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Evaluating options for the future energy mix of Japan after the Fukushima nuclear crisis

Sanghyun Hong [a], Corey J.A. Bradshaw [a,b], Barry W. Brook [a,c,*]

[a] The Environment Institute and School of Earth and Environmental Science, The University of Adelaide, Adelaide, SA 5005, Australia
[b] South Australian Research and Development Institute, P.O. Box 120, Henley Beach, SA 5022, Australia
[c] Centre for Energy Technology, University of Adelaide, SA 5005, Australia

HIGHLIGHTS

- ► A nuclear-free pathway will have greater negative impacts than the pre-Fukushima-crisis energy situation.
- ► To meet the GHG targets, >35% nuclear power supply for electricity will be essential.
- ► To minimise loss of life, fossil fuels should be avoided rather than nuclear power.
- ► Despite projected restoration costs, more nuclear power will lead to cheaper electricity costs.
- ► The less that nuclear power is used, the lower will be the sustainability of Japan's energy system.

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ABSTRACT

The Fukushima nuclear accident in March 2011 has increased social and political reluctance to embrace nuclear power in Japan (and elsewhere). The Japanese government has thus been considering four possible future energy mixes, including a nuclear-free pathway, and three others with 10%–35% nuclear supply coupled with a larger proportion of renewable energy and fossil fuels to replace nuclear. Here we use multi-criteria decision-making analysis (MCDMA) to assess the potential negative economic (levelised cost of electricity, and energy security), environmental (greenhouse-gas emissions, land transformation, water consumption, heated water discharge, air pollution, radioactive waste, and solid waste) and social (safety issues) impacts of the four proposed pathways to determine which scenario most holistically minimises adverse future outcomes. The nuclear-free pathway has the highest overall potential for adverse outcomes (score=2.49 out of 3), and the 35% nuclear power supply option yielding the lowest negative impact score (0.74) without weightings. Despite some sensitivity to the choice of criterion weights, our analyses demonstrate clearly that from an empirical perspective, a nuclear-free pathway for Japan is the worst option to pursue. We recommend that MCDMA methodology we used for Japan can be applied to other countries to evaluate future electricity generation scenarios.

1. Introduction

On 14 September 2012, the Japanese government addressed the possible phasing out of nuclear energy by 2040 (Tabuchi, 2012). The government originally planned to mitigate its energy-sector greenhouse-gas emissions to 70% of 1990 rates by 2030, based on an increasing reliance on nuclear power (Cyranoski, 2012; National Policy Unit, 2012). However, since the Fukushima Daiichi nuclear accidents in March 2011, the government has been reviewing the present energy scenario. On 28 May 2012, a governmental advisory body announced an outline to reduce Japan's nuclear power dependency and to replace nuclear power with a combination of renewable and fossil-fuel-generated energy (mostly from imported fuels) (National Policy Unit, 2012; Normile, 2012). The scenarios also included a large reduction of energy consumption by increased efficiency and conservation.

Prior to the March 2011 earthquake and tsunami, Japan's electricity sector emitted 513 million tonnes of CO_2 equivalent (CO_2-e) in 2009, which is equivalent to 477 kg MWh^{-1} (International Energy Agency, 2012b). Immediately after the nationwide nuclear facility shutdowns that followed the Fukushima accidents, the political

* Corresponding author at: The University of Adelaide, The Environment Institute and School of Earth and Environmental Science, Mawson Laboratories North Terrace Campus, Adelaide, SA 5005, Australia. Tel.: +61 8 8303 3745; fax: +61 8 8303 4347.
E-mail addresses: barry.brook@adelaide.edu.au, bwbrook@gmail.com (B.W. Brook).

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support for nuclear power fell, thus increasing the publicly stated emphasis on renewable energy sources (Cyranoski, 2012; Normile, 2012). Consequently, the composition of 'ideal' future energy mixes, and the role of nuclear power in particular, are currently hotly debated (Huenteler et al., 2012; Zhang et al., 2012). Thus far, several studies have examined the economic impacts (Huenteler et al., 2012; Matsuo et al., 2011), social or risk concerns (Satoh, 2011; Šimić et al., 2011) and environmental impacts (Zhang et al., 2012) of alternative energy options in Japan. However, no one has yet compared comprehensively the tangible (quantifiable) impacts of different energy mixes under consideration in Japan—our aim is to do so.

An increasing contribution from renewable energy sources in Japan could potentially reduce the reliance on nuclear power, but the most widely touted renewable options for large-scale future supply – wind and solar photovoltaic – require a substantial backup power supply (Kempton et al., 2010). As such, the necessity of backup power severely limits avoided greenhouse-gas emissions from new forms of renewable electricity generation (Gagnon et al., 2002). Moreover, some renewable energy sources can also emit more life-cycle greenhouse gases than nuclear power, even when backup is ignored (Nicholson et al., 2010; Weisser, 2007). In addition to these emissions problems, strong reliance on renewable energy can elicit massive land transformation and increasing electricity costs (Afgan and Carvalho, 2008) nor are they universally acceptable (Wüstenhagen et al., 2007).

Here we analyse Japan's announced energy mix options by quantifying the major negative impacts associated with the four scenarios based on ten objective criteria: (1) levelised cost of electricity and (2) energy security for the economic dimension, (3) greenhouse-gas emissions, (4) land transformation, (5) water consumption, (6) heated-water discharge, (7) air pollution, (8) radioactive waste, and (9) solid waste (for an environmental dimension), and (10) safety issues (for a social dimension). We compare the four proposed future scenarios using the normalised value of the impact factors based on Japan's projected electricity demand in 2030.

2. Methods

2.1. Assumptions

Throughout this paper, we use three terms regularly: 'capacity', 'gross generation' and 'capacity factor'. 'Capacity' refers to the load that a power generation unit or other electrical apparatus or heating unit is rated by the manufacture to be able to meet or supply. 'Gross generation' or 'gross electricity output' is the total generation of electricity produced by an electric power plant or system. 'Capacity factor' refers to the ratio of the average load on (or power output of) a generating unit to the capacity rating of the unit over a specified period of time (Organisation for Economic Co-operation and Development, 2007).

The four energy mix scenarios are comprised of some mix of four electricity generation methods: (1) nuclear power, (2) renewable energy sources (including solar photovoltaic, wind, geothermal, hydro and bioenergy), (3) fossil fuels and (4) others (15% of total consumption, including energy efficiency measures and cogeneration). In 2009, Japan consumed 1119 TWh of electricity from 289 GW of total installed generator capacity (International Energy Agency, 2012b). The National Policy Unit (2012) also targets the reduction of total electricity consumption by energy efficiency to 1000 TWh by 2030. For this reason, we modified the 2030 electricity generation target to 1000 TWh, excluding energy efficiency measures.

2.2. Scenarios

The governmental advisory body announced four possible future energy mixes for Japan in 2030 (National Policy Unit, 2012). Table 1 presents possible energy mixes for four alternative future scenarios, and the current condition. The fossil fuel sub-components in each mix followed the prescribed amounts in the government scenarios. The scenarios include a nuclear-free option, and 15%, 20% or 35% nuclear penetration pathways. Each scenario includes a 35%, 30%, 30% or 25% renewable energy supply, respectively, with fossil-fuel-generated energy (mostly from imported fuels) and increased consumption efficiency supplying the remainder of the demand. We assumed that natural gas was used for a backup supply of renewable energy supplies, and that the natural gas generating capacity was sufficient for the purpose (with imported fuels not being constrained).

The fossil-fuel mixes are included in the report of National Policy Unit (2012) in Japan; however, there was no clear delineation of the renewable sub-components in each mix therein. We were therefore obliged to estimate the renewable energy sub-components from the report of the Ministry of Economy Trade and Industry (2012). We set 45% hydroelectric power of the total renewable energy share, 5% pumped-hydro storage, 27% photovoltaic, 5% geothermal power, 8% wind power, and other waste and biomass power.

Based on the installed capacity and capacity factor data of each generation option in 2010 (International Energy Agency, 2011; Ministry of Economy Trade and Industry of Japan, 2010), we then calculated the required capacity of each option. Overall, the lower the nuclear power contribution, the higher the total installed capacity to support the same amount of electricity consumption (Table 1). For example, the nuclear-free scenario requires 335 GW of installed capacity, which is 16% higher than the current condition (289 GW), and the 35% nuclear power scenario requires 291 GW (about the same amount, because the higher capacity factor of gas, coal and nuclear power recovers the increased peak capacity of renewables).

Table 1
The generation mixes of the current condition and the four alternative scenarios analysed herein (Ministry of Economy Trade and Industry, 2012; National Policy Unit, 2012).

Generation (TWh)	Current	Nuclear-Free	15% nuclear	20% nuclear	35% nuclear
Nuclear	288.23	0	150	200	350
Municipal waste	8.80	7.00	6.00	6.00	5.00
Industrial waste	0.70	0.49	0.42	0.42	0.35
Solid biofuels	14.00	28.00	24.00	24.00	20.00
Geothermal	2.60	16.84	14.43	14.43	12.03
Photovoltaic	3.80	93.52	80.16	80.16	66.80
Onshore wind	4.00	21.77	18.66	18.66	15.55
Offshore wind	0.00	7.00	6.00	6.00	5.00
Hydroelectric	82.20	157.89	135.33	135.33	112.78
Pumped-hydro storage	8.50	17.50	15.00	15.00	12.50
Gas	304.50	376.07	297.00	270.00	216.00
Oil	97.50	65.00	55.00	50.00	40.00
Coal	304.50	208.93	198.00	180.00	144.00
Total generation	**1119.33**	**1000**	**1000**	**1000**	**1000**
Total capacity (GW)	**288.79**	**335.34**	**312.57**	**313.45**	**290.68**

Ministry of Economy Trade and Industry (2012). The foundation information for the renewable energy mix choices. Ministry of Economy Trade and Industry, Tokyo.
National Policy Unit (2012). Options for Energy and the Environment. National Policy Unit.

2.3. Multi-criteria decision-making analysis (MCDMA)

Multi-criteria decision-making analysis is a general, quantitative methodology used to support decisions that have various impacts and surrounding inputs (Løken, 2007). The methodology is suitable for objective examination of complex issues that have high uncertainty, different perspectives, various data forms and diverse stakeholder opinions (Wang et al., 2009). Since the methodology is widely used to analyse and plan energy futures (Afgan and Carvalho, 2008; Løken, 2007), we applied MCDMA as our main approach.

We assessed the domestic sustainability of each electricity generation option on putative negative environmental, economic and social outcomes. To apply it correctly, complex problems should be adequately subdivided and categorised. The dimensions and criteria we used for the MCDMA followed the guidelines of International Atomic Energy Agency (2005). For the economic impacts, we estimated levelised cost of electricity and energy security. Levelised cost of electricity is a representative economic criterion that incorporates initial capital outlay, financing, operation and management costs, fuel costs, lifespan, decommissioning and spent fuel disposal (for nuclear), and the generator's capacity factor. For the environmental impacts, we considered greenhouse-gas-emissions intensity, land transformation, air pollution, solid- and radioactive-waste generation from the guidelines, with some additional criteria: freshwater consumption and heated-water discharge. These additional criteria are publicly known baseload-power-related problems, such as for nuclear and fossil-fuel plants. Because of perceived safety concerns for nuclear power arising from the Fukushima accident, we also measured 'social' impacts that could be readily quantified, including the consequences of fatalities, injuries and evacuations (Friedrich, 2004; Intergovernmental Panel on Climate Change, 2012).

To implement the MCDMA, all sustainability indicators needed to be expressed as numbers and electricity generation units. For every indicator i, we normalised the maximum value to 1, the minimum value to 0, and all other numbers between 0 and 1 using linear interpolation. To avoid overemphasising any one criterion, we then averaged criteria within the same dimensions. To compare the overall negative implications of each alternative electricity generation system, we used the following 'impact' (I) equation:

$$I = \sum_{(i=0\to n)} S_i W_i \tag{1}$$

where S_i= the value of sustainability index i (for n indicators) and W_i is a weighting applied to S_i ($\Sigma_{(i=0\to n)} W_i = 3$).

2.4. Limitations

Our paper focusses solely on a sustainability analysis of Japan's proposed energy plan. Therefore, we did not consider technologies that were not mentioned in the plan. These included carbon capture and storage, generation-IV nuclear fission, nuclear fusion, solar-thermal power, ocean-power systems (including tidal, wave and current power), and liquefied bioenergy for electricity generation. Although MCDMA should be balanced carefully across all electricity generation options, here we took a conservative approach and added some additional, unique negative aspects to nuclear power to reflect better its present social unacceptability in Japan. These aspects include nuclear waste management and decommissioning costs, and recovery and compensation costs of the Fukushima Daiichi nuclear accidents. In contrast, we did not consider power balancing and additional transmission costs, material consumption, toxic chemical consumption, noise and other renewable-energy-related issues (Stephenson and Ioannou, 2010; Strbac et al., 2007; Wüstenhagen et al., 2007).

3. Sustainability assessments

3.1. Levelised cost of electricity

Japan's retail electricity price for households was US\$233 MWh^{-1} in 2010—one of the most expensive in the world (International Energy Agency, 2012b). For comparison, the average of the Organization for Economic Co-operation and Development member countries was US\$158 MWh^{-1}. Denmark had the highest price with US\$356 MWh^{-1}. South Korea (US\$83 MWh^{-1}), the United States (US\$116 MWh^{-1}), and France (US\$165 MWh^{-1}) were classified into the lower price group. The electricity price is also increasing rapidly to compensate for the Fukushima accident (The Tokyo Electric Power Company, 2012); the National Policy Unit of the Japanese government announced in 2011 a new predicted levelised cost of electricity of each electricity generation source, which includes the accident restoration costs and compensation (National Policy Unit, 2011). Given a total restoration and compensation cost of up to \$257 billion (Saoshiro, 2011), the levelised cost of nuclear power energy could be up to \$137 MWh^{-1} (National Policy Unit, 2011), including decommissioning and waste management costs.

Based on the proposed scenarios and given levelised cost of electricity report (National Policy Unit, 2011), we calculated levelised cost of electricity of each scenario. As a result of this calculation, the current condition records a wholesale price of \$121 MWh^{-1}, with the nuclear-free pathway recording \$190 MWh^{-1}, and the 35% nuclear power pathway \$173 MWh^{-1}. The overall trend indicates that as nuclear power capacity increases, the levelised cost of electricity declines.

3.2. Energy security

Japan depends on imported energy resources for 95% of its domestic energy consumption (International Energy Agency, 2012a). Therefore, reducing dependency and import expenditures are always central issues in Japan. Currently, importation of natural gas accounts for more than a half of total expenditure for the importing of electricity generation fuels. Nuclear fuel, by comparison, constitutes only 10% of the total payment for coal or oil, and 3% of natural gas. On the assumption that the renewable energy fuel costs are free (wind, sunshine, etc.), the 35% nuclear power scenario will pay \$38 MWh^{-1}, and the nuclear-free scenario will pay \$62 MWh^{-1}. For comparison, the current condition pays \$56 MWh^{-1}.

3.3. Greenhouse-gas emissions

Based on the report of the International Energy Agency (2012a), and the greenhouse-gas inventories of the Intergovernmental Panel on Climate Change (2006), we calculated the anticipated greenhouse-gas emissions (CO_2, CH_4, and N_2O) for each of the aforementioned energy mix scenarios. Although renewable energy sources are often touted as 'zero-carbon' options, the minimum required fossil-fuel capacity, as well as other life-cycle processes for hydro and biomass, ultimately confer a measurable carbon footprint (Nicholson et al., 2010; Varun et al., 2009). Using the IEA methodology, the current condition emits 396 kg CO_2-e MWh^{-1}. The nuclear-free scenario will emit 421 kg CO_2-e MWh^{-1} due to the increased fossil-fuel supply, and the 35% nuclear power scenario emits only 262 kg CO_2-e MWh^{-1} (i.e., ~40% lower emissions). Based on the conclusions of the Intergovernmental Panel on Climate Change, Working Group III, greenhouse-gas emissions should be reduced to between 50 and 150 kg CO_2-e MWh^{-1} to avoid dangerous climate change (Nicholson et al., 2010). Thus, the proposed nuclear-free pathway has no capacity to reach that target, but the 35% nuclear scenario comes closest.

3.4. Land transformation

Generally, nuclear and fossil power have much higher power density and power per unit area in GW km^{-2} compared to renewable energy systems (Fthenakis and Kim, 2009; Gagnon et al., 2002). Therefore, an energy mix with more renewable sources requires more land transformation (this relationship ignores land use from mining for construction-materials and fuel acquisition). In general, all four of the considered scenarios claim more land area within Japan compared to today: the current condition, the nuclear-free scenario, and the 35% nuclear scenario claim 1300, 3471 and 2524 km^2, respectively. Given that human population density in Japan is 350 people km^{-2}, the massive land transformation required to achieve the different electricity generation goals will necessarily conflict with other sustainability issues, such as those arising from habitat loss and degradation of wild landscapes and water sources (Brook and Bradshaw, 2012), ensuring adequate food supply and other developments (Horst, 2007; Painuly, 2001; Stephenson and Ioannou, 2010).

3.5. Water sustainability: freshwater consumption and heated water discharge

Water sustainability as measured here includes freshwater consumption and heated-water discharge. Nuclear power, geothermal and fossil fuels typically consume large amounts of water for their cooling processes. Hydro, ocean and pumped-hydro storage require water for generation, and wind and solar photovoltaic power need water for maintenance (Feeley Iii et al., 2008; Fthenakis and Kim, 2010; Jacobson, 2008). The most water-intensive option per unit electricity generation is hydropower, followed by geothermal power (Evans et al., 2009; Fthenakis and Kim, 2010). In particular, hydropower consumes the majority of the total freshwater consumption combined for all considered scenarios, mostly through evaporation. Although nuclear and fossil-fuel power sources are renowned as heavy consumers of freshwater, in Japan, all of these facilities consume seawater (Japan Atomic Industrial Forum Inc., 2012). Conclusively, all four proposed scenarios will consume higher volumes of freshwater than the current condition. The nuclear-free scenario and the 35% nuclear power scenario require 12.05 and 8.61 kl MWh^{-1}, respectively, due to mostly increased hydropower and pumped-hydro storage all future scenarios. For comparison, the current condition requires about 5.56 kl MWh^{-1}.

Nuclear and fossil-fuel-based power plants discharge a massive amount of heated water into the ocean. Discharged water can incur various economic and environmental problems (Lee, 2011). Therefore, we also estimated the amount of discharged heated water from power plants. We calculated the volume using the difference between the volume of withdrawn and consumed water. Nuclear power discharges 161.49 kl MWh^{-1}, which is the highest, followed by coal power (132.27 kl MWh^{-1}). Amongst renewable energies, geothermal power discharges the largest volumes, which is 3.78 kl MWh^{-1}. The 35% nuclear power scenario will discharge 88.71 kl MWh^{-1} (the highest), and the nuclear-free scenario will discharge 50.31 kl MWh^{-1} (the lowest).

3.6. Air pollution

We consider SO_2, NO_x, and CO (carbon monoxide) emissions as air pollutants, based on the air pollution emission factors of the US Environmental Protection Agency (2011), and the fuel consumption data of the International Energy Agency (2012a). For these calculations, we did not consider measures to remove air pollutants. In general, all four scenarios will discharge less air pollution than the current condition (about 2.24 kg MWh^{-1}). The 35% nuclear power scenario will emit 59% of the current condition, which is about 1.32 kg MWh^{-1}, and the nuclear-free scenario will discharge about 2.03 kg MWh^{-1}. Although renewable energy sources emit little air pollution, the high dependency on fossil fuels for backup increases these emissions. For example, the nuclear-free scenario emits 93% of its air pollutants from fossil fuels. In general, increasing the fossil-fuel component is the principal determinant of pollutant emissions, and increasing bioenergy and waste power utilisation exacerbates this.

3.7. Solid waste

Nuclear power and most renewable energy technologies do not emit non-radioactive solid waste (US Environmental Protection Agency, 2012). The main waste-generating source is coal power (Reddy et al., 2005), but combustible renewable energy resources, such as municipal waste, industrial waste or solid biofuel power, also generate solid waste (Cherubini et al., 2009). The current condition generates 17.28 kg MWh^{-1} of solid waste, the 35% nuclear power scenario will generate 9.28 kg MWh^{-1}, and the nuclear-free scenario 13.42 kg MWh^{-1}.

3.8. Radioactive waste

Nuclear power generates controlled (i.e., completely captured) radioactive waste, and coal power generates uncontrolled low-level radioactive waste as a form of sludge or ash, due to the trace natural uranium and thorium content of coal (Allison, 2009; Gabbard, 2008). Nuclear power produces 0.713 g MWh^{-1} of controlled radioactive waste, which can be future fuels for generation-IV nuclear power plants (Brook, 2012). Coal power releases 1.46 g MWh^{-1} of uncontrolled dispersed radioactive waste. Currently 0.58 g MWh^{-1} of both controlled and uncontrolled radioactive wastes are generated, the nuclear-free scenario will release 0.31 g MWh^{-1} of uncontrolled radioactive waste and the 35% nuclear power scenario will produce 0.25 g MWh^{-1} of controlled and 0.21 g MWh^{-1} of uncontrolled radioactive wastes. Note that the management of controlled nuclear waste incurs additional costs for processing and long-term storage—this was included in the levelised cost of electricity figures. Coal is assumed to pay no such cost.

3.9. Safety issues

The safety of nuclear power is the biggest concern and constraint upon energy generation in Japan today. The public often deems nuclear power to be unacceptable and overestimates the dangers associated with radioactive waste or emissions of nuclear power. In contrast to perceptions, nuclear power is statistically safer than any other fossil fuel or hydropower electricity generation, in terms of the number of direct fatalities or injuries (Burgherr and Hirschberg, 2008; Hirschberg et al., 2004; Intergovernmental Panel on Climate Change, 2012). For example, the direct fatality rate for every GWyr of nuclear power is 0.0000414 deaths (in OECD countries, which excludes the infamous Chernobyl accident in the former Soviet Union), but even when Chernobyl is included, the rate is only 0.0306 $GWyr^{-1}$, including the latent fatalities of the Chernobyl accident and the probabilistic safety assessment result of generation-II nuclear power. In comparison, the fatality rate of coal power is 0.12, oil is 0.0932 and natural gas is 0.0721 in

Organisation for Economic Co-operation and Development (OECD) countries.

We considered not only the direct damage, but also the externalities of fatalities, injuries and evacuates. Externalities include resource costs, opportunity costs, mental trauma, food and land contamination, and other possible economic losses (Friedrich, 2004). On the consideration of both the accident probability and the median damage and external costs (Friedrich, 2004), nuclear power requires US\$1.38 GWh^{-1}, photovoltaic requires US\$0.06 GWh^{-1} (the lowest), and hydroelectric power requires US\$5.87 GWh^{-1}. Oil and coal power record the highest (US\$57.7 GWh^{-1}), and the second-highest (US\$40.4 GWh^{-1}) accident costs, respectively. The 35% nuclear power scenario records the lowest costs (US\$14.36 GWh^{-1}), and the nuclear-free scenario the highest (US\$21.86 GWh^{-1}) among four proposed scenarios. For comparison, the current condition is US\$22.96 GWh^{-1}. The application of generation-III+ or -IV reactors would improve these safety records markedly, with core-damage frequencies that are many orders of magnitude lower than earlier designs due to new passive and inherent safety systems (Brook, 2012). Despite the Fukushima accident, the statistically safer record of nuclear power suggests that abandoning nuclear power is not an appropriate pathway to increase public safety.

4. Sustainability assessment

Fig. 1 shows the normalised negative impact values of the six indicators we quantified. In general, the current energy mix demonstrates the greatest negative impacts for four indicators, and the nuclear-free scenario has the greatest negative impacts for six indicators. The overall conclusion is that the scenario with the highest penetration of nuclear power has the fewest negative impacts when all are equally weighted. In contrast and perhaps paradoxically to most people, the highest renewable energy options have the most negative impacts, driven mainly by the requirement for minimum fossil fuels.

In the present case (Fig. 2), we used an equal weighting for all ten indicators (set at 1), but any *a priori* weighting distribution could be applied if it can be justified. Overall, the current condition has $I=2.05$ (maximum negative impact$=3$) driven mainly by high economic and social indices. The 35% nuclear power scenario has the lowest I at 0.74, and the nuclear-free scenario has the highest ($I=2.49$), the latter driven by the highest environmental, and the second-highest economic and social indicators.

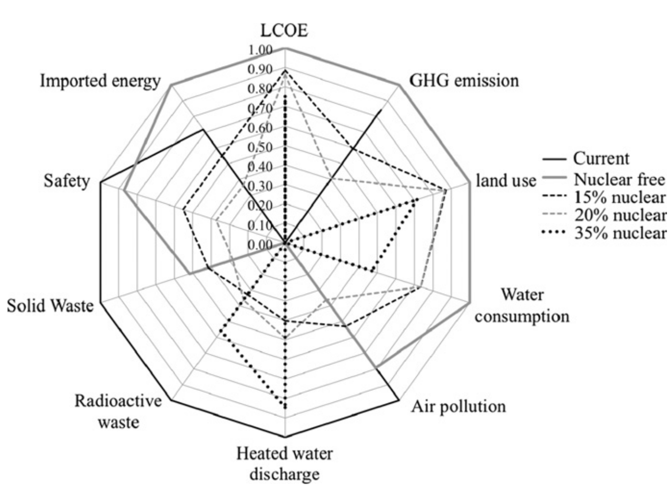

Fig. 1. A comparison of each sustainability impact criterion for the four proposed future energy scenarios for Japan, and the current condition, from 0 (no negative impact) to 1 (largest negative impact).

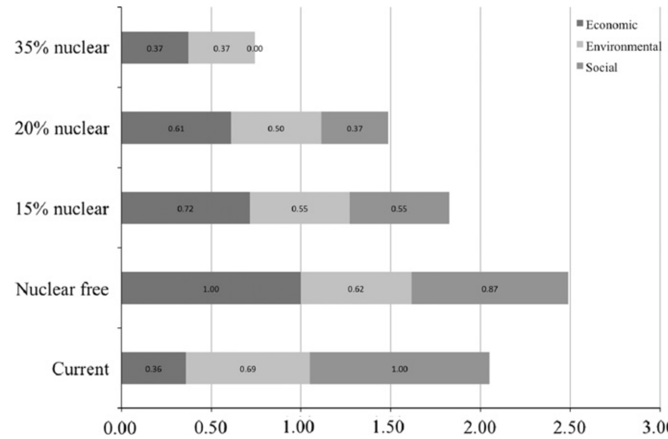

Fig. 2. A normalised result of negative economic, environmental and social impacts for future Japanese electricity scenarios, based on the sustainability criteria.

5. Weighting perspective

Clearly, the values chosen for weighting are important to the ranking of power generation mixes (Afgan and Carvalho, 2008), but are also somewhat subjective. For example, it could be argued that countries like Japan and South Korea should place higher importance (and thus, weighting) on land transformation and water consumption issues because of their high population densities and land values (The World Bank, 2012). Meanwhile, Australia could consider placing more weight on greenhouse-gas emissions and levelised cost of electricity given its globally high per capita emissions and electricity prices (The World Bank, 2012). It is conceivable that each country would choose a different weighting system based on its political imperatives, geographic situation and population density.

For Japan, we illustrate how the ranking differs according to three extreme socio-political perspectives: (i) 'green' (traditional environmental protectionist), (ii) economic realist and (iii) (post-Fukushima) anti-nuclear. Each perspective places different values – thus weights (between 0 and 1) – on each individual indicator according to its particular bias (Table 2). The 'greens' put the most emphasis on reducing greenhouse-gas emissions and minimising land transformation, and the lowest emphasis on levelised cost of electricity. The economic realist assigns the highest weighting to the economic index and does not consider environmental indices to be important relative to the other indices. The anti-nuclear decision maker would be most concerned about safety and levelised cost of electricity, but also disagree ideologically with the use of nuclear power and so weight this option lower, *a priori*.

Even though these disparate weightings change the relative rank of each of Japan's proposed energy mix, the 35% and 20% nuclear power scenarios maintain the lowest and the second-lowest negative sustainability impacts (Fig. 3). Importantly, none of the weighting sets show that the nuclear-free scenario has a lower level of negative impacts.

Currently, holding the position of being against nuclear power and in support of renewable energy is a widespread trend in the Japanese populace following the 2011 Fukushima Daiichi nuclear crisis and ensuing media and political attention (Huenteler et al., 2012). However, our results demonstrate that the only rational choice from an objective and scientific standpoint is to include a large penetration of nuclear power in Japan's future energy mix. In fact, the mistaken belief that nuclear power causes more harm than good is completely contrary to the available evidence, no matter the subjective choice of the relative weightings.

Table 2
Weight values on each sustainability criterion from different perspectives between 0 (negligible) and 1 (important).

Weight	Environmentalist	Economic realist	Anti-nuclear
Levelised cost	0.2	1	0.2
GHG emission	1	0.6	0.2
Land transformation	1	0.4	0.8
Water consumption	0.8	0.2	0.6
Heated water discharge	0.8	0.2	0.6
Air pollution	0.8	0.2	0.2
Radioactivity waste	1	0.2	1
Solid waste	0.6	0.2	0.2
Safety	0.4	0.6	0.8
Imported energy	0.2	1	0.2

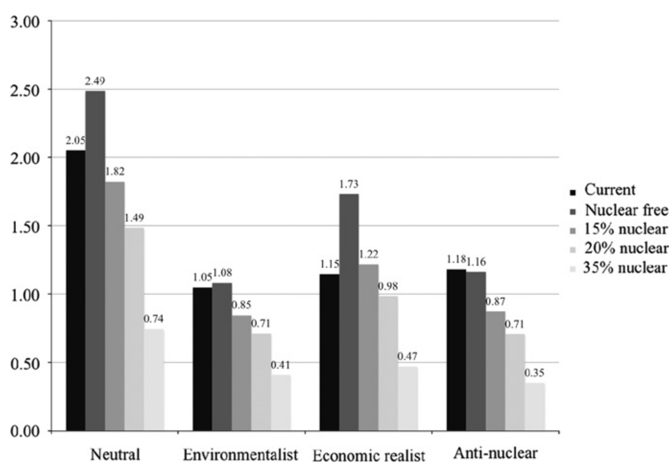

Fig. 3. Weighted negative impacts of the four proposed future electricity scenarios in Japan and the current condition, from three different perspectives: environmentalist, economic realist and anti-nuclear.

6. Conclusions

We have reviewed and quantified a range of tangible negative environmental, economic and social impacts of the four proposed energy mixes in Japan. Using data describing levelised cost of electricity, energy security, greenhouse-gas emissions, land transformation, water consumption, heated-water discharge, air pollution, radioactive waste, solid waste, and safety issues, we can conclude the following: that (i) the nuclear-free scenario has more negative impacts than the current condition, (ii) to meet the greenhouse-gas-emission guidelines, more than 35% nuclear power supply is essential, (iii) to minimise accident risk, or possible fatalities from electricity generation, fossil fuels should be avoided rather than nuclear power, (iv) despite restoration and compensation costs, a higher penetration of nuclear power will lead to cheaper levelised costs of energy, and (v) the less that nuclear power is used, the lower will be the sustainability of the future Japanese energy system.

The Fukushima accident forced a rethink of Japan's existing energy plan, which had aimed to reduce the country's greenhouse-gas emissions by relying increasingly on nuclear power. Following the March 2011 crisis, the social acceptance of nuclear power in Japan was reduced, despite the technology's long-term safety record. Of course, other concerns not addressed in our paper include fears of nuclear weapon proliferation, waste disposal and background radiation, but all these are questionable, especially for later-generation nuclear power technology (Brook, 2012). Our objective analysis herein confirms the value of nuclear power for reducing greenhouse-gas emissions while also providing a reliable energy source that meets most sustainability issues as well, or better, than any existing alternatives. The biggest challenges to implementing a sustainable energy future in Japan are restoring the public acceptance of and confidence in nuclear power, further improving safety mechanisms and management culture, and providing better public education on the difficult but unavoidable trade-offs involved in energy policy.

Appendix A. Sustainability indicators

See appendix Table A1.

Table A1
The raw input values of all sustainability indicators, and data sources listed below.

	LCOE	Greenhouse-gas emissions			Land	Water		Air pollution			Radioactive waste	Solid waste	Energy security	Accident impacts
		CO_2	*CH_4*	*N_2O*		*Use*	*Out*	*SO_2*	*NO_x*	*CO*				
	\$/MWh	kg/TJ (fuel)			km^2/GW	kl/MWh		kg/TJ (fuel)			g/MWh	t/MWh	\$/MWh	\$/MWh
Nuclear	137				1.00		161.5				0.71		4.15	1.38E-03
Municipal waste	322	91,700	30	4	1.50	1.75	0.05	10.75	210.66	257.95		1.56E-01		3.44E-03
Industrial waste	322	143,000	30	4	1.50	1.75	0.05	10.75	210.66	257.95		1.56E-01		3.44E-03
Solid biofuels	319	112,000	30	4	1.50	1.75	0.05	10.75	210.66	257.95		9.17E-03		3.44E-03
Geothermal	134				148.00	3.41	3.78							1.10E-02
Photovoltaic	248				10.00	0.08								5.66E-05
Onshore wind	169				10.00									4.37E-04
Offshore wind	205													1.48E-03
Hydropower	201				36.93	68.0								5.87E-03
Pumped-hydro storage	386				3.98	68.0								5.87E-03
Natural gas	140	64,200	3	0.6	1.00		52.8	0.25	118.02	35.41			123.86	2.21E-02
Oil	456	73,300	3	0.6	1.00		42.3	406.99	68.79	14.33		7.61E-06	109.80	5.77E-02
Coal	133	80,700	3	0.6	2.00		132.3	578.74	119.06	8.27	1.46	5.86E-02	40.72	4.04E-02

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