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Interactions among energy consumption, economic development and greenhouse gas emissions in Japan after World War II

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A B S T R A C T

The long-term dynamic changes in the triad, energy consumption, economic development, and Greenhouse gas (GHG) emissions, in Japan after World War II were quantified, and the interactions among them were analyzed based on an integrated suite of energy, emergy and economic indices. The results quantitatively showed that two different energy strategy periods, one before 1973 using new sources of higher quality energy and one after 1973 focused on improving the efficiency of energy generation methods, could explain the linear increase in national economic development in Japan over the 66 years from 1946 to 2011. Japan benefited both ecologically and economically from importing fossil fuels, which accounted for 8.7% of the nominal GDP of Japan averaged over the entire study period. The total environmental impacts of GHG (i.e., CO_2, CH_4 and N_2O) emissions measured by emergy decreased after 1997, and since 2009 they have remained lower than 76% of the emissions in 1990, even though no decrease in the global warming impact based on the weight of CO_2 was observed. Emergy methods and Energy Systems models revealed aspects of the complicated interactions among energy consumption, economic development, and the potential environmental impact of GHG emissions which formerly had not been recognized.

Contents

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1. Introduction

Energy consumption is not only recognized as one of the basic driving forces for social and economic development, but it is also a main source of greenhouse gas (GHG) emissions. Consequently, the relationships among energy consumption, economic development and environmental problems related to GHG emissions, have been the subject of long-term debate focused on reducing environmental problems without harming the economy. Many analyses have been performed at all scales of organization to try to answer this question [1–6], with special concern for identifying the causal relationships that may exist among them. Three main hypotheses [7], including the growth hypothesis, which assumes a unidirectional relationship from energy consumption to economic growth, or vice versa; the feedback hypothesis, which assumes a bidirectional relationship or feedback loop between energy consumption and economic growth; and the neutrality hypothesis, which assumes no causal relationship exists between the two, have been explored for many different countries during many different periods [7,8]. No definitive agreement among researchers has been achieved about the direction of the relationship between energy consumption and economic growth, although most studies validated the positive effects of energy consumption on the growth of GDP and CO_2 emission [7–9]. Furthermore, even after clarification of the casual relationships, constructing successful management strategies still has proved to be difficult, due to the lack of uniform models and evaluation tools that can quantify the three different aspects of the problem in the same terms to promote the development of unified methods of ecological-economic optimization. Some scientists tried to solve this “apples and oranges” problem by combining different methods and results through employing a suite of weighting factors [10–14]. However, those weighting factors can be somewhat subjective and the combinations are accompanied by fundamental theoretical conflicts that need to be solved in a uniform manner [15,16].

Available energy (i.e., exergy) or energy with the potential to do work is not only one of the main driving forces and causes of economic development and GHG emissions, but it is also the common essential factor for the creation of all items and actions, because all actions are necessarily accompanied by the transformation or conversion of energy potentials [17–20]. Thus, the past use of available energy can be used as a measure to quantify the ecological/economic production processes for all assets [21]. The above valuation process is called emergy evaluation, and it is an environmental assessment methodology that was developed by H. T. Odum and his colleagues. This method defines “emergy” as a common denominator measure for quantifying all kinds of energy, material and information storages and flows in equivalent units (e.g. solar equivalent joules that have been used in the past, or solar emjoules, sej). Defined as the available energy of one kind previously used up directly and indirectly to make a service or product, emergy is a thermodynamically defined quantity based on energy hierarchy theory and the maximum empower principle [21–26]. Over the past 30 years, Energy Systems Theory and emergy evaluation methods have been applied widely to address ecological economic issues on all scales [27–34], including national systems [35–41]. However, only a few emergy studies have been done to explore the ecological economic dynamics of national systems over a long period of time [42,43], and consequently the general emergy-based long-term trends of the triad, national energy consumption, economic development and environmental impacts, and the interactions among them scarcely have been explored. In past emergy analyses, potential environmental impacts were generally evaluated using the Environmental Loading Ratio, i.e., the ratio of the purchased and nonrenewable emergy use to the renewable emergy use, due to a lack of widely applicable emergy per unit coefficients (e.g., emergy per unit of available energy or mass) also called the Unit Emergy Values, UEVs, for specific pollutants. Recently, several studies have provided UEVs for GHG pollutants [16,44–46]. Furthermore, the potential for unfair international exchange from an emergy perspective and its effects on national economies have seldom been systematically quantified [47,48], although it is clearly becoming much more important as economic globalization increases.

An additional reason for studying Japan is that it may be an ideal microcosm for the world. Over the long-term both systems are undergoing intensified development; however, Japan has been leading the way. Therefore, both systems are trapped in a difficult triad of contradictions generated by the need to balance energy consumption and the benefits of economic development with the negative effects of pollutant emissions on the local and global ecosystems. The interactions of this triad are particularly intense in Japan, since it is the third-largest economy in the world, as measured by nominal GDP, and it has developed quickly from the wreckage left by World War II (WWII). Over this time Japan has passed through a period of rapid development known as the ‘post-war economic miracle’, which extended from the 1960s to the end of the 1980s, followed in 1990 by the wandering or ‘lost decades’, a period that started with the bursting of the Japanese asset price bubble triggered by a collapse in land and stock prices [49–52] (Fig. 1). Furthermore, Japanese economic development has occurred despite an extreme shortage of domestic energy sources [53],

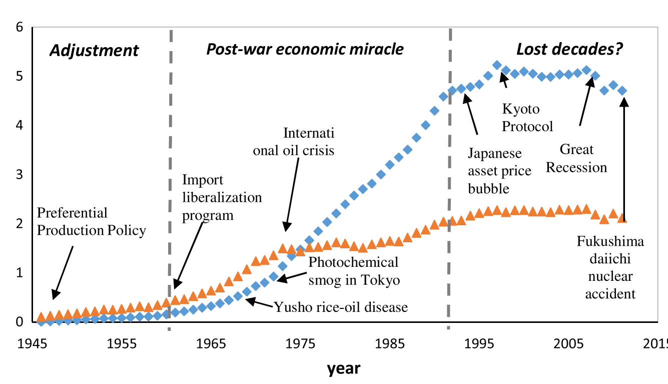

Fig. 1. Temporal patterns of ecological economic development in Japan.

and consequently energy security is a key concern for national economic development. Japan is not only an economic powerhouse but also a model of energy efficiency for developed nations, with the highest energy use efficiency in the world as ranked by GDP per unit of energy consumption [54]. Nevertheless, Japan experienced serious environmental problems in the 1960s and 1970s [55], and as a result Japan is currently one of the world's leaders in the development of new environment-friendly technologies, and it has superior environmental conditions as ranked by the Environmental Performance Index (23rd in the world in 2012), and by the life expectancy for women, which is the 2nd highest in the world [56].

The Fukushima Daiichi nuclear accident on March 11, 2011 and the shutdown of nuclear reactors that followed it, put Japan, and many other countries using nuclear power, at the forefront of making critical decisions for future energy needs by not only considering energy security, but also the social economic and environmental impacts that follow from energy decisions [57–59]. After the Fukushima Daiichi nuclear accident numerous publications appeared in the literature on this complex topic, but most of them were focused on future energy mixes that were technologically possible, and the effects of these actions on specific environmental and socioeconomic processes [15,54,60–64]. However, agreement on a way forward has not been attained, in part, due to the lack of a common objective basis for evaluation of the energy, environmental and economic impacts of proposed energy policy alternatives. Furthermore, few publications have explored the mechanisms of the long-term interactions among energy consumption, economic development and environmental impacts in Japan. This has been true, even though learning from the past is the fundamental way to clarify where we are at present and where we will go, and it is essential for analyzing a country's vested interest positions, before making any inferences about special polices [65].

The goal of this study is to quantify and explore the long-term relationships among energy consumption, economic development and GHG emissions in Japan after WWII from a top down perspective using a common objective valuation framework. In addition, we want to better understand the combined ecological economic effects of the new Japanese energy mix strategy launched after the Fukushima nuclear accident. After introducing the emergy theory and methods (Section 2), we present our analysis scheme, which considered not only the quantity and quality of the energy consumed, but also the diversity of the types of primary energy consumed, the diversity of the global origins of the dominant imported energy resources (SWI_{GOS}), the fairness of the exchange of money for primary energy in purchasing imports, and the environmental impacts of emissions; all evaluated on the same objective biophysical basis, i.e., as emergy (Section 3).

The interactions among energy consumption, economic development and the environmental impacts of emissions were explored using an integrated suite of indices, i.e., real GDP per unit emergy of the energy consumed ($RGDP_{EME}$), the UEV of primary energy consumption (UEV_{PEC}), the monetary benefits gained from the energy imported per unit nominal GDP (BEI_{NGDP}), the impact of emissions per unit emergy of the energy consumed (IME_{EME}), and the total emergy impact of emissions per unit real GDP (IME_{RGDP}) (Section 3). After a discussion of the results presented in Section 4, a suite of conclusions about the long-term interactions among energy consumption, economic development, and environmental impact in Japan from 1946 to 2011 is given (Section 5). Finally, we consider the efficacy of emergy theory and methods in helping us understand the observed interrelationships.

2. Methods and data sources

First, an Energy Systems model was constructed using the Energy System Language, ESL [25,66], to characterize the flows and storages of primary energy consumption, economic development and GHG emissions in Japan, and the interactions among them (Fig. 2). This model served as a guide to develop the logic behind the evaluation steps outlined below and as a template for choosing indices.

All primary energy inflows shown in the model were adjusted to account for their different qualities, considering the fact that both the quantity and quality of energy consumption have been identified as the main driving forces for economic development [7,10,67–69], and no country should be too dependent on one specific energy source, for security's sake. As a prerequisite to considering their respective impacts on economic development, all types of energy were classified as either renewable or nonrenewable and as deriving from local or external sources. The diversities of both the types of energy and the global energy sources of the primary energies consumed were quantified to indicate the status of energy security in Japan. In addition, we determined the fairness of the exchange in trading for energy imports. The environmental impacts of GHG emissions were also quantified based on the emergy of their expected total impact on the global biogeosphere. Based on the model structure in Fig. 1, an integrated suite of indices were developed to clarify the multi-faceted relationships among the triad of opposing influences and contradictory policy objectives represented by the interactions of primary energy consumption, economic development and GHG emissions, and we identified a suite of management policies to maximize system wellbeing. For example, primary energy consumption leads to further economic development and vice versa, but also to increased GHG emissions, which in turn have a negative effect on economic development and a declining rate of development, in turn, results in a decrease in energy consumption.

2.1. Methods to adjust the quality of energies consumed

Odum defined emergy as the available energy of one kind that is used up in transformations directly and indirectly to make a product or service [21,24]. All kinds of energy, material and information flows and storages (e.g., money) can be converted to emergy by multiplying the appropriate unit emergy values (UEVs),

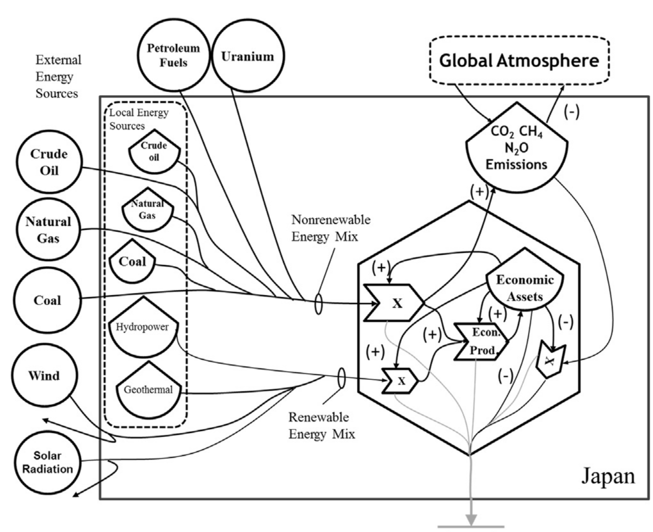

Fig. 2. Energy systems language diagram of the interactions among energy consumption, economic development, and pollutant emissions in Japan.

Table 1
Unit emergy values of primary energies consumed in Japan after WWII (sej/J) [42,71].

Energy	UEV	Energy	UEV
Coal	39200	Hydro-electricity	57581
Crude oil	54200	Nuclear power	48100
Petroleum products	64700	Geothermal energy	33700
Liquefied natural gas (LNG)	43500	New Energy[a]	57777

[a] Wind electricity, solar electricity etc., however wind accounted for the largest share.

which are defined as the emergy required to produce a unit of goods (sej/g), services (sej/J), information (sej/bit), or the buying power of money (sej/$). According to energy hierarchy theory, the higher the position that an item occupies in the system's network, the greater the ability of the item to do work within that system, while more available energy is required for its production. These relationships are in accordance with the maximum empower principle [21] which operates on all systems over time, so that the system that prevails in evolutionary competition has adapted to best utilize the spectrum of available energy (i.e., the energy signature) in capturing resources. Thus, the UEV can be used as a quality adjustment factor for different kinds of energies, materials and information [21,70]. All primary energies consumed in Japan (Fig. 2) were adjusted by their UEVs, and thereby, converted to emergy (Table 1), which is based on the work required for their production contributed from both natural and anthropic sources [21,71].

Then, the average UEV of the total primary energy consumed (UEV_{PEC}) was calculated to explore the quality changes of the total energy consumed over time. This was done by dividing the total emergy of primary energy consumption by the total available energy, *AE*, content of the sources.

$$UEV_{PEC} = \sum_{i=1}^{n}(AE_i \times UEV_i) / \sum_{i=1}^{n} AE_i$$

The heat content of the fuels is assumed to be approximately equal to the available energy in those fuels for the purpose of combustion in heat engines. All emergy evaluations in this study are based on the 9.26E24 sej/yr planetary emergy baseline, which is the renewable empower of the Earth [72,73].

2.2. Method to quantify the security of primary energy sources

Energy security is a key concern for Japan and for its economic development, because most of the primary energies used in Japan are imported from outside and the global scarcity of energy on a finite planet must increase over the long run. Uncertainty related to reliable energy supplies is especially apparent in the complicated situations generating conflict and energy insecurity concerns in the Middle East. Improving the diversity of both the types of primary energy consumed and the geographic distribution of the sources supplying energy is the simplest way to avoid a potential energy crisis. The Shannon-Wiener Index is one of the most widely used diversity indices because it is a good indicator of both the richness and evenness of a distribution [74,75]. An emergy-based Shannon-Wiener diversity index was calculated in this study to measure the diversity of both the types of primary energy consumption (SWI_{TEC}) and the global origins of the dominant energy sources (SWI_{GOS}), as indicators of the energy security of Japan.

The classical equation for the Shannon-Wiener Index was used in this study to measure the diversity of primary energy sources in Japan:

$$SWI_{TEC} = -\sum_{i=1}^{n} p_i Log_2 p_i$$

where, $_{pi}$ is the proportion of the emergy in the *i*th type of energy in total primary energy consumption.

The higher the SWI_{TEC} indicator, the more different primary energies were consumed and the more equal their proportional abundances in total energy consumption, and consequently the less damage an interruption of the supply of any one type of energy will cause to the energy consumption of the system.

$$SWI_{GOS} = -\sum_{J=1}^{n} p_j Log_2 p_j$$

where, p_j is the proportion of the emergy in the *j*th global origin in the total supply of a specific type of primary energy consumed.

The higher the SWI_{GOS} indicator, the more different global origins of the specific primary energy were used, and the more equal their proportional abundances in the total consumption of the specific energy type, and consequently the less damage an interruption of the supply of any one source can cause to that type of energy consumption within the economy.

2.3. Method to quantify the fairness of the exchange for energy imports

Japan has limited quantities of domestic energy resources, and as a result its economic development has been highly dependent on imported fossil fuels, which has been identified as a point of weakness for the Japanese economy [40,76]. This is right from the perspective of energy security, but it may be wrong when the fairness of exchange is considered, because it is becoming widely recognized that our market valuation system does not accurately account for natural contributions to the value of products and services [77–79]. As a result there exists an inherent unfairness (i.e., inequity of exchange) in the international trade for primary natural resources, including fossil fuels. Many studies have been done to quantify the direction of CO_2 emissions that result from international trades between Japan and its main trading partners, e.g. Korea [80], United States [81], and China [82], with at least one of these studies partly based on emergy methods [48]. However, embodied CO_2 emission is clearly just the tip of the iceberg in a complete consideration of the potential unfairness of international exchange.

Here, we used emergy methods to quantify both the biophysical donor value of the imported fossil fuels, i.e., coal, oil, liquefied petroleum gas (LPG), liquefied natural gas (LNG) and other petroleum products, and the emergy buying power of the money paid for them. We then quantified the exchange fairness by dividing the former by the latter, which is an index first defined as the emergy exchange ratio (EER) [21]. The ratio of the emergy received to the emergy sent will always express the balance in terms of the advantage gained by the system under study. In this study we consider this ratio for energy imports [78].

$$EER_I = \text{Emergy of the item bought} / \text{Emergy buying power of the money paid}$$

when EER_I is higher than 1, the importer benefits by paying less for more emergy, and when EER_I is lower than 1, the exporter is benefited by the sale of less emergy for the ability to purchase more emergy with the money received in trade.

The emergy in imported fossil fuels was calculated using the same methods we used to quantify the emergy of primary energy consumption, i.e. by multiplying the physical quantity by the appropriate UEV [21,71]. The relative monetary values for energy imports in Japanese Yen were first converted to US$, by dividing by the exchange ratio for a specific year [83,84]. The US dollar was the currency most often used for international trades during the study period. Then, the emergy buying power of the US$s paid in the exchange was calculated by multiplying this sum by the emergy to money ratio of the U.S. for the same year, which was calculated on a uniform basis from 1900 to 2011 [42].

2.4. Methods for quantifying the potential impacts of emissions

Environmental impacts of GHG emissions have been getting more attention from governments in recent years, due to the many effects of global change being observed around the world, e.g. global warming and sea level rise etc. [85]. Many assessment ratios and prices for GHGs have been calculated and published, with different aspects of the impacts and regional situations considered [86]. Among the indices, the global warming potential (GWP) published for each GHG by IPCC (Intergovernmental Panel on Climate Change) and public health impacts (PHIs) calculated by ExternE (External Costs of Energy) Project of the European Commission are most often applied by nations based on the results of research studies. In some cases, these results have been converted to emergy through using the emergy to money ratio of the country under study [87], or by using the annual emergy loss per capita from the DALY, disability adjusted life years index [14,88]. However, both global warming and health impacts are only part of the impact, and their utility is limited by the fact that these are subjective numbers that change from year to year and from country to country, due to limited knowledge and the development of new technologies [89–91]. In addition, the emergy to money ratio and the annual emergy per capita also change with both time and space [42,92].

To fill the requirement for an accurate evaluation of both the near and far-field effects of anthropogenic wastes, we estimated the emergy carried by the flows of 6 biologically active elements BAE, carbon, C, nitrogen, N, sulfur, S, phosphorus, P, oxygen, O_2, and silica, Si, as well as two compounds (+2), methane, CH_4 and water, H_2O, through performing emergy analyses of their global mass budgets for the Preindustrial Era, when all these biogeochemical cycles are assumed to have reached steady state condition prior to intervention by human agricultural and industrial activities [16,42]. Then, the UEVs for all storages and flows in the evaluated models were calculated based on the fact that the emergy around the completely interconnected closed loops is constant, i.e. the sum of the renewable emergy inputs to the planet, 9.26E24 sej/yr (Table 2) [72]. The ratio of the emergy of a mass perturbation to the global renewable emergy base gives the potential impact as a percent of the base, which will be numerically equal to the result calculated by Ulgiati and Brown [93] based on the services for dilution of a pollutant, if the acceptable background concentration is taken as the preindustrial concentration of the pollutant, the density of air is constant, and the average global wind velocity is used to determine the emergy of the wind. These two methods use different perspectives on the valuation of the impact of pollutants, e.g., the former uses donor cost for the global biogeosphere required to process the pollutant, which is consistent with emergy theory, while the latter uses the ecological economic perspective of ecosystem services to determine the emergy required for dilution.

Table 2
Unit emergy values applied to GHG emissions from Japan after the WWII [16].

	CO_2	CH_4	N_2O
UEV sej/g	4.78E+06	4.33E+09	9.72E+10

The trend of the emergy of total GHG emissions in Japan after 1990 was compared with the trend of emissions as the weight of CO_2 based on GWPs published in IPCC's fourth report to demonstrate the difference between the total environmental impact potential of the emissions and their global warming impact.

2.5. Indicators depicting the interactions of the triad

In addition to correlation analysis, an integrated suite of ratios was calculated to measure the interactions among the triad, national energy consumption, economic development and GHG emissions of Japan over 66 years following WWII, i.e., from 1946 to 2011.

(1) *Real GDP per unit emergy of energy consumption* (*$RGDP_{EME}$, Yen/sej*): $RGDP_{EME}$ equals the real GDP divided by the emergy of total primary energy consumption. The emergy of total primary energy consumption is a quality-adjusted (QA) measure of the energy consumed [42]. The higher the indicator, the higher is the quality-adjusted energy efficiency of economic activity. A comparison between the $RGDP_{EME}$ and the nominal GDP per unit of energy consumption was given, to explore the blind spots of the latter ratio due to the fact that it ignores economic inflation and deflation as well as energy quality.
(2) *Unit emergy value of primary energy consumption* (*UEV_{PEC}, sej/J*): UEV_{PEC} equals the emergy of the total energy consumed divided by the available energy contained in the energy sources, and it is also known as the average transformity (Tr) of the energy supply. For different types of energies, the higher the UEV of an energy type, the larger the ability to do work embodied in that type of energy, and the greater its potential ecological and economic impacts. For the same type of energy produced from different processes, like electricity generated from different sources, a higher UEV means a lower efficiency of the process [21]. The assumption here is that economic development can be driven not only by the discovery and application of a new high quality energy, but also by an increase in the efficiency of energy production, i.e. by decreasing the UEV of a certain type of energy, e.g., electricity.
(3) *Benefit gained from energy imports per unit nominal GDP* (*BEI_{NGDP}*): BEI_{NGDP} is the ratio of the monetary benefit gained from energy imports to the national nominal GDP. This index measures the monetary benefit or loss caused by unfair trade in the purchase of the energy imported as a fraction of nominal GDP. The monetary benefit gained from energy imports was calculated by converting the emergy embodied in the imported energies to monetary value through multiplying by the emergy to money ratio of the U.S. for each specific year and then subtracting the monetary value paid for the imports. The larger the BEI_{NGDP}, the larger the contribution that energy imports make to the national economy due to the unfair exchange of imported energies, e.g. by paying less for more emergy in the imported energy.
(4) *Impact of emissions per unit emergy of energy consumption* (*IME_{EME}*)**:** this index is the ratio of the total emergy of GHG emissions to the emergy of total primary energy consumption (i.e., QA energy consumption). IME_{EME} reflects not only the intensity of the environmental impacts of energy consumption, but also the efficiency of energy production, since these emissions are also wastes from production that may have the potential to be used in some way. A comparison between IME_{EME} and the ratio of GHG emissions measured as the weight of CO_2 based on GWPs to primary energy consumption (GW_{PEC}) was given to show the difference between the total environmental impact of primary energy consumption based

on emergy accounting and the environmental impact based on global warming potential.

(5) *Impact of emissions per unit real GDP* (*IME_{RGDP}*)**:** IME_{RGDP} is the emergy of GHG emissions divided by real GDP, and it gives a measure of the environmental cost of economic development in terms of the emergy of the GHGs. Again, the analysis of the trend of IME_{RGDP} is followed by a comparison between it and the ratio of GHG emissions in the weight CO_2 based on GWPs to nominal GDP (GW_{NGDP}) which is specifically focused on the global warming impact of economic activities, without considering deflation and inflation.

2.6. Data sources

*GDPs and the money exchange ratio***:** nominal and real GDPs from 1955 to 2005 were obtained from *Japan's 100 Years* [94], and before that they were deduced by assuming that the ratio of GDP to GNP and the GDP deflator were the same as in 1955, while after 2005 they were taken from the *Japan Statistic Yearbook 2014* (http://www.stat.go.jp/english/data/nenkan/index.htm). Money exchange ratios between the Japanese Yen and the US$ before 2005 were found in *Japan's 100 Years* [94], after that they are from *Japan Statistical Yearbook 2014*.

*Energy Consumption and energy imports***:** Primary energy consumption data from 1953 to 2000 came from the *Historical Statistics of Japan*, after that year they were found in the *Japan Statistical Yearbook 2014* (http://www.stat.go.jp/english/data/chouki/index.htm). Before 1953, coal, crude oil, petroleum products and LNG were deduced based on domestic production and import data [94], by assuming domestic supply equals production plus import, and the energy contents were the same as those in 1953. Hydroelectricity data before 1953 were taken from the *EDMC Handbook of Energy & Economic Statistics in Japan 2007* [95]. Energy imports data in both quantity and Japanese yen before 2006 were taken from *Japan's 100 Years* [94], after that year they were taken from the *Japan Statistical Yearbook 2014*.

*GHG emissions***:** GHG, i.e. CO_2, CH_4 and N_2O, emissions data from 1990 to 2001 were found in the *Historical Statistics of Japan*, after that they were taken from the *Japan Statistical Yearbook 2014*. The emissions of sulfur hexafluoride, SF_6, were reported and evaluated, but are not considered in this paper, because their share of the total impact is too small to affect the trend of the total GHG emissions both in terms of emergy and GWP. The emissions of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) were also reported, but not counted in this study due to the lack of UEVs for them.

3. Results

3.1. Nominal GDP and real GDP

The nominal and real GDP show two different aspects of Japan's economic development after WWII (Fig. 3). The nonlinear dynamic trend of nominal GDP is widely used to classify the economic development of Japan into two periods, i.e. the 'post-war economic miracle' or the time from the 1960s to the 1980s followed by the 'lost decades' after the mid-1990s. The annual increase in nominal GDP during the 1960s and 1970s averaged 7.5%, which was followed by a 3.2% average increase during the 1980s and early 1990s. This rapid growth period was followed by the 'lost decades', which were characterized by a pulsing and decreasing nominal GDP, especially at the end of 1990s and after 2007.

However, after correcting nominal GDP for inflation/deflation, the real GDP of Japan showed a near linear increase over the 66 year period examined. In addition, no clear perturbation of the Japanese nominal GDP was seen during the international oil crisis

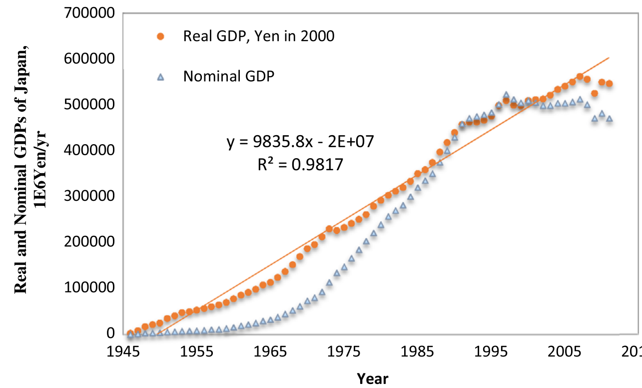

Fig. 3. Real and nominal GDP of Japan after WWII.

in the 1970s, but a clear leveling and slight decline of the growth trend of real GDP can be seen from 1973 to 1974 (Fig. 3). In contrast, the effects of the global great recession in 2008 (GR2008) and the Fukushima nuclear disaster in 2011 on the Japanese economy resulted in an 8.2% and a 2.4% decrease in nominal GDP from 2007 to 2009 and from 2010 to 2011, respectively. In comparison, real GDP decreased 6.5% and 0.6% during these events.

3.2. Emergy of primary energy consumption

Coal was the most important primary energy source for Japan in the first 15 years after WWII. After that, crude oil took coal's place, accounting for the largest share of the primary energy used (Fig. 4a). In 2011, LNG overcame coal to become the second largest primary energy source for Japan. The energy shares of primary energy consumption in 2011, from highest to lowest, fall in the same order as when measured in emergy units, i.e. the percent composition of the primary energy supply (%energy, %emergy) is as follows: crude oil (38%, 42%), LNG (23%, 21%), coal (22%, 18%) and petroleum products (5%, 7%). Both the energy and emergy fractions of renewable primary energy sources were 7% in 2011 (Fig. 4a, b).

In 1962, crude oil became the largest emergy input among the primary energy sources supporting the Japanese economy taking the place of coal, and it has remained in this position up to the present time. The consumption of crude oil in Japan was affected by the Arab oil embargo in 1974 and the Iranian revolution of 1979, as evidenced by two sharp decreases from 6.04E+23 sej in 1973 to 5.53E+23 sej in 1975, and from 5.77E+23 sej in 1979 to 3.96E+23 sej in 1987. Also during this critical period, the production of petroleum products, liquefied natural gas (LNG) and nuclear power were quickly developed, which balanced most of the negative impact of the oil crisis on Japan's energy supply. From 1987 to 1994, the crude oil supply quickly increased again to 5.75E+23 sej, and then decreased back to 4.33E+23 sej by 2011. As measured by the emergy delivered, coal was temporarily replaced as the second largest energy source by petroleum products from 1986 to 1989, by nuclear power in 1998, and LNG in 2009 and 2011 (Fig. 4b).

A similar nonlinear increasing trend was shown for primary energy consumption in Japan by both energy and emergy measures. Both the emergy and energy of primary energy consumption increased most quickly in the 1960s and the beginning of the 1970s. In 1973, the total primary energy consumption in Japan was 1.50E+19 J/yr and 7.77E+23 sej/yr, which are 13.9 and 15.2 times that in 1946, respectively (Fig. 4c). After a decade of pulsing due to the two international oil crises, the total primary energy consumption experienced another 10 years of growth from 1986 to 1996, before leveling to form a plateau with some fluctuations.

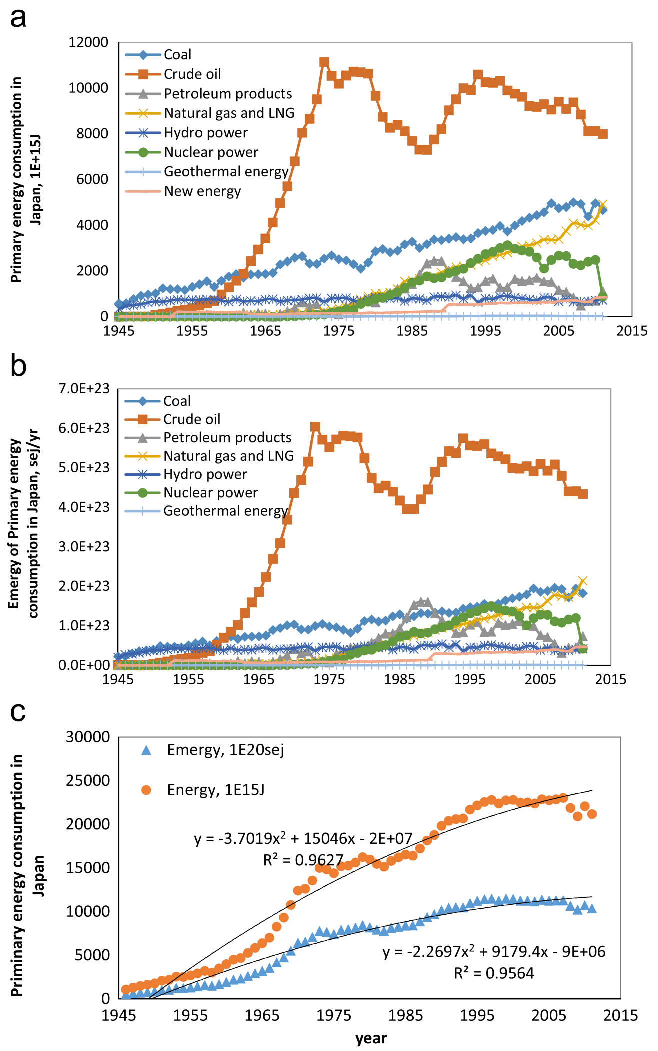

Fig. 4. Emergy and energy of primary energy consumed in Japan after WWII. (a) Energy of primary energy consumed, (b) emergy delivered by the primary energy consumed, and (c) emergy and energy content in total primary energy consumed.

Both the international GR2008 and the Fukushima nuclear disaster in 2011 brought negative effects on primary energy consumption, with the effect of the former over two times that of the latter. In 2011, the energy and emergy contained in the total annual primary energy consumed in Japan was, respectively, 19.6 and 20.2 times that in 1946.

3.3. Emergy based Shannon-Wiener diversity indices (SWIs) of primary energy consumption

The emergy-based Shannon-Wiener Index for the types of primary energy consumption (SWI_{TEC}) used in Japan increased 1.77 times in the first decade after WWII. This index increased from 1.15 in 1946 to 2.03 in 1958 due to the rapid development of domestic coal mining; it then decreased back to 1.17 in 1973 when the emergy fraction of crude oil in total primary energy consumption reached its peak (Fig. 4b). In the next five years, Japan increased its SWI_{TEC} to 2.28 in 1988, which is 1.96 times that in 1973. This advance was made through structural adjustments to primary energy consumption by decreasing the share of crude oil and quickly increasing the shares of petroleum products, LNG and nuclear electricity. In the past 20 years, the SWI_{TEC} of Japan has remained around 2.27, with little fluctuation (Fig. 5a).

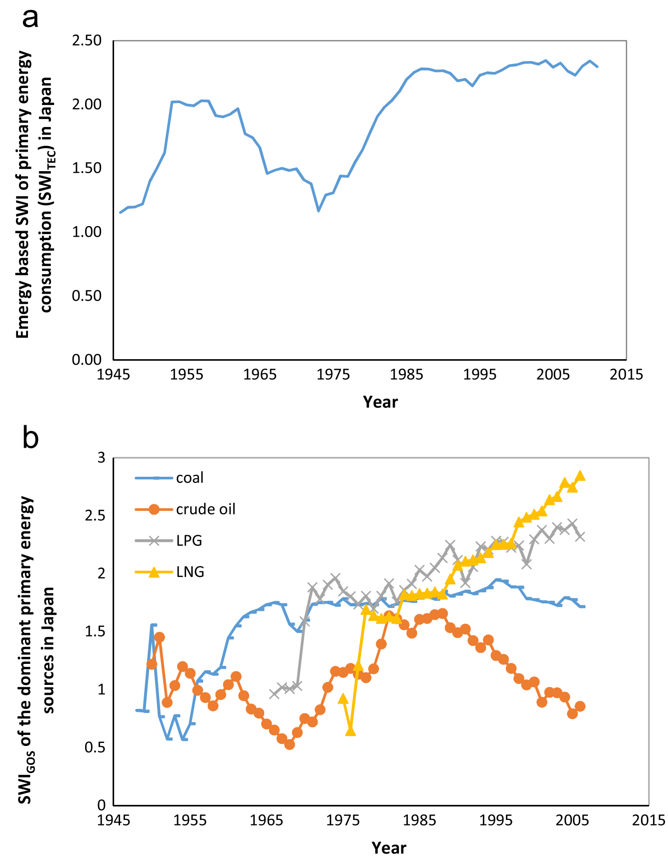

Fig. 5. Emergy based Shannon-Wiener diversity indices (SWIs) of primary energy consumption in Japan after WWII. (a) SWI for the types of primary energy consumption (SWI_{TEC}) in Japan. (b) SWI for the global origins of the dominant energy sources (SWI_{GOS}) in Japan.

Crude oil is the most important primary energy source for Japan, but it has had the lowest diversity for the global origins of its sources (SWI_{GOS}) at most times over the past half century. After the diversity of crude oil sources reached a bottom in 1968, Japan successfully increased the SWI_{GOS} of its crude oil supply 3.11 times in the next decade (from 0.53 in 1968 to 1.64 in 1981). However, Japan was unable to maintain this diversify of sources and by 2006, the SWI_{GOS} of crude oil had fallen back to 0.86, which was 0.50, 0.37 and 0.31 times that of coal, LPG and LNG, respectively, at this time (Fig. 5b).

3.4. Fairness of exchange: energy imports

The emergy exchange ratios (EER_Is) of imported coal, crude oil, LPG, LNG, other petroleum products, and the total primary energy import to Japan are given in Fig. 6. The average EER_I of the primary energy imported to Japan over the past 66 years from 1946 to 2011 was 5.57, which means that Japan received over 5 times the emergy (i.e., real wealth) in imported energies compared to the emergy that could be purchased on the global market by the money paid for the imported energy. The EER_Is of all 5 types of imported primary energies varied in a pulsing pattern over the study period, but most of the values remained higher than 1.6, except for LNG from 1975 to 1981, petroleum products in 1980 and 1981, LPG in 1980, and crude oil in 2008. Crude oil was the most beneficial energy imported to Japan most of the time before 1978, i.e., it had the highest EER_I. After 1978, coal had the highest EER_I most of the time. In 2011, the order of the EER_Is of the main primary energy imports from highest to lowest is as follows: coal

(6.45), LNG (3.27), LPG (2.11), petroleum products (1.84) and crude oil (1.79).

3.5. *Potential environmental impact of emissions*

The results of our study showed that the emergy of GHG emissions in Japan decreased abruptly after 1997, and continued to decline until 2011 with only one increasing fluctuation in 2000 (Fig. 7a). Since 2009, the emergy of GHG emissions has remained at 1.65E+22 sej/yr, or 77% of that in 1990. However, a different trend for CO_2 weighted GHG emissions was shown based on the GWPs given in IPCC's fourth report, i.e. a slight increase with fluctuations from 1205 Mt of CO_2/yr in 1990 to 1346 Mt of CO_2/yr in 2007, followed by a two-year decrease, and then a two-year increase up to 2011. Japan's CO_2 weighted GHG emissions in 2011 based on GWPs published in IPCC's fourth report was 1.07 times that in 1990 (Fig. 7a).

Detailed data revealed that the two different trends were dominated by different GHG emissions, i.e., the emergy trend of GHG emissions was mainly decided by the trend in N_2O emissions, which was supported by the trend in CH_4 emissions, while the trend of CO_2 weighted GHG emissions was determined by the trend in CO_2 emissions (Fig. 7b).

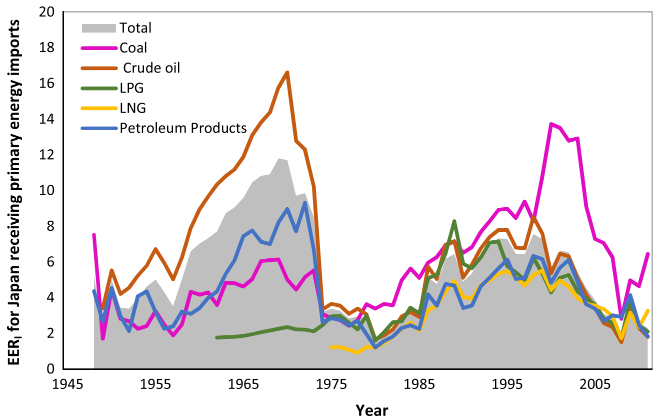

Fig. 6. Emergy exchange ratio (EER_I) of primary energy imports to Japan after WWII.

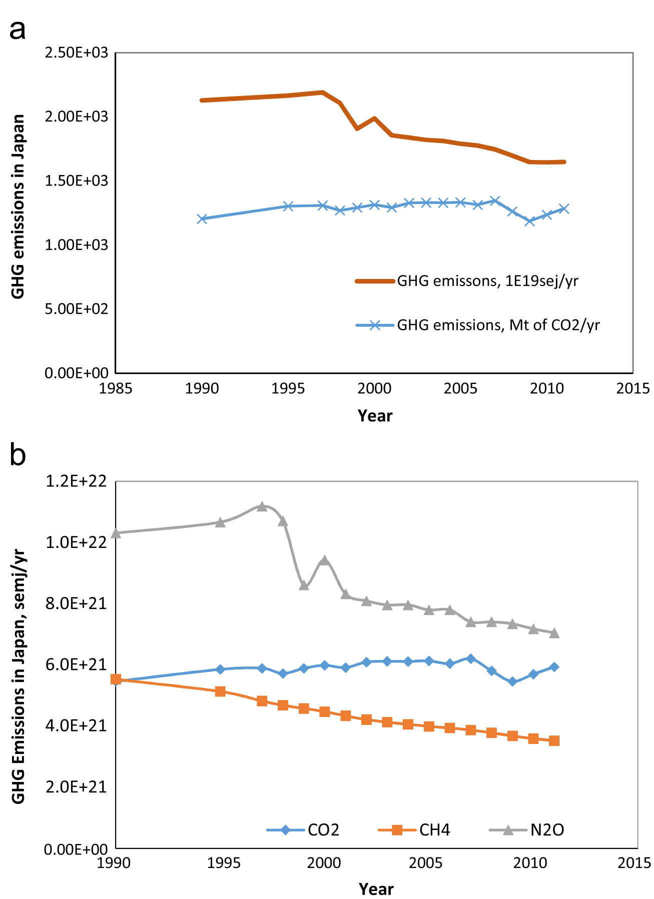

Fig. 7. GHG emissions in Japan from 1990 to 2011. (a) Trends of total GHG emissions as emergy and as metric tons CO_2 equivalent. (b)Trends of CO_2, CH_4 and N_2O emissions.

3.6. *Interactions of the triad: Energy consumed, economic growth, GHG emissions*

3.6.1. *Real GDP per unit emergy of the energy consumed ($RGDP_{EME}$)*

The $RGDP_{EME}$ showed a different pattern from that of the ratio of nominal GDP to energy consumption, i.e., the $RGDP_{EME}$ quickly increased in the first decade after WWII, at a 22.8% annual average rate, followed by a decrease over the next decade at an annual average rate of 3.3%. Then, after a short plateau, the $RGDP_{EME}$ increased with a 1.6% annual mean rate and few fluctuations until 1976. By 2011, the $RGDP_{EME}$ of Japan had increased to 8.98 times its value in 1946. In contrast, the nominal GDP to energy consumption ratio showed a nonlinear increasing trend from 1946 to 1993, followed by a plateau that has lasted for about 20 years, i.e., the stagnation period mentioned earlier. (Fig. 8).

3.6.2. *Unit emergy value of primary energy consumption (UEV_{PEC})*

The UEV of primary energy consumption (UEV_{PEC}) in Japan after WWII can be classified into two periods, i.e. the increasing period before 1973, and the decreasing period after that time (Fig. 9a). The detailed structure of the emergy of primary energy consumption (Fig. 9b) sheds some light on one reason for the observed trend of UEV_{PEC}, when the pattern of the emergy of crude oil's share of the total primary energy used is compared to the temporal pattern of UEV_{PEC} (Fig. 9a).

The increase of UEV_{PEC} during the first period was caused by increasing the share of crude oil in total primary energy consumption, which reached a peak (77.8%) in 1973, which was the year before the first international crude oil crisis began (1974). In the following decade, the UEV_{PEC} of Japan fluctuated due to the decreased share of crude oil replaced by both higher UEV energy (petroleum products) and lower UEV energies, e.g. nuclear energy and LNG. Even though the share of crude oil increased from 1988 to 1994, after 1988, the UEV_{PEC} decreased until 2010, which was mainly due to the increase in the share of nuclear power, LNG and coal accompanied by the decline in the use of petroleum products, e.g. petroleum spirits, kerosene, heavy oil and gas oil etc. In

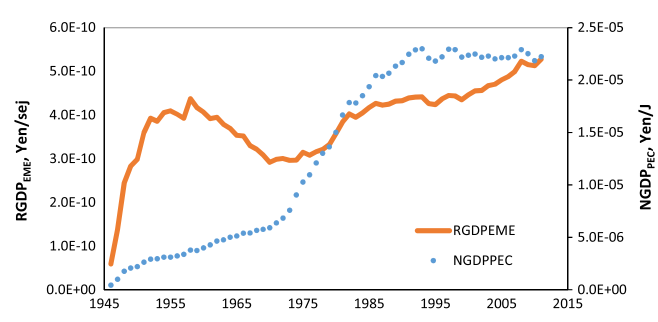

Fig. 8. Patterns of real GDP per unit emergy of primary energy use ($RGDP_{EME}$) and nominal GDP per **unit of** primary energy consumption ($NGDP_{PEC}$) in Japan after WWII.

response to the Fukushima nuclear disaster, the UEV_{PEC} of Japan increased 0.7%, corresponding to increased shares of LNG and petroleum products in the energy mix (Fig. 9a, b).

3.6.3. Monetary benefit from energy import per unit nominal GDP (BEI_{NGDP})

Japan progressively benefited from the import of fossil fuels after WWII (Fig. 10). In 2003, the benefit from energy imported to Japan (BEI) reached its first peak, 0.39 trillion U.S. dollars, then after a 5 year decline, it jumped to 0.41 trillion US$s in 2009, and then decreased again back to 0.32 trillion US$s over the next 2 years. The trend of the index, BEI_{NGDP}, showed the important role that primary energy imports played in the national economic development of Japan, i.e. the benefit as a percent of nominal GDP quickly increased from 1.3% in 1949 to 21.4% in 1970, and then decreased quickly to 4.7% in 1980 due to the two international oil crises in the 1970s. In the past 30 years, the BEI to Japan remained close to an average of 7.4% of nominal GDP, whereas, that for the entire 66 year period after WWII was 8.7% of nominal GDP.

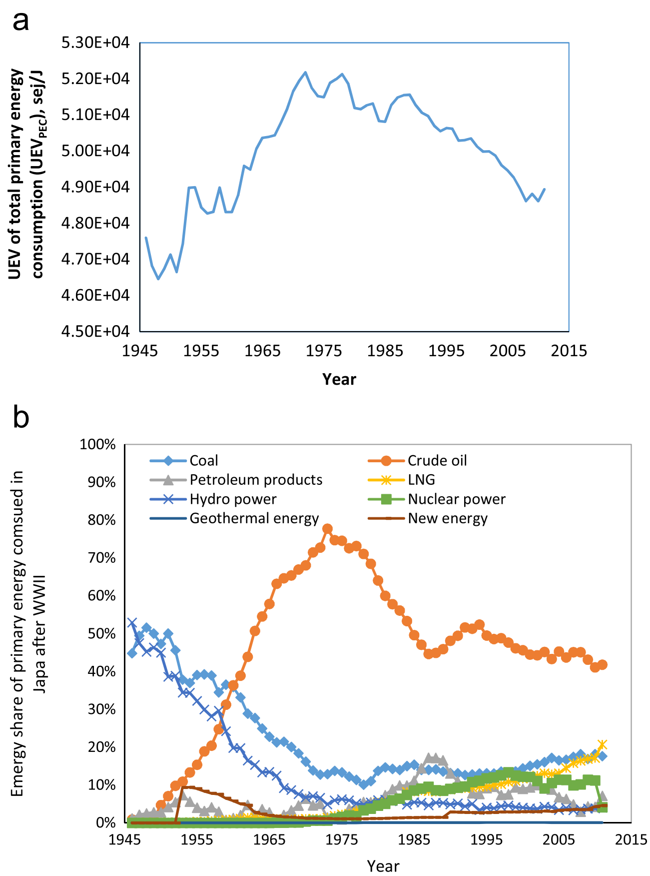

Fig. 9. The average quality of the primary energy used in Japan after WWII. (a) The average UEV of the total primary energy consumed (UEV_{PEC}) in Japan, (b) structure of the mix of the primary energy sources used in Japan from 1946 to 2011 as measured by their emergy.

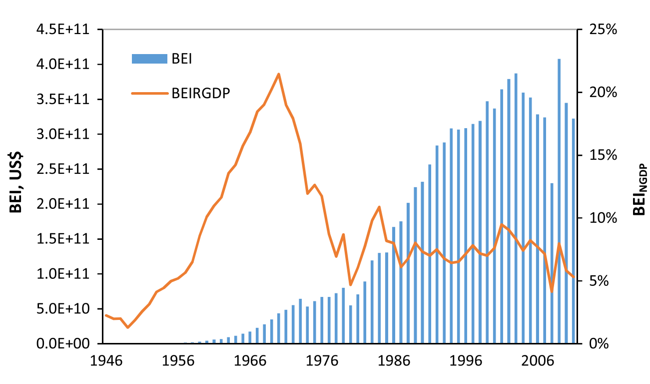

Fig. 10. Net benefit to Japan from the energy imported (BEI) and the benefits obtained per unit of nominal GDP (BEI_{NGDP}) in the Japanese economy after WWII.

3.6.4. Impact of emissions per unit emergy of energy consumed (IME_{EME})

The impact of GHG emissions per unit of the emergy of energy consumption (IME_{EME}) decreased almost monotonically after 1990 with a few small fluctuations (Fig. 11). By 2010 the IME_{EME} of Japan had decreased to 1.53% which is 73% of its value in 1990. The Fukushima nuclear accident and the structural adjustments of primary energy consumption in Japan that followed it increased the IME_{EME} of the nation to 1.59% which is 76% of its value in 1990. In contrast, the global warming impact per unit of energy consumption (GW_{PEC}) fluctuated from 1970 to 2010, and then increased to 0.61 g CO_2/kJ in 2011, which is 99.8% of that in 1990 (Fig. 11).

3.6.5. Impact of emissions per unit real GDP (IME_{RGDP})

The emergy of the impact of GHG emissions per unit real GDP (IME_{RGDP}) showed a linear decrease after 1990 ($R^2=0.9544$). By 2010, the IME_{RGDP} had decreased to 2.99E+07 sej/Yen in 2000 which is 61.8% of that in 1990 (Fig. 12). However, this impressive advance by Japan in reducing the environmental cost of economic development was accompanied by economic deflation (Fig. 3) and the failure to reduce overall CO_2 emissions after 1990, which is shown by the fact that after 1997 there is no clear decrease in the

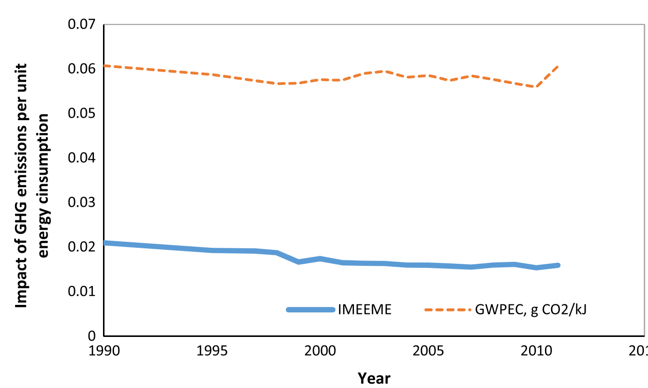

Fig. 11. Relative impact of GHG emissions per unit of the emergy of primary energy consumption (IME_{EME}) and global warming impact of GHG emissions per unit of primary energy consumption (GW_{PEC}) in Japanese economy after WWII.

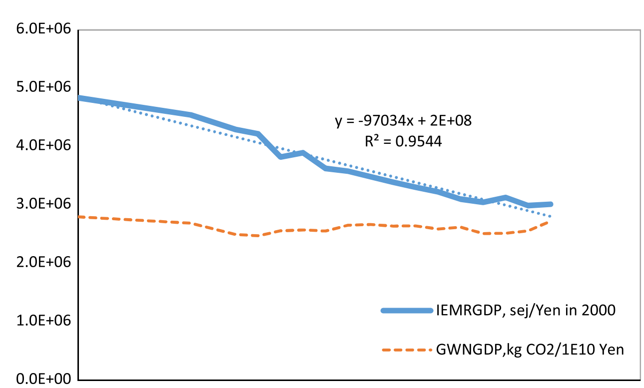

Fig. 12. Impacts of GHG emissions per unit of real GDP (IME_{RGDP}) and global warming impact of GHG emissions per unit of nominal GDP (GW_{NGDP}) in the Japanese economy after the WWII.

global warming impact of GHG emissions per unit of nominal GDP (GW_{NGDP}). GR2008 resulted in lower GHG emissions in Japan while the Fukushima nuclear accident in 2011 increased emissions, as evidenced, respectively, by a 4.0% decrease and a 6.5% increase in the GW_{NGDP} for these two events (Fig. 12).

4. Discussion

The ratio of nominal GDP to energy consumption is widely used to indicate the energy efficiency of economic development by both governments and scientists [54], but it is also widely criticized for having many weak points both for economic and energy valuation, e.g. the failure to consider deflation and inflation [1,13,21,42], and the lack of consideration of energy quality [7,10,67–69].

In considering the economic aspects of Japan's post-WWII growth, the trend of real GDP growth showed a near linear increase in the Japanese economy over the 66 years from 1946 to 2011. After WWII, during the "economic miracle", growth of the Japanese economy was overestimated due to the failure to adequately consider the role of inflation, which is evident when plotted relative to the base year, 2000 (Fig. 3). Whereas, after the base year economic development during the "lost decades" was underestimated because deflation was not adequately incorporated into the economic analyses. Japan's economy after the mid-1990s has been characterized as a period with a low nominal GDP growth rate and, indeed, the economy at this time grew at such a paltry rate that this period has been called the 'lost decades'. Others have argued that the so-called "lost decades" is a myth, because of the positive effects in the Japanese economy occurring at this time, such as improving standards of living and the positive aspects of other types of economic indicators such as the strength of the yen and Japan's trade surplus [50,51]. The results of this paper support the above argument. Furthermore, to provide some perspective on the unique deflationary economic state of Japan after 2000, we compared it with the other two leading economic countries of the world, the U.S. and China, both of which are fighting inflation problems following the exponential growth of nominal GDP [41,42], especially China, which reveals the weakness in using nominal GDP as the dominate measure of growth in a national economy and welfare [96,97].

From an energy perspective, both energy and emergy-based primary energy consumption increased after WWII with some fluctuations, but at different speeds. Due to a failure to correctly consider both economic deflation and inflation using nominal GDP, and the failure of energy consumption measures to account for the quality of the energy consumed, (1) the positive effect of energy use on economic development in the first decade after WWII was underestimated, (2) the risk of deceased real GDP generated per unit emergy of energy consumed, $RGDP_{EME}$, in the 1960s was ignored, (3) the effect of increased efficiency of energy use on economic development in the 1970s and 1980s was overestimated and (4) the increase in $RGDP_{EME}$ was hidden during the 'lost decades' (Fig. 8). After taking the above two factors into consideration by using $RGDP_{EME}$, a continuous decline in the emergy-based energy efficiency of economic development in Japan was observed during the 1960s. In contrast, the $RGDP_{EME}$ of the United States increased in the first 6 years in 1960s, and in 1970 it was 1.01 times that in 1958 [42]. A general improving trend of $RGDP_{EME}$ has been observed in Japan and the U.S. since 1970, both increasing at close to the same rate. In 2011, the $RGDP_{EME}$s of Japan and the U.S. were respectively, 1.8 and 1.96 times their values in 1970.

By considering the time history of UEV_{PEC} we showed that there are two periods of Japanese economic growth apparently governed by two different energy strategies. Even though these two strategies were no formally recognized by the government, they are implicit in the laws and policies put in place during these time periods. Before the international oil crisis in the 1970s, Japanese economic development was driven by consuming more and higher quality primary energy (e.g. first coal, and then, crude oil). National policies that supported this strategy were the 'Preferential Production Policy' implemented in 1947 and the 'Import Liberalization Program' implemented in 1960. Following this strategy, by 1968, Japan had grown to be the second largest economy in the world. Side effects of this strategy were serious energy security risks caused by high dependence on crude oil imports from a few sources and a low energy efficiency of economic development (e.g., as demonstrated by decreases in SWI_{TEC} and SWI_{GOS} (Fig. 5), and in $RGDP_{EME}$ during the 1960s, Fig. 8). Japan experienced its first postwar national crisis as a result of this growth strategy, when it was affected by the Arab Oil Embargo in the mid1970s [98]. Other consequences of this rapid growth strategy were seen in the impacts caused by several environmental pollution disasters, which occurred from the 1950s to the 1970s, especially itai-itai disease that occurred in Toyama prefecture (1955), minamata disease in Kumamoto prefecture (1956), air pollution in Yokkaichi, the yusho rice-oil disease in Kyushu (1968), and photochemical smog in Tokyo in 1971.

The combined energy, economic and environmental crisis in the 1970s prompted Japan to place more attention on energy efficiency, conservation and diversity, and as a result Japan successfully realized a plan to support economic development through quickly launching a suite of emergency measures, i.e., Approval of Oil Emergency Measures (1973), Enactment of Two Emergency Laws (1973), Participation in the International Energy Agency (1974). And later through the enactment of the Petroleum Stockpiling Law (1975), the Environment Water Paper (1984), and the Basic Environmental Law (1993), and by Japan's step-by-step work on setting up national energy conservation and environmental protection frameworks. Now, Japan has the highest energy use efficiency in the world as ranked by the nominal GDP to energy consumption ratio [54,56]. Coal is still one of the three main primary energy sources for Japan along with crude oil and natural gas, and the fractions of the energy contributed by coal and natural gas are about equal. In comparison, since 1990, the top-three energy sources for the U.S. are petroleum, natural gas and nuclear power, but the U.S. GDP to energy consumption ratio in 2010 was only 74% of that in Japan according to the report of the World Bank (〈http://data.worldbank.org/indicator/EG.GDP.PUSE.KO.PP.KD〉). These results showed that economic development can be accomplished not only by utilizing new energy sources of higher quality, but also by improving the efficiency of energy generation methods, e.g., by setting a positive example on how to realize a win–win situation increasing both economic development and energy conservation.

The scarcity of domestic energy sources and its high dependence on imported fossil fuels have been generally seen as a key energy security concern for Japan [53]. Consequently, energy security has been the core energy policy for Japan in all periods since WWII. Specific policies promoting energy security begin with the "Preferential Production Policy' in the late 1940s and 1950s, which gave local coal mining the highest priority for development. After the international oil crisis in the 1970s, a suite of strategies was applied to improve the energy security of Japan by improving the diversity of both the types of primary energy consumed (SWI_{TEC}) and the global origins of the dominant energy sources (SWI_{GOS}). Furthermore, despite the scarcity of domestic energy resources, our evaluation of the fairness of international energy trades showed that Japan benefited substantially from importing energies with EER_Is higher than 1, i.e. the net benefit contributed an annual average of 8.7% to the nominal GDP of Japan over the first 66 years following WWII.

The Fukushima nuclear disaster and the shutting down of nuclear power plants in 2011 caused an immediate 61% annual increase in the consumption of petroleum products and a 16% increase in LNG consumption, accompanied by a 6% and 2% decline in coal and crude oil consumption, respectively. A year later, the Innovative Strategy for Energy and the Environment was published in September 2012. This strategy specified that all Nuclear Power Plants (NPPs) would be shut down, and replaced with a combination of LNG and renewable plants, with only very small increases in coal and oil-fired plants. Increasing the share of LNG in primary energy consumption was a good choice for energy security, considering that the diversity of its SWI_{GOS} was the highest among the main primary energy types in Japan (Fig. 5b). Besides, the economic effect of this denuclearization policy was believed to be close to zero, considering the benefits to GDP from higher levels of investment [64]. However, the wholesale price of electricity increased 1.57 times compared with that before the Fukushima accident [15], and Japanese electricity was already very expensive, e.g. it was 1.47 times the average of the Organization for Economic Co-operation and Development member countries in 2011 [99]. Coal may be a good option for Japan to decrease the price of its electricity, considering the fact that the levelized cost of electricity from coal was 0.95 times that of natural gas [15], and the emergy gained from the import of coal was about twice that of LNG in 2006 (Fig. 4). In addition, the SWI_{GOS} of coal has remained higher than 1.7 over the past 30 years, indicating an expected high security for coal as an energy source (Fig. 5b). Before the Fukushima nuclear accident, coal and LNG contributed equally to electricity production in Japan [100,101]; however, after March 2011, the use of LNG increased, such that coal is currently the second largest energy source for thermo-electricity production in Japan [84]. Furthermore, the future use of more coal to decrease energy costs is supported by the existence of mutually beneficial technologies, equipment and facilities already in use to generate electricity from other energy sources. However, increasing the use of coal will increase the consumption of water and the emissions of CO_2 and SO_2 [15]. Thus, an accurate emergy evaluation of the positive and negative factors of increasing the generation of electricity from coal and comparison of the results with that of other energy sources is recommended to determine the efficacy of coal as a primary source for electricity in Japan.

Global warming is one of the most important environmental problems confronting the world, but it is not the only problem associated with GHG emissions. Japan was the host of the conference that produced the Kyoto Protocol in 1997, and a signatory of it; however, Japan has failed to realize the planned GHG reductions, since the adoption of the Protocol, based on GWPs published in IPCC's fourth report. However, the trend of the total environmental impact of Japanese GHG emissions measured in this study showed a different result, i.e., the emergy of total GHG emissions, and the impact of total GHG emissions per unit of the emergy of primary energy consumption and per unit of real GDP followed a decreasing trend with a fluctuation (decrease followed by and increase) right after 1997, and another from 2007 to 2011. The reason behind this difference in response between the effects of GHG emissions on global warming (CO_2) and their total environmental impact is that the UEV of N_2O is 20,335 times that of CO_2, while the GWP of N_2O is only 298 times that of CO_2, which may be plausible considering the role of N_2O in regulating stratospheric ozone levels and its participation in acid-rain formation etc., which are in addition to its contributions to global warming. Simultaneously, Zhang et al. [13] explored the environmental impact of SO_2 emissions in China, and he fund that it was larger than that of CO_2 emissions from 2000 to 2007. These case studies and Campbell et al. [16] illustrate that in measuring gas pollution impacts more attention should be paid to the balance of other pollutants (like nitrogen and sulfur) in addition to carbon, and to the reduction of emissions of their waste products, like N_2O and SO_2.

All the above results confirm that emergy methods are able to evaluate all types of system flows, e.g., energy, chemical species such as GHGs, (e.g., CO_2, N_2O, and CH_4) and money (US$) on an equal basis, and that energy systems methods and models are useful in understanding the interactions among the triad, energy consumption, economic development and the GHG emissions. In addition, an integrated suite of emergy-economic indices developed in this study was able to quantitatively characterize the interactions among the triad mentioned above. However, only part of the GHG emissions were counted, due to the lack of UEVs for some wastes. Although strong linear correlations between primary energy consumption and GDP were explored over the 66 years following WWII, the exact impacts/fractions of energy consumption in the Japanese economy were not revealed, due to the lack of a fully quantified emergy database for Japan as a national ecological-economic system for the study period of interest [40]. Consequently, the measurements and indices of the emergy-based energy efficiency of economic development ($RGDP_{EME}$) and the impact of GHG emissions on economic activities (IME_{RGDP}) are not yet completely specified. However, the long-term trends in the interactions among energy consumption, economic development, and GHG emissions may not be changed by a complete specification of the entire system given that a strong linear correlation between national emergy use of a developed economy and real GDP has been demonstrated [42]. Nevertheless, a complete specification of the system and normalization of the components in emergy terms will bring the whole system within a uniform fundamental theory, in addition to making impact and efficiency measurements more accurate.

5. Conclusion

1. Economic progress can be made not only by utilizing new energy sources of higher quality, but also by improving the efficiency of energy generation methods. Two different energy strategy periods in Japan, resulting in a near linear increase in national economic development over the 66 years following WWII were identified and quantitatively explored. Before 1973, the use of high quality energy (crude oil) was progressively intensified, while after that time a period with more use of nuclear energy and LNG resulted in decreased GHG emissions. Interestingly, after removing the noise of fluctuations related to economic deflation and inflation and accounting for the qualities of the primary energies consumed, progressively increasing trends in both national economic growth and energy efficiency were found in the Japanese economy over the past 20 years, a period widely known as the 'lost decades'.
2. The benefits from importing primary energy sources on average accounted for 8.7% of the nominal GDP of Japan over the 66 years following WWII. A rapid decrease in the diversity of energy types (SWI_{TEC}) during the 1960s exposed serious energy security risks, accompanied by a declining of efficiency for economic development (i.e. real GDP per unit of emergy of primary energy consumption, $RGDP_{EME}$), which made Japan particularly susceptible to the international oil crises in the 1970s. Later on, in response to these crises, the increase of these two indices showed, respectively, the successful diversification of primary energy types and the improvement in the energy efficiency of economic development in Japan.

3. The environmental impacts of GHG emissions (CO_2, CH_4, and N_2O) decreased after 1990, as did the environmental impacts of energy consumption (indicated by IME_{EME}) and economic development (indicated by IME_{RGDP}), even though no clear decrease in the global warming impact of the emissions was observed based on the GWPs published in IPCC's fourth report.
4. Emergy evaluation and modeling methods revealed the complicated interactions among the triad, energy consumption, economic development, and GHG emissions, by providing a common biophysical donor-based valuation method that expressed different types of energies and materials, including pollutants on an equal basis as solar emjoules. Further development and application of the emergy methods will make more accurate valuations possible not only for the national triadic interactions reported here, but also for other ecological-economic issues confronting society on multiple scales.

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