Published as: *Energy Economics* 58, 211-221

Evaluating Energy Security of Resource-Poor Economies: A Modified Principle Component Analysis Approach

(Accepted version)

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Abstract

This study proposes to aggregately measure energy security performance with the principal component analysis. In its application of the methodology to four resource-poor yet economically advanced island economies in East Asia --- Singapore, South Korea, Japan, and Taiwan, this study establishes a novel framework to conceptualize energy security. The framework incorporates three dimensions: vulnerability, efficiency, and sustainability, three indicators being allocated to each dimension. The study finds that all the three dimensions are critical for the resource-poor economies but have different weights in each of them. An urgent task for these four economies is to implement energy efficiency and conservation measures. Liberalization of electricity sector can be a helpful tool to reduce energy consumption and increase efficiency. All of them have been committed to promoting renewable energy development, which shall be further expanded in these economies.

Key words: energy security, principal component analysis, resource-poor economy

1 Introduction

Energy security is an issue so complex that a holistic approach is needed to “capture the complexity of the concept” (Sovacool and Mukherjee 2011, 5346). Despite the difficulty of interpreting its definition, in recent years much literature has attempted to conceptualize energy security, mainly establishing conceptual frameworks to assess energy security of a specific economy or region, such as Zhang (2007) and Chang (2010)’s work for China’s energy security, Chester (2010) for Australia, Sovacool (2011) for the Asia-Pacific region, and so on. Nonetheless, an economy-specific framework cannot be directly applied to other economies, while a regional framework based on geographical location is too general to capture each economy’s unique conditions.

Until now, not any energy security framework has been built up to evaluate a group of economies, such as resource poor economies, that have common unique characteristics and some of these characteristics are so significant that they make the group of economies deserve a tailored index. There are some frameworks that have evaluated energy resource-poor economies such as Singapore (Choong et al. 2014) and Taiwan (Chuang and Ma 2013), yet these two economies are analyzed individually.

On top of conceptual frameworks, quantification of energy security gradually gains popularity as it is particularly useful for studying the consequences/impact of different development pathways on the energy security performance (DBERR 2007). Again, the complexity of energy security makes it difficult to find a simple, straightforward, and easily understandable measurement. An aggregated index is essentially more consistent with the multi-dimensional nature of energy security, but requires an extra weight assigning procedure.

Usually, the weights assigned to each indicator are decided in two ways: by subjective procedures, such as expert survey and equal weights; or based on empirical data, such as using fuel import share or principal component analysis (PCA). According to a recent survey (Ang et al. 2015) of 30 energy security studies with weight assignment, equal weights account for 38% of the studies, fuel/import share, PCA[1] and analytic hierarchy process[2] account for 28%, 10% and 4% respectively, and the rest 20% studies cover other methods. Equal weights and fuel/import share are very popular due to simplicity, but the former does not differentiate the importance of an indicator and the latter cannot be applied to non-fuel indicators. PCA internalizes the indictor weights based on the variation in the indicators, avoiding arbitrary assignment. However, existing applications of PCA in the surveyed papers have some flaws or limitations, which will be discussed in the methodology section.

This paper aims to construct a novel conceptual framework to evaluate energy security of a group of energy resource-poor but economically advanced island economies, including Singapore, South Korea, Japan and Taiwan. The contributions of this paper are two-folded. First, it develops a three-level hierarchic framework to present and analyze energy security in the four resource-poor island economies. Second, it proposes a modified PCA approach, which aims to overcome the flaws or limitations of PCA applications in existing energy security literature. Third,
PCA is applied twice upon the three-level hierarchic framework and eventually an aggregated Energy Security Index (ESI) for each economy is generated.

The paper proceeds as follows: section 2 introduces the PCA methodology, limitations of existing applications in the energy security analysis and the proposed modification in application; section 3 conceptualizes energy security of energy resource-poor island economies; section 4 presents the results of the PCA analysis for the four economies, followed by discussion and policy implications. Section 5 concludes the paper.

2 Methodology

PCA is a dimension-reduction statistical technique widely used to identify underlying common patterns in multivariate data. The premise of PCA is that most variation present in a multivariate data set can be explained by a smaller number of uncorrelated vectors called principal components (PCs). The idea was first introduced by Pearson (1901), later developed independently by Hotelling (1933), and gained popularity since after Jolliffe (1986) systematically introduced the methodology. Recently, the method has been used to measure energy market integration, an unmeasurable concept that is similar to energy security (Sheng and Shi 2013; Zhang et al. 2015). PCA could work independently or as a part of an integrated analysis such as estimating the latent factors in Dynamic Factor Analysis. In the past few decades, PCA has been used in almost every filed, such as agriculture, biology, chemistry, economics, genetics, psychology, etc. (Jolliffe 2002)

2.1 PCA methodology

For a j-dimensional data matrix $\boldsymbol{X}$, j orthogonal eigenvectors (i.e. PCs) and associated eigenvalues can be derived from the covariance or correlation matrix.[3] Ranking the eigenvectors by eigenvalue from highest to lowest, the first eigenvector $\boldsymbol{E_1}$ points out the dimension of most variations in the original data set, while the last eigenvector $\boldsymbol{E_j}$ the least. To transform into a lower-dimensional data matrix, the last few less important eigenvectors that do not contain much

[1] Two papers labelled as using PCA in Ang et al. (2015) in fact did not use the methodology.
[2] Equal weights are used in the aggregation process of each hierarchy.
[3] If the variables are standardized initially, the two approaches coincide.

information on the variation of the original data set would be dropped. The new data matrix $\widetilde{\boldsymbol{X}}$ is obtained according to the transform formula:

$$\widetilde{\boldsymbol{X}} = \left(\boldsymbol{X} - \overline{\boldsymbol{X}}\right)[E_1, \dots, E_p]$$

where $\overline{\boldsymbol{X}}$ is the mean of $\boldsymbol{X}$ and p is the number of eigenvectors retained. The original j-dimensional data matrix $\mathbf{X}$ is thus transformed into a lower p-dimensional data matrix $\widetilde{\boldsymbol{X}}$, without much information loss. It is noteworthy that eigenvectors in the original j-dimensional space are rotated to become axes in the new p-dimensional space.

2.2 Applications of PCA in energy security

As a methodology based on the variation in data, PCA tends to assign heavier weights to indicators that have exhibited more variations but may not be theoretically more important. However, this methodological bias may not be a disadvantage, especially for policy assessment. Indictors that do not change much over time indicate that they do not improve or deteriorate the energy security much, and thus deserve a small proportion in index aggregation from policy makers' perspective. Conversely, heavier weights should be assigned to volatile indicators to highlight their impacts on energy security. In this sense, the PCA-assigned weights could also help policy makers to identify indicators that are sluggish or result in significant deterioration, which are most closely related to policy intervention. As surveyed by Ang et al. (2015), very few papers on energy security have utilized PCA to find weights for index aggregation, and their applications have significant room for improvement. Gupta (2008) created a cross-county weighted-average oil import vulnerability index (OIVI) for the year of 2004, where eigenvalues are used to measure the weight of each eigenvector and the elements in each eigenvector are used as the sub-weight of the corresponding indicator. Ediger and Berk (2011) constructed Turkey's crude oil import vulnerability index for the period from 1968 to 2007, with the first two eigenvectors rather than all. Eigenvalues are again used to compute the weight of each eigenvector, but the sub-weight of each indicator equals to the corresponding element in either the first or the second eigenvector, depending on which is larger.

The two applications, however, have some flaws or limitations. Among others, the negative sign problem is most critical. As the indicators may improve or deteriorate in the sample period, elements in eigenvectors could be positive or negative depending on their correlations with one another. In Gupta's study, the elements are directly assigned to indicators as weights, without any rearrangement of the negative signs. Intuitively, a negative element not only assigns a weight to the indicator but also effectively changes the indicator's interpretation. That is, even though the original indicators are made positively related with oil vulnerability, a negative sign reverses the indicators to be negatively related with oil vulnerability. The final index, which is derived from a mix of positive and negative weights, thus can no longer be interpreted as the higher the better. In Ediger and Berk (2011), negative elements also exist in the two selected eigenvectors. But the study avoids the negative sign problem by manually choosing the relatively larger and meanwhile positive element in the two eigenvectors for each indicator. This is not a general method that can be applied to all situations.

To avoid the negative sign problem discussed above, we propose to reply on the first eigenvector and use the scaled $w_j=|E_{1,j}|/(|E_{1,1}|+\dots+|E_{1,j}|)$ as the weight of indicator j. For any element $E_{i,j}$, its absolute value indicates the j-th indicator's contribution to variation on the dimension of the i-th eigenvector, while the sign (+/-) takes part in determining the direction of the i-th eigenvector within the original data space. Therefore, it is reasonable to let the element's absolute value determine the weighting and the original data determine the direction. In this way, the data space will not be rotated and consequently the derived index follows the same interpretation as originally defined.

3 Conceptualize energy security of resource-poor island economies

When the global energy system has become increasingly complicated, facing a number of distinct environmental, (geo) political, and governance challenges, many researchers try to define energy security with several facets, i.e., incorporating more dimensions into the concept. They establish multi-dimensional frameworks, each having its specific dimensions and indicators, to define and/or quantify energy security. One describes energy security as a situation where five characteristics dominate the whole energy system: surety, survivability, supply, sufficiency and sustainability (the 'five Ss') (Kleber 2009). Similar notions are addressed by various dimensions: energy resource availability, accessibility, environmental acceptability, and investment cost affordability (APERC 2007); or availability, adequacy of capacity, affordability and sustainability (Chester 2010). Sovacool and Brown (2010) argue that "energy security should be based on the interconnected factors of availability, affordability, efficiency and environmental stewardship" (p. 81). In a following work, a 'regulation and governance' dimension has been included in this framework (Sovacool and Mukherjee 2011). Some even make a framework with more than ten dimensions (with indicators under them). Table 1 summarizes a selection of the existing dimensional frameworks/systems to define and/or quantify energy security.

Table 1: Dimensional frameworks/systems for energy security

Author(s)	**Year**	**Economy/Region**	**Dimensions/Components**
APERC	2007	APEC member economies	Energy resource availability, accessibility barriers, environmental acceptability, and investment cost affordability.
Zhang	2007	China	Multi-hierarchy: energy structure, utilization of renewable energy, energy consumption from foreign sources, international energy transportation, domestic energy reserves, and energy strategic reserves.
Kruyt et al.	2009	Western Europe	Availability, accessibility, affordability and acceptability
Chang	2010	China	Multi-hierarchy: energy reserves, energy imports, energy consumption, energy awareness, technology, and environment.
Chester	2010	Australia	Availability, adequacy of capacity, affordability and sustainability.
Sovacool & Brown	2010	OECD member countries	Availability, affordability, energy and economic efficiency, and environmental stewardship.
Vivoda	2010	Asia-Pacific region	Energy supply, demand management, efficiency, economic, environmental, human security; military security, domestic socio-cultural and political factors, technological, international, and policy.
ERIA	2011	East Asia	Development of domestic resources, acquisition of overseas resources, transportation risk management, reliable domestic supply chain, management of demand, preparedness of supply disruptions, and environmental

			sustainability.
Sovacool	2011	Asia-Pacific region	20 dimensions including availability, dependency, diversification, innovation, pollution, efficiency, and greenhouse gas emissions.
von Hippel et al.	2011	Northeast Asia	Energy supply, economic, technological, environmental, socio-cultural, and military-security dimensions.
Sovacool and Mukherjee	2011	Global	Availability, affordability, technology development and efficiency, environmental sustainability, and regulation and governance.
Sovacool et al.	2011		
Sovacool	2013		
Chuang and Ma	2013	Taiwan	Dependence, vulnerability, affordability and acceptability.
Choong, Ang and Ng	2014	Singapore	Economic, energy supply chain and environment.
Yao and Chang	2014	China	Availability, applicability, acceptability, and affordability.

Besides multi-dimensional characteristics, energy security is a "highly context-dependent concept" (Ang et al. 2015, 1081). Different national geology and geography may also lead to different conceptions of energy security (Sovacool and Brown 2010). To summarize, energy security is a concept of multiple dimensions that assumes different characteristics depending on the economy, energy source, or time frame.

3.1 Conceptual framework of resource-poor island economies

This study creates a conceptual framework to evaluate energy security of a group of economies - Singapore, Japan, South Korea and Taiwan - that have common unique characteristics. The existing literatures on the assessment of energy security in the four economies are either conducted individually (e.g. Lye and Chang (2004) on Singapore's energy security), or conducted against a list of economies covering a diversified range of development levels and political systems (e.g. ERIA (2011) on sixteen East Asian economies; Wu and Morrison (2007) on the Asia-Pacific region; and Sovacool (2013)'s international assessment of energy security performance). No literatures have attempted to treat the four East Asian economies - Singapore, South Korea, Japan and Taiwan - as a unique category, yet they should be treated as such due to their similarities in economy, society, and especially in their energy import dependence/lack of indigenous energy resources.

This study develops a quantitative framework to specifically evaluate energy security for these energy resource-poor island economies, apply this framework to make cross-economy comparison among these four East Asian economies, and identify the most effective approaches to improve energy security for these economies. Three dimensions are incorporated in our framework for these resource-poor island East Asian economies: vulnerability, efficiency, and sustainability. Each dimension of the framework includes three indicators to evaluate their respective national performance on energy issues. This novel framework best captures the unique energy security challenges facing these four resource-poor island economies. Quantification of their energy security could indicate potential policy intervention to improve their energy security and may offer reference value for other energy resource-poor, industrialized, and (in effect) physically isolated economies.

The three dimensions of energy security of the four 'resource-poor island economies' are defined with consideration of their characteristics. First, these economies have little indigenous energy resources and thus usually supply side indicators, such as production-reserve ratio, are not applicable. All these four economies import almost all of their crude oil and natural gas and more than 90 per cent of their total primary energy consumption is met by imports (EIA 2013, 2014a, b). Their high import dependency makes these economies highly vulnerable to disruption of energy supply. This constitutes the first critical dimension for their energy security: vulnerability.

Second, due to scarcity of indigenous energy resources and vulnerability to energy supply disruption, these economies attach great importance to demand side management measures, notably energy efficiency. Actions that lead to increase in energy efficiency can have a significant impact on energy security (Ang et al. 2015; Hughes 2009). Therefore efficiency constitutes the second dimension of energy security of the energy resource-poor economies.

Third, environmental protection and sustainability have become "a prominent issue in the international community which advocates using safer and cleaner energy resources and greener methods of energy production and consumption" (Yao and Chang 2014, 597). As energy resource-poor economies, Singapore, South Korea, Japan and Taiwan have inherent limitations to reduce emissions. Yet they have remained committed to putting efforts in maintaining sustainability and keeping the economy green. Hence, environmental concerns constitute an indispensable component of their contemporary energy regime. This is the third dimension for their energy security: sustainability.

It should be noted that this framework catches dimensions that are critical to describe energy security of these economies. It does not deny other explaining factors, but only pick out key ones to avoid over-disaggregation and double-counting. This is because too many dimensions in some existing frameworks can result in over-disaggregation of the components of energy security, with some dimensions overlapping or some dimensions not closely or directly related with an energy security issue. Over-disaggregation makes the concept of energy security less structured and more complicated. Over-disaggregation and the potential overlapping of the dimensions may also lead to double-counting when indicators relevant to these dimensions are used to assess energy security.

3.2 Selection of indicators and collection of data

Indicators constitute a key tool and are primarily important for making policies and monitoring progress in policy implementation, and evaluating the effectiveness of the policies. The 1992 Earth Summit has recognized the important role of indicators in helping economies to make informed decisions concerning sustainable development (Vera and Langlois 2007). The indicators can assess policy effectiveness and indicate a desired state of energy security (Scheepers et al. 2006; Tönjes and de Jong 2007). In addition, the indicators condense "large amounts of complex data into recognizable patterns" so that policy-makers and analysts could "find the best solutions"; the indicators could also help us "understand how dimensions of energy security improve or worsen over time" (Sovacool and Mukherjee 2011, 5346).

A large set of indicators in the literature could measure energy security within the dimensional framework. Similar to the issue of selecting dimensions, the indicators incorporated in the dimensional framework shall not be too many, as this may complicate the concept and lead to over-disaggregation and double-counting as discussed; whereas the indicators shall not be too few, as this may omit some important aspects of the relevant dimension, such that the notion of the dimension cannot be fully reflected. To make PCA workable, three is the minimum number of indicators that each dimension should have.

With this said, we have identified nine indicators in the three-dimensional framework. Table 2 presents these indicators. For the purpose of interpreting the results intuitively, the data shall be consistent in their relationship with the energy security situation. That is to say, it shall be presented that: the smaller the number, the better the energy security situation; or, the bigger the number, the better the energy security situation. This study adopts the former one. Therefore, to make data consistent, we use [1/Total energy self-sufficiency] and [1/Total thermal efficiency of electricity and heat plants] when applying PCA.

Table 2: Energy Security Indicators for Energy Resource-poor Economies

Dimensions	Indicators	Description	Relation with Energy Security	Data Source
Vulnerability	Total energy self-sufficiency	Domestic production/TPES	The bigger the better (+)	IEA
	TPES diversity	HHI of TPES	The smaller the better (-)	IEA & ROC
	Availability factor of electricity	Actual total generation in MWh/total name plate capacity in MW times 8,760 hours	The smaller the better (-)	EIA
Efficiency	Energy intensity	TPEC/GDP (2005)	The smaller the better (-)	IEA
	Total thermal efficiency of electricity and heat plants (%)	The total electricity and heat output / the total input of the products in all plants	The bigger the better (+)	IEA
	Electricity distribution efficiency	Electricity distribution losses/total electricity generation	The smaller the better (-)	EIA
Sustainability	Carbon intensity	CO_2 emissions/GDP (2005)	The smaller the better (-)	IEA
	TPEC per capita	TPEC/population	The smaller the better (-)	IEA
	Share of fossil in TPES	Output of electricity produced based on fossil fuels / total output of electricity	The smaller the better (-)	IEA

Note: IEA: International Energy Agency database; EIA: Energy Information Administration database; WB: World Bank database; ROC: database of Bureau of Energy, Ministry of Economic Affairs, Republic of China.

4 Results and Discussions

The proposed application of PCA in Section 2 is used to develop a cross-time index that tracks the evolution of energy security status in each individual economy. Following the conceptual framework for energy security measurement, the PCA method is applied twice to obtain a single-dimensional energy security index for each of the economies. It is noteworthy that the index only describes the energy security evolution of each economy whereas it cannot provide any cross-economy comparison.

4.1 First-tier interim dimensional indexes

All the selected indicators are standardized at the very beginning. Table 3 displays the obtained first eigenvector as well as its eigenvalue and explained variation by economy and dimension. $E_{1,1}$, $E_{1,2}$, and $E_{1,3}$ represent the contributions of the first, second and third indicators to form the first eigenvector/PC, respectively. It is shown that the first eigenvector explained more than 60% of total variation in most economies and dimensions. While the PCA-based weights reveal the contribution of each indicator in composing the dimensional indexes, it is needed to trace back to the individual indicators to find out what policies have contributed to the improvement, deterioration or sluggishness in that dimension.

Table 3: First-tier Eigenvalues and Eigenvectors for Each Economy

Eigenvectors/PCs	$E_{1,1}$	$E_{1,2}$	$E_{1,3}$	Eigenvalue (λ_1)	Explained Variation
Japan					
Vulnerability dimension	*-0.40*	*0.58*	*0.71*	1.91	0.64
Efficiency dimension	*0.70*	*0.71*	*0.12*	1.88	0.63
Sustainability dimension	*0.39*	*0.69*	*-0.61*	1.79	0.60
Korea					
Vulnerability dimension	*0.71*	*0.70*	*0.08*	1.55	0.52
Efficiency dimension	*0.74*	*0.32*	*0.60*	1.64	0.55
Sustainability dimension	*0.61*	*-0.54*	*0.58*	2.57	0.86
Singapore					
Vulnerability dimension	*0.59*	*0.65*	*0.48*	2.03	0.68
Efficiency dimension	*0.70*	*0.66*	*0.27*	1.92	0.64
Sustainability dimension	*-0.65*	*0.51*	*0.57*	1.39	0.46
Taiwan					
Vulnerability dimension	*0.70*	*-0.69*	*0.21*	1.91	0.64
Efficiency dimension	*0.63*	*0.63*	*0.46*	1.94	0.65
Sustainability dimension	*0.12*	*0.70*	*0.71*	1.98	0.66

To visualize the evolution of vulnerability, efficiency and sustainability in each economy, the dimensional indexes are scaled to 0-1 and graphed in Figure A1-A3 (Appendix) by economy. Following the indicators' original definition, the graph should be interpreted as an increase in a certain index implies deterioration in that dimension, and vice versa. Indexes aggregated with equal weights, labeled by EW, are also plotted for reference purpose. It is shown that the indexes following the two weight-assigning rules have similar trends over time, but show obvious differences in a few cases where the PCA-based weights differ significantly with equal weights.

Japan. The vulnerability dimension improved continuously over time, mainly driven by TPES diversity. Japan has adhered to make its energy mix away from oil-dominant situation by promoting nuclear and alternative energies to diversify its TPES and make the economy less vulnerable to supply disruption. The vulnerability dimension has worsened since 2011 as the Fukushima accident affected total energy self-sufficiency and TPES diversity. However, the Fukushima accident prompted improvement in efficiency dimension, especially in the energy intensity and thermal efficiency of electricity and heat plants. The efficiency index presented gradual improvement in most of the time, and improved significantly after 2011. After the Fukushima accident, the Japanese people have been trying to save electricity by adjusting office thermostats, changing the dress code to short-sleeved shirts, switching off screens and lights, and so on. This has turned out to be an average energy saving rate of 10% (Webster 2014). Electricity distribution efficiency was quite constant over time, as no dramatic re-construction was performed on the well-established power grids. The sustainability dimension displayed a slightly worsening trend until 2003, from which on it began to show an improving trend up to 2010. The Fukushima accident also affected the sustainability dimension through the increase of carbon intensity and share of fossil in TPES.

Korea. The vulnerability dimension deteriorated in the early years, but improves continuously ever since. The trend is dominated by changes in total energy self-sufficiency and TPES diversity.

The availability factor of electricity of Korea was fairly stable if compared with the other two indicators. The deterioration of the efficiency dimension in the early years was caused by energy intensity and electricity distribution efficiency, and the following improvement as well as stability in the last few years was attributable to all three indicators. Thermal efficiency of electricity and heat plants improved moderately over the entire period, only accounting for a small weight in index aggregation. The performance of both generation and distribution efficiency indicates a need of policy intervention in Korea's electricity sector, which is dominated by the Korea Electric Power Corporation (KEPCO). This state-owned power company owns 94% of Korea's generating capacity, and also exclusively operates power grid networks throughout the country (KEPCO 2016). The government intended to unbundle KEPCO into several independent generation and distribution companies, but overall the reform failed. Currently, the competition among KEPCO and independent power producers is quite 'superficial' and very limited. The sustainability dimension indicates an unstable trend over the years, as the three indicators behave quite differently during the sample period. CO_2 intensity and share of fossil in TPES had an improving trend in most of the time, while TPEC per capita had a worsening trend over time. South Korea shall put more efforts in improving the sustainability dimension to avoid its quick deterioration after 2006.

Singapore. The continuous and consistent improvement in the vulnerability index is driven by all the three indicators under the dimension, especially TPES diversity. Singapore's TPES diversity is the least diversified among the four economies, but the government has endeavored to improve the situation ever since the 1990s. The improvement in efficiency dimension is mainly driven by the continuous improvement in energy intensity and thermal efficiency of electricity and heat plants, even though energy intensity increased substantially from 2001till 2004. This is in line with the fact that Singapore has implemented several energy efficiency and conservation measures on energy consumption by households and industrial sectors such as power sector and building sector over the years. For example, the power sector switched oil-fired power plants to more efficient gas-fired plants, which had improved the overall power generation efficiency from 34.4% to 44.9% between 2000 and 2012.[4] In the building sector, the government uses Green Mark Incentive Schemes, Energy Smart Schemes, and so on to encourage the development and construction of energy-efficient buildings (MTI 2007). The sustainability index fluctuates around the median value, as all the three indicators under the dimension are very stable over the years. TPEC per capita peaked in 2004 and did not show much improvement up to 2012, which implies that more efforts are needed to make Singapore less energy intensive and less carbon intensive.

Taiwan. The vulnerability index displays a hump shape, mainly due to the offsetting effect between the worsening total energy self-sufficiency and the improving TPES diversity. Therefore, Taiwan can improve its energy security with the advancement of its vulnerability index. Since the early 1980s, the Taiwanese government has simplified official procedures to more efficiently import coal and other energy resources, aiming at diversifying its energy resources away from oil. Availability factor of electricity was very stable during the period. The improvement in efficiency after 2000 was contributed by all the three indicators under the dimension. All the three indicators under the sustainability dimension had a worsening trend before 2007. Since then, the significant improvement in CO_2 intensity offset the continuous deterioration of TPEC per capita and the share of fossil in TPES. Therefore, the sustainability index displayed a slight improvement with fluctuation in the last few years. A small weight is assigned to carbon intensity as the indicator displayed an increasing trend up to 2003 and since then a declining trend, making the variation relatively smaller than other indicators'. Before the mid-2000, coal and oil dominated fuels for power generation, but since then the government has started promoting renewable energy. After

[4] Data are sourced from IEA database.

the Kyoto Protocol came into effect in 2005, Taiwan set its renewable energy target as 4-6% of all energy by 2020 and 5-7% by 2025 (Liou 2010, 1770). A series of promotion policies have been subsequently implemented to achieve the target, which should have decreased Taiwan's carbon intensity in last few years.

4.2 Second-tier aggregated index

The PCA procedure is applied again to the dimensional indexes, with results displayed in Table 4. $E_{1,1}$, $E_{1,2}$, and $E_{1,3}$ represent the contributions of the vulnerability, efficiency and sustainability index to form the first eigenvector/PC, respectively. The aggregated indexes are scaled to 0-1 and graphed together with equal-weight indexes in Figure 1. The two strands of indexes, ESI based on PCA weights and ESI_EW based on equal weights, exhibit similar trends as the interim dimensional indexes. The nearly overlapped curves for Korea and Singapore imply that the three dimensions have contributed almost equally to the dimension of the first eigenvector. Generally, Japan, Korea and Singapore improved energy security since mid-1990s, and Taiwan improved energy security later in the 2000s.

Table 4: Second-tier Eigenvalues and Eigenvectors for Each Economy

Eigenvectors/PCs	$E_{1,1}$	$E_{1,2}$	$E_{1,3}$	Eigenvalue (λ_1)	Explained Variation
Japan	*0.70*	*0.68*	*-0.20*	1.44	0.48
Korea	*0.59*	*0.55*	*0.59*	2.63	0.88
Singapore	*0.57*	*0.62*	*0.54*	2.31	0.77
Taiwan	*0.10*	*-0.68*	*0.73*	1.62	0.54

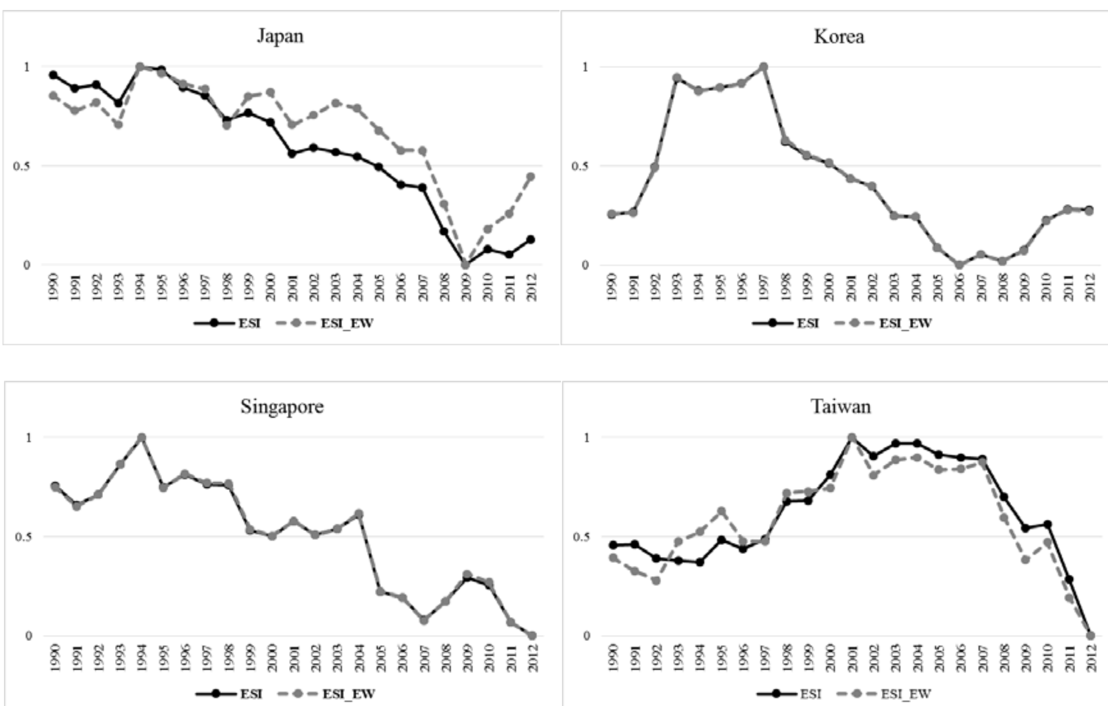

Figure 1. Aggregated ESI scaled to 0-1 of each economy, with an increase implying deterioration and vice versa.

Note: *ESI* is calculated based on the modified PCA application and *ESI_EW* is calculated using equal weights for reference. Cross-economy comparison is not meaningful.

Individually, Japan's ESI was quite stable in the first few years and later had a general trend of continuous improvement with small fluctuations until 2009, after which there was a little bit rebound mainly due to the Fukushima accident. The pattern exhibited by the Japanese ESI is mainly attributable to the performance of the vulnerability dimension (44%) and efficiency dimension (43%). The sustainability dimension is relatively stable and contributes the least (12%). Before 1997, all three dimensions in Korea deteriorated, and so was the ESI. After that Korea's ESI showed continuous improvement till 2006, followed by a slight rebound. The pattern describing the energy security situation is almost equally determined by the vulnerability (34%), efficiency (32%), and sustainability (34%) indexes.

Singapore's energy security improved continuously from 1994 until 2007, after which there was a gentle fluctuation. Similar to Korea, Singapore's energy security status was fairly equally driven by the improvement of the vulnerability (33%), efficiency (36%) and sustainability (31%) dimensions.

Taiwan's energy security had worsened off until 2004 and improved continuously after that, especially in 2011 and 2012. The variation mainly arises from the efficiency (45%) and sustainability (48%) dimension. The vulnerability dimension tends to be quite stable and accounts for a small weight (7%).

The empirical results indicate that vulnerability, efficiency and sustainability dimensions are all important for energy security of the resource-poor island economies, although their weights vary in different economies. Hence, effective energy security policies should ultimately address all the dimensions but with different priority in different economies. It is shown that efficiency dimension affects energy security of all these resource-poor island economies significantly and positively, which implies that the economies have generally done well in improving energy efficiency over the years.

The vulnerability dimension and sustainability dimension are important as well, except for vulnerability dimension in Taiwan and sustainability dimension in Japan. Improvement in vulnerability dimension is quite obvious in Japan, Korea and Singapore since the mid-1990s, but not in Taiwan. And it is too early to conclude that the change in the last few years is a fundamental improvement rather than short-term fluctuation. Basically, Taiwan could improve its energy security by advancing its vulnerability index, more specifically, total energy self-sufficiency.

Improvement in sustainability dimension is needed for not only Japan but also the other economies, as the sustainability index was either fluctuating or worsening off over the study period. However, the improvement could be difficult as the indicators are economy-wide and complicated. For example, the reduction of carbon intensity may require the economy to be restructured.

5 Conclusions

This paper constructs a three-level framework to evaluate energy security of four economies from vulnerability, efficiency and sustainability dimensions, with three indicators under each of them. In addition to the common characteristics of 'resource-poor yet economically advanced' analyzed in this paper, the idea of using a unified framework can be extended to any group of economies that share some common characteristics. The paper also suggests a modified application of PCA which overcomes limitations observed in earlier applications to address the arbitrary weight assigning problem. As discussed previously, PCA identifies the relative importance of indicators by variation in assigning weight. This technique is an appropriate tool to aggregate index for policy assessment, as changes in data, rather than the data *per se*, are more meaningful and deserve more attention to policy makers. Further, this methodology can also be extended to energy security study of other countries that have common characteristics.

The assessment of the four resource-poor economies- Singapore, Korea, Japan and Taiwan- finds that the three dimensions- vulnerability, efficiency and sustainability- are all important in general but have different weights in different economies. An urgent task for these four economies, and perhaps for all resource-poor economies, is to implement energy efficiency and conservation measures. All these economies show a general trend of improvement in the efficiency dimension over the study period, with Japan being the frontrunner. Japan has limited potential to improve its energy efficiency, whereas other economies, especially Singapore, may foresee big progress in the future. Although promoting energy efficiency has always been top on these governments' policy agenda, the progress varies in these economies.

Liberalization of electricity sector can be a helpful tool to reduce energy consumption and increase efficiency. All of Japan, Korea and Taiwan have had monopolistic electricity sector, and have encountered difficulty in promoting liberalization. Yet finally Japan has taken a big step, a milestone event impelled by the Fukushima accident. On 1 April 2016, the Japanese government ended regional monopolies and opened up retail electricity markets to competition. Hopefully these changes will encourage and set a good example for the electricity sector liberalization of both South Korea and Taiwan.

Further, although renewable energy only account for a small share of these economies' energy mix due to resource constraint, all the four economies are committed to promoting renewable energy development with administrative and financial measures. However, all of them are tortured by the selection of appropriate approach to promote the development. A number of challenges have to be addressed before they can meet their renewable energy target. For example, the Taiwanese people are highly against nuclear power, so policies may focus on how to gain the public acceptance through actions such as public education and campaigns. Singapore's tropical location, relatively flat land and limited land area prevent it from using renewable energies such as hydro, tidal, wind and nuclear. Therefore, promotion of research and development in solar technologies should be the government's first priority.

References

Ang, B.W., W.L. Choong, and T.S. Ng. "Energy security: Definitions, dimensions and indexes." *Renewable and Sustainable Energy Reviews* 42 (2015): 1077-1093.

APERC. *A Quest for Energy Security in the 21st century: Resources and Constraints.* Tokyo: Asia Pacific Energy Research Centre, 2007.

Chang, Junqian. "Study on Evaluation System of Energy Security and Policy in Our Country." *Ph.D. Dissertation.* Beijing: China University of Geosciences, May 2010.

Chester, Lynne. "Conceptualising energy security and making explicit its polysemic nature." *Energy Policy,* 38 (2010): 887-895.

Choong, Wei Liang, B.W. Ang, and T.S. Ng. *Development of an energy security index for Singapore.* IAEE 2014 conference paper, 2014.

Chuang, Ming Chih, and Hwong Wen Ma. "An assessment of Taiwan's energy policy usingmulti-dimensional energy security indicators." *Renewable and Sustainable Energy Reviews* 17 (2013): 301-311.

DBERR. *Expected energy unserved: a quantitative measure of security of supply, URN 07/1522.* London: Department for Business, Enterprise and Regulatory Reform, 2007.

Ediger , Volkan Ş, and Istemi Berk. "Crude oil import policy of Turkey: Historical analysis of determinants and implications since 1968." *Energy Policy* 39, no. 4 (2011): 2132–2142.

EIA. "Japan." *U.S. Energy Information Administration.* July 31, 2014b. http://www.eia.gov/countries/cab.cfm?fips=JA (accessed December 18, 2014).

—. "Korea, South." *U.S. Energy Information Administration.* April 1, 2014a. http://www.eia.gov/countries/cab.cfm?fips=KS (accessed December 17, 2014).

—. "Singapore." *U.S. Energy Information Administration.* March 12, 2013. http://www.eia.gov/countries/cab.cfm?fips=SN (accessed December 17, 2014).

Economic Research Institute for ASEAN and East Asia (ERIA). 'Developing an Energy Security Index' in Koyama, K. (ed.), *Study on the Development of an Energy Security Index and an Assessment of Energy Security for East Asian Countries*, ERIA Research Project Report 2011-13, Jakarta: ERIA, (2011): 7-47.

Gupta, Eshita. "Oil vulnerability index of oil-importing countries." *Energy Policy* 36, no. 3 (March 2008): 1195-1211.

Hotelling, H. Analysis of a complex of statistical variables into principal components. *Journal of Educational Psychology* 24, (1933): 417–441.

Hughes, Larry. "The four 'R's of energy security." *Energy Policy* 37, no. 6 (2009): 2459-2461.

Jolliffe, I.T. "Principal component analysis". Springer Verlag, New York. 1986.

Jolliffe, I.T. "Principal component analysis", 2nd edition. Springer Verlag, New York. 2002.

KEPCO. *Overview of Korea's Electric Power Industry.* 2016. https://home.kepco.co.kr/kepco/EN/B/htmlView/ENBAHP001.do?menuCd=EN020101 (accessed May 4, 2016).

Kleber, Drexel. *The US Department of Defense: Valuing Energy Security*. June 18, 2009. http://www.ensec.org/index.php?option=com_content&view=article&id=196:the-us-department-of-defense-valuing-energy-security&catid=96:content&Itemid=345 (accessed October 10, 2011).

Kruyt, Bert, D P van Vuuren, H.J. M de Vries, and H Groenenberg. "Indicators for energy security." *Energy Policy* 37, no. 6 (June 2009): 2166-2181.

Liou, Hwa Meei. "Policies and legislation driving Taiwan's development of renewable energy." *Renewable and Sustainable Energy Reviews* 14 (2010): 1763-1781.

Lye, Lin-Heng and Youngho Chang. Singapore: National Energy Security and Regional Cooperation. In B. Barton, C. Redgwell, A. Ronne, & D. N. Zillman (Eds.), *Energy Security: Managing Risk in a Dynamic Legal and Regulatory Environment*. From Oxford Scholarship Online: http://www.oxfordscholarship.com/view/10.1093/acprof:oso/9780199271610.001.0001/acprof-9780199271610-chapter-16, 2004.

MTI. *Energy for Growth: National Energy Policy Report.* Singapore: Ministry of Trade and Industry, 2007.

Pearson, K. On lines and planes of closest fit to systems of points in space. *Philosophical Magazine* 6, (1901): 559–572.

Scheepers, Martin, Ad Seebregts, Jacques de Jong, and Hans Maters. EU standards for energy security of supply, ECN-C-06-039/CIEP. The Hague: ECN/Clingendael International Energy Programme, 2006.

Sheng, Yu and Xunpeng Shi. “Energy market integration and Equitable Growth Across Countries.” *Applied Energy* 104 (2013): 319-325.

Sovacool, B.K. “An international assessment of energy security performance.” *Ecological Economics* (2013): 148-158.

Sovacool, Benjamin K. “Evaluating energy security in the Asia Pacific: Towards a more comprehensive approach.” *Energy Policy* (2011): 7472–7479.

Sovacool, Benjamin K, and Ishani Mukherjee. "Conceptualizing and measuring energy security: A synthesized approach." *Energy* (2011): 5343-5355.

Sovacool, Benjamin K, and Marilyn A Brown. "Competing Dimensions of Energy Security: An International Perspective." *Annual Review of Environment and Resources* (2010): 77-108.

Sovacool, Benjamin K, Ishani Mukherjee, I. M. Drupady and A. L. D'Agostino. “Evaluating energy security performance from 1990 to 2010 for eighteen countries.” *Energy*, 36, no. 10 (2011): 5846-5853.

Tönjes, Christoph, and Jacques J de Jong. "Perspectives on security of supply in European natural gas markets." *Working Paper.* The Hague: Clingendael International Energy Programme, August 2007.

Vera, Ivan, and Lucille Langlois. "Energy indicators for sustainable development." *Energy* (2007): 875-882.

Vivoda, Vlado. "Evaluating energy security in the Asia-Pacific region: A novel methodological approach." *Energy Policy* (2010): 5258-5263.

von Hippel, David, Tatsujiro Suzuki, James H. Williams, Timothy Savage, and Peter Hayes. "Energy security and sustainability in Northeast Asia." *Energy Policy* (2011): 6719–6730.

Webster, John. "Japan’s energy revolution." *The Economist Intelligence Unit.* September 11, 2014. http://www.economistinsights.com/energy/opinion/japan%E2%80%99s-energy-revolution (accessed March 9, 2015).

Wu, K. and, C. E. Morrison. Energy Insecurity Index. In K. Wu, & F. Fesharaki (Eds.), *Asia's Energy Future: Regional Dynamics and Global Implications*. From East-West

Center: http://www.eastwestcenter.org/fileadmin/stored/pdfs/asiaenergyfuture10insecurityindex.pdf, 2007.

Yao, Lixia, and Youngho Chang. "Energy security in China: A quantitative analysis and policy implications." *Energy Policy* 67 (2014): 595-604.

Zhang D, X Shi, and Y Sheng. “Enhanced Measurement of Energy Market Integration in East Asia: An Application of Dynamic Principal Component Analysis.” *Energy Economics* 52 (2015): 299-305.

Zhang, Shengling. “China’s Energy Security and Assessment.” *China Population, Resources and Environment* (2007): 101-104.

Appendix: Interim dimensional indexes

A1: Interim Vulnerability Index

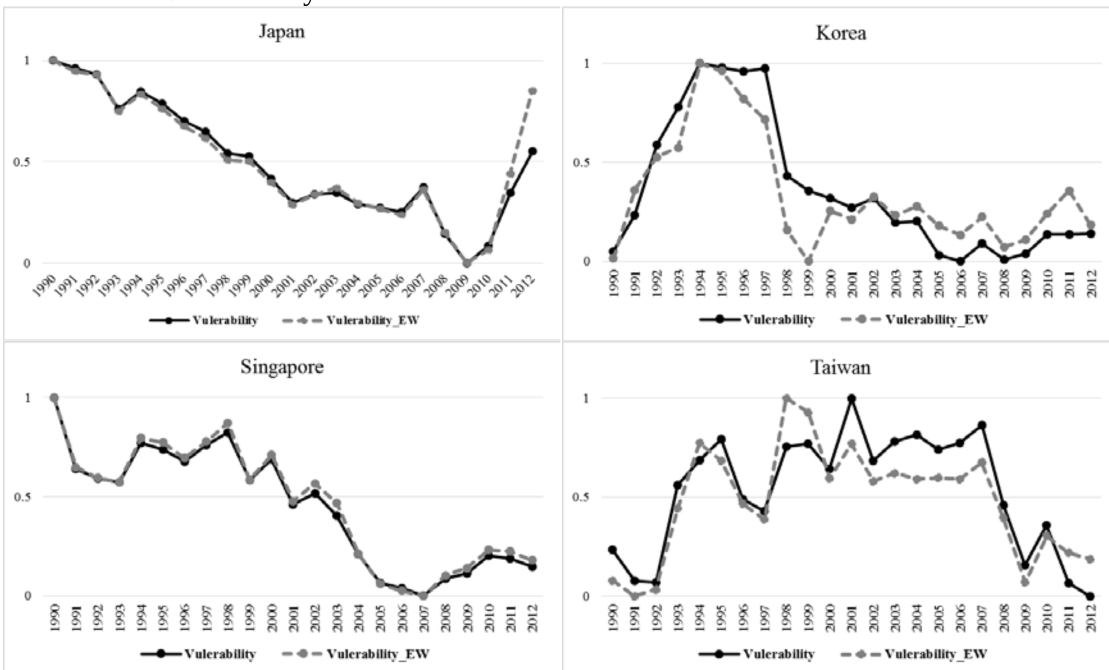

Figure A1. Interim vulnerability index scaled to 0-1 of each economy, with an increase implying deterioration and vice versa. *Vulnerability* index is calculated based on the modified PCA application and *Vulnerability_EW* index is calculated using equal weights for reference. Cross-economy comparison is not meaningful.

A2: Interim Efficiency Index

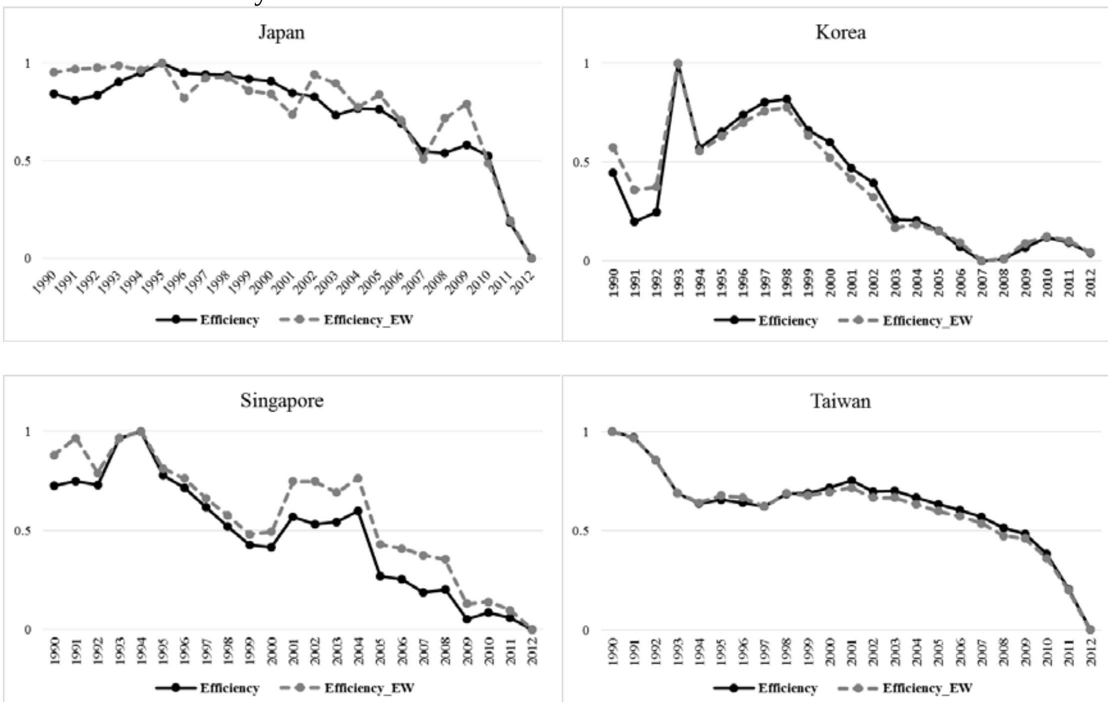

Figure A2. Interim efficiency index scaled to 0-1 of each economy, with an increase implying deterioration and vice versa. *Efficiency* index is calculated based on the modified PCA application and *Efficiency_EW* index is calculated using equal weights for reference. Cross-economy comparison is not meaningful.

A3: Interim Sustainability Index

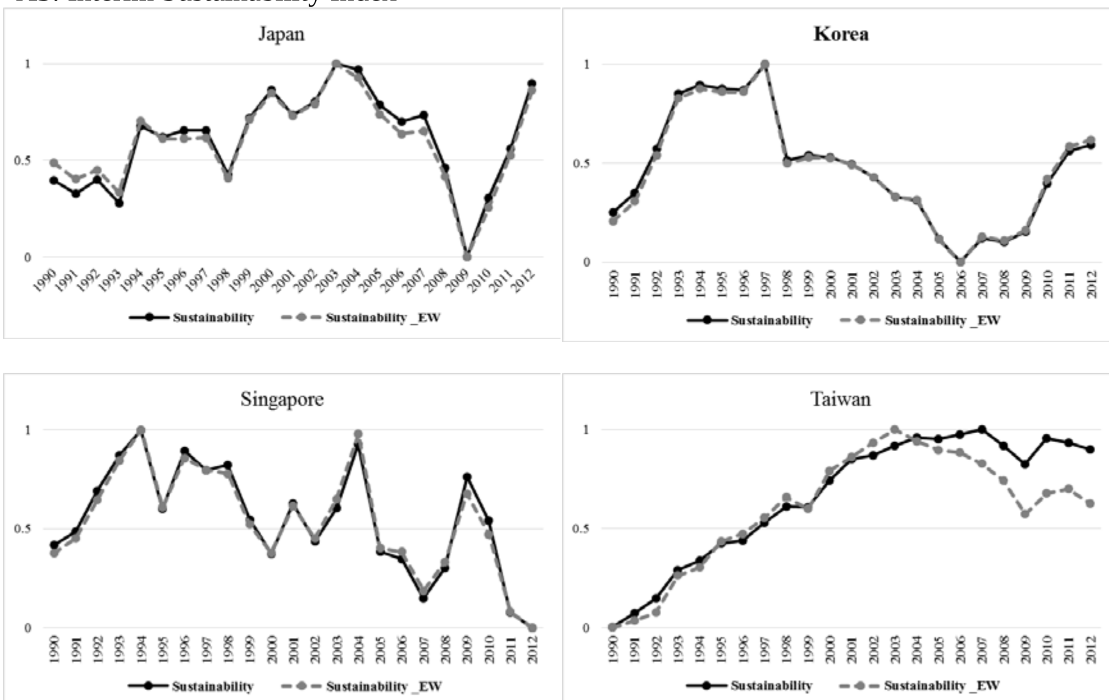

Figure A3. Interim sustainability index scaled to 0-1 of each economy, with an increase implying deterioration and vice versa. *Sustainability* index is calculated based on the modified PCA application and *Sustainability_EW* index is calculated using equal weights for reference. Cross-economy comparison is not meaningful.