are hot debate topics in present day Japan. One thing is clear, however, and that is that the new energy policy framework is unlikely to follow that outlined in the 2010 Strategic Energy Plan (METI, 2010), which advocated an almost two-fold increase (26% to 50%) in nuclear power usage from that in Fiscal Year (FY) 2007.

Going forward, the resulting reduced dependence on nuclear power may also have significant consequences on Japan's greenhouse gases (GHG) reduction strategy. Regarding the medium term GHG emission reduction target following the first commitment period of the Kyoto Protocol, Japan made a pledge at the 15th UNFCCC Conference of Parties (COP15) to reduce its GHG emissions by 25% by 2020 compared to the 1990 level, which is "premised on the establishment of a fair and effective international framework in which all major economies participate in an agreement by those economies on ambitious targets" (Government of Japan, 2010). The 25% target has also been enshrined in the Bill of the Basic Law on Global Warming Countermeasures, together with an 80% reduction compared to the 1990 level by 2050. METI also presented its mid- to long-term[2] plan on GHG emissions reduction (30% by 2030 and 80% by 2050 compared to 1990 level) in the 2010 Strategic Energy Plan, which is heavily reliant on increased input from the nuclear sector. The Bill of the Basic Law on Global Warming Countermeasures will likely be resubmitted to the Diet after the Innovative Strategy is developed. However, in the current political climate it is unclear whether the quantitative reduction targets for 2020 and 2050 will be enshrined in the Bill.

1.2 Rationale and Objectives

There are a number of reports to date covering the consequences of reducing the share of nuclear energy in Japan's energy mix, electricity generation costs, and CO_2 emissions (IEA, 2011a; IEEJ, 2011). These studies indicate that the shortfall in power will be met by increased fossil fuel-based power generation, but with the role of renewable sources limited at least in the medium term (to around 2030)[3] and possibly also in the long term[4].

Such observations, however, do not account for the many benefits of adopting renewable-energy based systems. First, considering the supply cost, transition to a renewable-based electricity system will likely be more expensive in the short term due chiefly to high investment costs. However, renewables will provide a significant fuel cost saving when hikes in fossil fuel prices are factored into the long term (e.g., IEA, 2011). Second, Japan is likely to pursue a course of significant decarbonisation of its economy over the long term and the costs for emitting CO_2 will likely rise too. Under such circumstances, it is apparent that renewable energy technologies become that much more economically attractive. Third, with regard to Japan's dependency on imported fossil fuels, there are challenges in terms of supply security and an additional burden on the energy bill. The use of renewables over fossil fuels has the potential to

[2] In this study, "mid- to long-term" refers to the period between 2020 and 2050.

[3] In this study, "medium term future" and "medium term" refers to the period between 2020 and 2030.

[4] In this study, "long term" refers to the period between 2040 and 2050.

avoid such risks.

The objective of this study is to assess the technical and economic implications of a long-term phase-out of nuclear energy supply in Japan by 2050, with emphasis on increasing the supply from renewables. The research posits the following questions:

1) If nuclear is to go by 2050, what are the implications for its replacement(s) (renewable energy or fossil fuel), on the energy mix, total energy supply system cost, fossil fuel imports and CO_2 emissions?
2) To achieve mid- to long-term (2020-2050) CO_2 emission reduction targets, what are the impacts of a gradual phase-out of nuclear by 2050 on the energy mix, total energy supply system cost, fossil fuel imports and CO_2 emissions?

The energy-economic analysis presented in this study was performed via the TIMES Integrated Assessment Model (TIAM-WORLD), a bottom-up technology-driven energy systems model. This paper first provides the rationale behind this research in Section 0. Following this, the research methodology used for energy-economic modelling is described in Section 0. The results are presented in Section 0. Section 0 discusses the implications of the results and the limitations of this study. Finally, conclusions are drawn and policy recommendations are made in Section 0.

2 Context Surrounding this Study

This section covers Japan's energy supply system and the implications of the Fukushima accident on the future energy supply in Japan.

2.1 Overview of Japan's Energy Supply System

Being one of the largest energy consumers in the world Japan has acted as a major catalyst in the global energy supply market. A lack of domestic fossil fuel reserves and high dependency on imports tightly tethered the country to the global energy market. As well as the scientific gains of developing Fast Breeder Nuclear technology and participation in the International Thermal Experimental Reactor (ITER), the role played by Japanese industry in developing and promoting nuclear technology also aided in placing Japan on the map as a safe country in terms of civil nuclear energy.

2.1.1 Electricity Sector in Japan

Japan's electricity sector has been guided by the Basic Act on Energy Policy, passed in 2002 (Act No. 71 of June 14, 2002). The three pillars of Japanese energy policy are: 1) securing a stable energy supply; 2) assuring environmental compliance; and 3) utilising market mechanisms with due consideration accorded to energy supply stability and environmental compliance (METI, 2010). The Strategic Energy Plan was formulated in 2003 to articulate the fundamental direction of Japanese energy policy based on the Basic Act on Energy Policy. The electricity mix for 2007 (Figure 1) shows that about 80% of total electricity generation is attributable to liquefied natural gas (LNG), coal and nuclear, with each fuel type accounting for a similar share.

The Strategic Energy Plan was revised for the second time in 2010 to add perspectives on energy-based economic growth structural reform of the energy industry as distinct from detailing the goals to 2030 (METI, 2010). This policy was heavily biased in favour of an increased share of nuclear energy, though unrealistic in nature, in the electricity mix. As shown in Figure 1, an additional 14 nuclear reactors were planned to be added to the existing fleet in spite of the continuous delays in commissioning new power plants. A projection of this energy mix scenario to 2030 showed noticeable differences in the electricity supply pattern from that in 2007. Renewable electricity generation is also projected to increase, but only up to about 20% of the total.

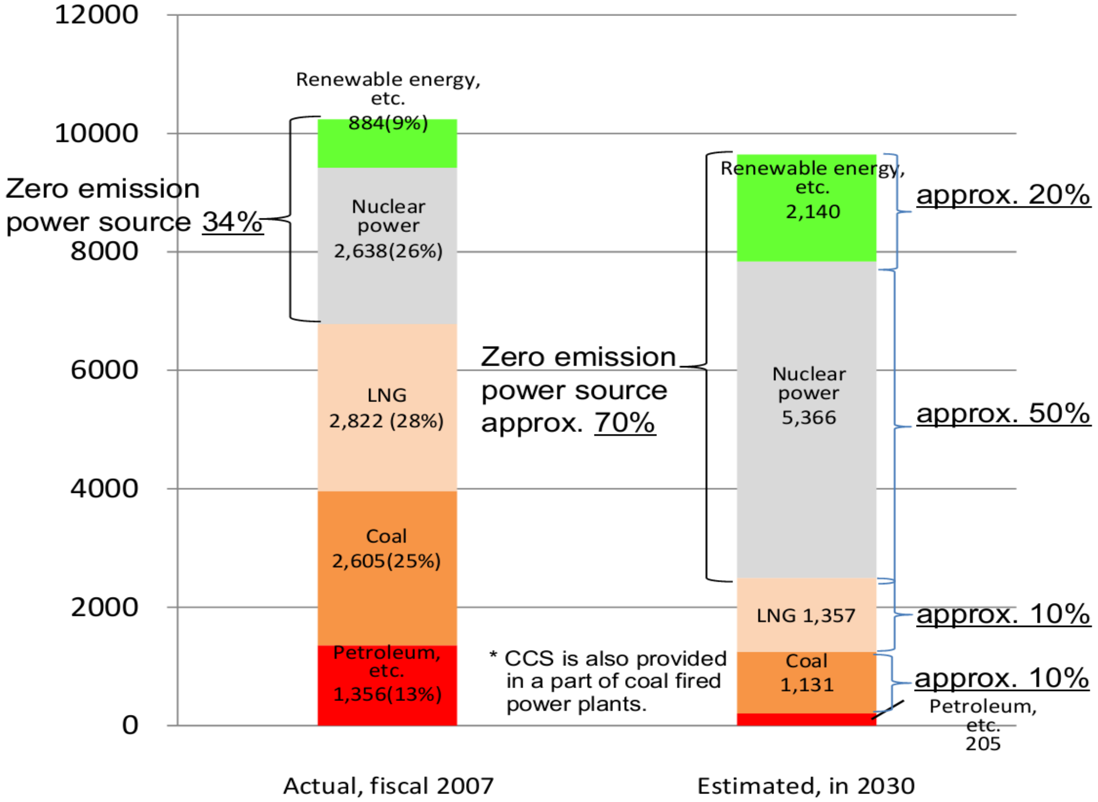

Figure 1 Electricity mix in Japan (in 100 million kWh): 2007 data and the projection for 2030 made in the 2010 Basic Energy Plan (METI, 2010)**.**

2.1.2 Renewable Energy Sources: Resource Availability and Potential

Japan has a huge potential for renewable energy. Table 1 gives the latest estimates (Ministry of the Environment, Japan (MoEJ, 2011a)). As can be seen, although there is significant potential for various renewable electricity sources, this potential has yet to be fulfilled.

Table 1: Estimates on renewable energy potential. Source: Theoretical data obtained from MoEJ (2011) and 2009 capacity data obtained from IEA (2011a). N.A.: not available

Technology		2009 capacity (GW)	Potential (GW) 1)					
			Abundance	Introduction potential				
				Maximum introduction potential	Possible amount of introduction under FIT scenario			
					FIT only	+Tech. Innovation	+Subsidy	+Innovation +Subsidy
PV	Residential (2030)	2.63	207 [2]	45-75 [2]	N.A.	N.A.	N.A.	N.A.
	Non-residential		-	150	0	0.2-72	0-26	69-100
Wind	Onshore	2	-	280	24-140	270	130-260	280
	Offshore			1600	3	140	0.3-330	1200
Small hydro (<30 MW)		1.4 [3]	17	14	1.1-3	4.3	2.7-5.4	7.4
Geothermal		0.54	33 [4]	14	1.1-4.8	5.2	1.5-4.3	4.6
Biomass (100%, no co-firing)		N.A.	N.A.					

1) Definitions of terms used above:

Abundance: the amount of energy resources which can be theoretically estimated by the feasible area for system installation, mean wind velocity, river discharge or other relevant factors. It excludes the amount of energy which is difficult to utilise based on the current technological level and does not take various limiting factors (land inclination, legal restrictions, land use, distance from a residential area and others) into consideration.

Introduction potential: the amount of energy resources which take various limiting factors for energy collection and utilisation into consideration.

Possible introduction amount under scenario: the portion of the introduction potential which can hopefully be realised for actual use under a specific scenario (assumptions) for project viability.

2) The reference quotes NEDO 2004 study for these figures (MoEJ, 2011a).

3) Figure for autoproducers.

4) A survey by the National Institute of Advanced Industrial Science and Technology (AIST) also shows similar estimates that Japan has a potential of 23 GW (Muraoka, 2009).

Regarding research and development (R&D) activities, Japan played a major global role in the development of solar energy from the late 1990s until several years ago. What has been lacking, however, is any substantial policy support for raising the share of renewables in Japan's energy mix, despite a promising government subsidy initiative for domestic PV systems that started in FY1994–a key factor that helped kick-start the solar industry. The subsidies died off from FY2006 to FY2008, however, leaving Japan trailing behind Spain and Germany in total grid-connected PV installed capacity (Japan Times, 2011). Regarding financial incentives for renewables, in 2003 the Renewable sources Portfolio Standard (RPS) act (Act on Special Measures Concerning New Energy Use by Operators of Electric Utilities (Act No. 62, 7 June, 2002)) entered into force with a 12.2 TWh target for 2010—about 1% of total electricity generation. In 2009, the Feed-In Tariff (FIT) scheme for PV electricity was introduced, but the scheme was only applicable to PV installation below 500 kW and to excess electricity generated (net metering). On the surface, Japan appeared to be promoting renewable energy technologies but suffered from a basic lack in implementing such on the ground to generate a worthwhile amount of electricity. Indices on the attractiveness of countries for renewable energy (Ernst & Young (2012)) show Japan's poor performance in this area: Japan ranked 16th out of 40 countries, behind China, U.S., Germany, and India. No awards were received from the Global Wind Energy Council either, which ranked Japan at the dismal level of 20 in terms of yearly growth of wind capacity in 2011 (GWEC, 2012).

2.1.3 Transmission and Distribution Infrastructure and Legal Facilities

A transmission and distribution infrastructure and its related regulatory and legal facilities are critical for the large scale deployment of renewable energy in the national energy mix. In Japan, a major bottleneck preventing such is a lack of unified transmission and distribution infrastructure that is technically capable of withstanding the intermittency in the grid supply caused by renewable energy and also able to maintain power supply quality. Other major hurdles are the difference in utility frequency between East and West Japan (50 Hz in the east, 60 Hz in the west) and poor interconnectivity among regional power companies. Unified national grid can work as a first tire buffer to gird instability caused by intermittency of power wheeling. Moreover, Japan also lacks market regulation and legal facilities to encourage third party power providers (usually comprised of small-scale independent power producers in remote areas) to harness remote renewable energy resources such as small hydro, small and midsize wind, solar PV, and biomass. Figure 2 shows the Grid interconnectivity in Japan. For example, Tohoku and Hokkaido regions have significant wind power potential but relatively low electricity demand. If large-scale wind power deployment were to take place a large fraction of wind power would have to be exported to other regions such as Tokyo to match supply and demand. This is not currently possible, however, as the transmission capacity between Tohoku and Tokyo regions is very small.

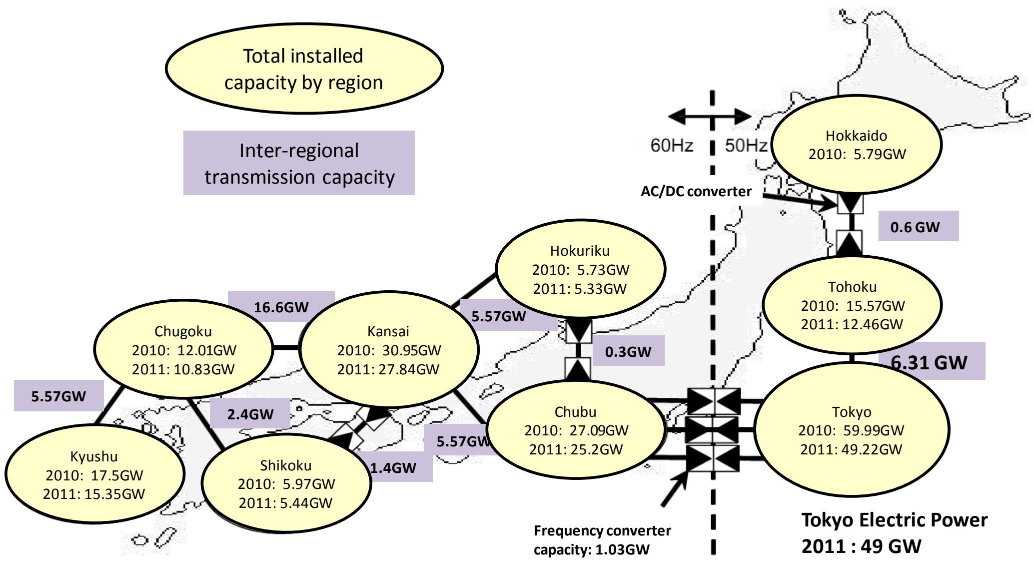

Figure 2: Grid interconnectivity in Japan. Source: Adapted from (METI, 2011).

2.2 Implications of the Fukushima Accident

The Fukushima nuclear accident generated two different sets of global debates: first, the risk of nuclear energy especially for countries like Japan, and second, energy security and corresponding economic impact without nuclear energy. With the increasing public concern over the reliance on nuclear power in Japan and with plans for a nuclear phase-out in Germany[5] a serious policy dilemma is emerging across the world over the long term dependency on nuclear power with the current level of safety and technology. That the dilemma has precipitated into public protests against the nuclear industry in India, Italy and France very vividly highlights this trend. Very recently the IAEA (International Atomic Energy Agency) published its forecast for nuclear power plants based on the impact of the Fukushima nuclear disaster, which is a 7 to 8% drop (depending on the low and high growth scenarios, respectively) in new capacity addition by 2030 compared to the data published before the accident in 2010 (IAEA, 2011).

In contrast, the alternative energy sector has been gaining more policy attention in many countries despite the myths of technical complexity and prohibitive costs. The renewed interest in the alternative energy sector in Japan since the end of last decade[6] and the need for more alternative sources in the aftermath of the Fukushima incident have resulted in renewable energy emerging as a real alternative to the conventional fossil-fuel/nuclear choice.

After Fukushima, much has happened in the arena of renewable energy policy too. For example, the Act on Special Measures concerning the Procurement of Renewable Electric Energy by Operators of Electric Utilities (Act No. 108, 30 August 2011) obliges electric utility operators to purchase all electricity generated (i.e., not net metering) from most renewable energy sources[7] to boost the deployment of renewable sourced electricity. Although the level of renewable electricity deployment largely depends on the FIT levels, which are expected to be determined in the coming months, expectations for large-scale renewable energy deployment in the coming decades are high.

2.2.1 Replacing Nuclear with LNG and Other Fuel Imports: Possible Consequences

The importance of fossil fuel in Japan's energy mix grew significantly after the Fukushima accident. Further, many of the nuclear reactors over Japan have had to be taken offline for routine inspections and stress tests in order to ensure safety. In such a climate, and as Japan is already a major consumer of fossil fuels, further reliance on them has been seen as a quick fix for the shortfall in nuclear in the supply mix. A higher dependence on fossil fuel in the short term thus has several advantages, such as

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[5] Though the nuclear phase-out plan in Germany was not a direct response to the Fukushima incident, Fukushima has undeniably catalysed greater anti-nuclear public sentiments in Germany.

[6] Interest in renewables rose at the end of last decade due to various reasons. At the G8 Summit in Tokyo, Solar Power was recognised as a potential long-term supply source for the country. This has paved the way for Japan to more proactive support of solar PV (Japan Renewable Energy Policy Platform, 2010).

[7] Includes wind, solar, small hydro (<30MW), geothermal and biomass that does not affect existing industrial processes such as pulp and paper production.

avoiding immediate cash outflow for *green field* projects for alternative energies, utilising existing supply infrastructures at full capacity and using the same technical expertise and human resources without any additional costs for training on new technologies. However, the basic math of substituting around 250 TWh of nuclear energy by fossil fuels mainly via LNG represents a mammoth task for the utility companies. Fortunately, Japan has sufficient infrastructure to import, process and transport additional LNG import; Japan's LNG import capacity is currently around 180 million tons and in FY2010 it imported around 70 million tons. Following the outage of nuclear reactors demand for LNG mainly for power generation has surged many times over. In the first quarter of FY2011 Japan imported around 20% more LNG compared to the same period of FY2010 (METI, 2011). The Institute of Energy Economics in Japan (IEEJ) estimated that an additional supply of 6.2–8.6 million tons of LNG was required for the whole year of 2011. Though Japan is already the largest LNG importer in the world (35% of the world's total tradable LNG in 2010 (pre-Fukushima)) and has sufficient reserve capacity for additional LNG imports, the financial burden placed on post-Fukushima Japan of importing the necessary LNG would be crippling to its economy. It thus appears the major impact of the post-Fukushima energy import scenario would be in the realm of economics rather than technical feasibility. Continuous rises in LNG imports also lead to market price hikes (the spot price in Asia stood at 13.5 $/MBtu at the end of May compared to 10 $/MBtu pre-Fukushima (Hashimoto and Shimao, 2011)) which can only lead to steeper costs for energy imports. Simply adding an adverse Yen value on world markets into the equation could easily tip the trade balance. Not surprisingly, by the end of FY2011 Japan had recorded its lowest ever current account balance in 20 years. The Long-term implications for continued fiscal weakening can only lead to currency devaluation, downgrading of the country's credit rating and could even precipitate a sovereign debt crisis, as is currently being witnessed in Europe.

2.3 Priority and Risks Associated with Various Energy Sources

The quest for the best mix of energy sources has always been a challenge for Japan. Table 2 presents the Priority-Risk matrix for different fuel type options. The assessment used here is indicative in nature to illustrate commonly held perceptions concerning what each type of fuel represents in terms of its effects on the country. The matrix helps evaluate the suitability of these fuel types in Japan based on the factors of energy security, climate goal, self-reliance, and public acceptance.

Table 2 Priority - Risk matrix for different fuel types in the Japanese context.

Fuel Types / Policy targets	Fossil Fuel Dependency		Renewable Dependency		Nuclear Dependency	
	Priority	Risk	Priority	Risk	Priority	Risk
Climate Targets	Low (Due to High emissions)	High (high emissions damage environment)	High (cleaner energy supply)	Low (Low environmental damage)	High (low GHG emission)	Low (low GHG emission)
Energy Security	High (currently constitutes <80% of Primary energy mix)	High (supply security, geopolitics resource extinction)	High (self-reliance in supply if developed adequately)	Medium (intermittency concerns)	High (less dependency on fossil fuel, meeting demand in key sectors)	Low (fuel & technology are relatively less vulnerable to geopolitics)
Self-reliance	Low (overseas dependency)	High (reliance on politically volatile supply sources)	High (Low overseas dependency, enhanced domestic supply capabilities)	Low (domestic supply)	Medium (Higher role in electricity supply)	Medium (domestic technology but overseas fuel dependency)
Domestic economy	High (currently constitutes <80% of Primary energy mix, indicates greater role played in domestic economic activities)	High (High energy bill)	High (Low overseas dependency)	Medium (if equipment and services outsourced, high capital cost, intermittency)	High (major supply sources for domestic economic activities)	High (expenses on spent fuel management, overseas dependence for reprocessing, need for long term fuel imports, etc.) pose burdens on economy
Public Acceptance	High (no major challenge compared to nuclear dependency)	Low (no major challenge compared to nuclear dependency)	Medium (perception of low vulnerability to external challenges, perception of no fuel cost)	High (perception of high electricity cost)	Low (perception of radiation effect, historical perception based on WWII experience)	High (radiation hazards to environment and human health, vulnerable to major natural disasters, seismic sensitivity)

Note: The table is indicative based on perceptions of risk and priority of each fuel type.

In terms of prioritising GHG emissions, fossil fuel dependency is of low priority and is high risk for a country having high fossil fuel dependency.[8] If energy security is prioritised, dependence on low cost fossil fuels is important and is low risk. However, the advantages of fossil fuels do not fully compensate the risk of its price fluctuation in the international market, which is often beyond the control of any individual country. Nevertheless, fossil fuels are expected to a play major role in the energy supply market in the foreseeable future. In contrast, renewable energy is high priority if GHG mitigation targets are prioritised, regardless of problems of intermittency in supply and the front-loading capital cost structure. Renewable energy hence demands continuous policy support on all fronts–technology, finance, and market regulation. Nuclear is similar in nature to renewables in terms of its front-loaded capital cost structure but differs in technological and regulatory issues. Historically, Nuclear energy in Japan has benefitted from steady policy support from the Government in terms of technology development and regulation, and no perception of risk had materialised prior to Fukushima. Presently, the most noticeable challenges for nuclear energy are a lack of public acceptance, concerns over spent fuel management, radiation issues, and seismic sensitivity.

3 Modelling Methodology

This section describes the methodology underpinning the modelling analyses performed in this study. We used the 16-region TIMES Integrated Assessment Model (TIAM-WORLD) with a primary focus on Japan's energy supply system. Major attention was given to the electricity supply system of Japan as we deal with the issue of nuclear energy displacement in the supply system. More precisely, in this model we assumed uniform energy supply and demand for all other regions, except for systematic endogenous changes modelled at the base level linked to the supply and demand drivers and other factors.

This section describes the energy system techno-economic model used for the analyses (TIAM-WORLD), then the modelling assumptions on energy demand drivers, energy supply scenarios and energy conversion technology data.

3.1 General Description of the Model Used in this Study

The TIMES Integrated Assessment Model (TIAM-WORLD) is used in this study to project energy mix, energy costs and CO_2 emissions (see, e.g. Loulou, 2007; Loulou and Labriet, 2007; KanORS, 2012 for more details on TIAM-WORLD). TIAM-WORLD is developed, maintained, and utilised in various EU and other international projects, and served as the starting point for the global energy system model used by the Energy Technology Program (ETP) at the IEA (KanORS, 2012). TIMES is a technology-rich model that integrates the entire energy/emission system of the world, divided in 16 regions (one of which is Japan), including the extraction, transformation, trade, and consumption of a large number of energy forms. The economic paradigm of TIMES is the computation of an inter-temporal partial equilibrium on energy and emission

[8] A country that depends on the fossil fuel sources to run its economic activities. With regard to a consumer country the terminology can be used if fossil fuels serve as the major source of energy to fuel its domestic economic activities or more precisely if the share of fossil fuels is higher than other primary energy sources the country depends on. For a producer country the terminology 'fossil fuel-based economy' can be used if that serves as the largest source of national revenue.

markets based on the maximisation of total surplus, defined as the sum of suppliers and consumer surpluses. TIMES is designed to arrive at a minimal discounted total energy system cost for the entire modelling period. The total energy system cost includes capital cost, and variable and fixed operation and maintenance (O&M) costs on both the demand and the supply sides. The detailed technological modelling of the energy system of TIAM-WORLD allows energy flows, prices, technology uses, net GHG emissions and concentrations (Loulou, 2007; Loulou and Labriet, 2007; KanORS, 2012) to be computed.

Figure 3 is a schematic flow diagram of the TIMES/MARKAL model family. TIAM-WORLD comprises the following four components: energy service demands, energy supply, techno-economic data of energy technologies, and policy scenarios.

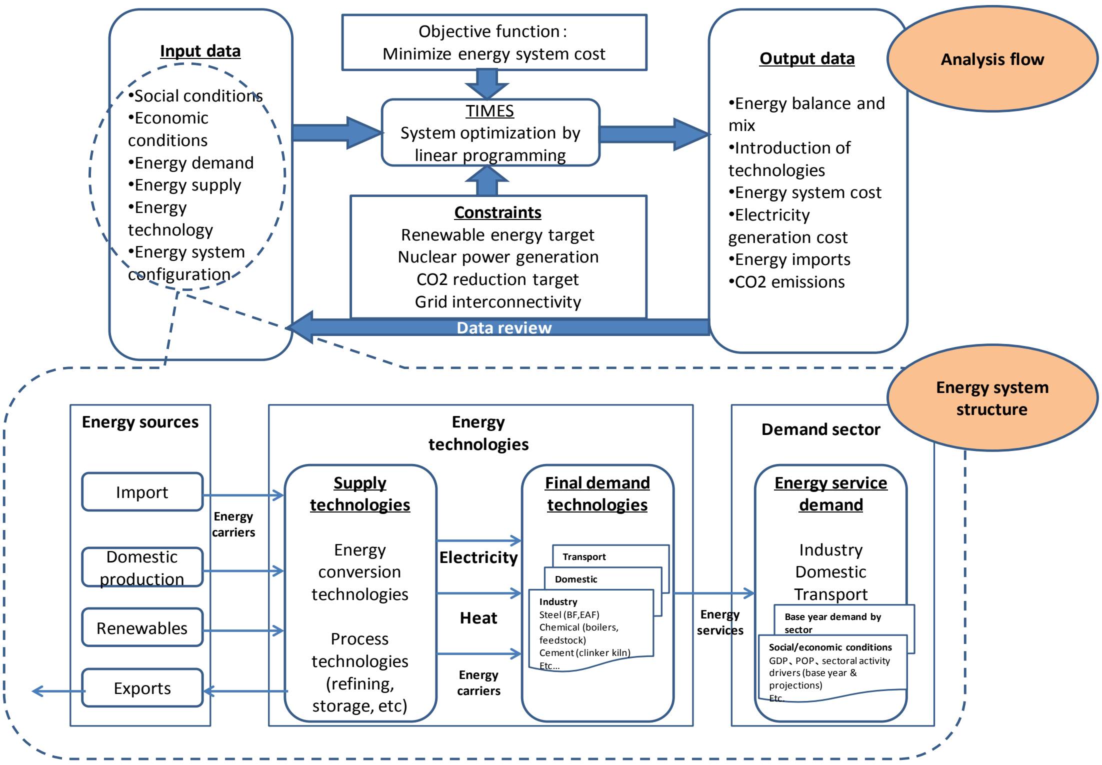

Figure 3: Schematics of analysis flow and energy system structure of the TIMES model (adapted from Sato, 2005).

Energy service demands are calculated based on the quantified activity drivers and elasticities of demands to their respective drivers. Elasticity represents how strongly the demand follows the changes of the driver. Energy technologies convert primary energy sources to energy services; TIMES contains technical and economic descriptions of more than 1,500 technologies and several hundred commodities in each region. Primary energy resources are disaggregated by type and multi-stepped supply curves are generated for each primary energy form, with each step representing the potential of the resource available at a particular cost. Lastly, regarding policy scenarios, TIAM-WORLD enables incorporation of various policy scenarios, including renewable energy installation capacity targets and CO_2 emission caps (Loulou and Labriet, 2007).

3.2 Key Modelling Assumptions

The model calculation was performed for the period 2005-2050 at the 2050 time horizon. All cost figures related to TIAM-WORLD are expressed in USD_{2000}, unless otherwise stated. When cost data expressed in other currencies or USD from other years is used for the model, the cost data is firstly converted to USD of the current year, then converted to USD_{2000} by applying an inflation index. In this study two sets of inflation indexes are used for different commodities. For power plant capital cost data, the IHS CERA Power Capital Costs Index (IHS CERA, 2012) was used. For other commodities, the U.S. Consumer Price Index (U.S. Bureau of Labor Statistics, 2012) was used. See Appendix A for more details. Regarding the cost optimisation in the model, the discounted total energy system cost for 2010-2050 is calculated using a discount factor of 5% and the selection of energy technologies is based on an internal rate of return (IRR) of 10% in this study[9].

3.2.1 Energy Demand Drivers

TIAM-WORLD calculates future energy service demands based on the projections of various demand drivers such as national and per capita GDP, population, number of households and sectoral production growth rates. In this study, we refer to the set of macroeconomic drivers presented in the Post-2013 Mid- to Long-Term Policymaking Subcommittee of the MOEJ Central Environment Council's Task Force on Global Environment (hereafter, "Post-2013 Subcommittee") (MoEJ, 2011b). The selected set of demand drivers is based on an assumed extended growth case from the activity projections used to generate the 2020/2030 emissions roadmap in FY2010 (MoEJ, 2011b). The demand driver set used in this study also takes into account the energy demand reduction due to behavioural changes. Note that the demand drivers and the future energy service demands depend largely on how the future society, economy, and technology development are envisioned.

Table 3 shows the assumptions on key energy service demand drivers and the exogenous fossil fuel prices used in the model. All the demand drivers are exogenous inputs to the model; dynamic effects such as changes in economic growth due to CO_2 emissions constraints are ignored. With regard to fuel prices, TIAM-WORLD calculates the energy prices at each step of the flow towards the end use. Final energy prices used in the model are endogenously determined based on the cost at the well and pit head. We intentionally used a certain price mark-up to adjust the final price of the primary fuels to the level of IEA projections published in the IEA World Energy Outlook 2010 (IEA, 2010a). This price adjustment is then used as a system profile for the rest of the analysis. The drivers for other energy service demands used in this study are presented in Appendix B.

[9] IRR and pay-back time are not directly comparable, but the rule of thumb is that projects with a lifetime of 15 years or more have a slightly higher IRR than the inverse of the pay-back period (Blok, 2006).

Table 3: Key macroeconomic drivers used for service demand projection and fuel prices used in this study

	Values			
	2010 (Historic data)	**2020**	**2030**	**2050**
Macroeconomic Drivers (all relative to 2005 level; MOEJ 2011)				
GDP (real terms)	1.00	1.21	1.37	1.55
Population (POP)	1.00	0.97	0.91	0.76
Number of households (HOU)	1.04	1.07	1.05	0.96
GDP per capita (GDPP)	0.99	1.25	1.50	2.04
Ethylene production	1.00	0.93	0.91	0.59
Crude steel production	0.98	1.06	1.06	0.75
Passenger transport (person-km)	0.98	0.95	0.93	0.87
Freight transport (ton-km)	0.92	1.06	1.10	1.20
Commercial floor space (m^2)	1.04	1.10	1.09	1.08
Benchmark Fuel prices [absolute values, based on IEA (2010)]				
Steam coal ($\$_{2005}$/GJ LHV)	3.1	3.5	3.6	3.6
Crude oil ($\$_{2005}$/bbl LHV)	75	106	120	162
Natural gas ($\$_{2005}$/GJ LHV)	9.3	11.7	13.1	12.6

3.3 CO_2 Emission and Energy Supply Scenarios Investigated in this Study

We performed two sets of analyses in this study. The first (Analysis I) addresses the first research question by comparing two electricity supply scenarios for nuclear phase-out without mid- long-term CO_2 targets: (1) Fossil fuel-dependent scenario (NPO-FF), and (2) Renewable energy-promotion scenario (NPO-REN). For general reference, the report also assessed (3) a scenario with continuation of pre-Fukushima power supply conditions along with certain targets for nuclear energy promotion and LNG power supply in the system. This scenario (REF) has no CO_2 reduction targets and no explicit energy demand control measures until 2050 and is also very specific to this study (conducted by IGES). Therefore, Analysis I aims to compare the choice between renewable energy and fossil fuels under conditions that the technical and economic implications of the choice on energy supply become most apparent.

With regard to scenarios, the NPO-FF scenario assumes a gradual phase-out of nuclear by 2050 and replacement with fossil fuels and no deployment of renewables. The NPO-REN scenario assumes a gradual phase-out of nuclear by 2050 as in the NPO-FF scenario, and replacement with renewables, mainly wind and solar. In order to factor-in the external cost of CO_2 emissions, the same CO_2 emissions reductions were used for FF and NPO-REN scenarios. The benchmark emission reduction level is derived from the simulation of the NPO-REN scenario and is input to the NPO-FF scenario as a constraint. Scenario REF assumes a continued pre-Fukushima energy supply policy based on the 2010 Basic Energy Plan.

The second analysis (Analysis II) addresses the second research question by assessing and comparing two scenarios in which CO_2 emissions (excl. LULUCF) are reduced by 80% by 2050 compared to the 1990 level, which was 1144 Mt/yr (Government of Japan, 2010b). One scenario (NPO-LC) assumes the gradual phase-out of nuclear power, as described in Table 4 below. The other scenario (REF-LC) assumes the continued dependence on nuclear power as in the REF scenario. In this analysis, no comparison of fossil fuel-dependent and renewable energy promotion scenarios is performed. This is because an 80% reduction target would involve the maximum deployment of various decarbonisation measures in order to achieve the target, rendering the comparison meaningless. No renewable energy deployment targets are set for NPO-LC and REF-LC scenarios; only upper limits are set in order to account for physical, technical, economic and social constraints. Table 4 presents the key assumptions used for the three scenarios investigated in this study.

Table 4 Key assumptions used for the scenarios investigated in this study.

Assumptions on mid- to long-term CO_2 emissions reduction targets		Without targets (Analysis I)			With targets (Analysis II) 3)	
Scenario		Pre-Fukushima plan for nuclear power (REF)	Nuclear phase-out, renewable energy promotion (NPO-REN)	Nuclear phase-out, Fossil fuel-dependence (NPO-FF)	Pre-Fukushima plan for nuclear power (REF-LC)	Nuclear phase-out (NPO-LC)
Future CO_2 emissions reduction targets		No targets		Constrained to annual emissions identical to NPO-REN scenario	Minimum reduction compared to 1990 level: 2020: 17%, 2030: 40%, 2040: 60%, 2050: 80%	
Power generation technologies						
Nuclear (share in total electricity production)		Gradual increase in line with the 2010 Basic Energy Plan 2020: 40%, 2030: 50% and 2050: 65% 1) 85% capacity factor	Gradual reduction corresponding to the following 1): -Decommissioning of all Fukushima Daiichi reactors - No restart of Fukushima Daini reactors Shutdown of all plants after 40 years operation - No construction of new power plants - Only 60-70% of the remaining capacity operating at 70% capacity factor for all time periods - Complete phase-out in 2050		Same as with REF scenario	Same as with NPO-REN and NPO-REF scenarios
Natural gas/oil-fired		Minimum share constraint in total electricity generation of 20% 2)				
Rene w- able	Wind (onshore and offshore)	No targets	Gradual increase with lower & upper bounds 2020: 15-20 GW, 2030: 25-30 GW, 2050: 80-90 GW	Total of wind and solar limited to maximum 10% of total electricity productio n	Maximum capacity cap (upper bound) - 2020: 20 GW, 2030: 30 GW, 2050: 90 GW	
	Solar		Gradual increase with lower & upper bounds2020: 25-30 GW 2030: 45-50		Maximum capacity cap (upper bound) - 2020: 30 GW, 2030: 50GW, 2050: 180 GW	

Assumptions on mid- to long-term CO_2 emissions reduction targets		Without targets (Analysis I)			With targets (Analysis II) [3]
			GW;2050: 175-180 GW		
	Hydro (all scale, excludes pumped storage)	Maximum capacity: 30GW (upper bound)			
	Geothermal	Limited to maximum 14GW (upper bound)			
Other assumptions on key technologies					
Biofuels: Upper bound [4]	Transport sector	2020: 27PJ, 2030: 60PJ, 2040: 100PJ, 2050: 150PJ			
	Other sectors	2020: 50PJ, 2030: 230PJ, 2040: 400PJ, 2050: 570PJ			
CCS	Year of introduction	2020			
	Capacity constraints	No constraints are set			

[1] The maximum installed capacity is expected to be around 50-60 GW by 2050 for the pre-Fukushima scenarios. For the nuclear phase-out scenario 0% supply of electricity in the grid means 0 kWh generation by nuclear power plants by 2050. We used the percentage of nuclear power supply in the scenario rather than absolute amount of generation or installed capacity mainly for ease of understanding the scenario and also to technically avoid even a minute amount of nuclear power supply coming from the existing installed capacities in the system and within their technical lifetime Scenarios with absolute amounts of supply can be misleading to readers as it may increase the supply ratio of nuclear under the case where total electricity supply drops. With a percentage scenario we are able to make the supply mix 100% nuclear-free.

[2] A minimum share of natural gas/oil-fired power generation needs to be set in order to secure an intermediate-peak load supply, which cannot be done by coal-fired plants or renewable electricity plants due to their inflexible operation. Considering historic data, 20% is the minimum gas supply required to maintain grid stability at peak times.

[3] All targets are for net domestic reductions excluding LULUCF. Therefore, actual emissions reductions will be large when LULUCF and emission credits purchased abroad are taken into account.

[4] Biofuels include bioethanol and biodiesel. The upper limits for biofuel introduction are based on the assessment presented in the MoEJ Post-2013 Subcommittee (MoEJ, 2012a).

[5] Note that CO_2 capture from CO_2-intensive industrial processes such as blast furnace and cement clinkers is not included. The prospects for CCS in the industry are presented in, e.g., Kuramochi et al. (2012).

3.3.1 Assumptions on Renewable Energy Potential

Solar Photovoltaic

Japan has set more ambitious targets for solar power deployment compared to other renewable technologies. The Ministry of Economy, Trade and Industry (METI) has an ambitious target for solar power technology; 28 GW by 2020 and 53 GW by 2030 (METI, 2008). Moreover, the PV Roadmap 2030+ published by NEDO (2009) quotes a higher potential of 150-200 GW in the domestic sector, 150-200GW in the transport sector and about 150 GW in the industrial sector by 2050.

Our assumption on maximum installed capacity until 2050 (180 GW) is conservative compared to the aforementioned estimates and is in agreement with the estimates presented in the MoEJ Post-2013 Subcommittee (MoEJ, 2011b), which estimated the range of 200-250 GW for 2050 based on various studies and expert opinion. The capacity targets for 2020 and 2030 are taken from (MoEJ, 2011b).

Wind power

As presented in Table 1 , Japan has a large wind power potential, most of which lies in the Tohoku and Hokkaido regions (MoEJ, 2011a). Despite the large potential, Japan currently lags behind many other major wind power producing countries due in particular to the limited progress made in the field in the past few years. The main limiting factors for wind power deployment in Japan include grid stability, mountainous geographical conditions and various environmental restrictions, particularly the protection of Golden Eagles. These factors have adversely affected the wind power sector's development plans and are likely to remain as potential bottlenecks in the future.
Our assumption on maximum installed capacity up to 2050 (90 GW) generally agrees with the estimates presented at the MoEJ Post-2013 Subcommittee (MoEJ, 2011b) that the maximum deployment of wind power in 2050 would be about 70 GW based on various studies and expert opinion.

Geothermal Power

Although Japan currently has only 18 geothermal power plants with a total capacity of about 550 MW (MoEJ, 2011a), geological estimates (see Table 1) show that ample exploration opportunities exist. Japan is ranked third worldwide in geothermal resources behind Indonesia and the United States (Muraoka, 2009). Geothermal is also considered to be already economically competitive with conventional fossil fuel-fired technologies (NPU, 2011b). The main constraint for geothermal power is that many of the promising heat sources are in environmentally sensitive areas such as nature reserves, where installation is prohibited.

In this study, geothermal power capacity is restricted to a maximum of 14 GW for 2010-2050 based on the maximum introduction potential estimated by MoEJ (see Table 1).

Hydropower

As of 2009, Japan had a hydropower capacity (excluding pumped storage) of 22 GW (IEA, 2011b). While much of this has been exploited via large hydropower facilities, the MoEJ survey has identified noticeable potential for developing small-medium hydropower (less than 30 MW) generation facilities (see Table 1). Similarly to the MoEJ estimate presented in Table 1, METI also estimates that there is about 12 GW of potential hydropower capacity over 2,700 locations that may be technologically and economically feasible.

Considering the aforementioned potential for small-medium hydro and the existing potential, the maximum total hydropower capacity (excluding pumped storage) was assumed to be 30 GW.

3.4 Techno-economic Performance Data for Energy Conversion Technologies

Techno-economic data for energy conversion technologies is the default data from the TIAM-WORLD database, except for power generation technologies.

3.4.1 Fossil Fuel-Fired Power Technologies

For fossil fuel-based power generation technologies, we updated the TIAM-WORLD database on new power plants by adopting a consistent technical and economic dataset for new fossil fuel-fired power plants with and without CO_2 capture from van den Broek et al. (van den Broek et al., 2008). Since the economic data is mainly based on American and European plants, capital costs are multiplied by a factor of 1.4 to account for the Japanese situation. The details are presented in Appendix D.

3.4.2 Wind and Solar Power Technologies

Table 5 shows capital cost data for wind and solar power technologies used in this study. For wind and solar power plants, the economic data was updated based the authors' calculations. The capital cost data for wind and solar power generation technologies used in this study includes both the plant capital cost and the capital costs for grid stabilisation measures to deal with intermittency.

Table 5: Wind and solar power plant capital costs including grid stabilisation measures (in USD2000/kW) (selected technologies only). (Source: own calculations based on IEA, 2010b; MoEJ, 2012b)

Technology/ Year	2010	2020	2030	2040	2050
Solar PV-decentralised	4750	2310	1640	1620	1390
Solar PV-centralised	3270	1640	1190	1250	1100
Solar CSP	4570	3960	3350	2950	2340
Wind onshore	1460	1380	1300	1420	1340
Wind offshore	2590	2400	2220	2230	2050

Plant capital costs are based on (IEA, 2010c) for solar PV technologies and (IEA, 2010b) for other technologies. The cost figures presented in the referenced report are representative of U.S. plants. In TIAM, all capital costs of power generation technologies for Japan are assumed to be 40% higher than those for the U.S. Therefore, we also applied a similar adjustment for the ETP 2010 cost projections. Incremental capital costs per kW of installed capacity for grid stabilisation to cope with the intermittency of solar and wind power are derived from the short- to medium-term estimates (2012-2030) by (MoEJ, 2012b).

The additional cost for grid stabilisation is from 6 to 35% for solar and 5 to 24% for wind energy over the next 40 years. Grid stabilisation costs are lower in the medium term future (until 2030) compared to the long term (between 2030 and 2050). Increasing the supply of renewable energy in the grid demands more investment in the grid stabilisation infrastructure and facilities, thus a slight increase in capital costs between 2030 and 2040 is observed. Appendix C gives details of the calculations.

3.4.3 Nuclear Power Technologies

Table 6 presents the cost data for nuclear power plants used in this study (NPU 2011). All costs for nuclear power technologies are assumed to remain unchanged for the entire period covered by this study. In addition to the O&M costs included in the TIAM-WORLD technology database, we also account for cost components such as fuel cycle costs, policy-related costs and disaster compensation costs. The cost figures are taken from the NPU (2011). These additional costs add up to about 2 JPY/kWh. A conservative real interest rate of 3% was used to calculate decommissioning costs and fuel cycle costs per kWh of electricity generated.

Table 6: Key cost data for nuclear power plants assumed in this study. Decommissioning costs and nuclear fuel cycle costs are calculated for 3% real interest rate at 80% capacity factor. Source: Cost Examination Committee of the National Policy Unit (NPU, 2011b).

Cost component	Units	Value
Capital cost	$/kW	3200
Extra cost for disaster compensation [1)]	$/kWh	0.005
Policy-related costs**, advertisement costs and donations	$/kWh	0.01
Decommissioning cost	$/kWh	0.001
Nuclear fuel cycle cost	$/kWh	0.01

[1)] The extra costs for the disaster compensation include additional decommissioning costs, compensation for victims and some decontamination costs, but do not include various costs regarding human health, costs due to the designation of no-fly zones, damage to local government properties, area decontamination costs, facility costs for intermediate storage of contaminants, and costs for final treatment of the contaminants.

[2)] Policy-related costs include financial support of the local governments hosting nuclear power plants and R&D costs (e.g., for the sodium-cooled Monju fast-breeder reactor).

4 Results and Discussions

This section presents the results of two modelling analyses in terms of final energy consumption, electricity mix, CO_2 emissions and total energy system cost (including fuel import costs).

4.1 Analysis I: Comparison of Scenarios with CO_2 Emissions Benchmarking

This analysis primarily focuses on the pros and cons of the renewable and fossil fuel dependent long-term energy scenarios in Japan under an experimental CO_2 benchmark cap, for meaningful comparison.

4.1.1 Final Energy Consumption

It is assumed that the trends in final energy consumption are similar across all scenarios up to 2050 as there are no exogenous constraints on final energy use to reduce consumption via conservation.
Figure 4 compares final energy consumption by sector and by energy type projected for the three scenarios with no long-term CO_2 emissions reduction target. Final energy consumption is projected to drop by about 30% compared to the 2009 level. The breakdown of final energy consumption by sector shows a big reduction for the transport sector (35-40%) and commercial and industrial sectors (both about 30%), and a smaller reduction in the residential sector (about 15%). The breakdown figure by fuel type shows considerably less coal consumption for the NPO-FF scenario compared to other scenarios primarily due to the CO_2 emissions constraint applied to the scenario. Electricity consumption is projected to decrease by 5% in 2030 and 24% in 2050 compared to the 2010 level.

Regarding the breakdown by energy source, the results obtained in this study show lower electricity consumption compared to IEEJ (2011) and IEA (2011) estimates of 20-25% compared to the 2010 level. This is attributed to an assumption that excludes targets for specific advanced end-use technologies, which are often electricity-driven. Thus, the electrification rate of final energy use slows down in our study compared to the other studies.

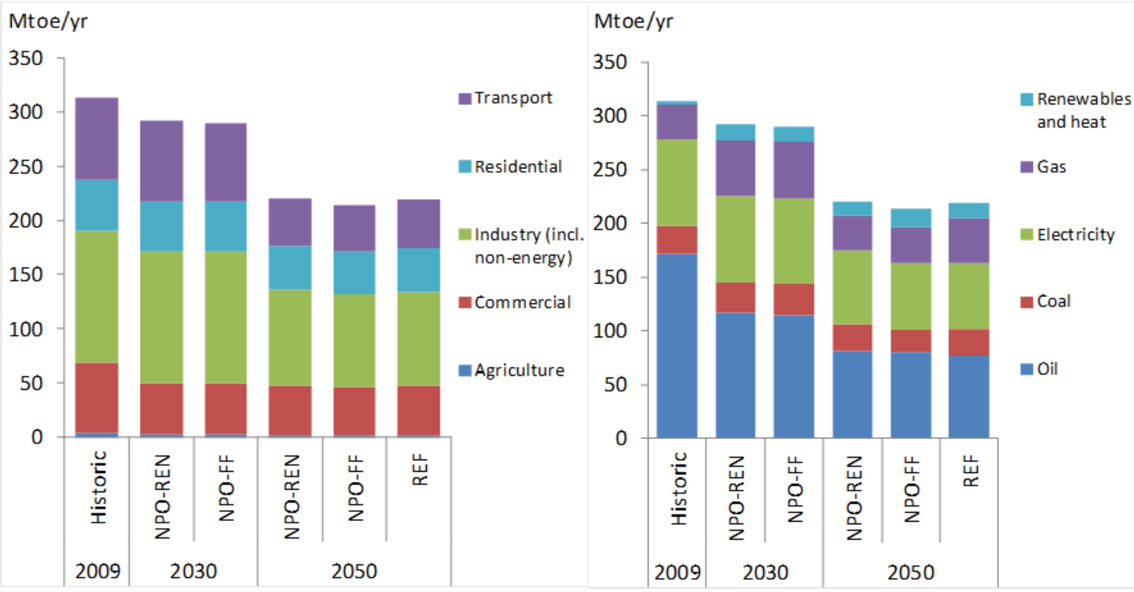

Figure 4 Comparison of final energy consumption by sector (Left) and by fuel (right) projected for the three scenarios without explicit mid- to long-term CO_2 emissions mitigation targets.

4.1.2 Electricity Supply Portfolio

The breakdown of total electricity production by energy source toward 2050 for REF, NPO-REN and NPO-FF scenarios is presented in
Figure 5. In REF, nearly half of total electricity generation in 2050 is generated by nuclear power plants. In NPO-REN, both coal-fired power and gas/oil-fired power increase in the medium term (until around 2030) when renewable power capacity cannot compensate for the reduction in nuclear power. Coal-fired power maintains the larger share (above 20%) until 2050, while gas/oil-based electricity becomes gradually replaced by the growing renewable electricity.

With regard to NPO-FF, the electricity mix up to 2030 is very similar to that for NPO-REN. After 2030, however, NPO-FF maintains its large dependence on gas-fired power in order to maintain the same CO_2 emissions level as for NPO-REN. The results for NPO-REN and NPO-FF strongly indicate that coal-fired power will remain as one of the major sources of power in Japan in nuclear phase-out scenarios with no long-term CO_2 emissions reduction target. Moreover, the security of additional natural gas supply in the mid- to long-term (up to 2050) will be crucial if Japan is to reduce its dependence on nuclear power, particularly if renewables deployment remains slow.

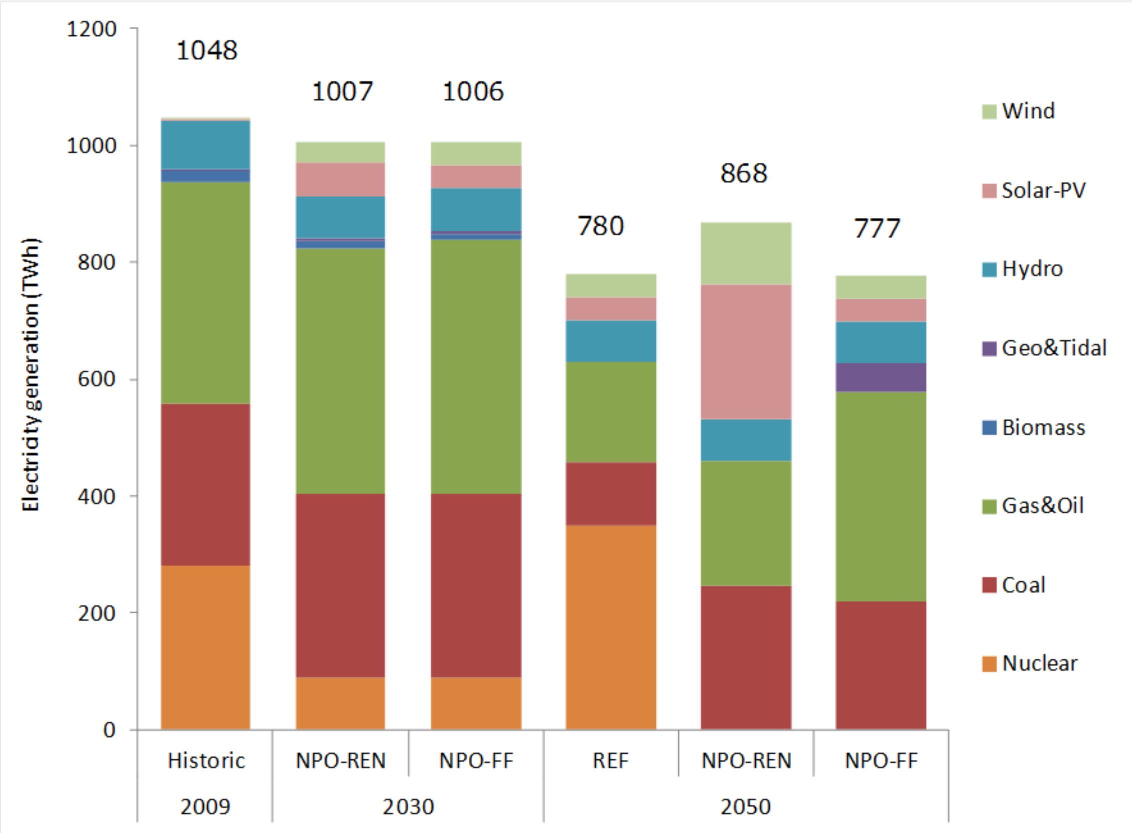

Figure 5: Electricity supply portfolio in Japan for scenarios without explicit mid- to long-term CO_2 emissions reduction targets between 2010 and 2050.

4.1.3 Energy-related CO_2 Emission Pathway for the Renewable Energy Scenario

Figure 6 shows total CO_2 emissions for NPO-REF and NPO-REN scenarios in 2030 and 2050. NPO-REN is projected to reduce total national CO_2 emissions by 12% in 2030 and 40% in 2050 compared to the 1990 level, though showed higher CO_2 emissions than REF throughout the period covered by this study. Since there are no explicit CO_2 emission targets, no CCS is deployed in REF or NPO-REN.

For NPO-FF, there are several factors that contribute to the reduction of CO_2 emissions to the NPO-REN level including: (1) lower share of coal and higher share of natural gas, (2) larger renewable energy consumption, (3) lower total primary energy and final consumption, as well as (4) some CCS (after 2040, 18 Mt/yr in 2050).

Compared with previous studies, the medium term (around 2030) CO_2 emission projections for REF (890 Mt/yr in 2030) are about 100 Mt/yr lower than those projected in pre-Fukushima studies (986 Mt/yr in 2030 and 950-1000 Mt/yr in 2035 according to IEA World Energy Outlook 2010 'Current Policies Scenario' and IEEJ (2011) base case scenario, respectively). This difference is mainly due to the more conservative projections of macroeconomic drivers and their corresponding impact on reduced final energy consumption, as described in 0.

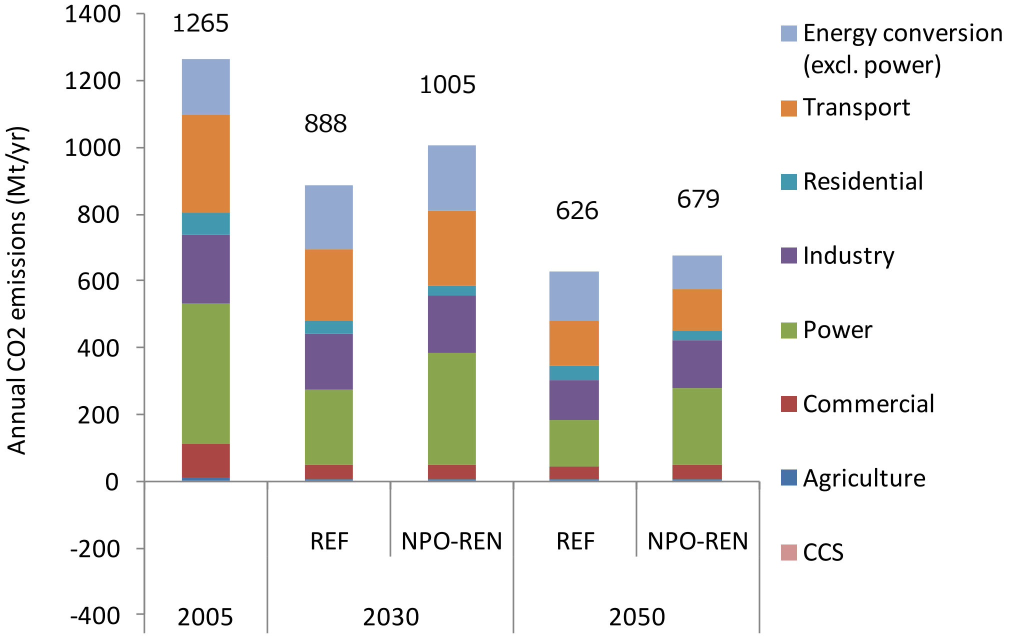

Figure 6 Total CO_2 emissions trajectory of the reference (REF) scenario and the Renewable Energy Dependent (NPO-REN) scenario for years 2010-2050. Historic emissions data for 2005 is taken from the model to be consistent with the breakdown of emissions.

4.1.4 Total Energy System Cost

Figure 7 shows the discounted total energy system cost for 2010-2050 for the renewable energy promotion (NPO-REN) scenario compared to the fossil fuel-dependence (NPO-FF) scenario by component. Fixed operation and maintenance (O&M) costs are expenditures proportionate to the scale of investment and comprise mostly labour costs, whereas variable O&M costs are proportionate to the amount of energy produced and comprise mostly material costs. The results show that the discounted total energy system cost for NPO-REN is marginally higher than that for NPO-FF (by 0.2%) savings in fuel import costs are outweighed by considerably higher investment costs for deploying renewable power plants. To obtain an order-of-magnitude estimate on the scale of the increase in total energy system cost for NPO-REN compared to NPO-FF, the annual total cost is compared with Japanese GDP. The increase in annual total cost is on average 0.04% of national GDP (0.02%–0.12%).

One significant advantage of NPO-REN over NPO-FF is the fossil fuel import reduction; the estimated reduction in total discounted fossil fuel costs for 2010-2050 is around 20 billion USD_{2000} or around 2 trillion JPY_{2010}[10]. This is equivalent to the current annual total fossil fuel import costs, which are 23 trillion JPY_{2010} (Ministry of Finance, 2012). The results indicate that the large-scale deployment of renewable energy can help place Japan in a better position in terms of energy security. This result further

[10] The currency conversion from USD_{2000} to JPY_{2010} was done by first applying the inflation factor, i.e., U.S. Consumer Price Index to update to USD_{2010}, then converting to JPY_{2010} by applying the currency conversion rate for USD_{2010} and JPY_{2010}. These conversion factors are shown in Appendix A.

Caution should be taken in interpreting this monetary value as it is heavily influenced by several external global factors beyond the scope of this study and control of the model.

corroborates the importance of a basal shift in energy planning from least cost to least risk. Least-risk-based planning can assist Japan to deploy more renewable energy in the system without much additional investment (Bhattacharya and Kojima, 2012).

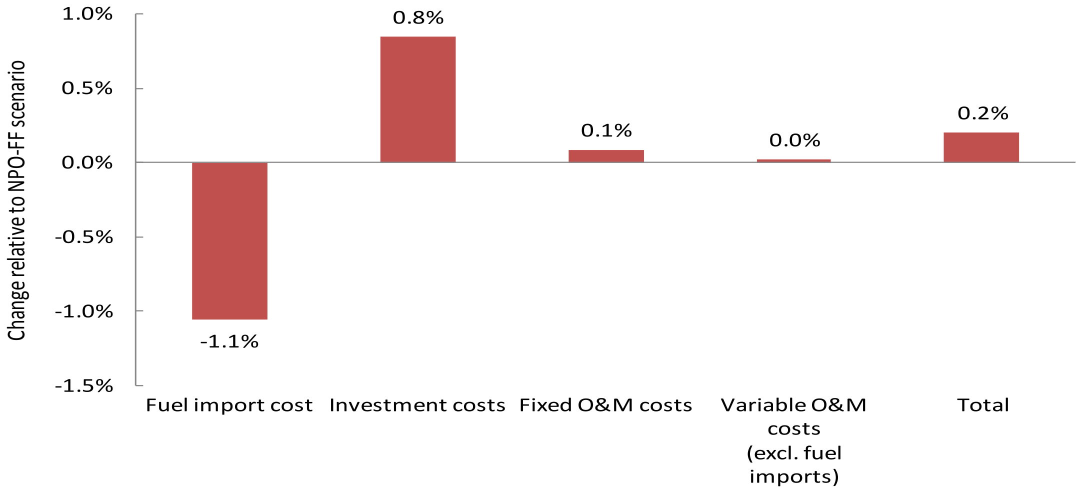

Figure 7: Discounted total energy system cost for 2010-2050 for the renewable energy promotion (NPO-REN) scenario relative to the fossil fuel-dependence (NPO-FF) scenario by component. Note: the numbers under each category in the figure are the percentage changes of a particular cost component. Therefore, simple addition of the percentage values for individual cost components does not obtain the total percentage change.

4.1.5 Summary of Analysis I

In Analysis I, the renewable energy promotion (NPO-REN) scenario and the fossil fuel-dependence (NPO-FF) scenario are compared at a benchmarked level of CO_2 emissions by 2050. Total final consumption drops from about 310 million tons of oil equivalent (Mtoe) in 2009 to 210-220 Mtoe in 2050, depending on the scenario. The major reasons for this are a steady fall in population by 2050 and changes in economic landscape due to reduction in domestic industrial production. The biggest drop in final energy use is in the transport sector while the drop is smaller for industry. The results showed that NPO-REN is only 0.2% more expensive than NPO-FF regarding the discounted total energy system cost for 2010-2050. Compared to REF, the increase was only 0.1%. The increase in annual total energy system cost for NPO-REN compared to NPO-FF was on average 0.04% of national GDP. Moreover, NPO-REN also showed significantly lower LNG imports especially after 2030 compared to NPO-FF (about 60% in 2050). The CO_2 emissions reduction in 2050 for NPO-REN was slightly higher than in REF (45% compared to 41% compared to 1990 level.

Overall, the results indicate the importance of renewable energy for Japan under the nuclear phase-out plan for its direct contribution to foreign exchange savings arrived at via less fuel imports, which can provide ample buffer to the national wealth loss in the context of large fluctuations in exchange rates and high LNG spot market prices. In fiscal year 2011 Japan recorded a 19 billion USD trade deficit–the biggest since 1990–caused by the lopsided export-import balance in the energy sector. Fiscal year 2011 also witnessed a 27% yearly increase in LNG usage by all 10 power utilities in Japan[11]

[11] Sourced from a report published by the Federation of Electric Power Companies of Japan, April 2012, and a news report published in the Japan Times, 17th April, 2012.

due to offline nuclear power plants in the aftermath of the March 11 disaster. This very heavily underscores the urgent need for Japan to switch its reliance over to indigenous energy resources such as renewables to prevent the financial burden spiraling out of control in the near future. Further, our current estimates of an additional 0.1% cost in the renewable scenario don't consider all the expenses related to spot market premium costs, and foreign exchange fluctuation costs, etc.

4.2 Analysis II: Comparison of Scenarios with mid- to long-term CO_2 Emissions Reduction Targets

This analysis primarily focuses on the pros and cons of the long term energy scenarios in Japan with and without nuclear energy supply and with an overall national target of 80% CO_2 emissions reduction by 2050.

4.2.1 Final Energy Consumption

Figure 8 gives a breakdown of total final consumption[12] for the NPO-LC scenario for 2030 and 2050 by sector and fuel type. The breakdown by energy type shows the use of fossil fuel drops from 73% in 2009 to 41% of total final consumption by 2050, under NPO-LC. Compared to the scenarios in Analysis -I (REF, NPO-REN and NPO-FF), the total electricity consumption in 2050 is considerably higher in NPO-LC, the main reason for this being that in order to reduce CO_2 emissions economically the final energy use, especially in the residential and commercial sectors, has shifted from primary fuels to electricity generated from renewable sources or from fossil fuel power plants with CCS.

The significant reduction in final energy use in the transport sector is due to three factors: First, the fuel economy of petrol- and diesel-driven vehicles is assumed to improve by around a factor of two by 2050 compared to the 2005 level; Second, most of the passenger vehicles will be electric (100% conversion to mechanical energy); and third, the majority of freight trucks will be hydrogen-powered (significantly higher conversion efficiency to mechanical energy than petrol and diesel) by 2050.

[12] Total final consumption is 'the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry, transport, buildings (including residential and services) and other (including agriculture and non-energy use). It excludes international marine and aviation bunkers, except at the world level where it is included in the transport sector.' (IEA 2011b)

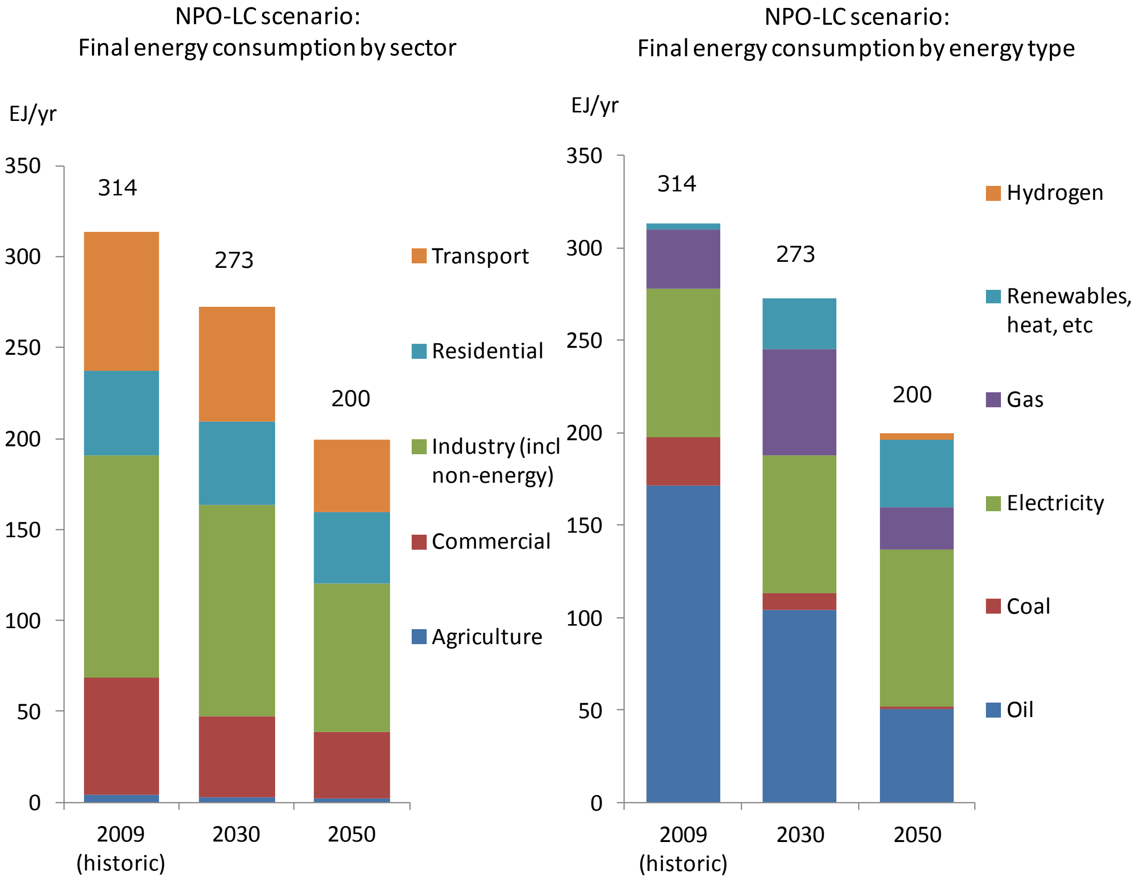

Figure 8. Final energy supply in the 2050-80% reduction scenario between 2010 and 2050. Left: breakdown by sector, Right: breakdown by fuel type.

4.2.2 Electricity Supply Portfolio

Figure 9 shows the electricity mix in the NPO-LC and REF-LC scenarios for 2030 and 2050. The increase in electricity generation from 2030 to 2050 is due to the fact that final energy consumption needs to be decarbonised by shifting from primary energy to electricity with CCS to meet the CO_2 emissions reduction target.
Regarding the introduction of renewable electricity, wind and solar power are deployed in NPO-LC to around 80 GW and 176 GW, respectively, approaching their capacity limits (of 90 GW and 180 GW). In REF-LC, on the other hand, wind is relatively high (59 GW) while solar is only 38 GW because of its relatively high pre-Fukushima generation cost relative to other technologies. The nuclear power capacity in REF-LC was found to be 63 GW in 2050.

Up to 2030, Japanese electricity supply needs to rely heavily on gas-fired power plants because gas-fired power generation is the only viable economical option to both make up for the shortfall in nuclear power and reduce CO_2 emissions until adequate capacity can be reached with renewables. Coal-fired power drops drastically in the medium term (up to 2030) for both scenarios to meet the CO_2 target then rebounds after 2030 when the technologies that enable low-cost CO_2 capture are introduced. The results also show that nearly all fossil fuel-fired power generation is decarbonised through CCS. Total electricity production is found to be larger for REF-LC due to a lower marginal electricity generation cost (MEGC).

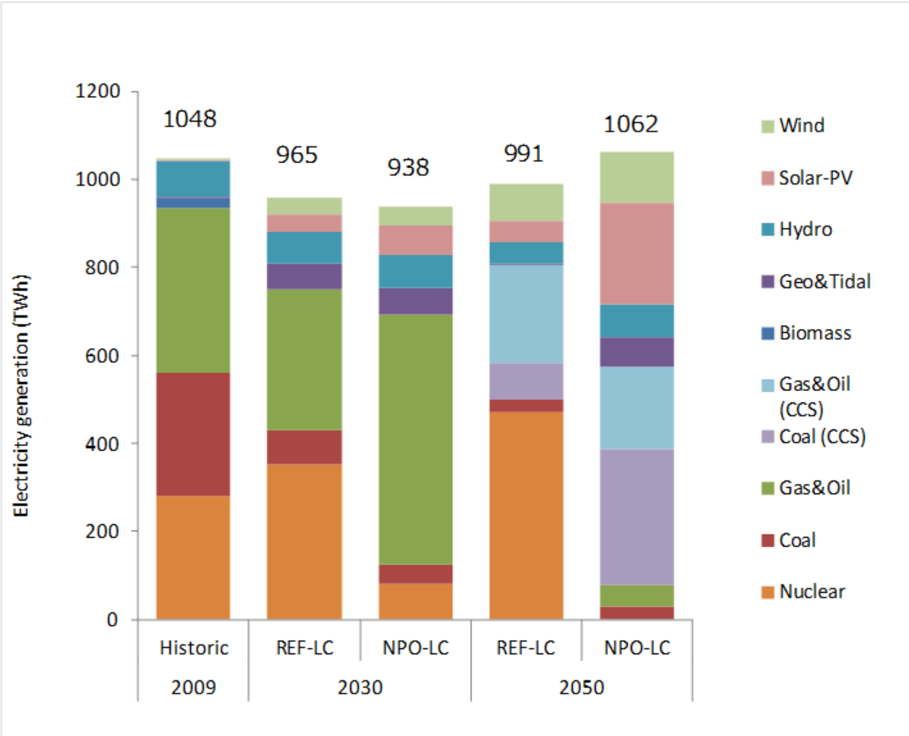

Figure 9 Electricity mix for the scenarios with mid- to long-term CO_2 emissions reduction targets in 2030 and 2050.

4.2.3 Energy-related CO_2 Emissions Pathway

Figure 10 gives a breakdown of CO_2 emissions in the NPO-LC and REF-LC scenarios in 2050, together with the historic emissions data for 2005 for reference. The breakdown shows that about two-thirds of total CO_2 generated is attributable to the power sector, with the residential and transport sectors together claiming a large share. Most of the CO_2 generated from power generation is geologically stored using CCS technologies. The results show that additional CCS requirements in 2050 in the case of no nuclear power will be about 170 $MtCO_2$/yr, which equates to annual emissions from coal-fired power plants of around 25 GW capacity. Put another way this means that almost two thirds of the lost nuclear installed capacity (63 GW in 2050) can be substituted without additional emissions via renewable energy.

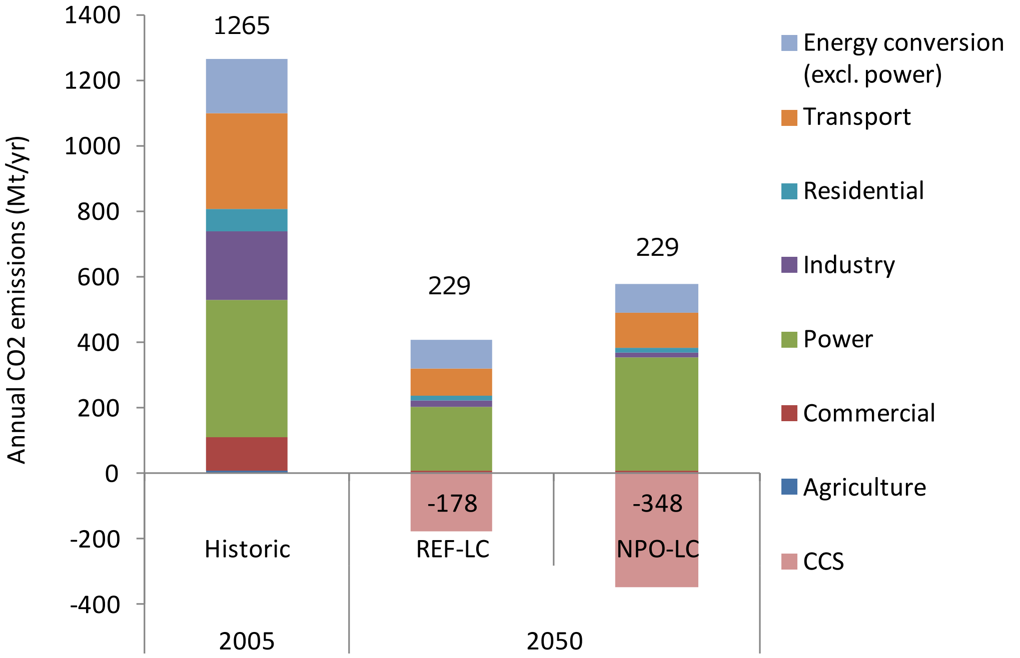

Figure 10 Breakdown of CO_2 emissions in 2050 for the scenarios with mid- to long-term CO_2 emissions reduction targets. Historic emissions data for 2005 is also given for reference.

4.2.4 Total Energy System Cost

Figure 11 gives a comparison of the discounted total energy system cost for 2010-2050 between the NPO-LC scenario and the REF-LC scenario. The figure shows that the 80% reduction of CO_2 emissions in 2050 compared to the 1990 level will be more expensive and require higher fuel import costs with no nuclear power utilisation. It has been estimated that the total discounted fuel import costs for 2010-2050 increase by around 90 billion USD_{2000}, which is around 7 trillion JPY at the current exchange rate.[13][14] The major increase in fuel import occurs in the LNG sector in the medium term (until 2030) and then in the coal sector in the long term due to massive use of coal-based CCS technology deployment. It can be seen that LNG imports increase by around 50% by 2030 under NPO-LC compared to REF-LC and the coal imports increase by around 90% by 2050. Finally, the total discounted energy system cost varies by 1% between these two scenarios, which is around 92 billion USD_{2000}. The bulk of the cost increase occurs due to an increase in fuel imports, and this was found to be on average 0.13% of national GDP (between 0.35% and -0.1%, depending on the year).

[13] Assuming a CO_2 emission factor of 95g/MJ LHV for coal, 80% capacity factor and 40% efficiency (LHV) with CCS.

[14] Caution should be taken in interpreting this monetary value as it can widely vary due to several external factors in the world beyond the scope of this study and control of the model.

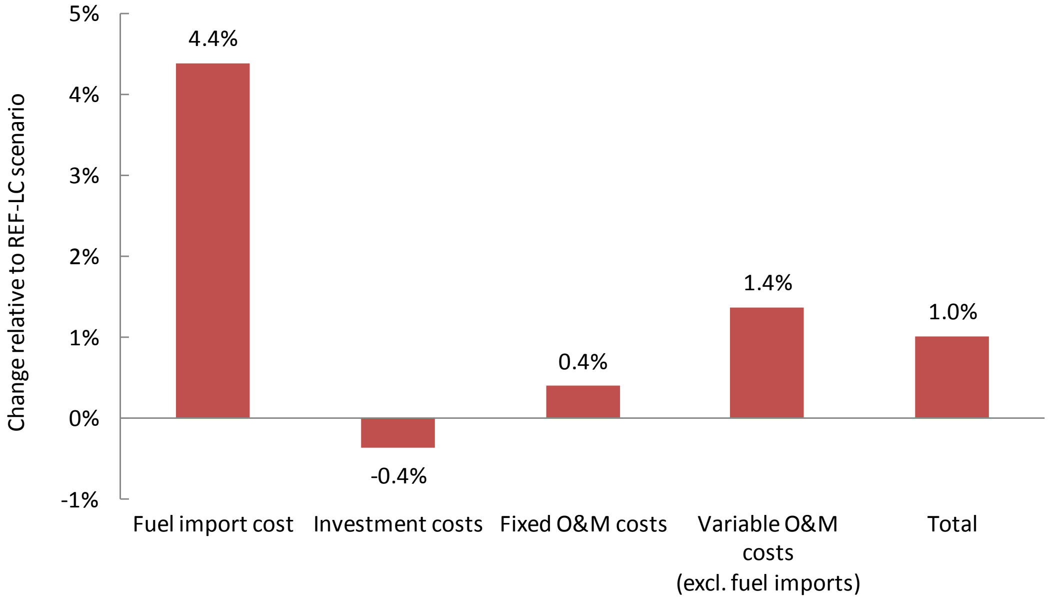

Figure 11: Comparison of the discounted total energy system cost for 2010-2050 between the NPO-LC scenario and the REF-LC scenario. Note: the numbers under each category in the figure are the percentage changes of a particular cost component. Therefore, simple addition of the percentage values for individual cost components does not lead to the total percentage change.

4.2.5 Summary of Analysis II

Analysis II investigated the future energy mix toward 2050 when the CO_2 emissions are reduced by 80% in 2050 compared to the 1990 level with and without nuclear power. The results show that for the NPO-LC scenario, wind and solar power plants are installed up to 80 GW and 176 GW respectively, approaching the capacity limits set in this study (90 GW and 180 GW, respectively). Final energy consumption was found to drop by nearly 40%, from about 310Mtoe in 2009 to 200Mtoe in 2050, which was slightly lower than that for the scenarios without explicit mid- to long-term CO_2 emissions reduction targets. Most of the final energy consumption is shifted from primary fuel to electricity with CCS to meet the 80% target. Consequently, electricity generation gradually drops until 2030, but rises again toward 2050. Large-scale deployment of CCS is essential to achieve the 80% target without the use of nuclear power; the results show that the additional need for CCS will be 170Mt/yr, and the total requirement will be 350Mt/yr in 2050 with zero nuclear power. The increase in discounted total energy system cost for 2010-2050 for NPO-LC compared to REF-LC was found to be 1%, which is equivalent to on average 0.13% of national GDP. This cost comparison is only limited to the energy production, transportation, and consumption-related issues. But such massive quantities of inter-fuel substitution would require changes in end-use technologies, consumption patterns of society and other economic structures. All these actions have impacts on the overall economy. Unfortunately, those costs are not included in this study. However, at best, the no-nuclear scenario is a cautiously optimistic one for Japan.

4.3 Sensitivity Analysis

In this study a sensitivity analysis has been conducted on international fuel price variations. It is observed that fuel prices play a key role in terms of determining the total system cost of a scenario. However, in the TIMES model structure, as the fuel prices are endogenously determined by the model based on the given cost of production at pit or well head, transportation and other transaction costs, different cost parameters of the model are accordingly adjusted to increase the final fuel price in the market by around 20% for LNG, crude oil and coal compared to the standard price used in the reference scenario.

Sensitivity analysis indicates that the renewable energy scenario becomes dearer in a higher fossil fuel price context, which demonstrates the importance of continued efforts to promote renewable energy in the country based on the threat of endless global market price hikes in fossil fuels. If fossil fuel prices increase by 20%, the discounted total system cost differential between FF and REN scenarios becomes only 0.04% compared to the normal price situation, which is around 0.2%. However, for LCS scenarios the cost differential between scenarios with and without nuclear increases to 2% from 1% in the normal price case. This indicates that if the fossil fuel prices (coal, oil and LNG) increase, the cost of achieving a long term CO_2 emissions reduction target of 80% by 2050 without nuclear power supply becomes more expensive, provided all other costs remain unchanged.

5 Policy Implications

The results obtained provide a number of insights into the large-scale deployment of renewable energy and the realisation of a long-term GHG reduction target without dependence on nuclear power. However, the modelling results obtained in this study should be analysed together with overall macroeconomic impacts, risks and public acceptance of nuclear power as presented in Table 2. The study highlights that greater integration of renewable sources into the supply system could provide notable advantages to the country in terms of ensuring energy security and achieving emission reduction targets. Transitioning to a supply system dominated by renewable energy could also set the country on the path to the holy grail of energy independence[15]. Renewable energy development is also critical from the Green Economy Perspective– as echoed in the New Growth Strategy (promulgated by the Japanese government), which states that "green innovation highlights the importance of investing in renewable energy from the Green Economy perspective." The analysis conducted in this study is also in tune with the policy approaches aimed at by the Japanese government related to science and technology, and employment and human resources, both of which are essential to the country's long term sustained economic growth [16]. The additional cost for the energy transition to achieve the 80% emission reduction estimated in this study corresponds to an average cost increase of 0.13% of annual national GDP, hence should be embraced as being within the parameters of Green economy investment objectives. The sections below discuss certain critical aspects that are vital to examination of the growing importance of renewable energy sources, and also re-examine the relevance of nuclear power in post-Fukushima Japan.

[15] While complete energy independence is a global ideal, the term refers to a much more practical situation where a country eventually reduces the dependence on external sources and relies more on the domestic supply capabilities (Nandakumar Janardhanan, "Rethinking the myth that we cannot make energy independence financially feasible," Japan Times, June 27, 2011).

[16] The New Growth Strategy: Blueprint for Revitalizing Japan, Government of Japan, June 18, 2010, Accessed: http://www.meti.go.jp/english/policy/economy/growth/report20100618.pdf, 30 March, 2012.

5.1 Increasing Renewable Energy Supply under a Nuclear Phase-out Scenario

Analyses I and II clearly illustrate the significant potential and importance of increasing renewable energy supply in a possible nuclear phase-out. Analysis I shows that the renewable energy promotion scenario is only marginally more expensive than the fossil fuel-dependence scenario—even when the grid stabilisation costs required to overcome the intermittency of renewable sourced electricity are factored in—and significantly reduces fossil fuel imports. The result of Analysis II has shown that in order to achieve an 80% reduction of CO_2 emissions by 2050 compared to the 1990 level without relying on nuclear power, it is necessary to introduce renewable energy to the highest extent possible, which is also economically rational and attractive. These results therefore indicate both a strong incentive and necessity to realise large-scale deployment of renewable energy technologies if Japan is to reduce its dependence on nuclear power.

The realisation of large-scale deployment of renewable energy in Japan's energy system will require the implementation of policy tools such as the Feed-In Tariff (FIT) scheme and ambitious renewable energy targets. In addition, national level support for improving the grid infrastructure for large scale renewable electricity development would be required. Although renewable energy can contribute to the reduction of fossil fuel imports, it may significantly increase the imports of equipment and materials for building renewable energy facilities, including those related to storage technologies, if the domestic renewable energy technology industry is not competitive. Anxiety has already surfaced in Japan's battery manufacturing industry due to heightened market competition with its Korean counterparts (AutoblogGreen, 2011). It is therefore crucial for the Japanese government to support R&D activities in renewable energy technologies, for two key reasons: to protect market competitiveness and enhance energy security.

5.2 Achieving the Long-term GHG Emissions Reduction Target

The results of Analysis II have shown that achieving an 80% reduction in CO_2 emissions by 2050 compared to the 1990 level without nuclear power will result in an additional average cost equivalent to 0.13% of national GDP. A substantial increase in fossil fuel imports is also observed for the entire period assessed in this study (2010-2050). However, from the perspective that the long term economic impact on the country may not be negligible (based on the available technology and its cost), drafting of the GHG reduction policy needs to be undertaken with the utmost care. On the other hand, it is also hard to predict over a timespan of two to three decades exactly what technological progress might be made, as a solution to all problems might emerge at a reasonable cost. Thus any market-based policy tools that enable an economically optimal reduction in GHG emissions will be of great importance.

The obtained results also strongly indicate the need for CCS technology development. The 80% reduction scenario without nuclear power (NPO-LC) requires geological storage of 350 $MtCO_2$/yr. Regarding the technical feasibility of such large scale CCS, the geological storage potential in Japan may become a bottleneck. An assessment made by RITE (Ito, 2008) indicates that in Japan the storage potential for relatively reliable reservoirs is about 5.2 $GtCO_2$ with an "ultimately feasible" potential of 146 $GtCO_2$. The NPO-LC scenario in our study showed that the amount of CO_2 that needs to be stored geologically between 2020 and 2050 is about 4Gt, which is nearly 80% of the relatively reliable reservoir capacity. Although technological development will likely expand the potential of geological storage of CO_2, securing feasible sites will become crucial. Large CCS deployment will also require massive investment for infrastructural development, which requires the government to take the initiative and set up a long-term plan for CCS technology development and deployment.

Possible options to reduce the heavy reliance on CCS include a further shift from coal to natural gas and tighter control over energy demand. The former option is likely to result in additional costs, even in a society constrained by the reduction of GHG emissions. The latter option (energy efficiency and conservation) may be achieved by more advanced changes in lifestyle and economic structure without necessarily compromising the quality of life.

5.3 Re-examining the Share of Nuclear Power in the Post-Fukushima Energy Mix

The results of this study have shown that achieving significant reductions in CO_2 emissions without nuclear power will be more costly than with nuclear power. However, concerns over the feasibility of continued reliance on nuclear power surged in the aftermath of the Fukushima accident, which necessitates a careful examination of the future trajectory of this sector in the face of the potential danger it presents to society. Measures such as nuclear plant operator liability and additional risk cost[17] are adopted to address the potential risks associated with nuclear power facilities. The nuclear liability law requires the plant operator to pay out about 120 billion JPY as compensation in the event of a nuclear accident. However, taxpayers and electricity users already have a tab of several trillion JPY awaiting them due to the Fukushima accident. The liability law, which specifies that "government will take the responsibility of compensating for the damage in case of extreme cases of natural disasters" holds the general public liable for the damage caused by the 3/11 tsunami. A crucial question that needs raising in this context is "To what extent should the citizens of Japan support a power industry if it presents monetary liability and health hazards?"

The use of nuclear power in Japan depends not only on the central government's position but also on the local governments and local populations; public opinion will continue to be the determining factor influencing the nuclear policy.[18] Concerns about

[17] In light of the potential risk of a nuclear accident, a technical committee was established by the Japan Atomic Energy Commission (JAEC) last year to assess the additional risk cost of nuclear facilities, which, based on an operational rate of 80% and 60%, was estimated at 0.006–0.008 JPY/kWh based on radiation release from an existing reactor, or 1.2–1.6 JPY/kWh for one reactor accident every ten years. Risk assessment of nuclear power is complex and depends on the potential accident. While there are tangible measures such as deriving a risk cost based on assumptions about nuclear accident possibility, various intangible components such as impact on society and environmental health remain as unknowables and are thus unquantifiable economically.

[18] Public opinion played a critical role in the building of nuclear power plants over past decades. The siting of a nuclear power plant was cancelled by a local referendum in Maki-machi, Niigata prefecture in 1997 (see Kohta Juraku, Tatsujiro Suzuki, Osamu Sakura, Social Decision-making Processes in Local Contexts: An STS Case Study on Nuclear Power Plant Siting in Japan, East Asian Science, Technology and Society: an International Journal (2007) p-57).

seismic sensitivities, and the potentially incalculable impact of natural disasters shape the perception of safety of nuclear power facilities. To a notable extent nuclear power has lost credibility [19] among various sections of the society and the anti-nuclear sentiments have reached a level that would make any significant nuclear development in the country difficult[20]. According to a recent survey 65% of the respondents opined that Japan should completely abandon nuclear power (Jiji Press, 2012) and 57% opined that nuclear power plants currently under periodical maintenance should not be restarted (Asahi Shimbun, 2012). In addition, according to a survey on the public acceptability of nuclear power conducted by the Institute for Global Environmental Strategies (IGES) in July 2011, more than 65% of the respondents opined that nuclear power is not an acceptable energy option for Japan (Asuka et al., 2011). This reflects the fact that, irrespective of benefits the economy may enjoy, nuclear power is unlikely to have continued support from the citizens of Japan. It is important for the government to take this element into consideration when formulating policy for the nuclear sector.

While Analysis II indicates that under REF-LC scenario the system cost will be lower, the relevance of nuclear power needs to be assessed not only on the basis of any economic advantage it brings but also the risks. Vulnerability of the facilities to a higher magnitude earthquake or tsunami and the potential psychological shock a disaster can cause to populations are important factors that need to be taken into account. Moreover, judging the relevance of nuclear power in any form of assessment must prioritise the inevitable cost in terms of mental suffering and health of future generations related to radioactive fallout. In this context it emerges as an ethical decision rather than a short term economic assessment to decide what sort of trade-off—between reliance on nuclear power and the risks—is more beneficial for the country in the long term.

5.4 Limitations of the study

Although the analysis performed in this study provided many useful insights into the future energy system and CO_2 emissions for a phase-out of nuclear power by 2050 in Japan, there are a number of limitations to the scope of the study.

First, it does not account for the engineering feasibility of large-scale development and deployment of low-carbon technologies such as CCS, wind and solar power. The large-scale development and deployment of these technologies can only be realised step by step over a long period of time with a significant amount of investment ("2050 Japan Low-Carbon Society" Scenario Team, 2009). Although this engineering limitation is beyond the scope of this study and cannot be handled by the existing model, it is a factor of key importance for the realisation of a low-carbon society and therefore should not be underestimated.

Second, this study did not investigate the policy measures required to realise such

[19] The perception of credibility is based on public anxiety over the continued reliance on nuclear power. Drawing from the experiences of Hiroshima and Nagasaki, there is widespread concern over the adverse impacts of radiation on the environment as well as on future generations. The Fukushima accident has undeniably magnified this perception, which contributes to shaping the credibility of nuclear power facilities.

[20]Endo, Tetsuya. (2011), Interview with Ambassador Tetsuya Endo conducted by Nandakumar Janardhanan, 19 October. Tokyo, Japan.

large-scale renewable energy deployment and long-term CO_2 emissions reduction. Although this is outside of the scope of our research it is important to note that achieving highly ambitious CO_2 emissions reductions and levels of renewable energy deployment wholly depends on the efficacy of policy measures.
Third, the issue of the intermittent supply characteristics of renewable energy that may hinder its use as a base load substitute is not fully covered in this study. This study addresses this important issue by use of two assumptions: (1) setting a minimum level of gas and oil-fired power generation, which enables flexible operation and acts as buffer to the grid instability, and (2) implicitly assuming that batteries are equipped for wind and solar power plants after 2030 to minimise the stress on the grid. However, our approach to the issue has been somewhat simplified and requires future improvements.

Fourth, the energy service demand driver assumptions, which are indicators of lifestyle and economic structure, were not altered for the different scenarios investigated in this study. Under the 80% CO_2 reduction target, further reduction in energy demand is required in order not to rely too heavily on renewables and CCS. Other studies ("2050 Japan Low-Carbon Society" Scenario Team, 2009; MoEJ, 2012c) have demonstrated that the energy mix as well as the level of CO_2 emissions reduction can differ significantly due to differing paths taken by society leading up to 2050. Although this study refrained from controlling energy service demands in any scenario as it was beyond the scope, the implications of future lifestyle and economic structure in relation to the long-term CO_2 emissions reduction require further research.

Fifth, this study does not fully cover the damages related to the Fukushima accident. In this study, about 2 JPY/kWh is assumed to be added to conventional O&M costs to account for cost components such as fuel cycle costs, policy-related costs and disaster compensation costs. The cost figures are taken from the NPU (2011). However, considering the extent[21] of damage a nuclear accident can cause it is practically impossible to quantify the risks in economic terms. Moreover, the continued use of nuclear energy will certainly require large scale investment in ensuring the above mentioned elements. Radiation leaks have immeasurable consequences: impacts on a certain region, effects on the population and future generations, displacement of inhabitants, direct and indirect implications on the agriculture sector and livestock, potential impacts of oceanic resources, concerns regarding the fresh water quality, etc.

There are also a number of limitations regarding the TIAM-WORLD model. First, the model only covers the energy system but not the entire economy. Therefore, the model does not take into account the dynamic effects such as the changes in economic growth rates and energy prices due to CO_2 emissions caps or economy-wide impacts due to the large-scale deployment of renewable energy technologies or the increased use of fossil fuel energy. These factors need to be considered to clarify the economic impacts of whatever energy source is chosen to replace nuclear.

Second, the study did not consider the regional variation of renewable energy potential within Japan, which might have a substantial impact on the overall national long-term energy scenario. Because Japan is modelled as a single regional block in TIAM-WORLD, the potential grid-related bottlenecks in the case of large-scale renewable

[21] In the wake of the accident about 160,000 people from Fukushima prefecture are still unable to return to their homes permanently. Any quantification of risks in monetary terms will not be able to address such hardships presented to society.

electricity deployment—such as the limited inter-regional transmission capacity and the utility frequency difference between East and West Japan pointed out in Section 0—are not fully taken into account. This may become particularly important for wind power because there is a large mismatch of regions with high wind power potential and regions with high electricity demand, thus a significant portion of wind power energy may need to be exported to other regions. Although this issue is factored-in for the upper limit for wind power capacity set in the analysis and the incremental capital costs added to new wind and solar power plants, a more detailed analysis that involves splitting Japan into multiple regional blocks would be necessary.

6 Conclusions and Recommendations

This study assessed the implications, for Japan, of a long-term phase-out of nuclear energy supply toward 2050 and its replacement by renewable energy—unhindered by the technical aspects of intermittency. It is assumed that there will be no new commissioning of nuclear power plants and mandatory decommissioning of old power plants at the end of their 40 life. This study performed two sets of modelling analyses using the technology driven bottom-up TIMES Integrated Assessment Model (TIAM-WORLD). The indicators used in the comparison are: (1) total energy supply system cost, (2) amount of fossil fuel import, and (3) CO_2 emissions.

The first analysis (Analysis I) assessed the implications of the choice of energy source: renewable energy or fossil fuel, to compensate for the nuclear power phase-out by 2050. In Analysis I, the renewable energy promotion (NPO-REN) scenario and the fossil fuel-dependence (NPO-FF) scenario were compared in the absence of any long-term GHG target but with same amount of CO_2 emissions, with a view to highlighting the difference between the two options for energy source choice. The results showed that the renewable energy promotion scenario is only 0.2% more costly than the fossil fuel-dependence scenario in terms of discounted total energy system cost for 2010-2050. The increase in annual total energy system cost for the renewable energy promotion scenario compared to the fossil fuel-dependence scenario is on average 0.04% of national GDP. Moreover, the renewable energy promotion scenario also showed significantly lower fossil fuel imports, which increases the national wealth to a value approximating the total increase in system cost.

The second analysis (Analysis II) investigated the scenario with mid- to long-term GHG emissions reduction targets (80% reduction of CO_2 emissions in 2050 compared to 1990 level) and a nuclear phase-out by 2050. The results show that in the nuclear phase-out (NPO-LC) scenario, wind and solar power plants are installed to the capacity limit of 80 GW and 176 GW, respectively. Final energy consumption was found to drop by nearly 35%, from about 310 Mtoe in 2009 to 200 Mtoe in 2050, which was similar to that for the scenarios without GHG targets. The major part of final energy consumption needs to be shifted from primary fuel to electricity with CCS to meet the 80% target. Without the use of nuclear power this points to the necessity of large-scale deployment of CCS to achieve the 80% target, as the additional need for CCS in the nuclear phase-out scenario was projected to be 170Mt/yr in 2050 higher compared to the pre-Fukushima nuclear development scenario (REF-LC scenario). The increase in total annual energy system cost for the nuclear phase-out scenario compared to with nuclear was found to be on average 0.13% of national GDP.

The study demonstrates that transitioning from a fossil-fuel nuclear dominated energy mix to a renewable energy dominated fuel mix is economically feasible and environmentally attractive as the country can achieve an 80% emission reduction with an additional total discounted energy system cost of 92 billion USD_{2000} over 2010-2050 and with a corresponding average cost increase equivalent to only 0.13% of annual national GDP. Japan's target of an 80% emission reduction can be achieved with a fuel mix that comprises a higher share of alternative energy sources, advanced energy efficiency technologies and economically viable carbon capture options.

Based on the results obtained, the following recommendations are highlighted in order to ensure long term energy security while meeting the environmental goals:

Achieving 80% with a No-Nuclear Energy Mix is Economically Attractive: Under the 80% emission reduction scenario, the increase in total annual energy system cost is estimated to be on average 0.13% of national GDP. This additional cost is not prohibitively high in light of the financial risk and environmental damage associated with nuclear accidents. Further, renewables offer a long-term economic advantage as well as job creation in the green sector. Considering Japan's commitment to playing a leading role in climate mitigation it is important for the country to give adequate policy attention to a 'no-nuclear – high ambition' energy mix.

Need to Promote Investment for Building CCS Facilities: About 170 Mt/yr of additional CO_2 may need to be buried by 2050 if nuclear energy is not utilised as per the pre-Fukushima plans. Early action in the development of a competitive CCS industry would be required to achieve this target. However, caution should be taken in undertaking such a massive scale of CCS in the country as its geological structure is vulnerable. To avoid a heavy dependence on CCS, it is considered safer and more economically preferable to give emphasis to structural changes in the economy by allowing more renewables, investing more in energy efficiency and conservation measures, investing more in leap-frogging technologies that can reduce emissions, technological risk and energy vulnerability.

Need to Address Socio-political and behavioural Aspects:
The two analyses conducted in this study showed significant reduction in final energy consumption largely due to energy efficiency improvement, energy conservation (partly incorporated in activity drivers) and the switch from primary energy to electrical energy toward 2050. However, these results are based on economical optimization, suggesting that the energy use would be reduced as the model results suggest without any policy because consumer behaviour is not always economically optimal. Therefore, adequate measures need to be taken to realize the energy demand reduction as projected in this modeling study, taking into consideration the behavioural aspects towards how energy is used."

Necessity of Regulatory and Institutional Reform in the Power Sector for Promotion of Renewable Energy: The Analysis shows that a higher level of renewable energy integration is necessary to decarbonise the energy mix, which requires a higher level of investment to exploit all possible alternative energy sources. Renewable energy deployment on a massive scale requires technical, institutional, regulatory and legal changes in the existing age-old system dominating the Japanese energy market. Changes in these areas will be the critical determinants in influencing the investment decisions of private players in the alternative energy sector and the sector's long term stability.

Promote R&D in Alternative and Advanced Energy Technologies: Promotion of R&D on the advanced energy technology front is important in the context of the energy scenarios analysed above. The increase in system cost can be significantly suppressed by promoting innovation and technological development in the alternative energy sector.

Ensure Adequate Supply of Natural Gas: Analysis II shows that Japan's electricity supply needs to switch over to gas-fired power plants, based on their potential to replace nuclear power facilities and reduce CO2 emissions until the point where renewable sources can meet a significant share of demand. Considering the potential adverse impacts due to demand surges in many parts of the world, it is important for Japan to develop strategies to secure reliable natural gas supplies through long-term supply contracts from major producing regions.

Appropriate Changes in Current Lifestyle and Economic Structure Envisaged. Japan is now at a developmental crossroads–with the chance of a new paradigm emerging for the economy, society and environment. The current circumstances thus act as an ideal opportunity for the country to redirect its development down the green economy pathway by promoting not only low-carbon energy technologies but also significantly less-energy intensive lifestyle and economic structure. For example, the way Japan dealt with the shortage of power supply in the summer of 2011, provides a valuable lessons about the realization of a green economy in the long term through controlling energy demand without sacrificing much of desired quality of personal life. Such lesson could be further used in other sectors of the economy, too. Further, the Tohoku reconstruction region could play a key role as a test bed for the whole nation to initiate this green economic revolution.

Build Financial Tools to Support the Alternative Energy Industry: The sustainability of the alternative energy sector heavily depends on continued governmental support in terms of tax incentives and subsidies. This analysis highlights the importance of financial tools such as Feed-In-Tariff (FIT) to promote a significant level of alternative energy integration.

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Appendices

Appendix A: Economic Indexes Used in this Study

Table A- 1: Historic U.S. Consumer Price Index for 2000-2010 (U.S. Bureau of Labor Statistics, 2012)

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
CPI (2000=1.00)	1.00	1.03	1.04	1.07	1.10	1.13	1.17	1.20	1.25	1.25	1.27

Table A- 2: Historic currency conversion rates for 2000-2010 (OANDA, 2011)

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
USD/JPY	107.8	121.5	125.2	116.0	108.2	110.1	116.3	117.8	103.4	93.6	87.8	79.7

Appendix B: Energy Service Demands and Drivers for Japan

Table A- 3: Energy service demands and their drivers for Japan region in the TIAM-WORLD model used in this study (KanORS, 2012)**. The demands with asterisks (*) are those with demand drivers modified from the original TIAM-WORLD to take the Japanese situation into account.**

Demand	Driver	
Transportation		
Passenger transport (all modes) *	person-km	
Freight transport (all modes) *	ton-km	
Residential	After 2050	Before 2050
Space heating	HOU	HOU
Space Cooling	GDPP	HOU
Water Heating	POP	POP
Lighting	GDPP	GDPP
Cooking	POP	POP
Refrigeration and Freezing	GDPP	HOU
Washers	GDP	HOU
Dryers	GDPP	HOU
Dish washers	GDPP	HOU
Other appliances	GDPP	GDPP
Others	GDPP	HOU
Commercial (all demands)*	Total commercial floor space (m^2)	
Agriculture	SPROD-Agriculture	
Industry	All regions	
Iron and steel *	Crude steel production (tons)	
Non-ferrous metals	Crude steel production (tons)	
Chemicals *	Ethylene production (tons)	
Pulp and paper *	SPROD-OEI (average IIP of the two sectors)	
Non-metal minerals *		
Other industries	SPROD-OI	

Abbreviations: HOU: households, POP: population, GDP: gross domestic product, GDPP: GDP per capita, SPROD-X: industrial output of sector X, IIP: Index of Industrial Production

Appendix C: Performance Data for New Wind and Solar Power Plants in Japan

Estimation of incremental capital costs for grid stabilization

Incremental capital costs per kW of installed capacity for grid stabilisation to cope with the intermittency of solar and wind power are derived from the short to medium term estimates (2012-2030) by (MoEJ, 2012b). Table A-4 presents detailed figures of how the costs were derived. The referenced document presents cost estimates using two different approaches: (1) Conventional approach assuming batteries for all installed wind and solar power plants and installations of pumped storage hydropower plants (PSH), (2) Integrated (and more cost-effective) approach for the entire grid system with no battery installation until battery costs drop (2030 in this case) and no additional PSH.

The referenced document indicates that the second approach is considerably cheaper than the first, yet feasible for the targeted wind and solar capacity in 2030 (32 GW and 106 GW, respectively). In this study, we assumed the second approach until 2030 and the first approach after 2030, assuming that the installation of batteries becomes necessary to accept highly intermittent electricity. In addition, it is assumed that after 2030 battery costs decrease to one-third of that assumed for the short to medium term in the referenced document.

Table A- 4: Estimation of incremental capital costs for grid stabilisation measures due to large-scale wind and solar power deployment

Cost component	Unit	Integrated approach (before 2030)	Conventional approach (after 2030)
Solar specific costs	Trillion yen	2.6	2.6
Wind specific costs	Trillion yen	0.1	0
Common costs [1)]	Trillion yen	1.94	6.3 [2)]
of which allocated to solar	Trillion yen	1.48	4.80
of which allocated to wind	Trillion yen	0.46	1.47
Additional capital cost per kW [3)]	Unit	Before 2030	After 2030
Solar	yen/kW	40846	74006
	$\$_{2000}$/kW	273	495
Wind	yen/kW	18515	49093
	$\$_{2000}$/kW	124	328

[1)] Includes costs for batteries, pumped storage hydro plants, operation of fossil fuel power plants for peak-flattening, inter-regional gridlines, etc.
[2)] Battery cost is assumed to be one-third of that assumed in the referenced document. $1USD_{2011}$=$79.7JPY_{2011}$, (year average currency rate; OANDA 2012). $1USD_{2000}$=$1.8USD_{2011}$ (IHS CERA 2012).
[3)] Calculated on the assumption that solar and wind power capacities increase by 100 GW and 30 GW, respectively.

Total capital cost figures used in this study compared to National Policy Unit estimates

Table A-5 shows the capital cost data for wind and solar power technologies used in this study in comparison with the estimates from the National Policy Unit (NPU, 2011b). The estimates from NPU do not include costs related to grid stabilisation. The comparison shows that our costs estimates for wind power are on the lower side of the range indicated by NPU. For solar power, on the other hand, our estimates are higher than the range indicated by NPU.

Table A- 5: Capital cost data for wind and solar power technologies used in this study in comparison with the estimates from the National Policy Unit (NPU, 2011b)**. Note that the estimates from NPU do not include costs related to grid stabilisation. N.A.: Not Available.**

Year	Capital costs (in USD_{2000}/kW)							
	Solar PV		Solar CSP		Wind onshore		Wind offshore	
	This study	NPU	This study	NPU	This study	NPU	This study	NPU
2010	4750	3181-3645	4570	2319-3645	1460	1325-2319	2590	N.A.
2020	2310	1524-1763	3960	1226-1948	1380	1246-2319	2400	1875-4638
2030	1640	1252-1458	3350	1047-1670	1300	1173-2319	2220	1723-4638
2040	1620	N.A.	2950	N.A.	1420	N.A.	2230	N.A.
2050	1390	N.A.	2340	N.A.	1340	N.A.	2050	N.A.

Appendix D: Fossil Fuel Power Plants

Table A-6 presents the key data for fossil fuel-fired power generation technologies used in this study. The performance data presented here is based on that used in the Dutch MARKAL model (MARKAL-NL-UU) developed by Utrecht University (van den Broek et al., 2008). The reason for using MARKAL-NL-UU data instead of that estimated by the National Policy Unit (2011) is because the former uses the technical and economic performance data of existing and advanced technologies collated by Damen et al. (Damen et al., 2006, 2007) for industrialised countries sourced from a wide literature with consistency in terms of, e.g., cost definitions and CO_2 capture rates.

Table A- 6: Key data for fossil fuel-fired power generation technologies used in this study. Source: own calculations based on van den Broek et al. (2008) and Damen et al. (2006, 2007).

	Capital cost ($2000/kW)				Efficiency (%-LHV)			
Year / Technology	2010	2020	2030	2040	2010	2020	2030	2040
NGCC	840	760	760	760	58.0%	60.0%	63.0%	64.0%
PC (USC)	1980	1850	1770	1670	46.0%	49.0%	52.0%	53.0%
IGCC	2440	2230	2060	1890	46.0%	50.0%	54.0%	56.0%
NGCC-CCS	1420	1260	1160	1040	49.0%	52.0%	56.0%	58.0%
PC-CCS	3100	2850	2600	2350	36.0%	40.0%	44.0%	47.0%
IGCC-CCS	3190	2680	2350	2180	38.0%	44.0%	48.0%	50.0%

Abbreviations - NGCC: natural gas combined cycle, PC: pulverised coal, USC: ultra-supercritical, IGCC: integrated gasification combined cycle, CCS: CO_2 capture and storage.

In order to use the aforementioned MARKAL-NL-UU data in the current Japanese context we took the following steps. First, the original cost data expressed in $€_{2000}$ was converted to USD_{2000} using the conversion rate of 1 $€_{2000}$=0.924USD_{2000}. Second, the cost data was adjusted to take into account the higher cost increase for power plant construction costs compared to the increases in other commodity prices. The adjustment factor is derived by comparing the data with the latest fossil fuel power plant cost estimates (with and without CO_2 capture) from Schlumberger & Worleyparsons (2011), which was discounted from USD_{2010} to USD_{2000} terms by using the U.S. Consumer Price Index (U.S. Bureau of Labor Statistics, 2012). It was found that the GCCSI cost estimates were a factor of 1.22-1.54 higher than the MARKAL-NL-UU data, therefore the adjustment factor of 1.5 was used for this study. In addition, the location factor of 1.2 was applied based on Schlumberger & Worleyparsons (2011) to account for the regional differences in power plant construction costs.

Table A-7 compares the capital cost data used in this study and that estimated by the National Policy Unit (NPU, 2011b) in USD_{2000} terms. The capital cost data used in this study is overall lower than that estimated by the NPU. For NGCC, we consider the NPU estimate to be very conservative. The Kawasaki natural gas power plant built in 2008 is quoted to have 58% efficiency (LHV) and cost 25 billion JPY_{2008} for 420 MW capacity, which is equivalent to 580 USD_{2008}/kW (Inose, 2011). Even if this plant is considered to be an economically optimal case, we consider the NPU estimate to be too pessimistic. For coal-fired power plants, the cost estimates for 2010 show similarity between the two estimates, but our study is more optimistic on future cost reduction and efficiency improvement.

Table A- 7: Comparison of capital cost and efficiency data estimated in this study and the National Policy Unit (2011). NPU estimates do not distinguish IGCC and pulverised coal power plants.

Parameter	Year	Data source	Technology		
			NGCC	PC (USC)	IGCC
Capital cost ($\$_{2010}$/kW)	2010	This study	1060	2510	3090
		NPU	1400	2680	N.A.
	2020	This study	960	2340	2830
		NPU	1400	2680	
	2030	This study	960	2240	2610
		NPU	1400	3350	
Efficiency (%-LHV)	2010	This study	58%	46%	46%
		NPU	56%	44%	N.A.
	2020	This study	60%	49%	50%
		NPU	63%	44%	
	2030	This study	63%	52%	54%
		NPU	63%	50%	

Abbreviations - NGCC: natural gas combined cycle, PC: pulverised coal, USC: ultra-supercritical, IGCC: integrated gasification combined cycle, CCS: CO_2 capture and storage.

This full report is Chapter 2 in "Lessons Learnt from the Triple Disaster in East Japan."

Full policy report (English version), executive summary of policy report (Both English and Japanese version), and each chapter report (Chapter 2 – English version, and Chapter 3 and Chapter 4 – Japanese version) are available to download at;

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