International Journal of Energy and Environmental Research
Vol.8, No.1, pp.22-29, March 2020
Published by ECRTD-UK
ISSN 2055-0197(Print), ISSN 2055-0200(Online)

RE-EXAMINATION OF THE CONCEPT OF "PRIMARY ENERGY" FOR A PRECISE ANALYSIS OF ENERGY ISSUES

Matsuda Satoshi[1*]
[1]Faculty of Engineering, Shizuoka University, 3-5-1 Johoku, Hamamatsu, 432-8561, Japan
*Corresponding Author: matsuda.satoshi@shizuoka.ac.jp

ABSTRACT: *The concept of "primary energy" should be re-examined in order to grasp a complete view of energy issues, and to evaluate the precise effectiveness of renewable energies, especially by non-thermal means. In many energy statistics, the term "primary energy" is always used, and the unit is often "toe" (ton of oil equivalent), which is based on the caloric value of oil. Since there are several kinds of energy supplied and consumed in society, the concept of "primary energy" is important and convenient to calculate the total amount of energies, in particular when fuels are burned and utilized. However, the situation is complicated when electricity is supplied from renewable energies without fossil fuel consumption. There are several conversion factors between fuels and electricity used in the statics of the IEA (International Energy Agency), which results in the confused meaning of the total amount of the "primary energy" expressed by "toe". In this study, the author proposes a common conversion factor from electricity to "toe" in energy statistics, which will make it easier for us to analyze energy issues and to evaluate the effectiveness of renewable energies and select a better energy source.*

KEYWORDS:primary energy" concept, oil-equivalent, energy conversion rate, renewable energies

INTRODUCTION

It is important for us to marshal the basic concept for energy issues in order to discuss this problem objectively, quantitatively, and logically. For example, the term "primary energy" is always used, but the method and logic of calculation of "primary energy" are difficult. Figure 1 shows the world total primary energy supply by fuel, and Figure 2 shows the world total final consumption by sector, both of which were the data given by the IEA (International Energy Agency) [1]. The common unit in both graphs is Mtoe, Million ton of oil equivalent. However, the meaning of this energy unit should be checked between the primary energy supply and the final consumption, because the method of calculation, and therefore the meaning of "Mtoe," is different. Although there were numerous studies about the primary energy issues (e.g. [2-32]), no article was found which mentioned about the meaning as well as the calculation method of the "primary energy". As is seen in both Figures, there is a large difference in the amount of energy between supply and final consumption. This is partially because energy loss occurs in the process of secondary energy production, such as electricity generation, but other factors exist, as will be explained in detail. In short, there is a serious problem in the method of the calculation of "primary energy" in "Mtoe." This study intends to clarify the problems regarding the method of calculation and propose a new method of calculation, which will be useful to evaluate the effectiveness of the renewable energies, especially by non-thermal means, such as hydro, wind, and photovoltaics.

International Journal of Energy and Environmental Research
Vol.8, No.1, pp.22-29, March 2020
Published by ECRTD-UK
ISSN 2055-0197(Print), ISSN 2055-0200(Online)

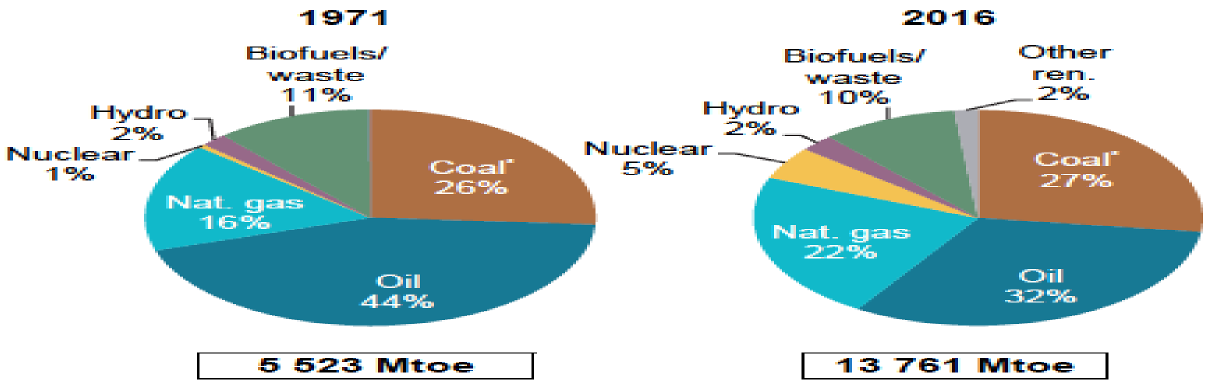

Figure 1. Total primary energy supply by fuel [1]

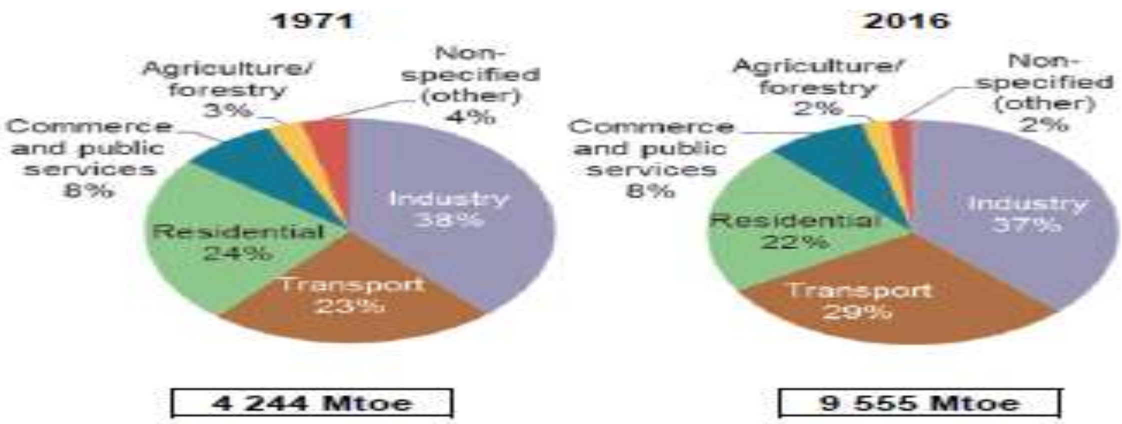

Figure 2. Total final consumption by sector [1]

What is the problem?

In general, there are three phases in energy use: 1) energy supplied by fossil fuels, and electricity from nuclear power or renewable energy sources, 2) the conversion process which supplies secondary energies such as electricity, various oil products, and city gas, and 3) the final consumption in various sectors. The term "primary energy" is used mainly to express the total sum of energy in the supply phase. In the report of IEA [1], they wrote as follows: "Figures for electricity, trade, and final consumption are calculated using the energy content of electricity (i.e. at a rate of 1 TWh = 0.086 Mtoe). Hydro-electricity production (excluding pumped storage) and electricity produced by other non-thermal means (e.g., wind, tide/wave/ocean, and photovoltaic) are accounted for similarities using 1 TWh = 0.086 Mtoe. However, the primary energy equivalent of nuclear electricity is calculated from the gross generation by assuming a 33% conversion efficiency (f = 0.33), i.e. one TWh = (0.086 ÷ 0.33) = 0.260 Mtoe. For geothermal and solar thermal, if no country-specific information is reported, the primary energy equivalent is calculated as follows:

■ 10% for geothermal electricity (1 TWh = 0.86 Mtoe)
■ 50% for geothermal heat (1 TWh = 0.172 Mtoe)
■ 33% for solar thermal electricity (1 TWh = 0.260 Mtoe)
■ 100% for solar thermal heat" (1 TWh = 0.086 Mtoe).

Moreover, according to the definition by the IEA [1], 1 toe (ton of oil equivalent) = 41.87 or 42 GJ =

11.63 MWh = 7.11, 7.33, or 7.4 barrels of oil equivalent, and 1 ton of coal equivalent = 0.7 toe, these values are based on the caloric value of oil. This means 1 MWh = 3.6 GJ = 861 Mcal, as stated above, which is physically true when electricity is consumed and converted to waste heat. However, 1 MWh of electricity cannot be generated from 861 Mcal of heat, because the efficiency of electric power generation is never 100% but 30 to 42% in most thermal power plants. This is why the IEA adopted the 33% conversion efficiency for the primary energy equivalent of nuclear electricity. However, for other non-thermal electricity such as hydro, wind, and solar, the rate of 1 TWh = 0.086 Mtoe (i.e. 1 kWh = 861 kcal) is used, meaning that 100% conversion efficiency (f=1.0) is adopted. This may be due to these energy sources not consuming fuels (oil, coal, or natural gas) which have certain caloric value and can be converted to the primary energy (toe). However, this method of calculation is not logically consistent because 1 TWh of electricity cannot be generated from 0.086 Mt of oil. Thus, the different conversion factors should be used when the primary energy is calculated from the electricity generation using non-thermal means, and also from the final consumption of electricity, which is directly measured by kWh.

On the other hand, in fact, the conversion factor of 2,074 kcal/kWh is used for the primary energy value of 1 kWh electricity for all electricity sources in Japanese energy statistics [33], meaning that the energy efficiency of 41.5% (f = 0.415) is adopted. The reason why this conversion factor is used is based on the concept that 2,074 kcal of fossil fuels can be saved by 1 kWh of electricity generation without any consumption of fossil fuels. Thus, the energy conversion factor for 1 MWh of electricity should not be 861 but 2,050 (=861/0.42) to 2,870 (=861/0.30) Mcal of oil when we calculate the amount of primary energy (Mtoe) from the electricity generation or consumption (TWh). In addition, the use of a 33% conversion (f=0.33) for nuclear electricity is logically wrong if the primary energy as the “oil equivalent” is calculated, because the output electricity divided by 0.33 means only the heat generation from a nuclear reactor, not the value of “oil equivalent”. That is the reason why f=0.415 must be always used for the calculation of the primary energy in “oil equivalent” for all electricity sources.

Data examination

The author checked the energy conversion factors (Mtoe/TWh) from the data in the IEA statics [33]. The values were calculated from the electricity generation in TWh and the total fuel input in Mtoe for each electricity source. Table 1 shows the results using the data in 2015.

Table 1. The energy conversion factors (Mtoe/TWh) in electricity generation by the IEA

	World	Japan	U.S.A.	China	Germany	IEA
Nuclear	0.262	—	0.260	0.260	0.260	0.260
Hydro	0.0859	0.0860	0.0861	0.0860	0.0858	0.0860
Coal	0.234	0.203	0.232	0.224	0.222	0.234
Oil	0.257	0.197	0.229	0.246	0.211	0.257
Natural gas	0.205	0.175	0.176	0.180	0.189	0.205
Total	0.205	0.173	0.202	0.200	0.203	0.205

Note: Power generation in TWh, and total fuel input in Mtoe from the IEA data in 2015 [33]. One Mtoe/TWh = 10^4 kcal/kWh, 0.260 Mtoe /TWh means f = 33%, i.e. 2609 kcal/kWh.

It was obvious that various values were used for the energy conversion factors, causing the meaning of the total amount of “primary energy” to be confusing and difficult to interpret. The most important defect of this calculation method is that the primary energy value in Mtoe would be evaluated to become smaller as the energy conversion factor became larger, meaning that the energy efficiency improved. For instance, the primary energy value of 1 TWh of hydro-electricity is estimated to be smaller than that of nuclear because the factor of 0.0860 (Mtoe/TWh) is used for the former and 0.260 is used for the latter. The difference is more than three times. In this case, the contribution of nuclear to the primary energy is estimated as much larger than that of hydro or any other non-thermal renewable energy sources. Thus, the author proposes that the common factor 0.207 (f = 41.5%, i.e. 2,074 kcal/kWh) should be used for all electricity sources in order to resolve the contradiction described above. In this situation, the meaning of the "primary energy" of the electricity is not a simple heating value but the amount of fossil fuels needed to supply the same amount of electricity. The meaning of the total "primary energy" would be consistent for the supply phase where electricity is supplied by non-thermal energy sources, and also for the final consumption phase where the amount of electricity is measured directly in kWh.

Data modification

Table 2 shows the electricity generation in TWh and fuel input for this in Mtoe in 2015 by the IEA [33] and by our modification using the factor 0.207 (Mtoe/TWh), which means 2,074 kcal of oil is needed to supply 1 kWh (= 860 kcal) of electricity for all energy sources (i.e. f = 0.415).

Table 2. The world total "primary energy" of electricity generation expressed by TWh and Mtoe in 2015, by the IEA and the modification

	IEA			Corrected	
Source	TWh	Mtoe	%	Mtoe	%
Coal	9,538	2,231	45.7	1,974	39.5
Oil	990	254	5.2	205	4.1
Natural gas	5,543	1,139	23.3	1,147	22.9
Nuclear	2,571	671	13.7	**532**	**10.6**
Hydro	3,888	334	6.8	**805**	**16.1**
Geo/Wind	1,111	97	2.0	**230**	**4.6**
Bio/Waste	528	159	3.3	109	2.2
Total	24,169*	4,885	100.0	**5,002**	100.0

*The original data was 23,851, which was the data of 2014.

From the result shown in this table, it is obvious that the contribution of non-thermal renewable energies, especially hydro, to the total primary energy was underestimated by the conventional method of calculation, and vice versa for nuclear. And also, it is indicated that the total primary energy supply itself is larger in the modification than that of the IEA. This result, in turn, affects the total energy consumption which is the sum of electricity and non-electricity use. Table 3 is the total primary energy consumption in Mtoe in 2015 by the IEA [33] and by the modification using the data in Table 2. The value of non-electricity use is not changed but the oil equivalent of electricity is modified, which leads to an increase in the total sum of primary energy consumption.The difference between the present (IEA) and the modified in this table is not as large now, because the major part of the primary energy is occupied by fossil fuels and thermal means of electricity generation. However, the major energy source will be renewable energies which mainly supply electricity without using fossil fuels in the future.

Table 3. The world total "primary energy consumption" expressed by Mtoe in 2015, by the IEA and the modification

	IEA	Corrected
Total	13.647	**13.764**
Electricity	4,885	**5,002***
Non-Electricity	8,762	8,762

*From Table 2.

Even in such a case, the concept of the "primary energy" will be still useful and convenient to grasp a complete view of energy issues, because several different kinds of energy will be used in the supply phase, and also there will be various purposes of energy use in the consumption phase such as electricity and thermal/non-thermal for heating or fuels of transportation. That is the reason why a logical methodology of calculating the "primary energy" is important. It should be emphasized again that the value of the "primary energy" in Mtoe is not a simple heating value but the amount of fossil fuels, as resources, needed to supply the same amount of electricity, heat, oil products, or work. That is the true meaning of the "oil equivalent."

The problem of the final energy consumption in the IEA statistics

Table 4 is the final energy consumption by energy (unit: 10^{10} kcal) in 2015 by Japanese statistics [33]. In this Table, the term "electricity" was allocated because the final electricity consumption at any receiving end in kWh was converted by 2,074 kcal/kWh and summed up. On the other hand, the terms in the World energy balance by the IEA [1] in Table 5 are different from those of Table 4.

Table 4. The total "primary energy consumption" expressed by 10^{10} kcal in 2015, by Japanese statistics [16]

Energy	Coal	Coal Prod.	Oil	Natural gas	**Elect.**	Others	Total
	15,552	18,625	157.900	32,805	**82,109**	3,079	310,070
Sector	Industr.	Residen. & Commer		Transportation		Noe-Ene.	Total
	143,425	86,382		76,811		3,450	310,070

It should be noted that the sum totals of TRES and TFC in this table are exactly the same as in Figs. 1 and 2. This may mean that nuclear and hydro-electricity (as well as solar, wind, and geo) was counted in the energy supply phase, as shown in Table 2 and Fig. 1, but not counted in the final consumption phase. It is rather difficult to understand why electricity is not counted in the final consumption because electricity is surely consumed at all receiving ends. One possible reason is that the method and logic of calculating "primary energy" are different between the IEA and Japanese statistics, although the latter comply basically with the former. In the world energy balance table

Table 5. The "World energy balance, 2016" expressed by Mtoe by the IEA [1]

TPES*1	Coal	Crude Oil	Oil Prod.	Nat. gas	Nuclear	Hydro	Bio.&Waste	Others	Total
	3,731	4,482	-92	3,035	680	349	1,349	227	**13,761**
TFC*2	Coal	Crude Oil	Oil Prod.	Nat. gas	**Nuclear**	**Hydro**	Bio.&Waste	Others	Total
	1,036	15	3,893	1,440	—	—	1,051	2,121	**9,555**

*1 TPES: Total Primary Energy Supply
*2 TFC: Total Final Consumption

[1], the energies from nuclear and hydro were consumed at electricity and CHP plants, and disappeared in the column of TFC (Total Final Consumption), which must be theoretically counted from the total sum of primary (e.g., crude oil, and coal) and secondary energies (e.g., various oil products, city gas, and electricity) at the consumers. The values in Table 4 were counted in such a manner, thus the meaning of the primary final consumption is quite clear. However, the meaning of "TFC" by the IEA is rather difficult to interpret because the method and logic of calculation are not clear, and also several different factors for energy conversion were used, as stated above. In this case, however, there is no difficulty in the difference in the unit of energy, because the conversion rate of 1 toe = 10^7 kcal is valid and therefore the values in Table 4 can be easily converted as: 10^{10} kcal = 1 ktoe = 10^{-3} Mtoe. The essential point is whether or not electricity is counted in the primary energy consumption, and the method and logic of calculation are consistent.

The extra profit from the calculation method in the Japanese statistics

The Japanese statistics [33] adopted the conversion factor of 2,074 kcal/kWh for all electricity sources, and the final primary energy consumption of electricity A was 82,109 × 10^{10} kcal in 2015 (Table 4). The total power generation in the same year B was 1,024,075 × 10^6 kWh × 860 kcal/kWh = 88,070 × 10^{10} kcal. Thus, A/B = 0.932 = energy effective factor of electricity, which means about 6.8% of electricity was lost in the electric power grid. The averaged value of this calculation from year 2010 to 2015 was 0.908, thus the overall conversion factor f' = (A/B) × f = 0.908 × 0.4146 = 0.376. The structure of energy loss at the final consumption phase can be analyzed in such a way. Another merit of using this common conversion factor is that the electricity from the non-thermal renewable energies (hydro, wind, and photovoltaic) can be estimated justifiably in contrast to using the factor 0.086 Mtoe/TWh.

CONCLUSION

This study intended to clarify the meaning of "primary energy" expressed by "toe" (ton of oil equivalent) in order to analyze the structure of energy demand, supply, and consumption quantitatively. This concept is originally based on the heat values of fuels and used conveniently as a common unit of energy. However, the situation became more complicated when electricity was required to be counted in the "primary energy", because 1 kWh of electricity turns to 860 kcal of waste heat but from this heat 1 kWh of electricity can never be generated by the law of thermodynamics. That is why several different conversion factors were used between electricity and fuels (i.e., "toe"). The author has checked the energy conversion factors (Mtoe/TWh) from the data in the IEA statistics, and found that

Vol.8, No.1, pp.22-29, March 2020
Published by ECRTD-UK
ISSN 2055-0197(Print), ISSN 2055-0200(Online)

there were several inconsistent factors used, especially for the non-thermal renewable energy sources such as hydro and wind. The author proposed to use the common factor of 0.207 (Mtoe/TWh), which means 2,074 kcal of oil is needed to supply 1 kWh (= 860 kcal) of electricity for all energy sources (i.e., f = 0.415). The meaning of the "primary energy" in the IEA statistics is rather confusing because different kinds of conversion factors were used, and electricity was not allocated in the final consumption. On the other hand, the common factor proposed here is useful because the meaning of the "primary energy" is very clear; i.e., the value of the "primary energy" in Mtoe is not a simple heating value but the amount of fossil fuels, as resources, needed to supply the same amount of electricity, heat, oil products, or work. That is the true meaning of the "oil equivalent" which can be applied in both the energy supply and the consumption phases.

In particular, since most energy sources in the future, "society independent of fossil fuel," will be renewable energies, and a logical methodology of calculating "primary energy" will be important in order to estimate and select better renewable energy sources and secondary energies.

REFERENCES

[1] IEA (International Energy Agency). World energy balances: Overview 2018. https://webstore.iea.org/world-energy-balan ces -2018-overview
[2] J. Kraft, and A. Kraft. On the relationship between energy and GNP. The Journal of Energy and Development. Vol. 3(2), 401–403, 1978
[3] D. A. Dickey, and W. A. Fuller. Likelihood ratio statistics for autoregressive time series with a unit root. Econometrica, Vol. 49 (4), 1057–1072, 1981
[4] P. C. Phillips, and P. Perron. Testing for a unit root in time series regression. Biometrika, Vol. 75(2), 335–346, 1988
[5] P. Saikkonen, P. Asymptotically efficient estimation of cointegration regressions. Econometric Theory, Vol. 7(1), 1–21, 1991
[6] C. Complainville, D. van der Mensbrugghe. Construction of an Energy Database for GTAP V4: Concordance with IEA Energy Statistics, OECD Development Centre, 1-16, 1998
[7] L. Lee, and M. C. Strazicich. Minimum Lagrange multiplier unit root test with two structural breaks. The Review of Economics and Statistics, Vol. 85(4), 1082–1089, 2003
[8] F. C. Menz. Green electricity policies in the United States: Case study. Energy Policy, Vol. 33(18), 2398–2410, 2005
[9] B. T. Ewing, R. Sari, and U. Soytas. Disaggregate energy consumption and industrial output in the United States. Energy Policy, Vol. 35(2), 1274–1281, 2007
[10] S. Overgaad. Definition of primary and secondary energy, Prepared as input to Chapter 3: Standard International Energy Classification (SIEC) in the International Recommendation on Energy Statistics (IRES), 1-7, 2008
[11] N. Apergis, and J. E. Payne. Energy consumption and economic growth in Central America: Evidence from a panel cointegration and error correction model. Energy Economics, Vol. 31(2), 211–216, 2009
[12] M. K. Dixit, J. L. Fernandez-Solis, S. Lavy, C. H. Culp. Identification of parameters for embodied energy measurement: A literature review. Energy and Building, Vol. 42, 1238-1247, 2010
[13] S. Carley. Historical analysis of U.S. electricity markets: Reassessing carbon lock-in. Energy Policy, Vol. 39, 720-732, 2011
[14] M. D. Schicktanz, J. Wapler, H.-M. Hennig. Primary energy and economic analysis of combined

heating, cooling and power systems. Energy, Vol. 36, 575-585, 2011

[15] L. Gustavsson, A. Dodoo, N. L. Truong, I. Danielski. Primary energy implications of end-use energy efficiency measures in district heated buildings. Energy and Buildings, Vol. 43, 38-48, 2011

[16] M. Giampietro, A. H. Sorman. Are energy statistics useful for making energy scenario? Energy, Vol. 37, 5-17, 2012

[17] A. C. Menezes, A. Cripps, R. A. Buswell, J. Wright, D. Bouchlaghem. Estimating the energy consumption and power demand of small power equipment in office buildings. Energy and Buildings, Vol. 75, 199-209, 2014

[18] A. Dodoo, L. Gustavsson, R. Sathre. Lifecycle carbon implications of conventional and low-energy muti-storey timber building systems. Energy and Building, Vol. 84, 194-210. 2014

[19] E. Latosov, J. Kurnitski, M. Thalfeldt, A. Volkava. Primary energy factors for different district heating networks: An Estonian example. Energy Procedia, Vol. 96, 674-684, 2016

[20] C. de Wolf, F. Pomponi, A. Moncaster. Measureing embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. Energy and Building, Vol. 140, 68-80, 2017

[21] E. Augustins, D. Jaunzems, C. Rochas, A. Kamenders. Managing energy efficiency of buildings: analysis of ESCO experience in Latvia. Energy Procedia, Vol. 147, 614-623, 2018

[22] N. L. Truong, A. Dodoo, L. Gustavsson. Final and primary energy use for heating new residential area with varied exploitation levels, building energy performance and district heat temperatures. Energy Procedia, Vol. 158, 6544-6550, 2019

[23] M. K. Dixit. Life cycle recurrent embodied energy calculation of buildings: a review. J. Cleaner Production. Vol. 209, 731-754, 2019

[24] S. Kan, B. Chen, and G. Chen. Worldwide energy use across global supply chains: Decoupled from economic growth? Applied Energy. Vol. 250, 1235-1245, 2019

[25] X.D.Wu, J.L.Guo, XiJi, and G.Q.Chen. Energy use in world economy from household-consumption-based perspective. Energy Policy. Vol. 127, 287-298, 2019

[26] U. Uzar. Political economy of renewable energy: Does institutional quality make a difference in renewable energy consumption? Renewable Energy. Vol. 155, 591-603, 2020

[27] A. Kasman, and S. Kasman. Convergence of renewable energy consumption in the EU-15: evidence from stochastic and club convergence tests Environmental Science and Pollution Research. Vol. 27, 5901–5911, 2020

[28] I. K. Maji, C. Sulaiman, and A.S. Abdul-Rahim. Renewable energy consumption and economic growth nexus: A fresh evidence from West Africa. Energy Report. Vol. 5, 384-392, 2019

[29] B. Ozcan and I. Ozturk. Renewable energy consumption – economic growth nexus in emerging countries: A bootstrap panel causality test. Renewable and Sustainable Energy Reviews. Vol. 104, 30-37, 2019

[30] H. Sasana, and J. Aminata. Energy Subsidy, Energy Consumption, Economic Growth, and Carbon Dioxide Emission: Indonesian Case Studies. International J. of Energy Economics and Policy. Vol. 9(2), 117-122, 2019

[31] Q. Wang, X-t. Jiang, X. Yang, and S. Ge. Comparative analysis of drivers of energy consumption in China, the USA and India – A perspective from stratified heterogeneity. Science of the Total Environment. Vol. 698, 134117, 2020

[32] W-C. Lie. The Relationship between Primary Energy Consumption and Real Gross Domestic Product: Evidence from Major Asian Countries. Sustainability. Vol. 12, 2568, 2020

[33] The Energy Data and Modeling Center (in Japan). Handbook of Japan's & World Energy & Economics Statistics, 2018 ver