Energy Policy 67 (2014) 104–115

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Japan's energy conundrum: Post-Fukushima scenarios from a life cycle perspective

Joana Portugal Pereira [a,d,*], Giancarlos Troncoso Parady [b,1], Bernardo Castro Dominguez [c,2]

[a] United Nations University, Institute of Advanced Studies, 6F International Organizations Centre, Pacifico-Yokohama, 1-1-1 Minato-Mirai, Nishi-ku, Yokohama 220-8502, Japan
[b] The University of Tokyo, Graduate School of Engineering, Department of Urban Engineering, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan
[c] Bernardo Castro Dominguez, The University of Tokyo, Graduate School of Engineering, Department of Chemical System Engineering, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan
[d] Energy Planning Program, Graduate School of Engineering, Universidade Federal do Rio de Janeiro, Centro de Tecnologia, Bloco C, Sala 211, Cidade Universitária, Ilha do Fundão, Rio de Janeiro, RJ 21941-972, Brazil

HIGHLIGHTS

- We developed a LCA integrated scenario approach to estimate environmental and economic co-benefits of energy mixes in Japan.
- Renewable rise and fossil fuel dependence reduction leads to LCA emissions decrease up to 34%.
- A balance between renewables and nuclear power is a desirable alternative, from an economic, environmental and security of supply perspective.
- Levelized costs of renewables are competitive with nuclear power.

ARTICLE INFO

Article history:
Received 3 December 2012
Accepted 22 June 2013
Available online 27 July 2013

Keywords:
Japanese energy portfolio
Economic-environmental co-benefits
Life cycle assessment

ABSTRACT

This study aimed at evaluating the co-benefit implications of alternative electricity generation scenarios in Japan, in a post-Fukushima context. Four scenarios were designed assuming different shares of energy sources in a 2030 timeframe. Applying a life cycle assessment (LCA) methodology, scenarios were assessed in terms of cumulative non-renewable energy (NRE) consumption, global warming potential (GWP), terrestrial acidification potential (TAP), and particulate matter formation (PMF). Additionally electricity generation costs were evaluated. Results demonstrate that the current dependence on fossil fuel is unfeasible in the long run, as it results in 14% higher NRE consumption, an increase of 32% on GHG emissions, 29% on TAP and 34% on PMF, and 9% higher cost than the baseline scenario under pre-Fukushima conditions. On the other hand, a share of up to 27% of renewable energies is technically possible and would result in a 34% reduction of NRE consumption, 29% decrease of GHG emissions, and contribute to the mitigation of 24% of TAP and PMF impacts, at minor increase of levelized costs. Increasing the share of renewables and phasing-out thermal power would therefore increase the resilience of the Japanese economy toward external oil markets, cope with environmental protection priorities, while promoting economic development.

1. Introduction

Energy security of supply is on the top of the political agenda in Japan. Being the 3rd largest economy in the World, Japan exhibits an intensive energy consumption pattern in order to keep its economy running. However, the country presents the lowest energy self-sufficiency ratio (4%) among industrialized nations, as it has virtually no endogenous fossil fuel resources and an incipient renewable market (Onoue et al., 2012). In 2011, the imports of crude oil were nearly 207 million kL, largely from Middle-East countries (87%) (IEEJ, 2012), which led Japan to the podium of net oil importers.

The electricity generation sector accounts for one quarter of total final energy consumption. In 2010, the electricity supply by major producer companies totalized 906 TW h, up 6.29 times from 1965 (FEPC, 2012a). Although the government virtually started the liberalization of the sector in 2000, the electricity market is still

* Corresponding author. Tel.: +81 452 212 300.
E-mail addresses: joanaportugal@gmail.com, portugal.pereira@ias.unu.edu, portugal.pereira@ppe.ufrj.br (J. Portugal Pereira), gtroncoso@ut.t.u-tokyo.ac.jp (G. Troncoso Parady), bernardo@chemsys.t.u-tokyo.ac.jp (B. Castro Dominguez).
[1] Tel.: +81 358 416 234.
[2] Tel.: +81 358 417 300.

0301-4215/$ - see front matter
http://dx.doi.org/10.1016/j.enpol.2013.06.131

Table 1
Changes in nuclear dependence, increased cost of fossil fuels and net revenue of power companies in Japan before and post-3/11 (2010–2012 calendar year).

Power companies	Share of nuclear power in the total power generation		Increased cost of fossil fuels (million US$)		Net revenue (million US$)	
	2010 (%)	2 011 (%)	2011	2012 (estimated)	2011	2012 (estimated)
Hokkaido	44	26	606	1,819	−873	−1394
Tohoku	26	2	3,032	3,032	−2813	−2110
Tokyo	28	10	10,671	12,490	−9483	−1880
Chubu	13	2	3,032	2,668	−1116	−788
Hokuriku	28	1	970	1,334	−61	−388
Kansai	44	20	5,093	8,488	−2934	−7057
Chugoku	3	9	0	970	24	−728
Shikoku	43	19	849	2,425	−109	−1686
Kyushu	39	16	3,032	5,699	−2013	−5445

controlled by 10 regional monopolies, which supply 85% of the total demand (FEPC, 2011). As established under the Electricity Business Act (METI, 2005), these regional monopolies vertically integrate the generation, distribution and transmission of electricity, which makes the penetration of independent producers of renewable energies challenging. As a result, the electricity generation portfolio has been dominated by fossil fuel thermal and nuclear power, while renewables (mainly hydropower) have a minor contribution.

The triple disaster that hit Japan in March 11, 2011 (hereafter referred to as 3/11) has threatened an already vulnerable electric sector. In the aftermath of the quake, nearly 30% of the supply was put out of service. Although most units were back in service shortly, all of the 54 nuclear reactors, which account for a total of 47 GW, were gradually shut down for safety inspections or maintenance, yet as a result of public pressure, whether or not these units can be put back online is uncertain in the short-term. To avoid potential blackouts and overcome this drastic cut of nuclear power, the share of fossil fuel thermal was increased. As a result of this decrease in the share of nuclear power and the consequent hike of 25.2% in fossil fuel imports, all power companies but Chugoku (with low reliance on nuclear power) reported net losses in 2011 and 2012 (Table 1; Asahi Shimbun, 2012; FEPC, 2012b; Supply and Demand Verification Committee, 2012). At the national level, the consequences of this growing dependence on energy imports threaten economic stability and environmental sustainability. In fact, after the accident, Japan logged a record 2.5 trillion JPY ($US 31 billion) trade deficit, the first since the 1979 oil shock, and largely as a result of a jump in fossil fuel imports, putting further strains on an already fragile economy (Vivoda, 2012).

Since the first oil shock in 1973 and until 3/11, nuclear power has been a key pillar to reinforce Japan's energy resilience against oil market fluctuations and to mitigate climate change. In 2010, the “Strategic Energy Plan” defined the target of doubling the percentage of electricity generated by renewable sources and nuclear, and a 30% of reduction of energy-related CO_2 emissions compared to 1990 level by 2030 (METI, 2010; Duffield and Woodall, 2011). Under this strategy, the share of nuclear power in the electricity generation portfolio would ramp up to nearly 50% and 14 new reactors were planned to be built by 2030. This strategy was originally scheduled for revision in 2013, but in light of 3/11 disaster, last September 2012, the Energy and Environment Council (EEC) of Japan drew up the “Innovative Strategy for Energy and Environment” endorsing a gradual phase-out of nuclear power by the 2030s (EEC, 2012a). Nevertheless, under pressure from the business lobby, this strategy failed to get the cabinet's approval hence falling short of becoming a legally binding document. Furthermore, the proposal was heavily criticized (see e.g. DeWit, 2012; Kingston, 2012), as it did not reveal a concrete roadmap or an action plan to achieve this goal. It rather expressed an ambiguous vision for a “society not dependent on nuclear power in the earliest possible future”, a “realization of a green energy revolution” and a “stable supply of energy”.

Japan needs to move towards a long-term reliable and affordable energy strategy that guarantees security of supply, powers economic growth needs, supports climate change mitigation policies, and ensures the public's trust; yet the roadmap to reach this goal is uncertain. Currently two antagonistic views are in debate regarding whether or not Japan should phase-out nuclear power and which alternative sources should replace it; on the one hand, the central government, pressured by industrial lobbyists, a part of the so called ‘nuclear village’, supports the restart of the nuclear reactors, claiming that nuclear power is the only option to cope with economic needs at an affordable cost, especially given short-term supply constraints. On the other hand, local governments and public opinion are committed to increase the share of renewable energies; they see the current challenge as an opportunity to move towards a green economy, which would bring climate resilience, regional development, green jobs, and reduce the energy dependence on imports and power monopolies. However, renewable energies are still costly and its technological maturity is yet to be fully developed. Japan is therefore facing a dilemma. Can the government reach a turning point and switch to a green and resilient economy based on endogenous and renewable energies? If so, what is the optimal electricity generation mix supply portfolio so that economic and environmental co-benefits are maximized?

Life cycle assessment (LCA) integrated with scenario design is a robust approach to determine the optimal energy portfolio, as it integrates a wide range of electricity generation systems and evaluates its impacts under holistic lens. While pertinent to the field, previous studies that evaluate electricity scenarios in Japan applied a supply-demand analysis to determine the reliability and feasibility of energy mixes, but they lacked in forecasting the full local and global life cycle environmental impacts and economic implications of energy mixes in Japan from a holistic view point (see Nakata, 2002; Takase and Suzuki, 2010; Onoue et al., 2012; Zhang et al., 2012). To the authors' knowledge, only Hondo (2005) and Bhattacharya et al. (2012) attempted to address these issues. While Hondo (2005) conducted a GHG–LCA that quantifies the global warming potential (GWP) of power generation systems in Japan, the cost implications of each system were not evaluated, or an optimal energy mix scenario was discussed. The cost implications of energy mix scenarios were evaluated by Bhattacharya and his colleagues through forecasting and backcasting methods. The global environmental impacts and costs of several energy mixes were assessed; nevertheless the study does not evaluate local environmental impacts.

To fill this gap, four prospective scenarios of alternative electricity generation mixes in a 2030 timeframe are developed with the objective of evaluating its implications in terms of global and local environmental impacts, as well as generation costs; furthermore, the economic and social implications of these scenarios are discussed in order to explore in a comprehensive manner potential directions for the future of Japanese energy policy in the aftermath of Fukushima Dai-Ichi accident. In that sense, the following indicators have been evaluated: cumulative non-renewable energy (NRE) consumption, GWP, terrestrial acidification potential (TAP), particulate matter formation (PMF), and generation costs.

2. Prospective scenarios for a future electricity generation mix in Japan

Departing from a pre-Fukushima state of affairs, four energy mix scenarios were developed to evaluate alternative policy directions. Scenarios were constructed taking into consideration (i) the ongoing debates on the future direction of Japan's energy policy, (ii) the current socio-economic and socio-political environment of contemporary Japan, (iii) estimated potential for renewable energy sources and (iv) technical constraints for the expansion of renewable energy.

The main assumptions for the development of the scenarios concern the distribution of nuclear energy and renewables, which lie at the center of the ongoing discussion about Japan's energy future. These assumptions are largely based on assumptions made by the Cabinet's Energy and Environment Council, which drafted three alternative energy scenarios and presented them to the public in the form of public hearings at the end of June 2012 (see EEC, 2012b).

Regarding nuclear power, in 2010, the baseline year, it accounted for approximately 26% of total generated electricity. Against this background, two possible alternatives are put forth: a zero nuclear option where all reactors are shut down and decommissioned, and a nuclear reduction option which brings the generation percentage down to 15%. Both alternatives reflect to a large extent the ongoing debate on nuclear energy policy, where on the one hand, 70% of the country believes that its reliance on nuclear power should be reduced (PRC, 2012), while on the other, business and industrial groups such as the Japan Business Federation (*Keidanren*) are urging the government to restart the reactors as soon as possible citing the economic impact of energy shortages and high energy prices on the industrial apparatus of the resource-poor nation.

An increasing share of nuclear power in the electricity generation portfolio was not considered in the present study, as it seems unlikely that all reactors will be put back online given stricter standards for operation established by the Nuclear Regulatory Authority (NRA), and the re-evaluation of existing active fault lines around plant sites. Furthermore, it seems improbable that given attitudes from local governments and the general public, the government will be able to build consensus for constructing new reactors.

In the nuclear reduction scenarios, spent fuel is assumed to be recycled, in line with current industry standards. High level waste is vitrified and stored for 30–50 years before final disposal, and low level waste is contained in metal drums and stored in a low level radioactive waste storage center (FEPC, 2013).

Regarding renewable energy, in 2010, approximately 10% of the total generated electricity came from renewables, out of which hydropower accounted for 8.50%, while other sources added up to

Table 2
Estimated potential from renewable sources and installed capacity of high renewable scenarios.
Source: developed by authors based on ANRE (2012a).

Energy source	Estimated potential (GW)	Estimated potential (GW h)	Installed capacity high renewable scenarios(GW)
Biomass	–	28,100	2.88
Solar-PV (Households, public facilities, factories)	8600	93,000	51.27
Wind power (Onshore)	1500	70,000	32.96
Geothermal (Including national parks)	4.3 (6.4)	26,000 (42,000)	3.85

Table 3
Japanese energy mix scenarios in 2030 (generated electricity).

Energy source	Pre-Fukushima Baseline scenario[a] (%)	Zero nuclear, high thermal Scenario 1 (%)	Zero nuclear, high renewables Scenario 2 (%)	Nuclear reduction, low renewables Scenario 3 (%)	Nuclear reduction, high renewables Scenario 4 (%)
Nuclear power	**26.4**	**0.0**	**0.0**	**15.0**	**15.0**
Coal	24.3	34.0	27.8	28.6	22.0
LNG	29.4	45.0	33.5	34.7	26.7
HFO	10.2	11.3	11.7	12.0	9.3
Total fossil fuels	**63.9**	**90.3**	**73.0**	**75.3**	**58.0**
Hydro (Run-of-the-river)	8.0	8.0	10.0	8.0	10.0
Hydro (Pumped-storage)	0.5	0.5	0.5	0.5	0.5
Biomass	0.3	0.3	2.1	0.3	2.1
Solar-PV	0.2	0.2	5.6	0.2	5.6
Wind power	0.4	0.4	6.0	0.4	6.0
Geothermal power	0.3	0.3	2.8	0.3	2.8
Total renewables	**9.7**	**9.7**	**27.0**	**9.7**	**27.0**
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

[a] Baseline scenario *sources*: EEC (2012b) and ANRE(2012a).

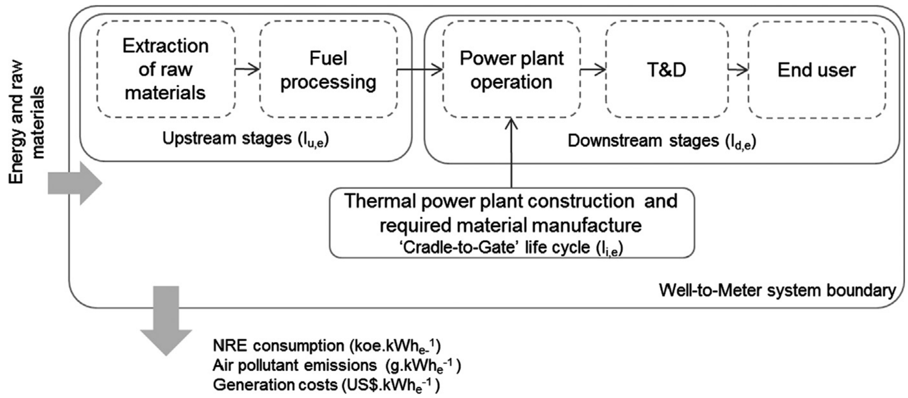

Fig. 1. Analytical framework and system boundaries of the study.

1.2% of the total. Against this state of affairs, two policy paths are put forth: a no expansion alternative where the share of renewables stays identical to 2010 levels, and a "High Renewable" alternative. An upper limit of renewable energy penetration was assumed at 27%, a value that lies between the 35% maximum threshold estimated by the Energy and Environment Council (EEC, 2012b) and the more conservative estimate of 21% from METI's 2010 Strategic Energy Plan (ANRE, 2012a). Previous research by Zhang et al. (2012) had also suggested feasible market penetration of renewables up to 30%, if thermal power systems are used as base load to absorb supply and demand fluctuations. A similar trend was observed by Esteban et al. (2012a), revealing that 40% of electricity demand can be met by solar-PV and win power systems, during peak hours, if 40 TW of storage capacity is installed to balance peak demand in the summer period in Japan.

The first scenario, "Zero Nuclear, High Thermal" considers a setting where all nuclear power plants are offline and their share is compensated for with an increase in thermal power, particularly heavy fuel oil (HFO) and liquid natural gas (LNG). These shares are based on the Institute of Energy Economics of Japan's estimations about increase in fossil fuel procurement in 2012 (IEEJ, 2011), and reflect to a large extent the state of affairs of the Japanese energy mix until July 1st, 2012 when the Ohi reactors were restarted.

The second scenario, "Zero Nuclear, High Renewables" assumes that the nuclear share is compensated instead with an increase in renewables while a decrease in fossil fuel thermal power. Based on estimated potentials for each energy source by the Agency for Natural Resources and Energy (ANRE, 2012a), wind power share is estimated at 6% of generated output, followed by solar power with 5.6%, geo-thermal power with 2.8% and biomass with 2.10%. Table 2 presents estimated potential from renewable resources and installed capacity in the "High Renewable" scenarios.

The remaining two scenarios assume a reduction in the nuclear energy share to 15%. Scenario 3, "Nuclear Reduction, Low Renewables" assumes no change in the renewable energy share, and an approximate increase of 12% in the fossil fuel share to compensate for the reduction in nuclear power. On the other hand, scenario 4, "Nuclear Reduction, High Renewables" assumes the same renewable energy distribution as scenario 2, translating in a reduction of almost 6% in the share of fossil fuels. Scenario characteristics are summarized in Table 3.

3. Methodology

3.1. Scope of the study

This study is comprised of two analyses: a life cycle assessment (LCA) of the environmental co-benefits and an estimation of levelized generation costs of different electricity generation mix scenarios in Japan in a 2030 timeframe. The LCA, as described in ISO 14040-44 guidelines (ISO, 2006), comprises the evaluation of the NRE consumption, GWP, TAP and PMF of the entire life cycle of electricity generation systems, referred to as, 'Well-to-Meter' (WTM) analysis. System boundaries include both upstream (extraction of fuels and raw materials, fuel processing and transportation) and downstream processes (operation of power plants to generate electricity and its transmission and distribution to end users) (Fig. 1). Additionally, it includes the "Cradle-to-Gate" cycle of thermal power plant infrastructure construction, as well as the manufacture of material requirements for the construction of renewable power generation facilities, namely solar-photovoltaic (PV). panels and windmills. The evaluation of the full life cycle of electricity generation is particularly important when evaluating fossil fuel systems, as upstream processes can be as much as 25% of direct environmental impacts of the power plant operation (Weisser, 2007). Furthermore, the 'Cradle-to-Gate' cycle of power plant infrastructure is a relevant stage in solar-PV, wind and hydropower technologies, as the construction of facilities and their supporting processes are both resource and energy intensive (Varun et al., 2009).

Table 4 displays the electricity generation technologies considered in this study. It includes nuclear pressurized water reactor (PWR), coal steam turbine (ST), liquid natural gas combined cycle (CC), heavy fuel oil boiler, biomass co-generation boiler, run-of-the-river hydropower (RORH), pumped-storage hydropower (SPH), geothermal, wind power and solar-PV. Energy systems were simulated in the global emission model of integrated systems (GEMIS) software (Öko Institute, 2012). GEMIS is an LCA software that allows users to model input/output streams of all stages of the life cycle (materials used, fuel extraction, processing and delivery). Database were customized, in terms of electricity generation technology selection and net energy efficiency of processes, to make sure Japanese site-specific and 2030 timeframe data were incorporated in the model.

The Functional Unit (FU) applied in the analysis is 1 kW h_e of electricity supplied to end users. The co-benefits of scenarios were evaluated in terms of NRE consumption, as primary fossil energy consumed (ktoe/kW h_e), CO_{2e}[3], SO_{2e}[4], and

[3] GWP is calculated as carbon dioxide equivalent (CO_{2e}) by the following expression:$CO_{2e}=CO_2+23\cdot CH_4+296\cdot N_2O$, according to the GWP factors suggested by IPCC in its forth assessment report (Solomon et al., 2007).

[4] TAP is calculated as sulfur dioxide equivalent (SO_{2e}) by the following expression: $SO_{3e}=SO_2+2.45\cdot NH_3+0.56\cdot NO_x$, as suggested by EcoInvent in its ReCiPe midpoint method (Goedkoop et al., 2008).

Table 4
Characteristics of electricity generation systems evaluated in this study.

Technology	System description	Plant nominal capacity (MW_e/yr)[a]	Capacity factor (%)[a]	Plant lifetime (yr[b])	Net energy efficiency (η_e) (%)[b,c]
Nuclear PWR	PWR with an enrichment of 3.4% and a burn-up of 40GWD/t-U. Nuclear fuel recycled. High level waste vitrified and stored for 30–50 yrs; low level waste contained in drums and stored in storage centers	1250	70	40	100
Coal-ST	Coal-ST plant with selective catalytic reduction (SCR), flue gas desulphurization (FGD), operating at supercritical conditions. No CCS	750	80	40	45
LNG-CC	LNG-CC power plant with SCR and low NO_x burner	1350	80	40	60
HFO-ST	HFO-ST power plant with SCR and FGD	450	50	40	46
RORH	RORH plant with small reservoir	12	45	60	100
PSH	PSH plant, pumped from a lower reservoir to a higher elevation for load balancing	12	45	60	100
Biomass co-generation	Combined heat and power plant using wood chips as feedstock; includes fuel storage	10	80	40	39
Solar-PV	Rooftop type PV (3 kW) with aluminum frame and rack. The PV cells use solar-grade (SOG) polycrystalline silicon	1.2	12	35	100
Wind power (Onshore)	Wind turbines in a park with 10 units (4.4 MW each); excludes cables, transformers	20	20	20	100
Geothermal	Double flash type geothermal steam turbine. Includes well (less than 1000 m deep) development and drilling failure	30	80	40	100

[a] EEC (2012b).
[b] Gómez and Watterson (2006).
[c] In this study, net energy efficiency is defined as the percentage of fossil fuel input energy that is retrieved as electricity output. Therefore, renewable energy systems present a virtual net energy efficiency of 100%.

PM_{10e}[5] emissions released ($g_{pollutant}$/kW h_e) and generation costs ($US\$_{2012}$/MW h) of the electricity WTM life cycle. Additionally, impacts were evaluated in terms of total electricity demand in 2030 (Section 3.2).

3.2. Electricity demand forecast

The electricity demand in Japan has risen drastically, associated with the fast industrial growth over the past decades. From mid-1990s, however, consumption has stabilized given the economic slowdown and population decline. In the future, demand is predicted to remain fairly steady, as population is projected to continue declining and the economic panorama is yet uncertain.

Demand of electricity depends upon a wide range of factors, including the socio-economic conjecture of a country, technological development, climate conditions, consumer behavior, and energy policy framework. Generally, models to predict energy demand are classified as top-down and bottom-up methodologies. Top-down methods tend to adopt a more generic approach that focuses on an aggregated level of analysis. On the other hand, bottom-up approaches take into consideration detailed activity data at end-use levels for which demand is forecasted.

In this study, a top-down approach has been adopted; per capita electricity demand in 2030 was estimated by fitting a multiple linear regression on historical data from 1980 to 2010, using GDP per capita, and industrial and residential price of electricity as predictors of per capita demand. While energy conservation policies play a major role in regulating energy demand (clearly visible in the aggressive energy saving campaigns (*setsuden*) in post-3/11), this parameter was not taken into consideration in the present study, as future policy are yet to be defined, which would increase uncertainty in the model. The model is, therefore, specified as: $y_t = \beta_0 + \beta_1 \cdot GDP_t + \beta_2 \cdot indprice_t + \beta_3 \cdot resprice_t + \varepsilon_t$, where y_t is the electricity demand per capita in year t, GDP is the gross domestic product per capita in year t in 2000 PPP dollars, and *indprice* and *resprice* are the electricity tariffs for industries and households in year t, respectively. Historical GDP per capita data has been obtained from the World Development Indicators database (WB, 2013), whereas forecasts were obtained from JCER (2013), which estimates a GDP growth rate in Japan of 0.4 and 0.2, between 2011 and 2015, and 2016 and 2025, respectively. Historical residential and industrial tariffs in Japan have been gathered by IEA (2010), and estimations assume a gradual increase of prices by 20% until 2030, given the foreseen increase in share of renewable and reduction of nuclear energy in the generation mix (JCER, 2013).

The overall aggregated electricity demand in 2030 was obtain as the product of estimated electricity demand per capita and predicted population. Demographic historical statistics and forecasts were obtained by the National Institute of Population and Social Security Research (IPSS, 2012; 2013). Table 5 summarizes the regression estimation results.

Adjusted R^2 of the regression is 0.97, suggesting a very good predictive power. Overall, aggregated electricity demand in Japan in 2030 is estimated at 916.68 TW h, 9% lower than in 2010 levels. This is in range with the National Policy Unit (2012) projections, which estimates a total electricity consumption of 1000 TW h by 2030.

[5] PMF is calculated as particulate matter $< 10\,\mu m$ (PM_{10e}) by the following expression: $PM_{10e} = PM_{10} + 0.2 \cdot SO_2 + 0.32 \cdot NH_3 + 0.32 \cdot NO_x$, according to the factors suggested by EcoInvent in its ReCiPe midpoint method (Goedkoop et al., 2008).

Table 5
Per capita electricity demand regression estimation results.

R^2	0.974				
Adjusted R^2	0.971				
SSE	0.190				
N	30				
Variable name	β	S.E.	t stat	p value	2030 input values
Constant	**2.290**	1.311	1.747	0.09	–
GDP (Thousand PPP 2000$)	**0.153**	0.022	6.828	0.00	41.44
Industrial Electricity tariffs (JPY/kW h)	**-0.438**	0.190	-2.312	0.03	16.26
Residential Electricity tariffs (JPY/kW h)	**0.260**	0.140	1.859	0.07	24.44

Significance level: *10%, **5%, ***1%.

Table 6
Cumulative NRE consumption of electricity generation systems (toe/kW h_e).
Source: developed by the authors based on GEMIS databases (Öko Institute, 2011).

Lifecycle stage	Nuclear	Coal	LNG	HFO	RORH	SPH	Biomass	Solar-PV	Wind	Geo-thermal
Upstream	0.094	0.091	0.117	0.103	0.000	0.000	0.004	0.000	0.000	0.000
Downstream	0.004	0.115	0.065	0.110	0.000	0.000	0.000	0.000	0.000	0.000
Infrastructure	0.000	0.000	0.000	0.000	0.007	0.006	0.000	0.004	0.004	0.000
Total	0.098	0.206	0.182	0.214	0.007	0.006	0.004	0.004	0.004	0.000

Table 7
Global warming potential of electricity generation systems (gCO_{2e}/kW h_e).
Source: developed by the authors based on GEMIS databases (Öko Institute, 2011).

Lifecycle stage	Nuclear	Coal	LNG	HFO	RORH	SPH	Biomass	Solar-PV	Wind	Geo-thermal
Upstream	13.80	49.10	112.71	57.66	0.00	0.00	11.48	0.00	0.00	0.00
Downstream	0.00	798.86	333.85	625.83	0.00	0.00	3.11	0.00	0.00	10.19
Infrastructure	3.15	2.23	0.37	1.96	58.41	54.76	3.52	60.92	25.04	2.88
Total	16.95	850.18	446.93	685.46	58.41	54.76	18.11	60.92	25.04	13.07

Table 8
Terrestrial acidification potential emissions of electricity generation systems (gSO_{2e}/kW h_e).
Source: developed by the authors based on GEMIS databases (Öko Institute, 2011).

Lifecycle stage	Nuclear	Coal	LNG	HFO	RORH	SPH	Biomass	Solar-PV	Wind	Geo-thermal
Upstream	0.13	0.13	0.52	0.57	0.00	0.00	0.02	0.00	0.00	0.00
Downstream	0.00	0.90	0.85	1.10	0.00	0.00	0.94	0.00	0.00	2.84
Infrastructure	0.01	0.00	0.00	0.00	0.09	0.08	0.01	0.07	0.05	0.01
Total	0.13	1.03	1.38	1.67	0.09	0.08	0.97	0.07	0.05	2.84

3.3. *Environmental inventory analysis*

As stated above, the WTM analysis includes three different stages: (i) upstream processes, (ii) operation of power plants, and (iii) cradle-to-gate infrastructure life cycle. Therefore, co-benefits were calculated as the sum of all corresponding sub-stages of each electricity generation system, as follows: $I_{WTM}=\sum f_e\cdot(I_{u,e}+I_{d,e}+I_{i,e})$, whereas f_e refers to the share of each energy source e in the designed scenarios as defined in Table 2, $I_{u,e}$ reflects the impacts associated to upstream processes, $I_{d,e}$ accounts for the impacts during the operation of power plants to generate electricity, and $I_{i,e}$ includes the impacts of the cradle-to-gate infrastructure life cycle. Following sections detail calculations and data sources of each stage.

3.3.1. *Upstream stage*

NRE consumption and air emissions of energy resources extraction and processing were estimated by the following expression $I_{u,e}=A_e/\eta_e$, where A_e refers to the energy used and environmental burdens to extract and process one unit of fossil fuels and η_e refers to the net thermal efficiency of power plants, as stated in Table 3.

3.3.2. *Downstream stage*

The downstream stage refers to the impacts associated to the power plant operation. NRE consumption is given as the ratio of the process efficiency and the energy losses in Transmission and Distribution (T&D) systems: $NRE=1/(\sum f_e/\eta_e)\times(1-l)$, where f_e refers to the share of each energy source, η_e describes the power plant net thermal efficiency and l the losses of T&D.

The estimation of emissions of fossil fuel energy technologies involves two different approaches, as suggested by Gómez and Watterson (2006) and EPA (2008). The assessment of CO_2 and SO_2 emissions follows a fuel input analysis, as emissions are mainly dependent on fuel carbon and sulfur content. Thus, emissions per kW h_e generated, transmitted and distributed are based on the Low Heating Value (LHV) of each fuel i, the carbon (C_i) and sulfur (S_i) content of combusted fuel, oxidation fraction (OF_i), the power plant net thermal efficiency (η_e), and losses of transmission and distribution (l): $E_{CO_2}=\sum LHV_i\cdot C_i.OF_i\cdot 1/\eta_e\cdot 44/12/(1-l)$, $E_{SO_2}=\sum LHV_i\cdot S_i.OF_i\cdot$

Table 9
Particulate matter formation potential of electricity generation systems ($gPM_{10e}/kW\ h_e$).
Source: developed by the authors based on GEMIS databases (Öko Institute, 2011).

Lifecycle stage	Nuclear	Coal	LNG	HFO	RORH	SPH	Biomass	Solar-PV	Wind	Geo-thermal
Upstream	0.04	0.07	0.24	0.16	0.00	0.00	0.01	0.00	0.00	0.00
Downstream	0.00	0.33	0.49	0.35	0.00	0.00	0.43	0.00	0.00	0.57
Infrastructure	0.00	0.00	0.00	0.00	0.07	0.07	0.00	0.05	0.03	0.00
Total	0.04	0.41	0.73	0.51	0.07	0.07	0.45	0.05	0.03	0.57

$1/\eta_e \cdot 64/32/(1-l)$. On the other hand, other pollutants are site specific and mainly depend on power plant technology, combustion characteristics, usage of pollution control equipment and environmental conditions. Hence, they have been calculated on an Emission Factor (EF_i) (Gómez and Watterson, 2006), as follows: $E_p = EF_i/\eta_e \cdot EF/(1-l)$. Air emissions of renewable energy technologies are negligible during the plant operation, except for biomass and geothermal power plants. Although carbon dioxide emissions released during the operation of biomass power plants are not accounted for, as they are admitted to be carbon neutral, significant amount of other air pollutants, including N_2O, PM_{10} and SO_2, are emitted during combustion of wood chips (Cherubini, 2010). As for geothermal power plants, CO_2 and SO_x emissions are released when digging wells and maintaining hot water pipes (Hondo, 2005).

3.3.3. Infrastructure 'cradle-to-gate' life cycle

The 'cradle-to-gate' life cycle of power plant infrastructure was estimated based on the ratio of the amount of raw materials need to construct each plant (m_r), its associated fossil fuel energy consumption and emission factors (EF_r), and the total electricity supplied yearly in each power plant (Q), as shown in the following expression: $I_{i,e} = \sum(\sum(m_r \cdot EF_r)/Q_e$.

3.3.4. Cumulative NRE consumption and GHG emissions of evaluated energy systems

Tables 6–9 summarize the inventory analysis of the cumulative NRE consumption and GHG, SO_{2e} and PM_{10e} emissions of the electricity generation WTM life cycle, respectively. Results were obtained by integrating adjusted GEMIS unitary process databases into electricity generation systems.

As expected, fossil fuel based electricity generation systems contributes the most to the total environmental loads, ranging between 0.182–0.214 toe, 447–850 gCO_{2e}, 1.03–1.67 gSO_{2e}, and 0.41–0.73 $gPM_{10e}/kW\ h_e$ of electricity supplied to end users. The downstream stage of fossil fuel based energy systems is the most impactful accounting for 62–94% of total environmental burdens, followed by upstream processes, while the infrastructure 'cradle-to-gate' life cycle plays a minor role. The nuclear based electricity reveals lower NRE consumption and GHG emissions than fossil fuel technologies and the lowest TAP and PMF potentials, being therefore competitive with renewable energy systems. Its impacts are mainly related to the upstream processes, for uranium extraction and enrichment. However, if human toxicity and radioactive potential impacts related to waste disposal and plant decommission were accounted in the present analysis, nuclear technology migth have a higher impact (Valentine, 2011).

Renewable energies, on the other hand, reveal lower NRE consumption and GHG emissions than fossil fuel systems, being geothermal and biomass technologies the most attractive. NRE consumption ranges between minimal values for geothermal systems to 0.007 toe/kW h_e for hydropower; whereas GHG emissions vary between 13.07 and 60.92 $gCO_{2e}/kW\ h_e$. In terms of local environmental impacts, geothermal and biomass systems present loads at the same range than fossil fuel thermal technologies and higher than nuclear power. These derive from the pipeline emissions released during downstream stages, mainly PM_{10}, SO_x and NO_x during combustion of biomass and SO_x from digging wells and maintaining hot water pipes in geothermal plants. On the other hand, solar-PV, wind power, and hydro systems are the most attractive ones among renewables with regards to local environmental impacts.

3.4. Costs estimation

The cost estimation methodology consisted on using a starting point price for the overnight capital, fixed and variable costs (Tidball et al., 2010). These base costs were scaled to the pre-specified nominal plant capacity using rationing by capacity with the assumption of Williams' six-tenths rule, which assumes that the relationship between costs and size of a manufacturing facility increases by an exponent of six-tenths, and for the capital costs a linear exponent on the operating costs (Williams, 1947). These methods have provided reliable and accurate cost projections in chemical plants, and can be extrapolated to power plants. Moreover, the producer's price index (PPI) was used to adjust the time value of the costs. In order to ensure that the scaled costs were reasonable, different datasets contained in Tidball et al. (2010) and EIA (2010) were used to compare and adjust the estimates. An overestimated cost was substituted by the immediate value of the upper limit found in the literature; while if underestimated, the lower limit was used. Levelized costs (LCOE) were calculated using the simplified formula suggested by Short et al. (1995):

sLCOE = {(overnight capital cost × capital recovery factor + fixed O&M cost)/(8.76 × capacity factor)} + variable costs f (O&M cost + fuel cost + CO_2 costs).

The capital recovery assumed an interest rate of 3% and the capital recovery factor was determined from the statutory year. These values, as well as the upstream stage of raw material extraction and processing fuel and CO_2 emission costs were obtained from the Cost Validation Council (2012) in order to customize for the Japanese context. Furthermore, since uncertainty is constantly present when estimating the costs of a new power plant; to minimize this error and ensure reliability, the assessment was measured up to an evaluation performed by the Cost Validation Council.

It is important to underline, however, that while environmental damage has been analyzed, its external costs are out of the scope of this study. Therefore, costs associated with environmental and human health, and material damage from harmful inorganic pollutants, acidification precursors, and GHG have not been taken into consideration. Furthermore, uncertainties related to indirect effects of climate change, such as increasing frequency and intensity of tropical cyclones, as stated by Esteban et al. (2012b) has been not included in the present study.

Cost estimates, as presented in Table 10, exhibit a maximum deviation of 30% from the Cost Validation Council estimates. Hydro and nuclear power plants present the lowest costs, at 92 and 93 US \$/MW h_e, respectively; while, as expected, the oil-fueled power plant

Table 10
Breakdown of cost estimates of electricity generation systems in 2030.

Tech.	Units	Nuclear	Coal	LNG	HFO	RORH	SPH[e)]	Bio-mass	Solar-PV	Wind	Geo-thermal
Capital costs	$US\$_{2012}$/kW[b]	4573	3214	1525	563	7522	–	3000	2500	2090	7360
Variable	$US\$_{2012}$/MW h[a]	1	3	7	8	4	–	7	0	0	0
Fixed	$US\$_{2012}$/kW	157	59	35	63	19	–	73	12	42	147
Fuel costs	$US\$_{2012}$/MW h[a]	8	49	90	186	0	–	155	0	0	0
Statutory life	Years	16	15	15	15	40	–	15	17	17	15
CO_2 costs	$US\$_{2012}$/MW h[a]	0	38	15	29	0	–	0	0	0	0
Total LCOF (2030)	**$US\$_{2012}$/MW h[a]**	**93**	**136**	**135**	**265**	**92**	**153**	**208**	**192**	**115**	**109**
Total LCOF (2030)	**JPY_{2012}/kW h[a]**	**7.5**	**10.9**	**10.8**	**21.2**	**7.4**	**12.2**	**16.6**	**15.3**	**9.2**	**8.7**
Estimated costs for 2010											
Total LCOF (2010)	**$US\$_{2012}$/MW h[a]**	**129**	**147**	**135**	**235**	**108**	**153**	**231**	**524**	**159**	**155**
Total LCOF (2010)	**JPY_{2012}/kW h[a]**	**10.4**	**11.8**	**11.4**	**18.9**	**8.7**	**12.2**	**18.5**	**42.0**	**12.7**	**12.4**

[a] Costs for SPH were obtained from Matsuo (2012). It includes the pump storage generation system and the required nuclear electricity to pump the water back up.
[b] 1 kW h is equivalent to 8.76 kW, assuming an operating time of 24 h throughout 365 days per year.

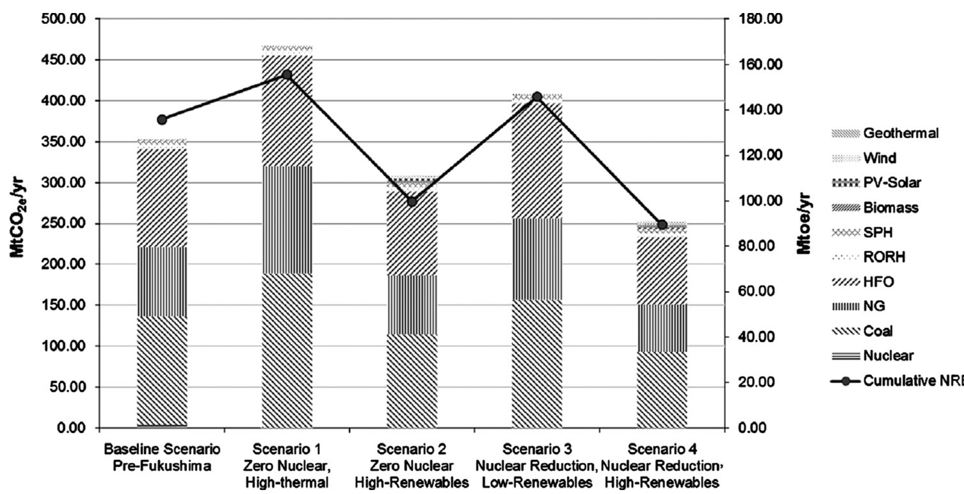

Fig. 2. Cumulative NRE consumption and global warming potential (GWP) of proposed scenarios (2030).

exhibit the highest costs (265 US$/MW h_e) as a direct result of high fuel prices (70% of total LCOE). High costs are followed by biomass (208 US$/MW h_e) and solar-PV power (192 US$/MW h_e), since these technologies require high capital costs for higher nominal capacities.

Table 10 also shows that when compared to 2010 estimated costs, most technologies exhibit reduction in generation costs, largely as a result of learning curves of technological improvement. The largest differences are observed on renewable energy sources (excluding hydro), particularly solar-PV, as a result of steeper learning curves given non-matured stages of development. Slight reductions in generation costs are also observed for fossil fuels, with the exception of HFO. Nevertheless it is important to highlight that although an increase in fuel costs was forecasted to estimate costs, fossil fuel prices are highly volatile, and generation costs are very sensitive to changes in fuel prices, hence these estimates should be interpreted carefully. Regarding nuclear energy generation costs, policy variables that might be reflected on costs, such as the strengthening of countermeasures against natural disasters and decommission of Fukushima nuclear power plant reactors are not included in the analysis.

4. Results

4.1. Global and local environmental impacts

This section discusses the life cycle impact assessment results of the baseline and alternative scenarios in terms of cumulative NRE consumption, GHG emissions and generation costs of total supplied electricity in 2030.

Fig. 2 displays the total amount of fossil fuels consumed and GHG emitted to meet the electricity demand in 2030. If the Japanese Government returns to the pre-Fukushima electricity generation mix (baseline scenario), the total NRE consumption and GHG emissions would be 136 Mtoe and 352 $MtCO_{2e}$, respectively. Under this scenario, the main source of fossil fuel consumption and GHG emissions are thermal energy technologies (96%), while nuclear and renewables play a minor role. Among alternative scenarios, scenario 1, “Zero Nuclear, High Thermal”, reveals the highest NRE consumption (156 Mtoe) and GHG emissions (466 $MtCO_{2e}$), a rise of 15% and 32%, respectively, when compared to the baseline scenario. Similarly, scenario 3, “Nuclear Reduction, Low Renewables”, which replicates the case when nuclear reduction is achieved by increasing the share of fossil fuels, denotes an increase of fossil fuel dependence and GWP by 7% and 16%, respectively. Scenario 2, “Zero Nuclear, High Renewables”, on the other hand, which portrays a nuclear phase-out, higher penetration of renewables, and reduction of fossil fuel dependence, results in a drop of 17% on NRE and 27% on GHG emissions. Scenario 4, “Nuclear Reduction, High Renewables”, exhibits the lowest fossil fuel dependency among all alternative scenarios, yielding considerable savings, and suggesting a mitigation potential of 29–34% compared with the baseline scenario.

Similar trends are followed in terms of local environmental impacts, measured as TAP and PMF potential (Figs. 3 and 4). The baseline scenario shows a TAP of 0.8 $MtSO_{2e}$ and PMF potential of

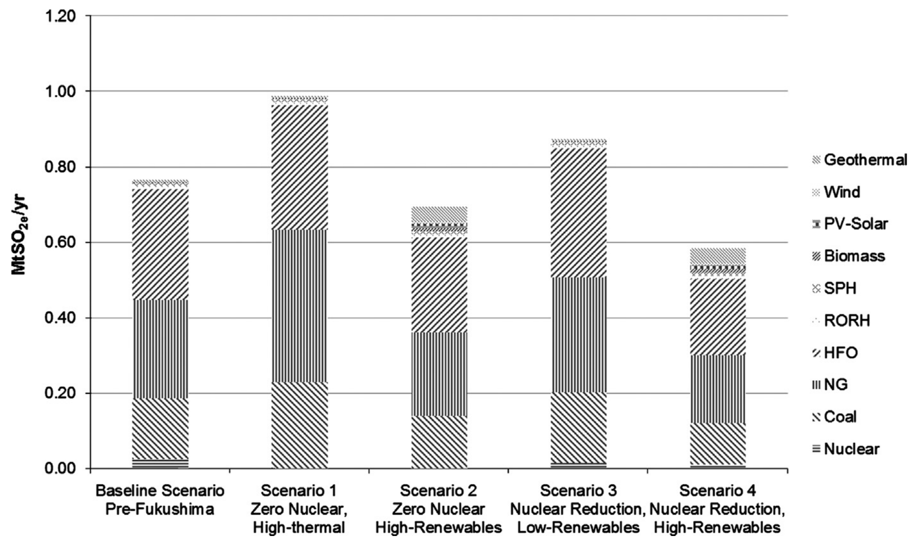

Fig. 3. Terrestrial acidification potential potential (TAP) of proposed scenarios (2030).

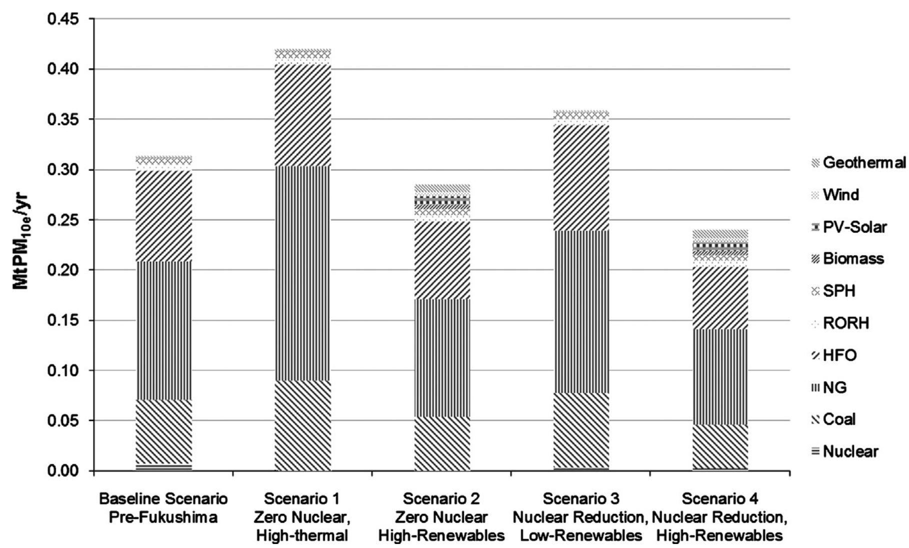

Fig. 4. particular matter formation potential (PMFP) of proposed scenarios (2030).

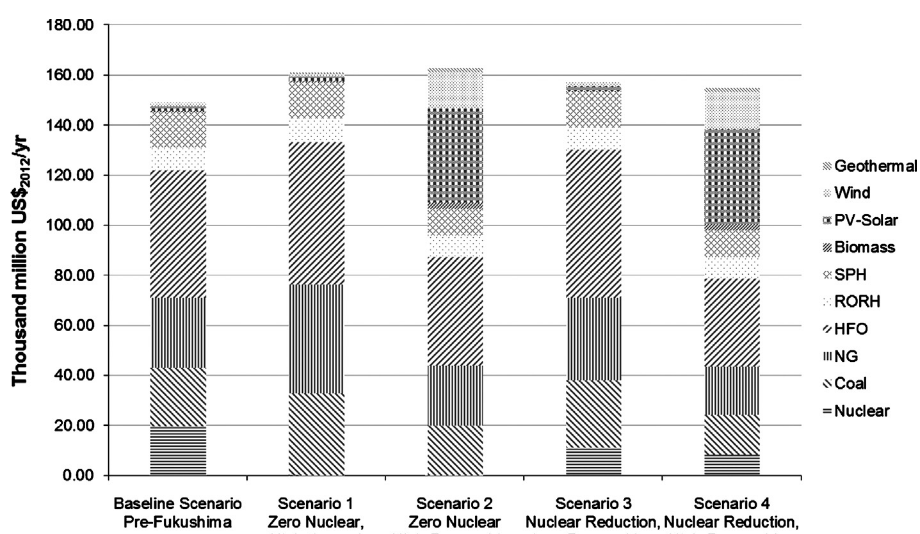

Fig. 5. Levelized costs of proposed scenarios (2030).

$0.3\ MtPM_{10e}$. The impacts are mainly due to LNG, coal and HFO thermal power systems, as they have a higher share in the energy mix and present higher emission factors than nuclear and renewable energy systems.

Scenario 1, "Zero Nuclear, High Thermal", and scenario 3, "Nuclear Reduction, High Renewables", displays a considerable increase of SO_{2e} and PM_{10e} emissions when compared to the baseline, due to greater dependency on fossil fuel thermal power. This suggests that even if nuclear power is reduced and substituted by renewable energies, but fossil fuel thermal share in the energy mix remains constant, the overall local environmental impacts of the electric sector will not change. In contrast, Scenario 4, "Nuclear Reduction, High Renewables", suggests a significant reduction of environmental impacts, as TAP and PMF fall by 24%. Thus, only if fossil fuel dependence and nuclear power share are simultaneously reduced, environmental impacts will be mitigated.

4.2. Generation costs

This section describes the final distribution expenses based on the LCOE results. Fig. 5 presents the breakdown of LCOEs of all scenarios as compared to the baseline scenario. Using a baseline case at US$149 thousand million, scenario 2, "Zero Nuclear, High Renewable" is the most expensive one, increasing by 9% up to US $163 thousand million, mainly as a result of the high capital costs required to implement these technologies.

Scenario 1, "Zero Nuclear, High Thermal" presented a LCOE of US$160 thousand million and it is slightly cheaper than scenario 2, "Zero Nuclear, High Renewables". This indicates that renewables might be competitive in economic terms with fossil fuels by 2030; however, removing nuclear from the energy mix increases the generation costs. For instance, scenario 3 "Nuclear Reduction, Low Renewables" and scenario 4, "Nuclear Reduction, High Renewables" have estimated LCOEs of US$157 and US$154 thousand million, respectively. The reduction of nuclear energy represents increases of 5% and 4% for the scenarios 3 and 4 with respect to the reference case.

When comparing scenario 3 "Nuclear Reduction, Low Renewables" and scenario 4 "Nuclear Reduction, High Renewables", although the capital costs of renewables are significantly higher than other energy sources, due to a reduction in the share of high thermal energy, scenario 4 turns out to be a cheaper option. This is mainly a result of high cost of fossil fuels, suggesting that by the year 2030, a high renewables scenario could be competitive with a high nuclear scenario such as the baseline case. This makes it feasible to provide a cost-effective solution to energy security of supply and climate change, without undermining economic development. It is important to note that project costs do not necessarily indicate the economic liability of a venture, but rather the comparison to other alternatives. In this study the contrast of diverse scenarios helped to reveal the economic feasibility of a potential changes.

5. Discussion

In order to put in perspective the findings presented above, a brief overview of the current socio-political environment in Japan surrounding the drafting of Japan's new energy policy is first discussed. Economically, the impact of the Fukushima accident is yet to be fully quantified, nevertheless, in terms of energy imports alone, in 2011, Japan's demand for LNG and HFO increased by 15.9% and 2.9%, respectively, when compared to 2010 (ANRE, 2012b) to compensate for the shutdown of its nuclear reactors. This increase in imports is not only translated into an increase of generation costs that was passed on to the final users in the form of a raise in the energy bill by the Tokyo Electric Power Company (TEPCO), but also it is identified as the main cause of Japan's first trade deficit in the last 31 years (Vivoda, 2012). Consequently, the Japan Business Federation (Keidanren), Japan's largest business lobby, rallied for a quick restart of the idled reactors in order to reduce the adverse effects of higher energy prices on business and industry sectors. This is a valid point taking into consideration that (i) Japan's economic growth has been driven by exports since the post-war period, and (ii) Japan's most powerful export industries, such as machinery, transport equipment, and chemicals are also the most energy intensive ones. For example, chemical and steel industries, while accounting for 10.2% and 5.5% of Japan's total exports, respectively, add up to 65.3% of the total industrial energy consumption (Schaede, 2012). Other potentially negative effects of a growing dependence on imported fossil fuels are: (i) the increased vulnerability to exogenous events, like the oil shocks of the 1970s, and (ii) a potential threat to Japan's national security in terms of guaranteeing a stable supply of energy, an issue that was highlighted as a result of Iran's threat to close the Hormuz strait.

On the other hand, the public opinion regarding the use of nuclear power has dramatically changed since 3/11. In 2007, only 7% of the Japanese citizens supported a zero nuclear energy policy, while 21% favored a reduction; 53% supported maintaining current levels, and 13% agreed with an increase in the nuclear energy share. A month after the accident, a change in the citizens' attitude towards nuclear energy was already evident, with 11% demanding a total stop of reactors and 30% supporting a reduction (Asahi Shimbun, 2011). The most recent public hearings conducted by the government between July and August of 2012 to gauge the public sentiment regarding nuclear energy revealed that among the three alternative scenarios proposed by the EEC, more than 70% of the public favored the zero percent nuclear scenario (Mainichi Daily, 2012). The change in the public sentiment was also evident in the series of anti-nuclear demonstrations that occurred all over Japan since 3/11 and continue until the time of writing of this article, constituting the largest public demonstrations since the 1960s.

This has led the government to announce a phase-out of nuclear energy by 2030, only to take it back a day later, after protests from the Japan Business Federation (Keidanren). This is evidence of the existing tensions between economic and social interests and between different stakeholders involved in the energy policy making process.

Based on this context, the analysis of the results presented earlier suggests several implications:

(i) A short-term transition towards a high fossil fuel thermal scenario and phase-out of nuclear, although desirable in terms of the public sentiment towards nuclear energy, translates into both higher economic and environmental costs. Additionally, a long-term dependence on fossil fuel seems unrealistic given the increasing trend and volatility in fossil fuels prices, as earlier discussed. Furthermore, as the Bank of Japan pursues an aggressive quantitative easing policy in a bet to beat chronic deflation, at least in the short term, the JPY is forecasted to depreciate against the US$, which will considerably raise the costs of fossil fuel imports.

(ii) The elimination of nuclear power from the electricity generation mix (as shown in Scenarios 1 and 2) seems unfeasible in economic terms given its higher costs when compared to the baseline scenario. A balance between renewables and nuclear power seems to be the most desirable alternative, not only from an economic and environmental perspective, but also from an energy security point of view. Social and technical considerations also favor this balance; on the one hand, public opinion and safety issues regarding nuclear reactor operation and its vulnerability to low frequency high impact events such as 3/11 might hamper an aggressive nuclear policy such as the one advocated by the government in its "Strategic Energy Plan". On the other hand, renewables are still in an initial state of development and there are significant constraints to be overcome regarding electricity storage, backup power and distribution systems if a larger market penetration is to be achieved.

(iii) Although cost wise nuclear reduction scenarios imply slight cost escalation when compared to the baseline scenario, in the long run, and from an environmental perspective, the "Nuclear Reduction, High Renewables" scenario, clearly presents larger environmental gains as a result of reduced NRE dependence, GHG and other local air pollutant emissions, when compared to the "Nuclear Reduction, Low Renewables" scenario.

6. Final remarks and policy recommendations

This study aimed to evaluate the co-benefit implications of alternative electricity generation scenarios in a post-Fukushima context. Four scenarios were designed assuming different shares of energy sources in a 2030 timeframe. Applying a LCA methodology, these scenarios were assessed in terms of cumulative NRE consumption and GHG emissions. Additionally, levelized generation costs were estimated.

In terms of policy making, a dynamic approach should consider the energy problematic in both short-term and mid/long-term perspectives. Results revealed that the short-term strategy followed by the Japanese Government of idling nuclear power and substituting it with fossil fuel technologies (as modeled in scenario 1) is not sustainable both in environmental and economic terms, as it results in an increase of 14% of cumulative NRE consumption, 32% of GHG, 29% of TAP, 34% of PMF, and it is 8% more costly than the pre-Fukushima baseline scenario. Not only does this raises concerns related to Post-Kyoto Protocol commitments, but also makes the Japanese economy more vulnerable to unpredictable fluctuations of international fossil fuel prices and changes in exchange rates. On the other hand, due to infrastructure and technical constraints, an immediate transition to renewable energies is not realistic in the short-term. In that sense, taking into consideration the public sentiment toward nuclear power and the economic and environmental implications of fossil fuel use, a reduced share of nuclear energy is the optimal choice. However, given the public distrust in the nuclear regulatory institutions, the Japanese government should ramp up its efforts to guarantee the safety of its nuclear reactors up to global standards of safety, public health and welfare, and reform the regulatory system as recommended by the Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company (Hatamura et al., 2012).

In the mid/long-term, a shift from non-renewable resource dependence to endogenous energy sources might prove a successful strategy on environmental and economic terms. In that sense, the transition might be achieved from either nuclear power generation or renewables, as both energy systems are cost-effective alternatives to reduce foreign energy dependence, GHG emissions and other local air pollutants at an affordable cost. As demonstrated in scenario 4, "Nuclear Reduction, High Renewables", an incremental share of renewables, together with a reduction of nuclear power and fossil fuel thermal technologies, would result in 29% savings in NRE consumption and decrease of 34% of GHG emissions, which would reinforce forthcoming Post-Kyoto Protocol commitments. Furthermore local environmental impacts, including TAP and PMF would decrease by 24%. Although when compared with the base scenario, generation costs are indeed higher, these costs might also may be understood as an internalization of environmental externalities.

That being said, the large scale deployment of renewables also faces some constraints: (i) the initial necessary investments on renewable energy infrastructure might impose economic limitations; (ii) regions with high renewable energy potential, particularly wind energy (Hokkaido and Tohoku areas), are rather far from high demand areas in Japan, such as the Tokaido megalopolis corridor; and (iii) high shares of renewables might be limited to some extent due to the fluctuating nature of generation, which might compromise a reliable steady supply of electricity, and require significant storage capacity. This situation is also exacerbated by the lack of connectivity with other regions or countries that might serve as a backup supply source. Given these constraints, it seems technically unfeasible to do without nuclear energy if environmental targets are to be achieved; hence scenario 4, "Reduced Nuclear-High Renewables" is recommended as the optimal alternative.

To accelerate this transition, it is desirable that the Japanese government adjust its fiscal policy to develop market-based instruments that support the high capital costs of renewables, and conduct an institutional reform to accelerate the liberalization of the energy supply market thus breaking the virtual regional monopolies that control the energy markets in Japan. In addition, further investments on R&D are required to promote technological development and innovation in the renewable energy sector.

Certainly, some policy measures are already being implemented, the latest example being the Feed-in-Tariff scheme which entered into effect on July 1st of 2012. Furthermore, the liberalization of the energy market is on the discussion table, particularly the separation of the generation and the distribution systems. In the near future, vital decisions will take place when designing the new energy strategy for 2030. As demonstrated in this study, the Government of Japan has the potential and capacity to turn the currently energy crisis into an opportunity and move towards an environmentally friendly and economically competitive electricity generation mix.

References

ANRE, 2012a 'エネルギーミックスの選択肢の策定に向けた再生可能エネルギー関係の基礎資料' [Enerugii mikkusu no sentakushi no sakutei ni muketa saisei kanou enerugii kankei no kiso shiryou] [Fundamental Documents on Renewable Energy for the Establishment of Energy Mix Alternatives] (In Japanese). Agency for Natural Resources and Energy.

ANRE, 2012b. '平成２３年度エネルギー需要実績(速報)' [Heisei 23 nendo enerugii juyou jisseki (soukoku)] [Energy Demand in Fiscal Year 2011 (News Release)] (in Japanese). Agency for Natural Resources and Energy.

Asahi Shimbun, 2011. '原発「減らす・やめる」４１％　朝日新聞世論調査' [Genaptsu [Herasu yameru] 41% Asahi Shimbun seron chousa] [Asahi Newspaper Opinion Poll: 41% Favor Reduction or Elimation of Nuclear Power] (in Japanese). Asahi Newspaper, 11 April. Available at: ⟨http://www.asahi.com/special/08003/TKY201104170324.html⟩ [accessed 10 September 2012].

Asahi Shimbun, 2012. Electricity supply sufficient even if next summer is a scorcher. Asahi Newspaper, 25 October. Available at: ⟨http://ajw.asahi.com/article/economy/business/AJ201210250073⟩ [accessed 25 October].

Bhattacharya, Janardhanan, Kuramochi, 2012. Balancing Japan's Energy and Climate Change Goals: Exploring Post-Fukushima Energy Supply Options. Institute of Global Environmental Studies, Japan.
Cherubini, 2010. GHG balances of bioenergy systems—Overview of key steps in the production chain and methodological concerns. Renewable Energy 35 (7), 1565–1573.
Cost Validation Council, 2012. '発電コストシート' [Hatsuden cosuto shiito] [Energy Generation Cost Sheet] (in Japanese). National Policy Unit. Government of Japan. Available at: 〈http://www.npu.go.jp/policy/policy09/archive02_shisan_sheet.html〉 [accessed 20 June 2012].
DeWit, 2012. Japan's energy policy at a crossroads: a renewable energy future? The Asia-Pacific Journal 10 (38), 4.
Duffield, Woodall, 2011. Japan's new basic energy plan. Energy Policy 39, 3741–3749.
EIA, 2010. Updated Capital Cost Estimates for Electricity Generation Plants. U.S. Energy Information Administration.
EEC, 2012a. Innovative Strategy for Energy and the Environment. Energy and Environment Council. National Policy Unit. Government of Japan.
EEC, 2012b. 'エネルギー・環境に関する選択肢' [Enerugii kankyou ni kan suru sentakushi] [Alternatives on energy and the environment] (in Japanese). Energy and Environment Council. National Policy Unit. Government of Japan.
EPA, 2008. Direct Emissions from Stationary Combustion. Report no. EPA430-K-08-003. Environmental Protection Agency.
Esteban, Zhang, Utama, 2012a. Estimation of the energy storage requirement of a future 100% renewable energy system in Japan. Energy Policy 47, 22–31.
Esteban, Zhang, Longarte-Galnares, 2012b. Cost-benefit analysis of a green electricity system in Japan considering the indirect economic impacts of tropical cyclones. Energy Policy 43, 49–57.
FEPC. 2011. The Electricity Review in Japan. Federation of Electric Power Company of Japan.
FEPC. 2012a.The Electricity Review in Japan. Federation of Electric Power Company of Japan.
FEPC.2012b. '電力統計情報' [Denryoku Toukei Jouhu] [Power Statistics] (in Japanese). Federation of Electric Power Companies of Japan. Available at: 〈http://www.fepc.or.jp/〉 [accessed 22 November 2012].
FEPC 2013, Nuclear Waste Management. Available at: 〈http://www.fepc.or.jp/english/nuclear/waste_management/index.html〉 [accessed April 18, 2013].
Goedkoop, et al., 2008. A Life Cycle Impact Assessment Method Which Comprises Harmonized Category Indicators at the Midpoint and the Endpoint Level. PRé Consultants, Radboud University Nijmegen, Leiden University, RIVM.
Gómez, Watterson, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 2 Energy, Chapter 2 Stationary Sources. Intergovernmental Panel on Climate Change, Geneva.
Hatamura et al., 2012. Final Report of the Investigation Committee on the Accident at Fukushima Nuclear Power Stations of Tokyo Electric Power Company. National Diet of Japan.
Hondo, 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 30, 2042–2056.
IEA, 2010. Electricity Information. International Energy Agency. Paris.
IEEJ, 2011. Japan Energy Brief No. 14. Institute of Energy Economics of Japan.
IEEJ, 2012. Energy Indicators of Japan. Available at: 〈http://eneken.ieej.or.jp/en/〉 [accessed 22 November 2012].
IPSS, 2012. Population Projections for Japan: 2011 to 2060. National Institute of Population and Social Security Research. Tokyo.
IPSS, 2013. Population Statistics of Japan. Available at: 〈http://www.ipss.go.jp/ p-info/e/psj2012/PSJ2012.asp〉 [accessed 13 April 2013].
ISO, 2006.Environmental Management – Life Cycle Assessment – Principles and Framework. ISO 14040:2006. International Organization of Standardization.
JCER, 2013. The 39th Medium-Term Economic Forecast (2012 FY-2025FY): Japan's Changes in Industrial Structure and Economic Growth. Tokyo.
Kingston, J., 2012. Power politics: Japan's resilient nuclear village. The Asia-Pacific Journal 10 (Issue 43), No. 1.
Mainichi Daily, 2012. Japan to Aim for Nuclear Phaseout in 2030s: Draft Energy Policy. Mainichi Daily, 13 September. Available at: 〈http://mainichi.jp/english/english/newsselect/news/20120913p2g00m0dm038000c.html〉 [accessed 14 September 2012].
Matsuo, 2012. コスト等検証委員会」による原子力発電のコスト試算の概要と評価 [kosutotou kenshou iinkai ni yoru gennshiryoku hastuden no kosuto shisan no gaiyou to hyouka] [Outline and Assessment of Nuclear Power Generation Cost Estimations by the Cost Validation Council] (in Japanese). Institute of Energy Economics of Japan.
METI, 2005. Electricity Business Act. Act No. 87 of 2005. Ministry of EconomyTrade and Industry.Government of Japan.
METI, 2010. The Strategic Energy Plan of Japan. Ministry of Economy, Trade, and Industry. Government of Japan.
Nakata, 2002. Analysis of the impacts of nuclear phase-out on energy systems in Japan. Energy 27, 363–377.
Öko Institute, 2011. Global emission model for integrated systems (GEMIS) version 4.7. Germany. Available at: 〈http://www.oeko.de/service/gemis/en/index.htm〉 [accessed 10 June 2012].
Onoue, Murakami, Sofronis, 2012. Japan's energy supply: mid-to-long-term scenario proposal for a new energy supply system in the aftermath of the March 11 earthquake. International Journal of Hydrogen Energy 37 (10), 8123–8132.
PRC, 2012. Japanese Wary of Nuclear Energy: Disaster 'Weakened' Nation, Pew Research Center.
Schaede, 2012. Japan's Energy Situation and Its Economic Impact—A View from Abroad. In Energy Policy Roundtable 3. Todai Alternative Policy Research Institute. Tokyo, Japan, 12 July 2012.
Short, Packey, Holt, 1995. A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, Report no. NREL/TP-462-5173. National Renewable Energy Laboratory.
Solomon, et al., 2007. Contribution of Working Group I to the Fourth Assessment Report. Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York, NY, USA.
Supply and Demand Verification Committee, 2012. '電力コストの抑制策について' [Denryoku cosuto no yokuseisaku ni tsuite] [Measures for the suppression of power costs] (in Japanese). National Policy Unit. Government of Japan. Available at: 〈http://www.npu.go.jp/policy/policy09/pdf/20121024/shiryo3.pdf〉 [accessed 22 November 2012].
Takase, Suzuki, 2010. The Japanese energy sector: current situation, and future paths. Energy Policy 39 (11), 6731–6744.
Tidball, Bluestein, Rodriguez, Knoke, 2010. Cost and Performance Assumptions for Modeling Electricity Generation Technologies, Report no. NREL/SR-6A20-48595. National Renewable Energy Laboratory.
Valentine, 2011. Emerging symbiosis: renewable energy and energy security. Renewable and Sustainable Energy Reviews 15 (9), 4572–4578.
Varun, Bhat, Prakash, 2009. LCA of renewable energy for electricity generation systems. Renewable and Sustainable Energy Reviews 13, 1067–1073.
Vivoda, 2012. Japan's energy security predicament post-Fukushima. Energy Policy 46, 135–143.
Weisser, 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 32, 1543.
Williams, 1947. Six-tenths factor aids in approximating costs. Chemical Engineer 54 (124–125), 124–125.
World Bank, 2013. World Development Indicators, The World Bank. Available at: 〈http://data.worldbank.org/data-catalog/world-development-indicators〉 [accessed 12 April 2013].
Zhang, et al., 2012. Scenario analysis on future electricity supply and demand in Japan. Energy 38, 376–385.