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# 2D representation of life cycle greenhouse gas emission and life cycle cost of energy conversion for various energy resources

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**Abstract**−We suggest a 2D-plot representation combined with life cycle greenhouse gas (GHG) emissions and life cycle cost for various energy conversion technologies. In general, life cycle assessment (LCA) not only analyzes at the use phase of a specific technology, but also covers widely related processes of before and after its use. We use life cycle GHG emissions and life cycle cost (LCC) to compare the energy conversion process for eight resources such as coal, natural gas, nuclear power, hydro power, geothermal power, wind power, solar thermal power, and solar photovoltaic (PV) power based on the reported LCA and LCC data. Among the eight sources, solar PV and nuclear power exhibit the highest and the lowest LCCs, respectively. On the other hand, coal and wind power locate the highest and the lowest life cycle GHG emissions. In addition, we used the 2D plot to show the life cycle performance of GHG emissions and LCCs simultaneously and realized a correlation that life cycle GHG emission is largely inversely proportional to the corresponding LCCs. It means that an expensive energy source with high LCC tends to have low life cycle GHG emissions, or is environmental friendly. For future study, we will measure the technological maturity of the energy sources to determine the direction of the specific technology development based on the 2D plot of LCCs versus life cycle GHG emissions.

Key words: 2D Projection, Life Cycle Analysis (LCA), Life Cycle Cost (LCC), Electricity Conversion, Coal, Natural Gas, Nuclear Power, Hydro Power, Geothermal Power, Wind Power, Solar Thermal Power, Solar Panel

## INTRODUCTION

There is a general consensus that worldwide energy consumption is growing, and our energy system is moving gradually towards an electricity-centered system. In 2006 the total energy consumption in the world was 11,730 Mtoe, and we expect that energy demand will increase by an average of 1.6% every year by 2,030 [1]. A significant percentage of greenhouse gas (GHG) emissions comes from fossil-based energies and has resulted in anthropogenic climate change [2]. To mitigate environmental impact and to improve convenience of daily life, new technologies have been developed, such as electric vehicles. But these technologies consume electricity as the main energy source. In fact, worldwide electricity consumption reached 15,665 TWh in 2006, and it is expected to increase up to 20,760 TWh in 2015 and 28,140 TWh in 2030 [1]. At last, post-carbon energy system is shifting to electricity-centered energy system.

To design an electricity-based energy system, analysis and research on energy technologies that produce electricity are quite crucial. To support national governments in energy policy making and to assist individual or industrial consumers in choosing appropriate energy source, the life cycle environmental impact of each option should provide with corresponding life cycle cost (LCC). Consumers have become concerned not only about the affordability of products, but also the environmental conservation perspective. Reports said they are willing to pay up to 20% more for using sustainable products, so called LOHAS [3]. The consumer trend is reflected in the electricity market as well and electricity power is considered as a product rather than a part of infrastructure systems controlled by the government. Currently, the government determines national electricity generation mix and all consumers can do is to follow it. However, once smart grid systems soon are introduced, an electricity consumer will be able to decide his or her own electricity mix and then buy the electric power from a local electricity distribution company. In the electric power market, consumers need typical information of the comparison of environmental impact with its cost of electricity generation sources. Also, national governments require data in order to formulate energy policies. Intuitive and holistic data analysis, which enables us to make a decision at a glance, is needed for designing future energy systems.

Life cycle assessment (LCA) estimates the environmental impact of a product or a service through its supply chain. The concept of LCA was created in the 1960s for the purpose of estimating the external environmental impacts. Its principle and framework was codified as the ISO standard in 1997 and the methodological requirements and the guidelines were established in 2006 [4]. In addition, the United Nations Environmental Program (UNEP) and Society of Environmental Toxicology and Chemistry of the U.S. (SETAC) jointly proposed an UNEP/SETAC Life cycle Initiative in 2000 to actively utilize LCA in assessing environmental impacts. Because LCA examines the total impact of an entire system, it is widely used in assessing GHG emissions and calculating carbon footprints by

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governments and companies [4].

LCA supports company or government in making a decision when they introduce renewable energy technologies. We should adopt energy technologies carefully because it is difficult to meet balances between environmental impact and its cost. Renewable energies such as wind power, solar thermal power, and solar photovoltaics (PVs) are widely believed to generate electricity without any GHG emission. Considering the comprehensive life cycle of material extraction, production, use, and waste disposal, however we realized clearly that renewable energies also produce GHG emissions during electricity generation [5]. Therefore, LCA analysis provides comprehensive performance of various energy technologies and it is used for evaluating renewable energy technologies [6]. Life cycle cost (LCC) analysis is an economic method for assessing the total cost of constructing, maintaining, and disposing of a building over a whole period of a life time [7], and can be used to evaluate the cost of a full LCC of electricity development. Based on this holistic information, if we analyze the characteristics of each energy resource while considering life cycle environmental impact and cost of electricity production simultaneously, we could help decision-making to guarantee sustainable development [5]. There is a similar concept of LCA methodology, called Eco-efficiency, which considers ecology and economy simultaneously and induces a final single index, Eco-efficiency index. However, we believe that the customers hardly compare the environmental and economic performance between products using the Eco-efficiency index. In this work, we rather focus on the comparison between the GHG emission and the LCC cost.

## METHODS AND DATA ANALYSIS

### 1. Two-dimensional Representation of Life Cycle GHG Emission and Life Cycle Cost

We developed a two-dimensional methodology using life cycle impacts to compare its comprehensive life cycle GHG emissions and life cycle cost. At present, LCA analyses on energy conversion technologies are actively conducted. However, various LCA studies show one-dimensional results of environmental impact analysis and installation costs of the technologies in charts, which makes it difficult for have an intuitive interpretation. Even if a suggested graph is illustrated, each one shows only one parameter separately, and therefore, it is complicated for making holistic analysis of the shown parameters. When we conduct a comparative analysis of environmental influence and cost of a specific technology simultaneously by using series of complicated charts, we fail to generate intuitive information for the viewpoint of users. Even an additional cost should be needed for consumers to get information which one is good for their environment at the final stage of their decision-making [3]. National governments also require information that enables them to conduct a comparative analysis of environmental impact and to install the cost of a certain energy technology so that they can allocate tax revenues and eventually determine energy policies. To make a decision about the best suitable energy source among various ones after the consideration of environmental impacts and the costs, we have to consider multi-dimensional parameters of the source. To provide the information regarding energy technologies, we should consider the following:

- Environmental impact and economic cost for energy resources should involve its entire life cycle.
- Cross-correlation can be easily conducted between environmental impact and cost.
- Graphic information should be also an effective tool for the comparison of a specific parameter among various energy sources.
- All results should be illustrated for a further intuitive interpretation.

The two-dimensional life cycle representation graph is an intuitive analysis tool that can provide a variety of information simultaneously. We can compare an LCA result with another type of LCA analysis, for example, an attributional LCA for a techno-sphere or an ecosphere with LCC for economic-sphere. In this work we made a two-dimensional graph of life cycle GHG emissions for ecosphere compared with LCC for economic-sphere. Life cycle GHG emissions and LCC data are collected and evaluated from the previous LCA literatures [see Supporting Materials]. The data represent life cycle GHG emissions and LCC of 1 kWh of electricity generation for various energy sources, which are used to make a 2D plot graph in this work.

Fig. 1(a) shows how energy sources can be characterized according to their environmental and economic characters. The x-axis indicates LCC (U.S. cent per kWh) of electricity generation and the y-axis represents life cycle GHG emissions (g $CO_{2\text{-}eq.}$ per kWh). In Fig. 1(a), the right side shows high cost (expensive) energy and the left side shows low cost (cheap) energy. The top part shows high level of life cycle GHG emissions (gray) and the bottom part are considered as cleaner energy than others with low level of life cycle GHG emissions (green). Considering the two directions, we can place cheap-gray energy, expensive-gray energy, cheap-green energy, and expensive-green energy in the top-left corner, the top-right corner, the bottom-left corner, and the bottom-right corner, respectively

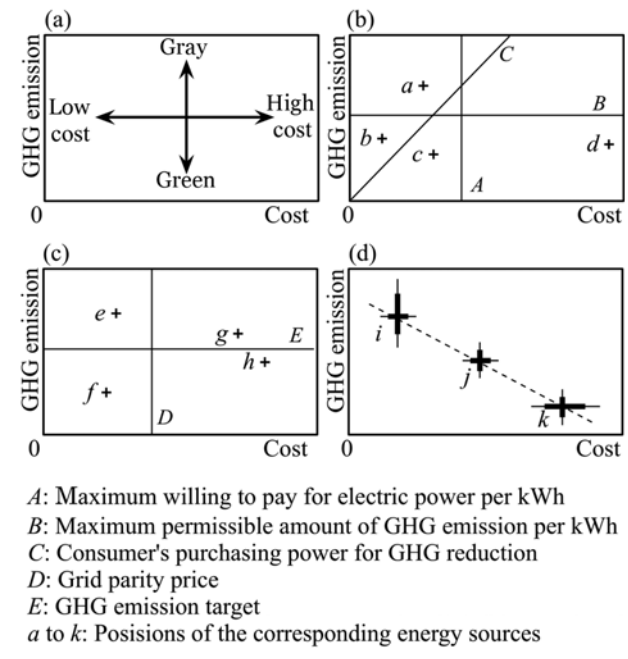


**Fig. 1. Schematic analysis of 2D plot combined with GHG emissions versus cost. The points and lines are arbitrary solely to explain the analysis concepts.**

(Fig. 1(a)). The GHG emissions regulation standards postulated by the government can be adopted as a classification guideline for y axis and the electricity price in the market or the grid parity for the guideline of x axis.

The two-dimensional graph can help consumers to select a suitable energy source based on GHG emissions and its costs. Four types of energy sources are marked as 'a, b, c, and d' in Fig. 1(b). When a consumer has a budget limit for electricity purchase at the price 'line A' and wants to use electricity that guarantee less GHG emissions than 'line B', the most reasonable choice could be either 'b' or 'c'. Among the two options, the consumer may have an individual standard price ('line C') for GHG reduction, which means that the consumer is willing to pay an additional price to reduce GHG emissions, and will select 'b' as a final choice. When energy 'c' is chosen, which emits less GHG than energy 'b' does, the consumer has to pay more than the consumer's purchasing power, and this is not likely.

This synthetic case can be also applicable to governments. Governments are currently adopting energy policies to promote to use renewable energy sources and to develop its related businesses. To provide financial energy subsidies using the tax system, the government should classify each energy source and induce technology development. The 2D LCA graph can provide information suitable for the best decision-making. Governments regulate the emission of GHG during the production of electricity. For example, if a government sets a carbon footprint baseline for electricity generation, it can be marked as 'line E' (GHG emission target) in the graph shown in Fig. 1(c). Without the baselines, it is easy to consider energy 'g' due to the lowest GHG emissions and the surplus investment costs compared to the conventional one (normally located on around 'e'). However, the baseline 'line E' demonstrates that energy 'g' has more GHG emissions than the standard 'line E' so that it will not be an ideal option.

In the same manner, we can use grid parity price. The grid parity price is a standard price that gives price competitiveness to renewable energy sources when they are cheaper than conventional ones. In Fig. 1(c), the grid parity price is shown as 'line D' and it classifies energy 'e' as cost competitive energy based on its cost. As a result, since the cost is cheap enough for customers to prefer to use, the government can guide its technology development towards reducing GHG emissions rather than cost reduction. In addition, governments can help expensive-green energy 'h' by giving incentives to make 'h' cheaper than the original cost. And cheap-green energy 'f' can be classified as the most superb energy source in terms of the lowest GHG emissions and its cost. A two-dimensional graph can provide criteria for objective classification and assist energy policy makers in making informed decisions.

In the 2D graph, various energy sources are visualized on a graph simultaneously. Therefore, we can analyze the correlation relationship between the energy sources. In Fig. 1(d), three energy sources ('i', 'j', and 'k') are visualized. Each energy source's coordinate value is statistically evaluated and the coordinates allow us to analyze its cross-correlation. The example in Fig. 1(d) illustrates that three energy sources have a linear correlation and that more expensive energy source tends to have less GHG emissions. This correlation helps us to comprehend the overall performance trends of energy sources, and if it is once placed, the cost of generating electricity can be expected. Of course, as technology improves, the trend changes over time. Therefore, a correlation analysis of energy sources in 2D plot can monitor the information of energy sources from the past to up-to-date, and predict the overall trend of energy technologies in the next stage.

Evaluation for each energy source can be positioned as dots in the two-dimensional plot by the mean values with error bars (i.e., minimum, maximum, and the 90% confidence interval) after the mathematical statistics without applying any weighting factors. The graphical 2D plot makes us understand the GHG emissions and the costs of energy sources more precisely than a table with parameters. For example, the short error bar in the x axis indicates that its price is rather stable; in other words, the price of the technology has been almost matured and saturated. On the other hand, for instance of energy 'i', the length of the GHG emissions is rather wide. It proves that technological optimization has not been finalized at the current stage. This analysis allows us to review technological trends of each specific energy source. Energy 'i' has been more optimized with the respect of its cost than GHG emissions. It is also obvious that energy 'k' is the technological alternative option for reducing GHG emissions, because it is optimized more for the perspectives of GHG emissions than the cost.

**2. Data Analysis**

To comprehend current energy characteristics, we conducted a 2D analysis of eight energy sources, including nuclear, coal, natural gas, geothermal, hydro, wind, solar thermal, and solar PV energy. We treated LCA data statistically from the previously reported literature to include the total impact during the entire life cycle of energy sources. LCA analysis may utilize specific characterization factors for a certain region and a time span. Naturally, LCA results are valid only for the defined system boundary. Therefore, it is academically demanded to normalize various LCA data with the others to compare them with the geological and temporal scopes. Literatures of LCA used in this study are analyzed in different regional spots and in temporal scopes so that the life cycle GHG emissions and life cycle costs of electricity generation show different trends corresponding to the scopes. For example, solar PV emits lower life cycle GHG in European countries than non-European countries, which may represent the difference of technical level for each energy source (See Table S18 in supporting material). Unfortunately, the number of samples in one region is too limited to compare general environmental and economic performances from one spot to another. Alternatively, as a first step in this manuscript, we reviewed the statistically averaged life cycle analysis data of worldwide scale and within 20-year time span to get normalized values of each energy sources for electricity generation.

Numbers of life cycle GHG emissions and LCC are calculated statistically, and those values are, respectively, used to analyze average, maximum, minimum values and 90% confidence intervals. Deviations are calculated with a 90% confidence level based on the standard error from the statistical analysis. From now on, we call the evaluated deviations as error bars for simplicity. Numbers of LCA analysis for statistical calculation originate from research papers and publically released reports. We also referred to LCA figures of nuclear, geothermal, and solar PV energy development presented by other researchers such as Lenzen [8], Hammons [9], and Johansson and Turkenburg [10]. Data about existing fossil-based fuels and renewable energy have been supplemented by the work of Hondo [11], Gagnon et al. [12], Denholm and Kulcinski [13], Uchiyama [14], Weisser [6], and Varun et al. [5]. Statistical data released by WEC [15] and IPCC [16] were used to calculate life cycle GHG emissions and cost analysis. Raw data collected over time were statistically calculated for mean values, ranges of maximum and minimum values, and 90% confidence intervals.

When LCA data were missing, average values collected from the reported research were used. In the geothermal power case, data about electricity generation cost and life cycle GHG emissions were absent, so a mean value of life cycle GHG emissions and cost was taken from reported studies. And maximum and minimum values of cost were taken from the report. In case of solar thermal energy, only maximum and minimum values were found in the literature. Therefore, the maximum and minimum values were identically utilized, a 90% confidence interval for the value was created, and the median value was considered as an average value. There might be a bit error involved in values for geothermal or solar thermal energy, but we believe that the absolute value was not too much different from our values.

## RESULTS

The estimated energy characteristics are shown below. Specific figures illustrating the emission of life cycle GHG emissions per 1 kWh electricity and LCC by each energy source are summarized in Table 1.

**Coal** produces more life cycle GHG than any other energy, emitting about 823.2 g $CO_{2\text{-}eq.}$ per kWh, which is 57 times larger than the one of wind power, the lowest energy source. The production cost of coal-based electricity is approximately 3.5 cents per kWh. It is the second cheapest energy among energy sources and 1/9th of the most expensive source of solar PV energy. The estimated maximum-minimum range of life cycle GHG emissions is about 955.0 g per kWh and its 90% confidence interval reaches approximately 187.6 g per kWh. The error range of life cycle GHG emissions of coal is the widest amongst all energy sources. The error bar of cost is relatively small, and offers a maximum-minimum range of 4.1 cents per kWh and a 90% confidence interval of 0.6 cents. The raw data used for life cycle GHG emissions and cost for coal are listed in supporting material (Tables S1 and S2).

**Natural gas** is the second biggest producer of life cycle GHG emissions of about 420.8 g. This is about half of the life cycle GHG emissions generated by coal. It costs approximately 4.6 cents to generate 1 kWh of electricity, and it is the third cheapest energy source. The error bar in life cycle GHG emissions is 254.0 g per kWh and reaches approximately 58.8 g per kWh based on its 90% confidence interval standard (Tables S3 and S4).

**Nuclear energy** produces quite low life cycle GHG emissions of about 19.7 g per kWh. Surprisingly, it is the cheapest energy source, which costs only 2.9 cents per kWh. The error ranges based on maximum and minimum values in both life cycle GHG emissions and cost are quite small, 37.0 g and 2.7 cents per kWh, respectively. It means that the nuclear energy technology is already matured and optimized in terms of life cycle GHG emissions and its cost. The raw data, which are used to get life cycle GHG emissions and cost for nuclear, are listed in the supporting material (Tables S5 and S6).

**Hydro electric power** is the fourth most expensive energy source, which costs about 6.5 cents. The technology represents the error range of 70.9 g per kWh based on maximum and minimum values of life cycle GHG emissions, and the environmental level of the technology seems to be optimized by intermediate level. The cost of hydroelectric power is 6.5 cents per kWh and is quite similar to other renewable energy (i.e., Geothermal, Wind) excluding solar PV energies (Tables S7 and S8).

**Geothermal power** emits 170.0 g of life cycle GHG pre kWh, which is relatively small. It generates more than 11 times GHG per unit of energy generated than wind power, which generates the least amount of life cycle GHG emissions of 14.4 g per kWh. It ranks third from the bottom in terms of life cycle GHG emissions. It costs approximately 6.0 cents to generate 1 kWh of electricity, which is 3.0 cents more than the cheapest technology (nuclear), but 23.4 cents less than the most expensive technology (solar PV). Therefore, the production cost of electricity is relatively low (Tables S9 and S10).

**Wind power** emits 14.4 g of life cycle GHG merely and generates the least amount of life cycle GHG per kWh. The average cost is 7.7 cents per kWh, which is similar to hydro power (6.5 cents per kWh), and is less than 1/4th the cost of solar PV (29.4 cents per kWh). The error range of life cycle GHG emissions is 32.5 g per kWh based on maximum and minimum values and reaches approximately 7.2 g per kWh based on 90% confidence interval standard, which the gap is narrower than any other sources. It indicates that wind power has excellent technology reliability in reducing life cycle GHG emissions (Tables S11 and S12).

**Table 1. Life cycle GHG emissions (g $CO_{2\text{-}eq.}$/kWh) and life cycle cost (US cent/kWh) of energy resources. Mean is mean values, max. is maximum, min. is minimum, conf. is confidence interval.**

| Energy source | Life cycle GHG emissions (g $CO_{2\text{-}eq.}$/kWh) | | | | Life cycle cost (US cent/kWh) | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | conf. | mean | max. | min. | conf. |
| Coal | 823.2 | 1085.0 | 130.0 | 729.4-917.0 | 3.5 | 5.7 | 1.6 | 3.2-3.8 |
| Natural gas | 420.8 | 499.0 | 245.0 | 391.5-450.2 | 4.6 | 6.0 | 2.7 | 4.4-4.9 |
| Nuclear | 19.7 | 40.0 | 3.0 | 8.3-31.1 | 2.9 | 4.8 | 2.1 | 2.5-3.2 |
| Hydro | 38.0 | 74.9 | 4.0 | 28.1-48.0 | 6.5 | 14.3 | 4.0 | 4.5-8.5 |
| Geothermal | 170.0 | N/A | N/A | N/A | 6.0 | 10.0 | 2.0 | 4.0-7.0 |
| Wind | 14.4 | 39.4 | 6.9 | 10.8-18.0 | 7.7 | 38.1 | 3.1 | 4.8-10.6 |
| Solar thermal | 119.3 | 202.0 | 36.2 | 43.6-195.0 | 15.0 | 18.0 | 12.0 | 12.3-17.7 |
| Solar PV | 67.8 | 300.0 | 9.4 | 39.4-96.2 | 29.4 | 48.5 | 12.1 | 18.0-40.8 |

**Solar thermal power** emits 119.3 g of life cycle GHG per kWh, which is 1/7 of coal-based electricity. The average cost is 15.0 cents, and it is the second most expensive source. However, this is in the middle between solar PV, 29.4 cents, and other technologies. The error bars of both the life cycle GHG emission and its costs are very large, 165.8 g and 6 cents, respectively, based on maximum and minimum values (Tables S13 and S14).

**Solar PV** is the most expensive energy source of 29.4 cents to generate 1 kWh of electricity, which means it is 10 times more expensive than the nuclear energy. The error range in life cycle GHG emissions is 56.8 g based on 90% confidence interval standard, which is approximately 1/3rd that of coal. The error bar of cost is the widest out of all technologies, which is 37 times wider than that of coal (Tables S15 and S16).

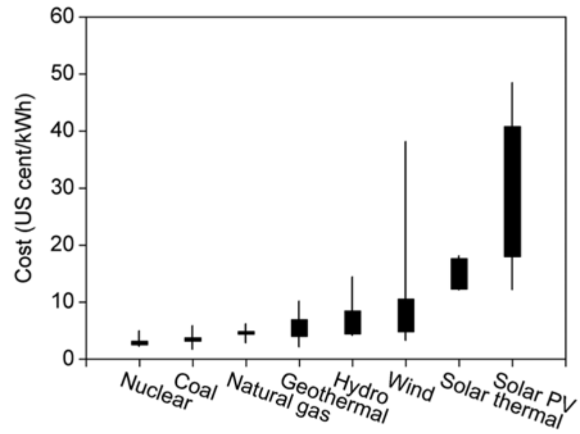


**Fig. 3. Life cycle cost (US cent/kWh) of electricity generation for energy resources.**

## DISCUSSION

Fig. 2 shows the amounts of life cycle GHG emissions of various energy sources. The lines indicate maximum and minimum values and the box displays the range of a 90% confidence interval. Coal and natural gas have the highest output of life cycle GHG emissions, and with the exception of nuclear power, renewable energy releases less life cycle GHG than conventional energy sources. Solar PV generates relatively lower life cycle GHG based on 90% confidence interval. However, the deviation of the maximum-minimum range is wide, which indicates it is not an optimized and matured technology and has the significant potential to generate more life cycle GHG emissions. Out of all renewable energy, solar thermal power has the largest error range of life cycle GHG emissions, and wind power's performance is highly guaranteed in both the life cycle GHG emissions and its error range. Nuclear energy generates the second lowest level of life cycle GHG emissions. Depending on the definition of 'renewable', hydro power is considered as either conventional energy or renewable energy in countries. Considering the life cycle GHG emission, hydro power shows better environmental performance than other renewable energies such as solar thermal, geothermal, and solar PV. Nuclear, geothermal, hydro, and wind power exhibit a relatively smaller error range in life cycle GHG emissions than other energy sources.

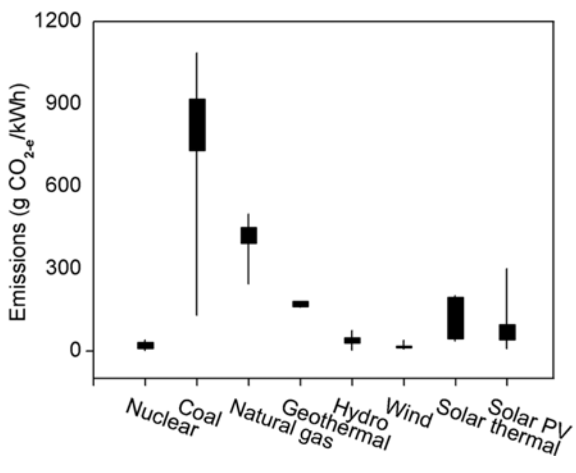


**Fig. 2. Life cycle GHG emissions (g $CO_{2\text{-}eq.}$) of electricity generation for energy sources.**

Fig. 3 summarizes LCCs of all energy sources that are required to generate electricity. As mentioned above, the lines indicate maximum and minimum values and the box displays the range of a 90% confidence interval. The cost of nuclear, coal, natural gas, geothermal, hydro, wind, solar thermal and solar PV increases in turn. Nuclear, coal, natural gas, and hydro power have been already developed and used as main energy sources, and their production cost are relatively cheaper than other sources. On the other hand, the cost of electricity generation of renewable energy is quite high, and the error range is wide. Wind power shows huge difference between maximum and minimum prices, and the cost is widely spread. The difference seems to be caused by combining both on-shore and off-shore types, and for this reason, wind power should be managed by their technological types. Figs. 2 and 3 show environmental impact and economic cost of energy sources separately. To review both life cycle GHG emission and LCC information simultaneously, we made an integrated 2D graph as shown in Fig. 4.

A two-dimensional graph is designed to reflect both life cycle GHG emissions and LCCs. The dots in Fig. 4 indicate life cycle GHG emissions and costs of various energy sources, and the line

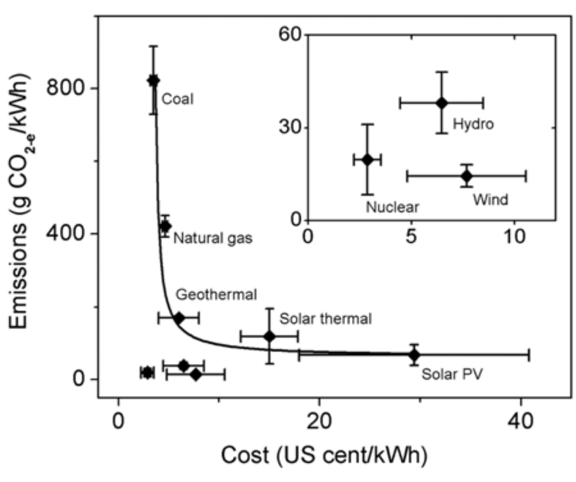


**Fig. 4. 2D graph of generation of electricity for eight energy resources. Inset shows positions of nuclear, wind, hydro powers with lower values.**

presents the range of a 90% confidence interval. The trends demonstrated in the graph explain that the emissions of GHG from the production of electricity and the production cost are largely inversely proportional. The empirical correlation between the two factors can be expressed as

$$\text{GHGemissions } (\text{gCO}_{2\text{-}eq.}) = 72.53 + \frac{228.95}{\text{Cost(U.S.cent)} - 3.18}.$$

The correlation confirms that energy source with high life cycle GHG emissions seems cheaper than others and renewable energy having low life cycle GHG emissions exhibits more expensive cost.

In the bottom-left region with low GHG emissions and low costs, we could find nuclear energy, hydro power, and wind power, which are far from the fitted curve. These energy sources are quite promising and suitable for the generation of electricity. Especially, nuclear power recorded the lowest cost and life cycle GHG emission in the region. We have to remark that in this small region the best energy source can be easily replaced by another as the accuracy of LCA methodology increases and/or as the more quantified environmental impact are considered (*e.g.,* long-term repository of nuclear wastes). Further study is necessary in this regard.

In 2009, the cost for Korean household electricity was about 8 cents per 1 kWh. To be cost competitive against existing energy sources, renewable energy should be offered at a cost similar to retail electricity price. After the Kyoto protocol, countries are limiting the emission of GHG from the production of electricity. The Korean government allows 110 g of $CO_{2\text{-}eq.}$ per 1kWh electricity. If we separate energy sources according to two standards of GHG emissions and cost, they can be divided into four categories. Expensive-gray energy includes solar thermal power. Despite its little, life cycle GHG emissions, it generates more life cycle GHG emissions than the government standard. However, the error range of life cycle GHG emissions for solar thermal is wide, so once optimized in near future the solar thermal technology can become expensive-green energy category. Expensive-green energy category includes solar PV energy only. Affordable, but high GHG emissive, cheap gray technology includes coal, natural gas, and geothermal energy. Cheap-green energy, that is superb in both aspects of life cycle GHG emissions and cost, includes nuclear, hydro, and wind power (Fig. 4 inset). As discussed in Fig. 4, we conclude that the 2D graph helps us to comprehend energy characteristics in terms of life cycle GHG emissions and its costs.

Even though the 2D plot representation is quite useful, for more accurate analysis, we need to consider more factors for LCA evaluation. For example, especially in the case of nuclear energy, we must consider much longer time span than the current analysis does, because some of the nuclear waste materials have much more than 30 years of half life. The other LCA results such as Social LCA and consequential LCA also can be conducted for the best inventory of life cycle GHG emissions and life cycle costs. Using our 2D plot, the results of each LCA analysis can be utilized to obtain more varied, meaningful information by comparing them simultaneously.

## CONCLUSION

We illustrated a two-dimensional plot that combines with the life cycle GHG emissions and life cycle costs for eight energy sources to generate electricity, including nuclear, coal, natural gas, geothermal, hydro, wind, solar thermal, and solar PV. We found a largely inversely proportional relation between GHG emissions and the life cycle costs of energy sources, which is expressed as,

$$\text{GHGemissions } (\text{gCO}_{2\text{-}eq.}) = 72.53 + \frac{228.95}{\text{Cost(U.S.cent)} - 3.18}.$$

In the bottom-left region of the two-dimensional plot, far from the fitted curves, we found that nuclear energy, hydro power, and wind power have lower GHG emissions and lower costs than other energy sources. Especially, nuclear energy recorded the lowest cost and the lowest life cycle GHG emission in the current analysis.

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## SUPPORTING INFORMATION

Further life cycle GHG emissions (g $CO_{2\text{-}e}$/kWh) and Cost (US cent/kWh) data for eight energy sources during the generation of electricity including nuclear, coal, natural gas, geothermal, hydro, wind, solar thermal, and solar PV (Tables S1-S16) and the corresponding references are included. This material is available via the Internet at http://www.springer.com/chemistry/journal/11814.

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# Supporting Information

## 2D representation of life cycle greenhouse gas emission and life cycle cost of energy conversion for various energy resources

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We used LCA data from literatures for our analysis. Here we provide all data we included in the main text for eight energy technologies. Parameters for eight energy resources, originated from the literatures of LCA analysis in different system boundaries, were analyzed and treated as variations (error bars) in the main text.

**1. Coal**

**Table S1. GHG emissions (g $CO_{2\text{-}e}$/kWh) for coal**

| Country | GHG emissions (g $CO_{2\text{-}e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| UK | 932 | 2500 | [1] |
| Australia | 803 | 1000 | [1] |
| Australia | 766 | 1000 | [1] |
| Australia | 130 | 1000 | [1] |
| Australia | 500 | 1000 | [1] |
| Sweden | 860 | 560 | [2] |
| France | 1085 | 600 | [2] |
| Germany | 898 | 600 | [2] |
| Netherlands | 980 | 630 | [2] |
| Spain | 834 | 1200 | [2] |
| Spain | 1026 | 1050 | [2] |
| UK | 960 | 1800 | [3] |
| UK | 972 | 1800 | [3] |
| UK | 1075 | 1800 | [3] |
| UK | 1010 | 1800 | [3] |
| UK | 823 | 1800 | [3] |
| USA | 959 | 425 | [4] |
| USA | 757 | 404 | [4] |
| USA | 847 | 600 | [5] |
| USA | 247 | 600 | [5] |

**Table S2. Cost (US cent/kWh) for coal**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Canada | 3.11 | 450 | [6] |
| USA | 2.71 | 600 | [6] |
| USA | 2.73 | 550 | [6] |
| Czech Rep. | 2.94 | 300 | [6] |
| Czech Rep. | 3.02 | 150 | [6] |
| Czech Rep. | 4.06 | 300 | [6] |
| Czech Rep. | 3.63 | 150 | [6] |
| Denmark | 3.19 | 400 | [6] |
| Finland | 3.64 | 500 | [6] |
| France | 3.33 | 900 | [6] |
| France | 3.17 | 600 | [6] |
| Germany | 3.52 | 800 | [6] |
| Germany | 4.06 | 450 | [6] |
| Germany | 4.82 | 425 | [6] |
| Germany | 2.95 | 1050 | [6] |
| Slovak Rep. | 4.78 | 228 | [6] |
| Slovak Rep. | 5.69 | 224.4 | [6] |
| Turkey | 4.34 | 340 | [6] |
| Turkey | 3.71 | 500 | [6] |
| Turkey | 4.08 | 160 | [6] |
| Korea | 4.95 | 800 | [6] |
| Korea | 2.36 | 956 | [6] |
| Bulgaria | 2.16 | 1532.8 | [6] |
| Romania | 3.13 | 600 | [6] |
| South Africa | 4.45 | 296 | [6] |
| South Africa | 1.57 | 3852 | [6] |

**2. Natural Gas**

**Table S3. GHG emissions (g $CO_{2\text{-}e}$/kWh) for natural gas**

| Country | GHG emissions (g $CO_{2\text{-}e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Australia | 439 | 624 | [1] |
| France | 433 | 250 | [2] |
| Germany | 398 | 778 | [2] |
| Italy | 448 | 680 | [2] |
| Netherlands | 421 | 1669 | [2] |
| Portugal | 440 | 918 | [2] |
| Spain | 407 | 624 | [2] |
| Sweden | 440 | 900 | [2] |
| UK | 411 | 652 | [3] |

**Table S3. Continued**

| Country | GHG emissions ($g\ CO_{2\text{-}e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| USA | 499 | 505 | [7] |
| USA | 245 | 600 | [7] |
| USA | 469 | 620 | [8] |

**Table S4. Cost (US cent/kWh) for natural gas**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Oregon | 2.7 | 7400 | [6] |
| Canada | 4 | 580 | [6] |
| USA | 4.67 | 230 | [6] |
| USA | 3.93 | 400 | [6] |
| Belgium | 4.64 | 400 | [6] |
| Czech | 4.97 | 250 | [6] |
| France | 3.92 | 900 | [6] |
| Germany | 4.9 | 1000 | [6] |
| Greece | 4.97 | 377.7 | [6] |
| Greece | 5.14 | 476.3 | [6] |
| Italy | 4.97 | 791 | [6] |
| Italy | 5.26 | 1150 | [6] |
| Italy | 5.61 | 384 | [6] |
| Netherland | 6.04 | 500 | [6] |
| Portugal | 4 | 1200 | [6] |
| Slovak | 5.59 | 391 | [6] |
| Switzerland | 4.36 | 400 | [6] |
| Switzerland | 4.78 | 250 | [6] |
| Switzerland | 5.21 | 110 | [6] |
| Turkey | 3.82 | 700 | [6] |
| Turkey | 4.04 | 280 | [6] |
| Japan | 5.21 | 1600 | [6] |
| Korea | 4.65 | 889.2 | [6] |
| South Africa | 4.08 | 1935 | [6] |

## 3. Nuclear Energy

**Table S5. GHG emissions ($g\ CO_{2\text{-}e}$/kWh) for nuclear energy**

| Country | GHG emissions ($g\ CO_{2\text{-}e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Australia | 40 | 1000 | [1] |
| Germany | 20 | 1375 | [2] |
| Sweden | 3 | 3095 | [9] |
| Sweden | 3 | 3530 | [10] |
| UK | 12 | 1258 | [3] |
| World | 40 | N/A | [11] |

**Table S6. Cost (US cent/kWh) for nuclear energy**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Canada | 2.6 | 1406 | [6] |

**Table S6. Continued**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| USA | 3.01 | 1000 | [6] |
| Crezch Rep. | 2.3 | 1000 | [6] |
| Finland | 2.76 | 1500 | [6] |
| France | 2.53 | 1590 | [6] |
| Germany | 2.86 | 1590 | [6] |
| Netherlands | 3.58 | 1600 | [6] |
| Slovak | 3.13 | 894 | [6] |
| Switzerland | 2.28 | 1600 | [6] |
| Japan | 4.8 | 1330 | [6] |
| Korea | 2.34 | 1906 | [6] |
| Korea | 2.08 | 2682.4 | [6] |
| Romania | 3.06 | 665 | [6] |

## 4. Hydro Power

**Table S7 GHG emissions ($g\ CO_{2\text{-}e}$/kWh) for hydro power**

| Country | GHG emissions ($g\ CO_{2\text{-}e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Africa | 8-15 | 1600 | [13] |
| Brazil | 3.5-6.5 | 12600 | [13] |
| Canada | 10-19 | 5428 | [13] |
| Guayan | 60-120 | 116 | [13] |
| Canada | 33 | 15300 | [14] |
| Sweden | 5.1 | 1492 | [15] |
| Sweden | 4 | 704 | [16] |
| India | 74.88 | 0.05 | [32] |
| India | 55.42 | 0.1 | [32] |
| India | 35.29 | 3 | [18] |
| India | 35.35 | 0.25 | [18] |
| India | 42.98 | 1 | [18] |
| India | 33.87 | 0.4 | [18] |
| India | 31.2 | 2 | [18] |
| India | 62.4 | 1 | [18] |

**Table S8. Cost (US cent/kWh) for hydro power**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Austria | 5.97 | 14 | [6] |
| Austria | 4.05 | 15 | [6] |
| Czech | 4.64 | 3 | [6] |
| Germany | 8.32 | 0.714 | [6] |
| Greece | 5.98 | 4 | [6] |
| Greece | 4.54 | 123.5 | [6] |
| Slovak | 3.97 | 2.7 | [6] |
| Japan | 14.29 | 19 | [6] |

## 5. Geothermal Energy

**Table S9. GHG emissions (g $CO_{2-e}$/kWh) for geothermal energy**

| Country | GHG emissions (g $CO_{2-e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| World | 170 | N/A | [19] |

**Table S10. Cost (US cent/kWh) for geothermal energy**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| World | 4-7 | N/A | [20] |
| World | 2-10 | N/A | [21] |

## 6. Wind Power

**Table S11. GHG emissions (g $CO_{2-e}$/kWh) for wind power**

| Country | GHG emissions (g $CO_{2-e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Australia | 12.2 | 0.6 | [1] |
| Denmark | 14.5 | 0.5 | [2] |
| Denmark | 22 | 0.6 | [2] |
| Finland | 8.4 | 0.6 | [22] |
| Germany | 6.9 | 0.25 | [2] |
| Greece | 8.2 | 0.23 | [2] |
| Sweden | 10.3 | 0.23-1.75 | [27] |
| UK | 9.1 | 0.3 | [3] |
| ECLIPSE | 7.4 | 0.6 | [23] |
| ECLIPSE | 12.4 | 1.5 | [23] |
| ECLIPSE | 9.1 | 2.5 | [23] |
| Denmark | 16.5 | 0.03 | [24] |
| India | 19 | 1.5 | [25] |
| Japan | 39.4 | 0.1 | [26] |
| Turkey | 20.5 | 0.0225 | [23] |

**Table S12. Cost (US cent/kWh) for wind power**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| USA | 3.11 | 50 | [6] |
| Austria | 8.68 | 19.25 | [6] |
| Crezch | 9.23 | 9 | [6] |
| Belgium | 5.34 | 10 | [6] |
| Denmark | 5.05 | 160 | [6] |
| Denmark | 5.48 | 159.984 | [6] |
| Denmark | 4.42 | 1.5 | [6] |
| Germany | 7.17 | 300 | [6] |
| Germany | 8.41 | 15 | [6] |
| Germany | 6.26 | 15 | [6] |
| Greece | 3.86 | 14.28 | [6] |
| Greece | 3.75 | 12 | [6] |
| Greece | 3.35 | 4.2 | [6] |

**Table S12. Continued**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Greece | 38.1 | 3 | [6] |
| Greece | 5.55 | 4.2 | [27] |
| Italy | 7.6 | 60 | [6] |
| Italy | 5.57 | 72 | [6] |
| Netherlands | 9.43 | 120 | [6] |
| Portugal | 5.45 | 20 | [6] |

## 7. Solar Thermal

**Table S13. GHG emissions (g $CO_{2-e}$/kWh) for solar thermal**

| Country | GHG emissions (g $CO_{2-e}$/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| Australia | 36.2 | 100 | [27] |
| Spain | 202 | 17 | [40] |
| USA | 43 | 100 | [29] |
| Spain | 196 | 50 | [40] |

**Table S14. Cost (US cent/kWh) for solar thermal**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| World | 12-18 | N/A | [20] |

## 8. Solar PV

**Table S15. GHG emissions (g $CO_{2-e}$/kWh) for solar PV**

| Country | GHG emissions (g $CO_{2-e}$/kWh | Net capacity (MWe) | Reference |
|---|---|---|---|
| Australia | 104 | 0.4 | [1] |
| Germany | 55 | 0.0048 | [2] |
| Germany | 51 | 0.013 | [2] |
| Italy | 43 | 0.001 | [30] |
| Italy | 51 | 0.001 | [30] |
| Italy | 44 | 0.001 | [30] |
| Italy | 45 | 0.001 | [30] |
| USA | 12.5 | 0.008 | [8] |
| UK | 44 | 0.0144 | [31] |
| India | 300 | 0.000035 | [32] |
| Italy | 60 | 3.3 | [33] |
| Italy | 50 | 3.3 | [33] |
| Japan | 91 | 0.003 | [34] |
| China | 12.1 | 100 | [35] |
| Singapore | 165 | 0.0027 | [36] |
| China | 9.4 | 100 | [35] |
| China | 15.6 | 100 | [35] |

**Table S16. Cost (US cent/kWh) for solar PV**

| Location | Cost (US cent/kWh) | Net capacity (MWe) | Reference |
|---|---|---|---|
| USA | 16.55 | 50 | [6] |
| USA | 12.06 | 5 | [6] |
| Denmark | 48.48 | 0.5 | [6] |
| Germany | 28.78 | 0.5 | [6] |
| Germany | 41.06 | 0.002 | [6] |

▶ Geological and Temporal Analysis

Researchers in the LCA literatures analyze and extract parameters based on specific system boundaries and the values are valid only in the specific geological region and temporal time span. For a specific example, we selected GHG emissions from solar PV and summarized the value with the origin geological and temporal system boundaries in Table S17. We classified the total GHG emissions from eight energy sources by *Europe* versus *non-Europe* because we treat statistically enough numbers to get meaningful values in Table S18. Generally Europe countries are known to be more advanced in solar PV technologies and our result clearly shows GHG emissions for solar PV in Europe are half smaller than those in non-Europe region. We think the geological analysis may be reduced to technological levels of advances. Further study is needed to make clear discussions about geological analysis.

Furthermore if we consider more detailed regional scope such as Germany or Singapore, then we have to compare using one or two values. We believe that this is too risky. The numbers of samples are listed for GHG emissions from natural gas and costs of nuclear energy in Table S19. Still we use Europe versus non-Europe frame.

**Table S17. Geological and temporal, and technical specification of life cycle GHG data for solar PV**

| Country | GHG ($gCO_2$/kWh) | Year | Capacity (MW) |
|---|---|---|---|
| Australia | 104 | 2001 | 0.4 |
| Germany | 55 | 1997 | 0.0048 |
| Germany | 51 | 1997 | 0.013 |
| Italy | 43 | 2004 | 0.001 |
| Italy | 51 | 2004 | 0.001 |
| Italy | 44 | 2004 | 0.001 |
| Italy | 45 | 2004 | 0.001 |
| USA | 12.5 | 2002 | 0.008 |
| UK | 44 | 2006 | 0.0144 |
| India | 300 | 2000 | 0.000035 |
| Italy | 60 | 2000 | 3.3 |
| Italy | 50 | 2000 | 3.3 |
| Japan | 91 | 1997 | 0.003 |
| China | 12.1 | 2008 | 100 |
| Singapore | 165 | 2006 | 0.0027 |
| China | 9.4 | 2008 | 100 |
| China | 15.6 | 2008 | 100 |

**Table S18. GHG emissions (g-CO2/1 kWh) of European region and non-European region**

| Mean values | Solar PV | Solar thermal | Wind | Coal | Nuclear | Natural gas | Hydro |
|---|---|---|---|---|---|---|---|
| Europe | 49.9 | 147.0 | 12.4 | 966.3 | 9.5 | 424.8 | 4.6 |
| Non-Europe | 83.7 | 39.6 | 19.9 | 680.1 | 40.0 | 413.0 | 44.9 |

**Table S19. Examples of the number of LCA literatures in this study**

| Category | Europe | Non-Europe |
|---|---|---|
| GHG emissions from natural gas | France (1), Germany (1), Italy (1), Netherlands (1), Portugal (1), Spain (1), Sweden (1), UK(1) | Australia (1), USA (3) |
| Cost of nuclear energy | Crezch Rep.(1), Finland (1), France (1), Germany (1), Netherlands (1), Slovak (1), Switzerland (1), Romania (1) | Canada (1), USA (1), Japan (1), Korea (2) |

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