# Tetrahedron Model As An Explanatory Tool For An Optimal Power Mix

By

Kazutomo Irie, General Manager,
Asia Pacific Energy Research Centre, The Institute of Energy Economics, Japan
Inui Bldg., Kachidoki 11F, 1-13-1 Kachidoki, Chuo-ku, Tokyo 104-0054, Japan
Phone +81-3-5144-8539/ Email: kazutomo.irie@aperc.ieej.or.jp

**Abstract**

This paper presents a tetrahedron model as an explanatory tool for an optimal power mix. Applying a simple cost minimisation method is difficult when determining the optimal power mix for many countries, because it involves a value judgment when weighting each evaluation criteria. For this reason, a tetrahedral model is proposed. In this model, each vertex of the tetrahedron maximises the share of either renewable energy power, coal-fired power, gas-fired power or nuclear power in that country's power mix. The evaluation criteria for optimising the power mix can be added to the model in the form of vectors. The length of the vectors can be adjusted based upon the weighting of each nation's value judgement. Thus, the model can show the boundary of the possible power mix options within a given country and visualise which direction its options may move depending on changes in each evaluation criteria by vector composition.

*Keywords*: power mix, explanatory tool, evaluation criteria

## 1. Overview

The Asia Pacific Energy Research Centre (APERC) has compiled the APEC Energy Demand and Supply Outlook 6$^{th}$ Edition for energy policy cooperation within the framework of the Asia Pacific Economic Cooperation (APEC) (APERC, 2016). The 6$^{th}$ Edition has three (3) Alternative Scenarios in addition to the Business-As-Usual (BAU) Scenario.

The Alternative Scenarios include: the Improved Efficiency Scenario to achieve APEC's Energy Intensity Goal, a 45% reduction by 2035 from 2005 levels; the High Renewables Scenario, which aims to reach APEC's shared Doubling Renewable Energy Goal by 2030 from 2010 levels; and the Alternative Power Mix Scenario. The last scenario, unlike the former two (2) Senarios, does not have any clear goal or target except for a general consensus to transisiton APEC towards becoming a low carbon region.

In framing this scenario, APERC discussed how to design the Alternative Power Mix Scenario, where it reached the conclusion that this scenario should show a possible boundary for each APEC member economy's potential power mix[1]. In this process, the author proposed a triangular model, which can visualise a possible boundary for the power mix.

This paper introduces this triangular model and examines the possibility to expand this triangular model into a tetrahedron model as an explanatory tool for ascertaining the parameters of optimal power mixes within countries that may not have domestic consensus for their respective power mixes.

[1] In APEC a member country or area is called 'economy'.

## 2. Methods

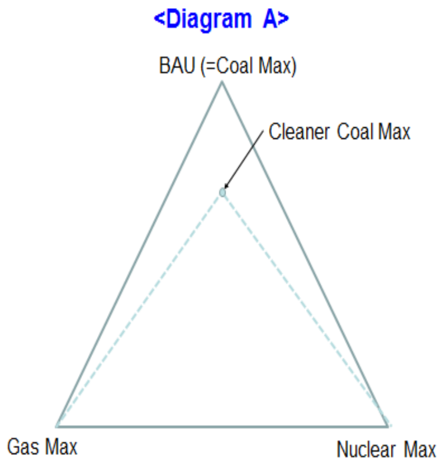
In order to delineate between the Alternative Scenarios, the total power demand and the share of renewable energy source for APEC's power mix are determined by the BAU Scenario; in other words, neither reduced total power demand based on the Improved Efficiency Scenario nor expanded renewable power sources based on the High Renewables Scenario was adopted to design the Alternative Power Mix Scenario.

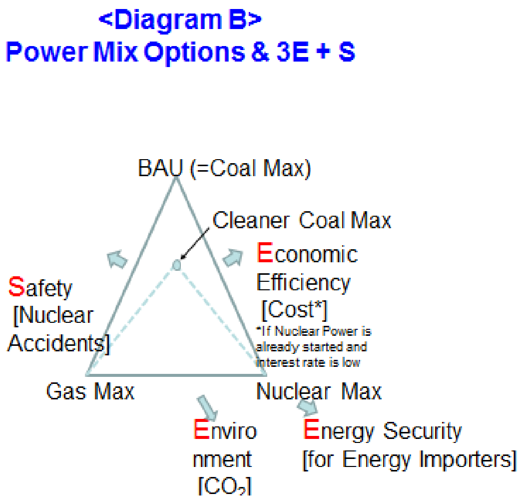
When renewable power sources are excluded, the remaining major energy sources for APEC power mix are coal, natural gas and nuclear, noting that oil-fired power generation still exists albeit at an already declining and small share.[2]

Under the BAU Scenario, the power mix is determined by a cost minimisation principle and therefore maximises coal within the power mix due to its relatively low LCOE and existing high penetration. Thus, maximising coal within the Alternative Power Mix Scenario focuses on 'Cleaner Coal' such as Ultra Super Critical (USC), Integrated Gasification Combined Cycle (IGCC) and Carbon Capture and Storage (CCS). The 'High Gas' case provides two options of either 50% or 100% replacement of new coal developed in the BAU Scenario with gas. Lastly, the 'High Nuclear' case accelerates nuclear energy in economies beyond their BAU plans.

In order to determine which power source to maximise over the forecast period, a triangular model was presented (Diagram A), where any point in the triangle represents a possible combination of coal, gas and nuclear power sources. Please note the vertices of the triangule do not mean 100% share of power mix by coal, gas or nuclear sources.

Next, the revised triangular model was introduced (Diagram B) in which four (4) desirable power mix criteria were shown based on the following principles: Energy Security; Environmental Protections; Economic Efficiency; and Safety. Since 2011, Japan has used these criteria, called '3E + S', for it's own power mix (METI, 2015). Diagram B, adopts a Japanese mentality whereby nuclear generation is already an economical component of the power mix as the economy has already outlayed the high intial capital costs and is benefiting from a low discount rate based on a low interest rate. In Japan, although coal, natural gas and nuclear fuels are import dependent, the supply of nuclear power's feedstock is relatively stable. Evaluation of each power source can vary greatly in relation to the '3E + S' criteria, depending on an economy's macro-economic conditions and energy resources endowment.




[2] After the Great East Japan Earthquake, oil-fired power has grown in Japan to compensate for nuclear power plants shutdown. Accordingly the growth is a temporary phenomenon. For strict share calculation, oil-fired can be combined with natural gas-fired, as their fuel producing and exporting countries largely overlap.

Figure 1 Figure 2

It may be possible to simply calculate the energy security, environment and safety costs in addition to the energy cost for each power source and to add all of them to identify a potential cost minimising combination of power sources as an optimal power mix. However, the costs of each criteria may differ for each economy depending on the value-based decision-making in that economy. For example, minimising climate change, using existing natural resources, or safety concerns. Here, the costs for energy security, environment and safety for each power source can be calculated in addition to the power generation cost itself. Afterwards it would be possible to designate the power mix that minimises the sum of these costs as the optimal power mix.

For example, when:

- *T* means the total cost of a certain power mix and, as cost functions related to the criteria for power mix;
- *S* means energy security cost function,
- *E* means environmental concerns cost function,
- *C* means power generation cost function in a narrower sense (total of capital cost, fuel cost and operation and maintenance cost); and
- *N* means response cost to nuclear power accident risk.

Here, if the numbers from 1 to 4 are given to each of renewable power, coal-fired, gas-fired and nuclear power respectively, in order to identify each power source, the ratio of installed power capacity and power generation of each power source can be represented as *K1, K2, K3, K4* and *g1, g2, g3, g4* respectively (where K1 + K2 + K3 + K4 = g1 + g2 + g3 + g4 = 1).

Then, *T* is calculated and the set of *K1, K2, K3, K4* and *g1, g2, g3, g4* which minimises *T* is determined from equation (1).

$$T = \sum_{i=1}^{4} \{S_i(k_i, g_i) + E_i(k_i, g_i) + C_i(k_i, g_i)\} + N(k_4, g_4) \qquad (1)$$

How to set the functions $Si$, $Ei$, $Ci$, and $N$ will invite a lot of discussion. Especially, for $Ci$, where not only the ratio of installed power capacity, but also the age structure of facilities are required to be taken into account, as new facilities and existing facilities may have different cost functions and construction timeframes that may affect the function. However, the ratio of power generation can be approximately identified as the master variable for each function including $Ci$. In this case, total power generation cost *T* can be expressed as follows.

$$T = \sum_{i=1}^{4} \{S_i(g_i) + E_i(g_i) + C_i(g_i)\} + N(g_4) \qquad (2)$$

In the course of discussion on Japan’s power mix, the question of how to calculate *C* (power generation cost) has been a major issue. Moreover, there is no established methodology for how to calculate *S* (energy security), *E* (environmental concerns), and *N* (cost of nuclear power accident). Energy security cost, *S*, might be calculated by estimating losses that a power failure by fuel supply disruptions or power plant accidents will bring over a certain period of time. Environmental costs, *E*, can be calculated by estimating environmental damages caused by carbon dioxide and/or harmful substances emitted during power generation. However, future damage by global warming caused by carbon dioxide emissions are very difficult to estimate given the range of estimates of its present value are vary significantly. It will be very controversial whether damage incurred in foreign countries should be included or not. As for the cost of responding to a nuclear power accident *N*, it will be extremely difficult to set the probability of an accident at a nuclear power plant in the future, as human beings only possess a short history of nuclear accidents with limited examples available to help reach any consensus.

Furthermore, if it is even possible to estimate these costs, the cost corresponding to each criterion may differ greatly based on the value judgement of each economy. Each economy may judge differently which criterion is most important. For example, minimising climate change may be the most important criterion, or using its own natural resources, or the safety of nuclear power.

If a member economy can decide the weighting for each criteria, then the weight of each criteria can be shown as *wS, wE, wC, wN* (where, *wS* + *wE* + *wC* + *wN* = 4). And so, the above equation (2) can be transformed into the following equation (3).

$$T = \sum_{i=1}^{4} \{ w_S S_i(g_i) + w_E E_i(g_i) + w_C C_i(g_i) \} + w_N N(g_4) \qquad (3)$$

It would be more difficult to obtain economy-wide consensus on the weighting for each criterion than to estimate the cost of each criterion. At present, it is hard to consider consensus on weighting across all APEC member economies.

Therefore, APERC decided not to develop such an optimal power mix and instead evaluate possible parameters for the power mix options and the implications of higher shares of cleaner coal, gas or nuclear.

## *3.* Results

Under APERC’s modelling each APEC member economy has parameters for its non-renewable power mix, in order to pursue their individual optimal power mixes. It is then up to each economy to decide how to design its power mix in reality. However, each APEC economy (or each country or area in general, when countries or area outside the APEC region are included) would require a more detailed model in order to conduct a thorough investigation with the aim of reaching consensus among the countrys’ or local residents.

In order to distinguish between cost calculations for simple cost minimisation efforts, a triangular model where each criteria is shown in the form of a vector (Diagram C), can be presented to explore and explain how to reach an optimal power mix for each country. Unlike Diagram B, Diagram C lends itself to a case where nuclear power would not be economical when it is newly introduced, whether because of the initial investment in social and engineering infrastructure, or a high discount rate based on a high interest rate, makes the present value of initial investment for nuclear power plants expensive. Therefore, in Diagram C nuclear power as well as gas-fired is not economical and coal-fired can only contribute to the power mix’s economic efficiency. Nevertheless, that evaluation of each power source can vary greatly in relation with the ‘3E + S’ criteria according to macro-economic conditions and the energy resource endowment of each country.

Please note that the vertices of the triangular model represent an 100% share of power mix by coal, gas or nuclear sources, as an extreme presumption to provide assumption parameters for modelling purposes. Through this assumption, a point in the triangle uniquely indicates a predetermined percentage of coal-fired, gas-fired and nuclear power. This is because, the equation (4) always holds true for any point P inside the triangle ABC when straight lines from vertex A, B, C are drawn to P and the points where their line extensions intersect the opposite sides at A’, B’, C’ respectively.

$$\frac{PA'}{AA'} + \frac{PB'}{BB'} + \frac{PC'}{CC'} = 1 \qquad (4)$$

As a visual expression, see Figure 4 where *P* represents a power mix in which the coal-fired share is *PA’/AA’*, gas-fired share is *PB’/BB’*, and nuclear power share is *PC’/CC’*.

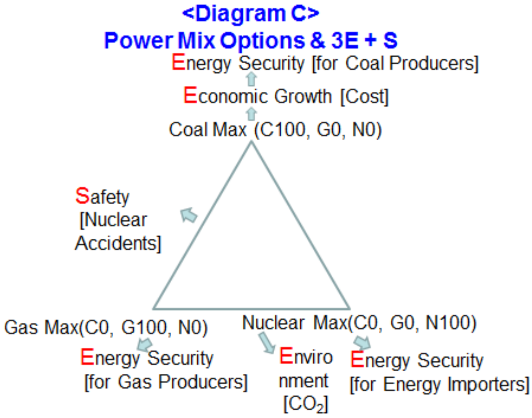



Figure 3

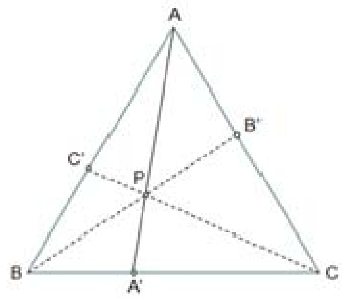



Figure 4

Of course, it is possible to use rigouous mathematical equations to show an optimal power mix by applying vector synthesis on this triangular model. However, the merit of the triangular model rather exists in the fact that there is no need to rigorously determine cost estimates and weighting of each criteria, which would be necessary for mathematical calculations of an optimal power mix. In the triangular model, it is possible to know intuitively to which direction the current power mix should shift by roughly adjusting the length of each vector corresponding to the weighting of each criteria.

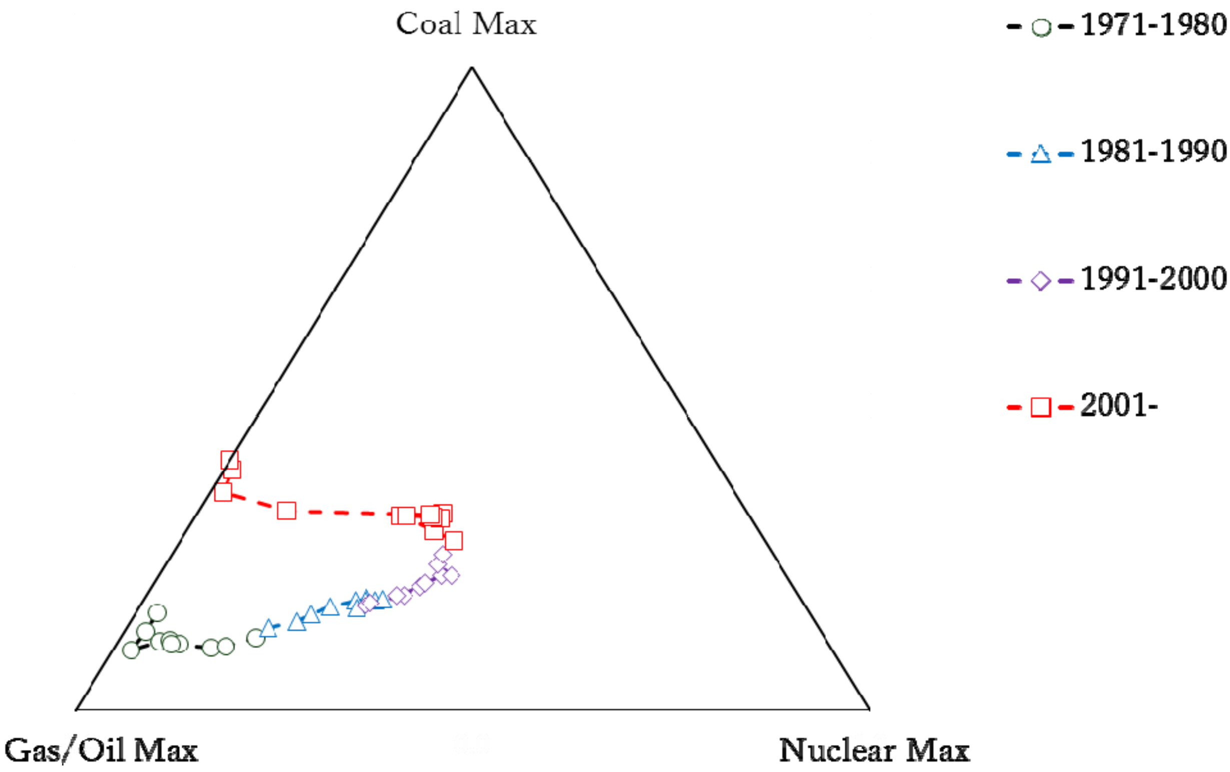



Figure 5

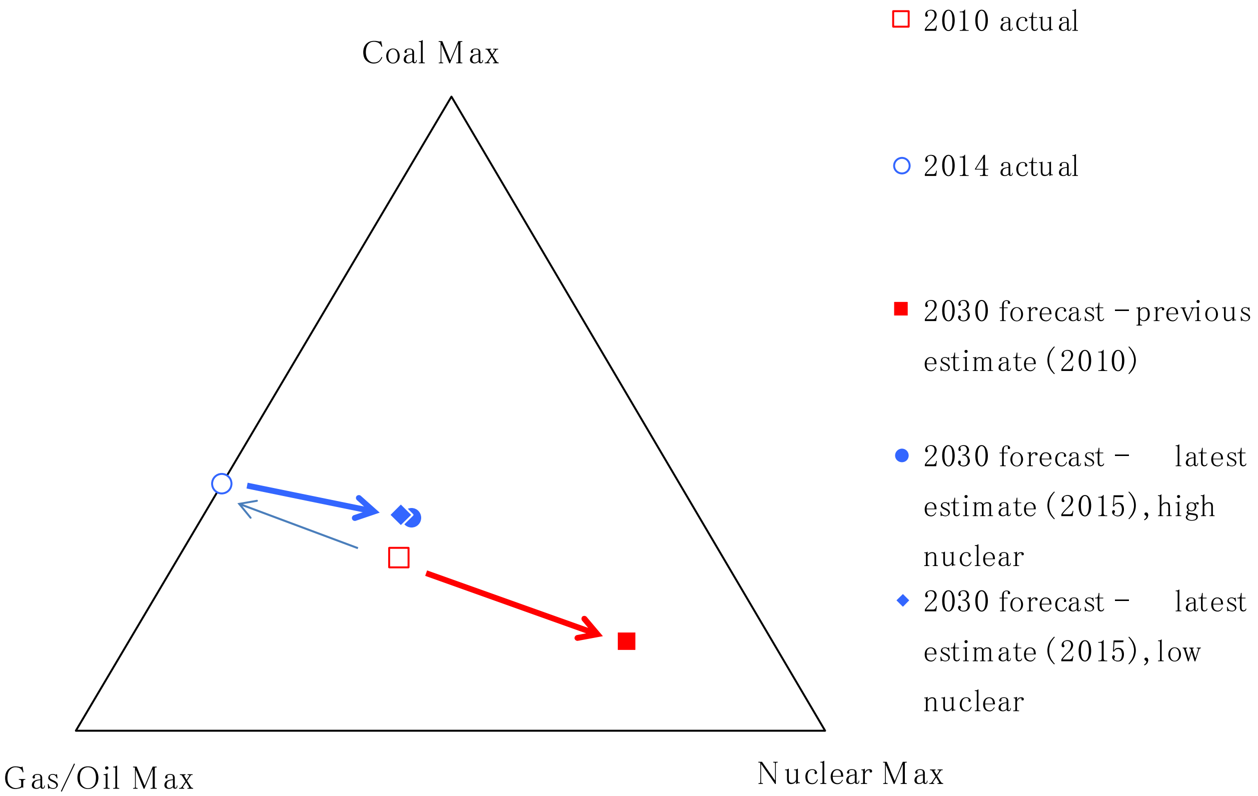



Figure 6

For reference, Japan's case is shown using the methodology of Diagram C (the author is attributing this calculation and drawing to Mr. Yuji Matsuo of the Institute of Energy Economics, Japan). Please note the lower left vertex represents an 100% share of power mix by gas and oil, since oil-fired power generation has had considerable share in Japan's power mix. In fact, Japan has been the largest oil-fired power generaton country in the world for recent several years. Figure 5 shows changes in Japan's power mix since 1971 and Figure 6 shows the targets at 2030 envisaged by Japan's Ministry of Economy, Trade and Industry (METI) in 2010 and 2015 respectively. In this diagram, ■ indicates the target for 2030 which METI set in 2010, while ● ◆ indicate the targets for 2030 which METI set in 2015 (● Renewables 22%, Nuclear 22%; ◆ Renewables 24%, Nuclear 20%). As highlighted in Figure 6, METI envisaged a large increase in the share of nuclear by 2030 in 2010. However, Japan's nuclear power generation plummeted after the Fukushima Daiichi Nuclear Accident in March 2011. As of 2015, METI only expects the share of nuclear to return to the 2010 level by 2030.

Furthermore, the triangular model depicted in Diagram C should be expanded to include renewable energy, thus forming a tetrahedron model (Diagram D). The apex over the tetrahedron represents the case where renewable power accounts for 100%. In this case, any point within the tetrahedron uniquely shows a certain combination of renewable energy power, coal-fired, gas-fired and nuclear power. It is exactly the same as the case in the above-mentioned triangle in Figure 4. However, a three-dimensional model is difficult to comprehend intuitively, especially when vectors are added.

Renewable energy is a preferred power source in most countries from the viewpoint of energy security and environmental sustainability, especially as the high cost structure improves with rapid technological developments. Therefore, most countries can now decide its mamimum use of renewable energy in the power generation first, and then allocate coal, gas and/or nucear. For example, set the share of renewable at 20%, then allocate the remaining 80% to coal, gas and/or nuclear sources.

Geometrically, the tetrahedron model can be reduced to a triangular model again, where each vertex of the triangle represents an 80% share of the power mix by coal, gas or nuclear sources (Diagram C*). The triangle in Diagram C* shows a cross section of the tetrahedron model in cutting it by a plane surface parallel to the base and where the length of each vector can be adjusted to reflect the value attached to each criterion by countries.

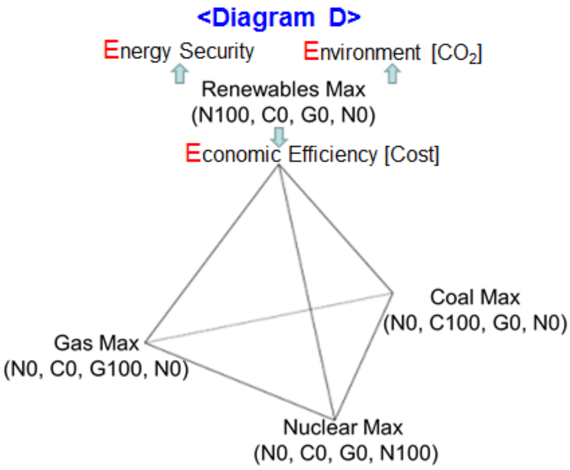



Figure 7

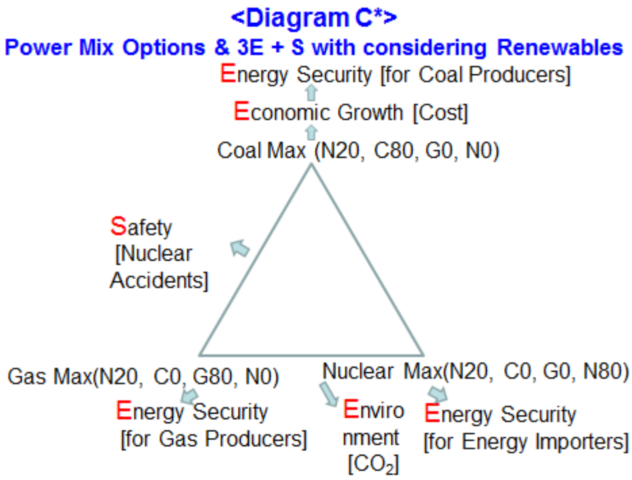



Figure 8

## 4. Conclusion

A tetrahedron model is presented as an explanatory tool for the optimal power mix for countries that face difficulty in reaching national consensus on their respective power mixes.

As it would be difficult to comprehend the three-dimensional tetrahedron model intuitively on a two-dimensional medium such as paper, the model should be reduced to the two-dimensional triangular model. However, if a three-deimensional medium such as a solid model is available, the tetrahedron model can be directly employed.

The presented tetrahedron model can be used as an explanatory tool for the optimal power mix in discussion for reaching national consensus on its power mix. It will always remid discussion participants to take various energy policy criteria such as energy security, environmental consideration or economic efficiency into account. Thus, the discussion may reach a well-balanced conclusion, avoiding one-sided views.

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Contact :report@tky.ieej.or.jp