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# Disaggregated energy consumption and GDP in Taiwan: A threshold co-integration analysis

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**Abstract**

Energy consumption growth is much higher than economic growth for Taiwan in recent years, worsening its energy efficiency. This paper provides a solid explanation by examining the equilibrium relationship between GDP and disaggregated energy consumption under a non-linear framework. The threshold co-integration test developed with asymmetric dynamic adjusting processes proposed by Hansen and Seo [Hansen, B.E., Seo, B., 2002. Testing for two-regime threshold cointegration in vector error-correction models. Journal of Econometrics 110, 293–318.] is applied. Non-linear co-integrations between GDP and disaggregated energy consumptions are confirmed except for oil consumption. The two-regime vector error-correction models (VECM) show that the adjustment process of energy consumption toward equilibrium is highly persistent when an appropriately threshold is reached. There is mean-reverting behavior when the threshold is reached, making aggregate and disaggregated energy consumptions grow faster than GDP in Taiwan.


*JEL classification:* Q42; Q43; C32

*Keywords:* Disaggregated energy consumption; GDP; Threshold co-integration; Asymmetric adjustment

## 1. Introduction

Growing concerns over the effects of greenhouse gas emissions for global warming have placed pressure on the world's leading economies to improve their efficiency of energy use. In

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June 2005, the National Energy Conference in Taiwan took place and the objective was to establish an applicable energy policy that can conform to the newly developing trends under the Kyoto Protocol. The conference has given some directions for macrostrategies of energy policy that have to be implemented in the future. First, carbon dioxide emissions are expected to reduce to levels of 38 million tons of oil equivalent (MTOE) in 2015 and to 78 MTOE in 2025, respectively. Second, the structures of energy allocation percentage in 2025 are expected to drop as follows: fuel 41% to 45%, oil 32% to 31%, natural gas 16% to 19%, nuclear energy to 4%, and renewable energy 5% to 7%. Third, Taiwan's government regulatory authority should establish a market mechanism to promote the rationalization of energy prices and consolidate the management of efficient energy use. Although economists have long argued that pricing policies are an effective instrument to improve the efficiency of energy use, the effectiveness of a pricing policy to promote the efficient use of energy depends on the price elasticity of energy demand. Finally, the legislative body should create energy enterprising laws that can accomplish energy market liberalization progressively.

Beginning in the 1980s, an enormous amount of change in Taiwan's economic structure took place. Financial liberalization and an internationalization policy were carried out in the middle part of the 1980s. The country's average annual economic growth was 7.59% and the average growth rate of energy consumption was 5.84% starting from 1980 until the end of 1996. This signifies that domestic output consumes a relative lower level of energy. However, some economic incidents have caused a substantial decline in economic growth, including military tension across the Taiwan Strait, Asian financial crisis (1997–1999), and recessions in the global business cycle in 2001. During the period from 1997 to 2002, the average annual economic growth dropped to 3.63%, while energy consumption still sustained at 5.58%, worsening Taiwan's energy efficiency. Energy over-consumption cannot effectively enhance economic growth and may generate disequilibrium between energy consumption and economic growth. Actions toward energy-saving and value-added promotion are needed to improve energy efficiency.

Ever since 1970s numerous studies have examined the relationship between energy consumption and economic growth. A major question concerning this issue is which variable leads to the other: is energy consumption a stimulus for economic growth or does economic growth lead to energy consumption? One of the time series methodologies to employ is the concept of Granger causality. Following Kraft and Kraft (1978) who provide pioneering evidence in support of causality from GNP to energy consumption in the United States, many empirical studies later extended to cover other industrial countries such as the United Kingdom, Canada, Germany, Italy, Japan, and France (e.g., Yu and Choi, 1985; Erol and Yu, 1987). However, the related literature on developed and developing countries, with diverse methodologies, and using various time periods fails to reach a unanimous conclusion.

According to the controversial and conflicting evidence, the directions of causality between energy consumption and economic growth can be categorized into four types: first, if there is a unidirectional causality from economic growth to energy consumption, then policies for reducing energy consumption may be implemented with only little adverse or no effect on economic growth, such as in a less energy-dependent economy (Lise and Montfort, 2007; Oh and Lee, 2004; Yoo and Kim, 2006). Second, if there is unidirectional causality from energy consumption to economic growth, then restrictions on the use of energy may have significantly adverse effects on economic growth, while an increase in energy consumption may contribute to economic growth (Altinay and Karagol, 2005; Lee, 2005; Narayan and Singh, 2007; Shiu and Lam, 2004; Wolde-Rufael, 2004; Yuan et al., 2007). Third, if there is a bidirectional causal relationship, then economic growth may demand more energy whereas more energy consumption may also induce economic growth. Energy consumption and economic growth complement each other such that radical energy conservation measures may significantly hinder economic growth (Jumbe, 2004; Yang, 2000; Yoo, 2005). Finally, if there is no causality in either direction, which is known as the 'neutrality hypothesis', then neither conservative nor expansive energy consumption have any effect on economic growth (Asafu-Adjaye, 2000; Wolde-Rufael, 2005).

Another time series methodology explaining the relationship between energy consumption and economic growth is the co-integration technique with a bivariate (e.g., Lise and Montfort, 2007; Yang, 2000; Zachariadis, 2007; Zamani, 2007) or multivariate (e.g., Ghali and El-Sakka, 2004; Masih and Masih, 1997; Oh and Lee, 2004; Stern, 2000; Soytas and Sari, 2007) framework. Co-integration analysis often aims to uncover causal relations among variables by determining if the stochastic trends in a group of variables are shared by the series such that the total number of unique trends is less than the number of variables. Moreover, if a linear combination of non-stationary variables is stationary, the variables have a long-run equilibrium relationship. When the co-integrating variables occasionally deviate from their long-run equilibrium, they are eventually self-revising (McNown and Wallace, 1992).

Rather than utilizing a measure of total energy use, Stern (1993) adopts a multivariate vector autoregression (VAR) model to explore the causal relationship between GDP, energy use, capital, and labor inputs in the United States, where using a quality-adjusted index of energy input in place of gross energy use. Compared to the bivariate VAR analysis, the multivariate context is important because changes in energy inputs are more frequently countered by the substitution of other production factors, resulting in an insignificant overall impact on output. Stern (1993) also finds that total energy use does not Granger cause GDP, while energy Granger causes GDP when using a weighted energy quality index. Stern (2000) further extends his previous analysis by incorporating the co-integration analysis with some relevant variables. The results show that there is co-integration in a relationship including GDP, capital, labor, and energy.

Ghali and El-Sakka (2004) employ the Johansen co-integration technique to analyze the relationship among output, capital, labor, and energy use in Canada on the basis of neo-classical one-sector aggregate production technology. Their results indicate that long-run movements of output, capital, labor, and energy use are related by two co-integrating vectors.

Lise and Montfort (2007) undertake a co-integration analysis not only to explore the link between energy consumption and GDP, but also by taking into concern environmental protection and economic development for Turkey. Co-integration is found between energy consumption and GDP, while the energy Kuznets curve (EKC) hypothesis is rejected.

The aforementioned literature strengthens Stern's conclusions that energy can be considered as a limiting factor in economic growth. Shocks to the energy supply tend to reduce output. Table 1 summarizes more details about these studies of causality and co-integration analysis between energy consumption and economic growth.

The aim of this paper is to investigate the non-linear (or asymmetric) co-integration between energy consumption and GDP in Taiwan, using an advanced time series method proposed by Hansen and Seo (2002). There are two reasons to take into account asymmetric adjusting behavior between energy consumption and economic growth: First, the topic of asymmetric properties of the adjustment process has been paid scant attention, while large numbers of recent studies provide evidence of the asymmetric adjustment of most macroeconomic variables (e.g., Ewing et al., 2006; Maki and Kitasaka, 2006). Neglecting an asymmetric adjustment among macroeconomic variables may lead to biased inferences and hence misleading results. As discussed by Balke and Fomby (1997), movement toward the long-run equilibrium is not necessarily constant, implying

Table 1
A comparison of earlier studies about causality and co-integration analysis between energy consumption and GDP

| Authors | Countries | Study period | Causality | Co-integration relationship |
|---|---|---|---|---|
| Cheng and Lai (1997) | Taiwan | 1955–1993 | GDP→EC | No co-integration |
| Ghali and El-Sakka (2004) | Canada | 1961–1997 | GDP↔EC | Co-integration |
| Hondroyiannis et al. (2002) | Greece | 1960–1996 | No causality | Co-integration |
| Hwang and Gum (1992) | Taiwan | 1955–1993 | GDP↔EC | |
| Lee (2005) | 18 developing countries | 1975–2001 | EC→GDP | Co-integration |
| Lee and Chang (2005) | Taiwan | 1954–2003 | GDP↔EC | No co-integration |
| Lise and Montfort (2007) | Turkey | 1970–2003 | GDP→EC | Co-integration |
| Masih and Masih (1997) | South Korea | 1955–1991 | EC→GDP | Two co-integrating vector |
| | Taiwan | | No causality | One co-integrating vector |
| Oh and Lee (2004) | South Korea | 1961–1990 | No causality | Co-integration |
| Soytas and Sari (2003) | 16 countries | 1950–1992 | EC→GDP in Turkey | Co-integration for 7 out of 16 countries |
| Stern (2000) | U.S. | 1948–1994 | EC→GDP | Co-integration |
| Wolde-Rufael (2004) | Shanghai | 1952–1999 | EC→GDP | |
| Yang (2000) | Taiwan | 1954–1997 | GDP↔EC | |
| Zamani (2007) | Iran | 1967–2003 | GDP→EC | |

that the convergence to equilibrium may be faster under positive deviations than under negative ones (or vice versa). Therefore, if asymmetric co-integration is evident, then the conventional vector error-correction models (VECM) will be a wrong specification.

Second, several renowned recent studies have found a non-linear relationship between energy consumption and economic growth in Taiwan. Lee and Chang (2005) argue that neglecting the structural break problem means being unable to uncover whether or not parameters are unstable within each of the sub-periods. They provide evidence that the co-integration relationship between energy consumption and GDP is unstable in Taiwan, and some economic events such as the oil crisis and Asian financial crisis significantly affect stability. Lee and Chang (2007) consider the possibility of both a linear and non-linear effect of energy consumption on economic growth for Taiwan based on the conventional neo-classical one-sector aggregate production function. By conducting the threshold regression model during the two energy crisis periods, they indicate that the structural change due to the existence of an energy consumption threshold should be considered when constructing estimation and prediction models of economic growth. In addition, they also provide evidence that the relationship between energy consumption and economic growth in Taiwan can be characterized by an inverse U-shape. Most of these previous contributions suggest that there seems have a non-linear relationship between energy consumption and economic growth in Taiwan.

Another effort of this paper is to shed more light on the relationship between energy consumption from a different perspective. Taiwan's economy faces scarcity in domestic energy resources and has to rely heavily on imports of energy. Thus, how to maintain a stable energy supply and improve energy efficiency are important missions for Taiwan in the future. Yang (2000), Sari and Soytas (2004) and Wolde-Rufael (2004) employ disaggregate energy consumption data with respect to different energy sources; whereas, Hondroyiannis et al. (2002) distinguish between residential and industrial energy consumption. Additionally, Yang (2000) indicates that one shortcoming with the use of aggregate energy data is that countries may depend on different energy sources. Therefore, it is not possible to identify the impact of a specific type of energy with aggregate data. These concerns have encouraged us to investigate the relationship between disaggregate energy consumption and economic growth in order to identify the impact of different energy sources on GDP in Taiwan.

The remainder of this paper is organized as follows: Section 2 briefly describes the threshold co-integration proposed by Hansen and Seo (2002). Section 3 shows the data sources and the results of unit root tests. Section 4 presents the results of co-integration and asymmetry tests through the use of aggregate and disaggregated energy data. Section 5 examines results of the two-regime vector error-correction models on the link between energy categories and GDP. Section 6 concludes this paper.

## 2. Testing for threshold co-integration with asymmetric adjustment

The rationale behind threshold co-integration was introduced by Balke and Fomby (1997) as a feasible means to combine both non-linearity and co-integration. As pointed out by Balke and Fomby (1997), it is necessary to analyze the long-run equilibrium relationship by a co-integration test while assuming the feature of asymmetric adjustment. As is well known, variables are co-integrated to be characterized by an error-correction model (ECM), which describes how the variables respond to deviations from the equilibrium. Therefore, it is possible that an asymmetric adjustment leads to poor results of the equilibrium relationship, because traditional approaches only take into account a tendency to move towards the long-run equilibrium for every time period.

Several studies have discussed co-integration with its corresponding ECM as the assumption of such a tendency to move toward a long-run equilibrium. Balke and Fomby (1997) emphasize the possibility that movement towards the long-run equilibrium need not occur in every period, because of the presence of some adjustment cost for the economic agent. In other words, there could be a discrete adjustment to equilibrium only when the deviation from the equilibrium exceeds a critical threshold, do the benefits of adjustment are higher than the costs. Therefore, economic agents act to move the system back to equilibrium. Threshold co-integration could characterize the discrete adjustment in terms of the case where the co-integrating relationship does not hold inside a certain band, but then remains active if the system gets too far from the equilibrium.

One of the most important statistical issues for threshold models in the econometric literature is testing for the presence of a threshold effect. Balke and Fomby (1997) propose applying several univariate tests (e.g. Hansen, 1996; Tsay, 1989) to the known co-integrating residual (i.e., the error-correction term). Further related studies include Forbes et al. (1999), who develop a Bayesian estimation procedure for financial arbitrage, while Lo and Zivot (2001) extend Balke and Fomby's approach to a multivariate threshold co-integration model with a known co-integration vector, employing Tsay (1998) and multivariate extensions of Hansen's (1996) test. Hansen and Seo (2002) contribute further to the literature by examining the case of an unknown co-integration vector. In particular, these authors propose a vector error-correction model with one co-integrating vector and a threshold effect based on the error-correction term, and they develop a Lagrange multiplier (LM) test for the presence of a threshold.

Hansen and Seo (2002) consider a two-regime threshold co-integration model, which can be treated as a non-linear VECM of order $l+1$ as the following form:

$$\Delta x_t = \begin{cases} A_1' X_{t-1}(\beta) + u_t & \text{if } w_{t-1}(\beta) \leq \gamma \\ A_2' X_{t-1}(\beta) + u_t & \text{if } w_{t-1}(\beta) > \gamma \end{cases} \tag{1}$$

with

$$X_{t-1}(\beta) = \begin{pmatrix} 1 \\ w_{t-1}(\beta) \\ \Delta x_{t-1} \\ \Delta x_{t-2} \\ \vdots \\ \Delta x_{t-l} \end{pmatrix},$$

where $x_t$ is a $p$-dimensional $I(1)$ time series which is co-integrated with one $p \times 1$ co-integrating vector $\beta$, $w_t(\beta) = \beta' x_t$ denotes the $I(0)$ error-correction term, the coefficients matrices of $A_1$ and $A_2$ describe the dynamics in each of the regimes, $\gamma$ is the threshold parameter, and $u_t$ is an error term.

As can be seen, the threshold model (1) composes two regimes, and the non-linear mechanism depends on deviations from the equilibrium below or above the threshold parameter, where $A_1$ and $A_2$ describe the dynamics in each of the regime. To achieve the identification, we need to impose some normalization on $\beta$. Since there is only one co-integrating vector, a convenient choice is to set one element of $\beta$ equal to unity that has no cost in the bivariate system ($p=2$). The condition of $p>2$ only imposes the restriction that the corresponding element of $x_t$ goes into the co-integrating relationship. Accordingly, there is no tendency for the variables $x_t$ to revert to an equilibrium state (i.e., the variables are not co-integrated); on the contrary condition, there is a tendency for $x_t$ to move towards the equilibrium states in another regime (i.e., the variables are co-integrated).

Hansen and Seo (2002) propose two heteroskedastic-consistent LM test statistics to test whether there is linear co-integration (i.e., the form of model (1)) under the null against the alternative threshold co-integration. This means that there is no threshold under the null, so that model (1) reduces to a conventional linear VECM. The first testing statistic would be used when the true co-integrating vector is known a priori and is denoted as:

$$\text{Sup LM}^0 = \sup_{\gamma_L \le \gamma \le \gamma_U} \text{LM}(\beta_0, \gamma), \tag{2}$$

where $\beta_0$ is the known value at fixed $\beta$ (i.e., set $\beta_0$ at unity), while the second case can be used when the true co-integrating vector is unknown, and the test statistic is denoted as:

$$\text{Sup LM} = \sup_{\gamma_L \le \gamma \le \gamma_U} \text{LM}\left(\tilde{\beta}, \gamma\right), \tag{3}$$

where $\tilde{\beta}$ is the null estimate of $\beta$.

In both tests, $[\gamma_L, \gamma_U]$ is the search region so that $\gamma_L$ is the $\pi_0$ percentile of $\tilde{w}_{t-1}$, and $\gamma_U$ is the $(1-\pi_0)$ percentile. Andrews (1993) suggests that setting $\pi_0$ between 0.05 and 0.15 is a typically good choice. Finally, the bootstrap methods proposed by Hansen and Seo (2002) calculate the asymptotic critical values and $p$-values with 3000 simulation replications.

## 3. Data sources and unit root tests

All the data used in this study are quarterly frequencies and cover the period from 1982:1 to 2006:4. The nominal gross domestic product series in the national currency is transformed into real gross domestic product in 2001 prices, using GDP deflators (2001 = 100). The original data for various energy usage categories are measured in terms of kiloliters of oil equivalent (KLOE). The variables used in the models are: GDP as the real gross domestic product; EC as the total energy consumption; Coal as the coal consumption; Oil as the oil consumption; NG as the natural gas consumption; and ELEC as the electricity consumption. All the variables are in logarithms. The empirical data in this study are compiled from the AREMOS economic-statistic database, created and maintained jointly by Taiwan's Ministry of Education and National Taiwan University.

Energy consumption time series may have some forms of seasonality. For instance, the electricity usage in Taiwan has obvious seasonal patterns resulting from higher consumption in summer and higher natural gas in winter. In fact, the seasonal variation of some time series variables may account for the preponderance of its total variance. Forecasts that ignore important seasonal patterns will have a high variance. A basic test for the presence of seasonality in a time series is to regress the variable on four seasonal dummies. If there is no seasonality in the series, then the four coefficients associated with these dummies should be equal. This property can easily be tested with a standard $F$-test. The test regression equals:

$$\Delta y_t = \sum_{i=1}^{4} \beta_s D_{s,t} + \varepsilon_t, \tag{4}$$

where $\Delta y_t = y_t - y_{t-1}$ and $D_{s,t} = 1$ if $t$ corresponds to season $s$, and 0 otherwise. If seasonal adjustment is properly done to eliminate seasonality, then the $F$-test should not reject the null hypothesis that $\beta_1 = \beta_2 = \beta_3 = \beta_4$. As Table 2 shows, the null hypothesis of no seasonality is rejected at the 1% level, implying that there exist seasonal patterns in all energy consumption variables. Therefore, we further adjust the seasonal characteristics by the moving average method and the regression results cannot reject the null hypothesis of no seasonality. Hence, deseasonalized data are used for empirical work afterwards.

Before carrying out the time series analysis, it is necessary to determine the order of integration for each variable to ensure robust and reliable results. To this end, we employ univariate methods to test for the existence of unit roots and identify the properties of stationarity in each time series variable. We therefore investigate the stationarity process of all variables by using the Augmented Dickey and Fuller (1979, ADF) and KPSS (Kwiatkowski et al., 1992) tests for examining the existence of unit roots. In general, most of the conventional unit root tests suffer from three problems: first, several approaches have severe size distortions when the moving average

Table 2
Tests for the presence of seasonality

| Dependent variable | No moving average adjustment | | With moving average adjustment | |
|---|---|---|---|---|
| | $F$(3,99) | $p$-values | $F$(3,99) | $p$-values |
| ΔEC | 257.11*** | (0.00) | 0.06 | (0.98) |
| ΔCoal | 8.96*** | (0.00) | 0.02 | (0.99) |
| ΔOil | 32.27*** | (0.00) | 0.08 | (0.97) |
| ΔNG | 89.30*** | (0.00) | 0.04 | (0.99) |
| ΔElec | 833.14*** | (0.00) | 0.05 | (0.98) |

Note:

1 '***' denotes significance at 1% level.

2 Seasonal adjustments with moving average method are conducted by EViews5.0 program.

polynomial of the first differences series has a large negative autoregressive root (Schwert, 1989). Second, the testing statistics have low power when the root of the autoregressive polynomial is close to unity (DeJong et al., 1992; Kwiatkowski et al., 1992). Third, conducting the unit root tests often implies the selection of an autoregressive truncation lag, $k$, which is strongly related to the size distortions and the extent of power loss (Ng and Perron, 1995).

It is important to note that in the ADF test, the unit root hypothesis to be tested and that the way in which classical hypothesis testing is carried out to ensure the hypothesis are hard to be rejected. To address these critiques, we also employ KPSS tests, which can powerfully distinguish variables that appear to be stationary and be integrated, and those that are not very informative about whether they are stationary or have a unit root.

Table 3 reports the results of the stationarity tests in the level as well as in first difference for all the variables. We include a constant and a trend term in these tests. The optimal lag length of each case for the ADF tests is chosen by the Akaike Information Criteria (AIC) after testing for first and higher order serial correlation residuals. Table 3 reports the results of testing for unit roots in the level variables with the ADF test as well as against the alternative with the KPSS test. The first half of the table indicates that the null hypothesis contains a unit root, while it appears to be stationary after taking the first differences. The results of the KPSS tests show that the null hypothesis in all level variables is strongly rejected at the 1% significance level, which is in favor of a unit root, while the stationary under the null fails to be rejected after differencing once. Consequently, we suggest that all the variables are integrated of order $I(1)$.

## 4. Results of the asymmetric threshold co-integration tests

This section specially examines whether or not the energy consumption and GDP are co-integrated when allowing for asymmetric adjustments. We apply the tests of threshold co-integration proposed by Hansen and Seo (2002) with Sup LM$^0$ (given $\beta$ at unity) and Sup LM (estimated $\beta$). Both of the two tests utilize a parametric bootstrap method with 3000 simulation replications to calculate $p$-values. The lag length selection of the VAR model is determined by the Akaike and Bayesian information criteria, leading to the results of $l=3$ on the case for total energy

Table 3
Tests for unit root

| Variables | ADF | | KPSS | |
|---|---|---|---|---|
| | Level | First difference | Level | First difference |
| GDP | −0.9104 | −3.7522** | 0.3013*** | 0.0902 |
| EC | −0.4569 | −7.9656*** | 0.2954*** | 0.1141 |
| Coal | −2.5146 | −7.7002*** | 0.2593*** | 0.1129 |
| Oil | −1.9997 | −15.1758*** | 0.2217*** | 0.0759 |
| NG | −1.5044 | −4.1436*** | 0.2033** | 0.0964 |
| Elec | −2.9445 | −9.0106*** | 0.2789*** | 0.0899 |

Note:

1 The optimal lag orders on the variables in ADF regressions are selected by Akaike Information Criterion.

2 The 1%, 5%, and 10% asymptotic critical values for KPSS test statistic are 0.216, 0.146, and 0.119, respectively.

3 The null hypothesis for the KPSS test is stationarity.

4 ‘***’ and ‘**’ denote significance at 1% and 5% levels, respectively.

consumption, $l=1$ on the case for coal consumption, $l=2$ on the case of natural gas consumption, and $l=1$ on the case for electricity consumption. Table 4 reports these tests.

Beginning with the testing of threshold co-integration, the results appear at the 5% significant level of the Sup $LM^0$ test (i.e., when the co-integrating vector is fixed at unity) between total energy consumption and GDP, while for electricity consumption and GDP they appear at the 10% significant level of the Sup LM test (i.e., when the co-integrating vector is estimated). Therefore, the null hypothesis of linear co-integration is strongly rejected. The alternative two collocations, GDP with respect to coal and natural gas consumption, both show that the null hypothesis of linear co-integration is respectively rejected at the 10% and 5% significant levels whether the co-integrating vector is prior given or estimated. We would prefer the result of the estimating co-integration vector $\beta$ rather than being fixed at unity, because of a lack of economic information to obtain the co-integration vector of

Table 4
Results of the asymmetric threshold co-integration tests

| | Sup $LM^0$ | Sup LM |
|---|---|---|
| *Panel A. GDP vs. energy consumption* | | |
| Test statistic value | 26.97 (0.04)** | 16.30 (0.92) |
| Tests for ECM coefficient | 23.58 (0.00)*** | 22.26 (0.00)*** |
| Tests for dynamic coefficients | 88.92 (0.00)*** | 90.39 (0.00)*** |
| Threshold value | −0.008 | −0.008 |
| Estimate of the co-integration vector | 1.00 | 1.03 |
| *Panel B. GDP vs. coal consumption* | | |
| Test statistic value | 18.34 (0.03)** | 17.49 (0.08)* |
| Tests for ECM coefficient | 10.46 (0.00)*** | 42.61 (0.00)*** |
| Tests for dynamic coefficients | 5.26 (0.26) | 21.09 (0.00)*** |
| Threshold value | −0.009 | −0.017 |
| Estimate of the co-integration vector | 1.00 | 1.17 |
| *Panel C. GDP vs. oil consumption* | | |
| Test statistic value | 14.40 (0.83) | 13.07 (0.46) |
| Tests for ECM coefficient | 2.46 (0.29) | 88.22 (0.00)*** |
| Tests for dynamic coefficients | 22.61 (0.00)*** | 47.70 (0.00)*** |
| Threshold value | 0.004 | −0.014 |
| Estimate of the co-integration vector | 1.00 | 0.61 |
| *Panel D. GDP vs. natural Gas consumption* | | |
| Test statistic value | 22.72 (0.07)* | 26.17 (0.01)** |
| Tests for ECM coefficient | 1.38 (0.50) | 4.66 (0.09)* |
| Tests for dynamic coefficients | 19.39 (0.01)** | 200.68 (0.00)*** |
| Threshold value | 0.026 | −0.025 |
| Estimate of the co-integration vector | 1.00 | 1.01 |
| *Panel E. GDP vs. electricity consumption* | | |
| Test statistic value | 13.37 (0.37) | 15.95 (0.08)* |
| Tests for ECM coefficient | 7.24 (0.03)** | 25.84 (0.00)*** |
| Tests for dynamic coefficients | 10.86 (0.03)** | 17.60 (0.00)*** |
| Threshold value | −0.0002 | 0.015 |
| Estimate of the co-integration vector | 1.00 | 0.58 |

Note:

1 The values in parentheses are the bootstrapping *p*-values with 3000 times simulation replications.

2 The asterisks '***', '**', and '*' indicate rejection of the null hypothesis at 1%, 5% and 10% levels, respectively.

the prior known in general. Given these findings, we also test whether the adjustment back to equilibrium is symmetric when the threshold effect is confirmed in co-integrating equations — that is, whether the error-correction term is equal within the two regimes. To sum up, we reject the null hypothesis of symmetric adjustment for the basis of four out of the five energy consumption categories and GDP at least 10% significant level (except for oil case).

The empirical findings of co-integration with asymmetric adjustment justifies and paves the way for the estimation of an asymmetric VECM between GDP and aggregate or various disaggregate categories of energy consumption as will be shown in the next section.

## 5. Results of the two-regime error-correction models

Based on the results of the co-integration tests used in the previous section, we have to employ the asymmetric vector error-correction models instead of the mis-specified convention vector error-correction models. That is, we estimate two-regime VECM in order to further investigate the asymmetric dynamic behavior between GDP and different categories of energy consumption. As mentioned before, the threshold vector error-correction models differ from the conventional vector error-correction models by allowing asymmetric adjustments toward the long-run equilibrium.

The estimates of the two-regime vector error-correction models for the four combinations between GDP and different energy consumption are given below. In each VECM equations, NLL represents the value of negative log-likelihood function. The optimal lag orders in each VEC model are determined by Akaike information criterion (AIC). $\mathrm{ObsR}_1$ and $\mathrm{ObsR}_2$ represent the percentages of sub-sample on total sample size when error-correction term below and above the certain threshold value, respectively. The *t*-statistics are reported in parentheses where the heteroskedasticity-consistent (Eicker–White) standard errors are considered here. When we have no formal distribution theory for the parameter estimates and standard errors, these should be interpreted somewhat cautiously.

### 5.1. GDP vs. energy consumption

$$\varDelta\mathrm{GDP}_t = \begin{cases} \underset{(1.69)}{0.01} + \underset{(1.31)}{0.75}\, w_{t-1} - \underset{(-2.68)}{1.12}\, \varDelta\mathrm{GDP}_{t-1} + \underset{(1.11)}{0.49}\, \varDelta\mathrm{EC}_{t-1} - \underset{(-3.28)}{1.07}\, \varDelta\mathrm{GDP}_{t-2} + \underset{(3.05)}{0.75}\, \varDelta\mathrm{EC}_{t-2} \\ -\underset{(-4.49)}{0.93}\, \varDelta\mathrm{GDP}_{t-3} + \underset{(3.36)}{0.40}\, \varDelta\mathrm{EC}_{t-3} + u_{1t},\ w_{t-1} \le -0.008 \\ \underset{(2.07)}{0.002} - \underset{(-7.21)}{1.24}\, w_{t-1} - \underset{(-0.36)}{0.05}\, \varDelta\mathrm{GDP}_{t-1} - \underset{(-5.50)}{0.89}\, \varDelta\mathrm{EC}_{t-1} - \underset{(-4.93)}{0.45}\, \varDelta\mathrm{GDP}_{t-2} - \underset{(-3.16)}{0.45}\, \varDelta\mathrm{EC}_{t-2} \\ -\underset{(-8.65)}{0.62}\, \varDelta\mathrm{GDP}_{t-3} - \underset{(-1.85)}{0.15}\, \varDelta\mathrm{EC}_{t-3} + u_{1t},\ w_{t-1} > -0.008 \end{cases}$$

$$\varDelta\mathrm{EC}_t = \begin{cases} -\underset{(-0.30)}{0.001} + \underset{(0.20)}{0.14} w_{t-1} - \underset{(-0.35)}{0.16}\, \varDelta\mathrm{GDP}_{t-1} - \underset{(-1.85)}{0.86}\, \varDelta\mathrm{EC}_{t-1} + \underset{(0.03)}{0.008}\, \varDelta\mathrm{GDP}_{t-2} - \underset{(-0.36)}{0.13}\, \varDelta\mathrm{EC}_{t-2} \\ +\underset{(1.18)}{0.23}\, \varDelta\mathrm{GDP}_{t-3} + \underset{(0.70)}{0.12}\, \varDelta\mathrm{EC}_{t-3} + u_{2t}, \quad w_{t-1} \le -0.008 \\ \underset{(0.29)}{0.001} + \underset{(2.88)}{1.16} w_{t-1} - \underset{(-3.18)}{0.97}\, \varDelta\mathrm{GDP}_{t-1} + \underset{(0.03)}{0.01}\, \varDelta\mathrm{EC}_{t-1} - \underset{(-3.54)}{0.73}\, \varDelta\mathrm{GDP}_{t-2} - \underset{(-0.13)}{0.03}\, \varDelta\mathrm{EC}_{t-2} \\ -\underset{(-3.07)}{0.40}\, \varDelta\mathrm{GDP}_{t-3} - \underset{(-0.44)}{0.06}\, \varDelta\mathrm{EC}_{t-3} + u_{2t}, \quad w_{t-1} > -0.008 \end{cases}$$

$$\mathrm{NLL} = -963.537;\ \mathrm{AIC} = -899.537;\ \mathrm{ObsR}_1 = 27.37\%;\ \mathrm{ObsR}_2 = 72.63\%.$$

The estimated VECM results between energy consumption and GDP are presented above. As can be seen, in the first regime error-correction effects are minimal both in terms of significance and size of the coefficients. On the contrary, the significant error-correction effects appear in the second regime (i.e., when GDP is larger than energy consumption). Fig. 1 depicts the error-correction effect, i.e., the estimated regression functions of $\Delta\mathrm{GDP}_t$ and $\Delta\mathrm{EC}_t$ to the discrepancy between them as a function of $w_{t-1}$ in the previous period when holding the other variables constant. In the figure,

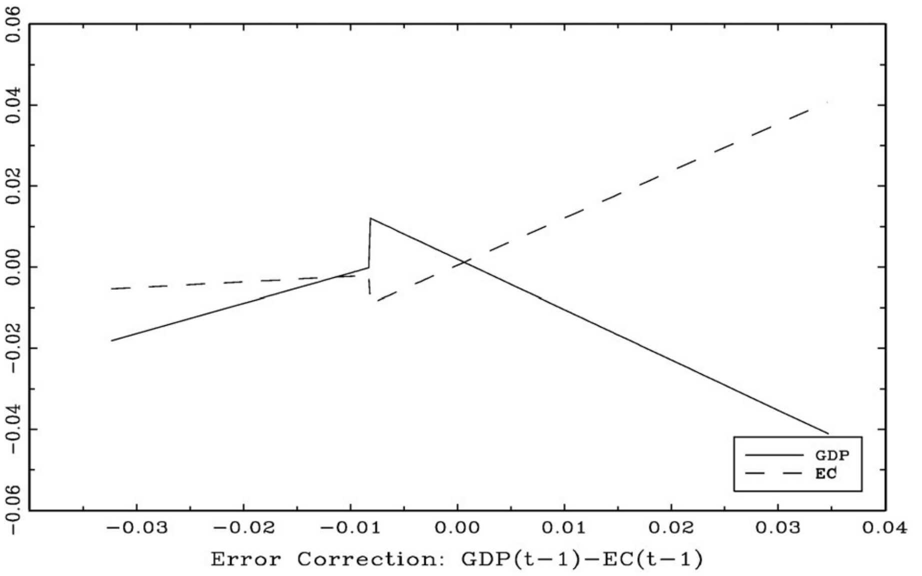


Fig. 1. Response of GDP and energy consumption to error correction, 1982:1–2006:4.

when the error-correction term is below the threshold value, we can see the flat near-zero error-correction effect on the left side of the threshold. Nevertheless, on the right side of the threshold, the responses of the energy consumption will increase sharply when the error-correction exceeds a threshold value — that is $w_{t-1} > -0.008$, while GDP is significant sharply decreasing afterwards.

These findings exhibit that the error-correction terms respond much more to energy consumption than GDP when the error-correction exceeds a certain threshold, making the energy efficiency worse off. Under such a regime, energy consumption will diverge from the mean level due to exogenous shocks such as world oil market shocks or accidental economic events; whereas GDP converges toward the long-run equilibrium in this small open economy. Hence, the government should develop the energy demand-side management (EDSM) to improve energy efficiency.

### 5.2. GDP vs. coal consumption

$$\Delta GDP_t = \begin{cases} \underset{(-0.33)}{-0.003} \underset{(-1.83)}{-0.91} w_{t-1} + \underset{(1.43)}{0.21} \Delta GDP_{t-1} - \underset{(-2.08)}{0.06} \Delta Coal_{t-1} + u_{1t}, & w_{t-1} \leq -0.017 \\ \underset{(-7.22)}{-0.01} \underset{(-10.07)}{-1.74} w_{t-1} + \underset{(6.86)}{0.66} \Delta GDP_{t-1} - \underset{(-5.65)}{0.17} \Delta Coal_{t-1} + u_{1t}, & w_{t-1} > -0.017 \end{cases}$$

$$\Delta Coal_t = \begin{cases} \underset{(5.48)}{0.14} + \underset{(1.99)}{2.36} w_{t-1} - \underset{(-4.43)}{170} \Delta GDP_{t-1} - \underset{(-6.57)}{0.49} \Delta Coal_{t-1} + u_{2t}, & w_{t-1} \leq -0.017 \\ \underset{(-0.22)}{-0.001} + \underset{(0.30)}{0.16} w_{t-1} + \underset{(0.42)}{0.15} \Delta GDP_{t-1} - \underset{(-6.81)}{0.66} \Delta Coal_{t-1} + u_{2t}, & w_{t-1} > -0.017 \end{cases}$$

$$NLL = -783.410; AIC = -751.410; ObsR_1 = 20.62\%; ObsR_2 = 79.38\%.$$

The estimated VECM results between coal consumption and GDP are presented above. Fig. 2 plots the error-correction effect. Similar to the estimated collocation between GDP and energy consumption, the response of the error-correction effects to GDP is significantly larger than the response of coal consumption in second regime, which contains 21% of the observations.

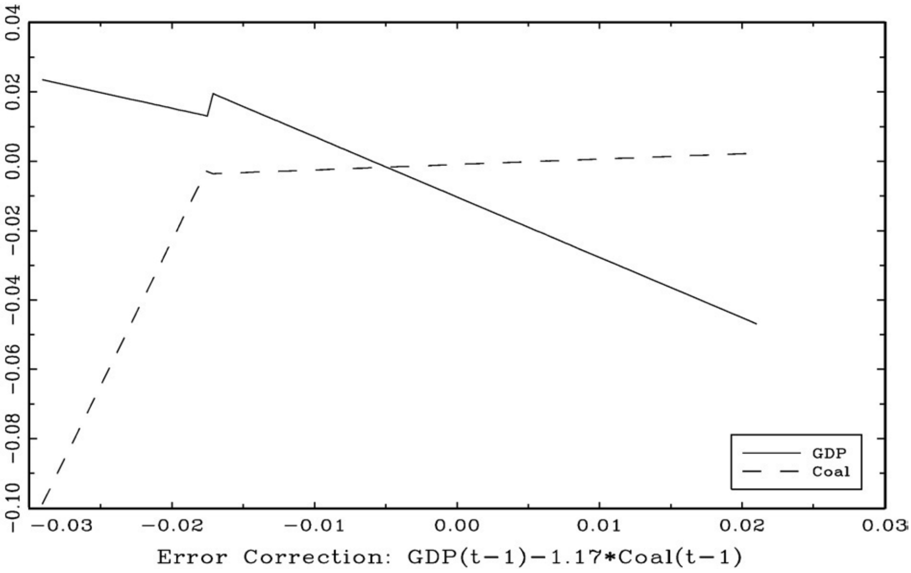


Fig. 2. Response of GDP and coal consumption to error correction, 1982:1–2006:4.

However, a contrary condition can be found in that the adjusting speed in the error-correction to the response of coal consumption would lead to a stronger positive response when the deviation of coal-output is below the threshold value (i.e., $w_{t-1} \leq -0.017$). This signifies that over-consuming coal seems not to effectively enhance economic growth. At this situation, excessive energy consumption may also generate considerable pressure on the environment as the environmental Kuznets curve literature often mentions. Therefore, in order to maintain the long-run equilibrium relation of coal-output possess high quality environment, government authorities should make more effort to consolidate the implementation of coal demand-side management.

### 5.3. GDP vs. natural gas consumption

$$\Delta \mathrm{GDP}_t = \begin{cases} \underset{(2.50)}{0.03} - \underset{(-1.48)}{0.25}\, w_{t-1} - \underset{(-0.76)}{0.35}\, \Delta \mathrm{GDP}_{t-1} + \underset{(3.38)}{0.63}\, \Delta \mathrm{NG}_{t-1} - \underset{(-5.05)}{0.95}\, \Delta \mathrm{GDP}_{t-2} \\ + \underset{(2.52)}{0.45}\, \Delta \mathrm{NG}_{t-2} + u_{1t}, \quad w_{t-1} \leq -0.025 \\ \underset{(0.04)}{0.0001} - \underset{(-2.51)}{0.22}\, w_{t-1} - \underset{(-2.34)}{0.17}\, \Delta \mathrm{GDP}_{t-1} + \underset{(1.60)}{0.11}\, \Delta \mathrm{NG}_{t-1} - \underset{(-4.99)}{0.40}\, \Delta \mathrm{GDP}_{t-2} \\ + \underset{(1.96)}{0.08}\, \Delta \mathrm{NG}_{t-2} + u_{1t}, \quad w_{t-1} > -0.025 \end{cases}$$

$$\Delta \mathrm{NG}_t = \begin{cases} \underset{(-4.04)}{-0.14} - \underset{(-4.21)}{2.40}\, w_{t-1} - \underset{(-2.75)}{3.48}\, \Delta \mathrm{GDP}_{t-1} - \underset{(-0.89)}{0.40}\, \Delta \mathrm{NG}_{t-1} - \underset{(-0.73)}{0.36}\, \Delta \mathrm{GDP}_{t-2} \\ - \underset{(-2.26)}{1.02}\, \Delta \mathrm{NG}_{t-2} + u_{2t}, \quad w_{t-1} \leq -0.025 \\ \underset{(3.35)}{0.01} - \underset{(-6.01)}{1.65}\, w_{t-1} + \underset{(8.44)}{1.45}\, \Delta \mathrm{GDP}_{t-1} + \underset{(2.61)}{0.45}\, \Delta \mathrm{NG}_{t-1} + \underset{(3.94)}{0.78}\, \Delta \mathrm{GDP}_{t-2} \\ + 0.22_{(1.70)}\, \Delta \mathrm{NG}_{t-2} + u_{2t}, \quad w_{t-1} > -0.025 \end{cases}$$

$\mathrm{NLL} = -789.975; \mathrm{AIC} = -741.975; \mathrm{ObsR}_1 = 15.63\%; \mathrm{ObsR}_2 = 84.37\%.$

The estimated VECM results between natural gas consumption and GDP are presented above. The significant error-correction effect only appears in the response of natural gas consumption in first regime. On the contrary, in the second regime error-correction effects and dynamic structures are minimal both in terms of significance and size of coefficients. In contrast to the collocations of energy-output and coal-output, Fig. 3 shows that the error-correction effects in response of GDP and natural gas consumption are both downward-adjusting, no matter for below or above the threshold. Note that both natural gas consumption and GDP have negative error-correction terms. Since the size of the negative error-correction term for natural gas consumption is larger than that for GDP in both regimes, natural gas consumption is more efficient.

### 5.4. GDP vs. electricity consumption

$$\Delta\mathrm{GDP}_t = \begin{cases} \underset{(3.38)}{0.003} - \underset{(-9.94)}{1.80}\, w_{t-1} + \underset{(6.91)}{0.64}\, \Delta\mathrm{GDP}_{t-1} - \underset{(-7.00)}{0.51}\, \Delta\mathrm{Elec}_{t-1} + u_{1t}, & w_{t-1} \le 0.015 \\ \underset{(-3.18)}{-0.02} + \underset{(0.36)}{0.14}\, w_{t-1} - \underset{(-0.06)}{0.01}\, \Delta\mathrm{GDP}_{t-1} + \underset{(0.06)}{0.01}\, \Delta\mathrm{Elec}_{t-1} + u_{1t}, & w_{t-1} > 0.015 \end{cases}$$

$$\Delta\mathrm{Elec}_t = \begin{cases} \underset{(-0.55)}{-0.001} + \underset{(0.84)}{0.17}\, w_{t-1} - \underset{(-0.50)}{0.07}\, \Delta\mathrm{GDP}_{t-1} - \underset{(-4.93)}{0.42}\, \Delta\mathrm{Elec}_{t-1} + u_{2t}, & w_{t-1} \le 0.015 \\ \underset{(-4.90)}{-0.06} + \underset{(5.05)}{3.70}\, w_{t-1} - \underset{(-2.69)}{0.58}\, \Delta\mathrm{GDP}_{t-1} + \underset{(0.55)}{0.15}\, \mathrm{Elec}_{t-1} + u_{2t}, & w_{t-1} > 0.015 \end{cases}$$

$$\mathrm{NLL} = -889.739; \mathrm{AIC} = -857.739; \mathrm{ObsR}_1 = 85.57\%; \mathrm{ObsR}_2 = 14.43\%.$$

The estimated VECM results between electricity consumption and GDP are presented above. In Fig. 4 the collocation of electricity consumption and GDP shows that the response of error-correction effect to electricity use on the left side of the threshold is flatly near zero, while to GDP the response has a decreasing adjusting pattern. In the electricity equation the point estimate for the error-correction term is moderately large and on the dash-line of statistical significance when the error-correction exceeds a threshold level (that is, $w_{t-1}>0.015$). Hence, there is a

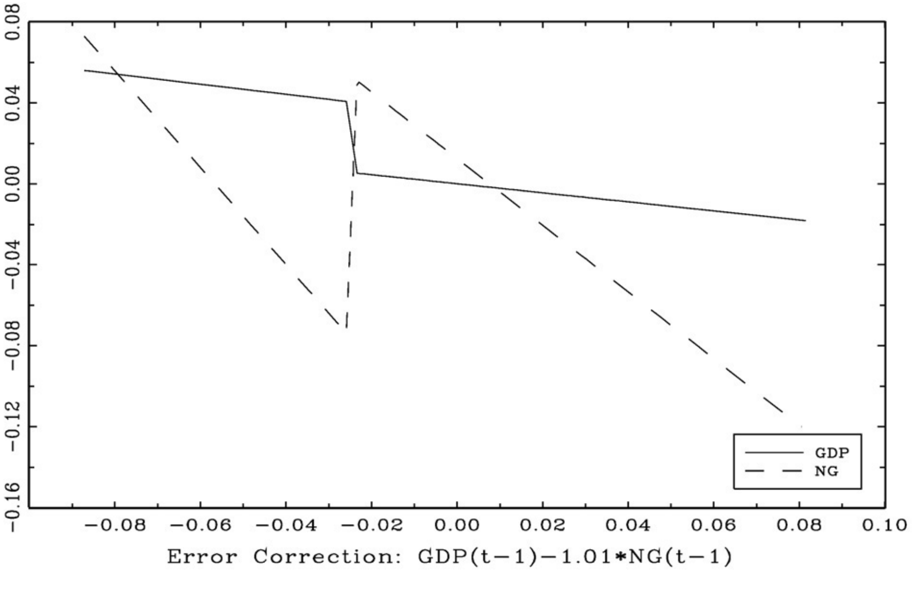


Fig. 3. Response of GDP and natural gas consumption to error correction, 1982:1–2006:4.

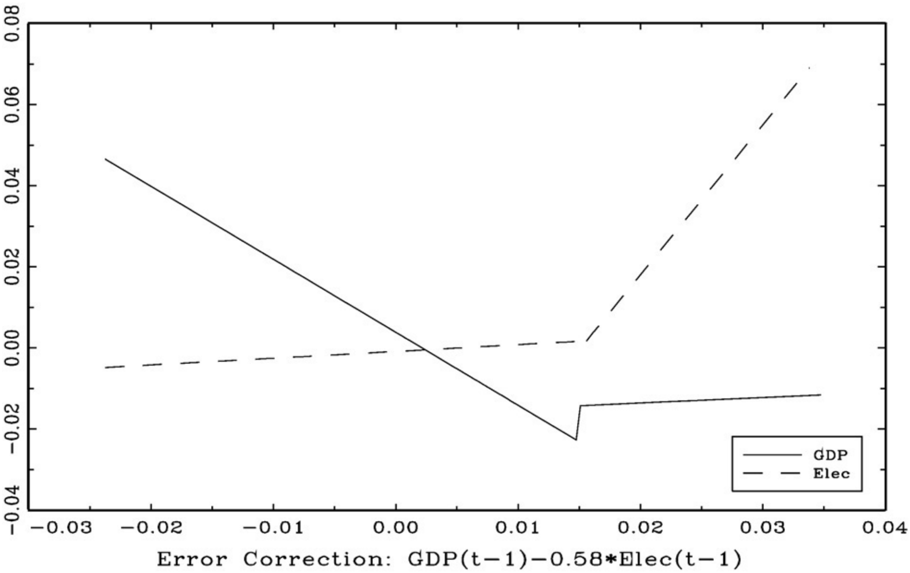


Fig. 4. Response of GDP and electricity consumption to error correction, 1982:1–2006:4.

disequilibrium relationship between electricity consumption and GDP in the second regime. This result suggests that increases in electricity consumption and decreases in GDP are highly persistent, implying that the regime of electricity inefficiency is captured. Such a circumstance may have some serious policy implications as rationalizing electricity conservation policies are made to improve the electricity efficiency.

These results suggest decision-makers need to implement electricity conservation policies to improve efficiency and manage demand. In the near future, policy makers in a growing economy should aim to reduce wasted electricity, to improve the power infrastructures for the economy, and to enable users to enjoy higher quality of electricity.

## 6. Concluding remarks

This study examines the non-linear long-run equilibrium relationship between GDP and disaggregated energy consumption in Taiwan, in order to shed some light on the unfavorable evidence of linear co-integration in the literature. Updated quarterly data for the period of 1982:1 to 2006:4 are analyzed. The empirical methodology is a threshold co-integration test developed by the recent contribution of Hansen and Seo (2002), who consider the possibility of an asymmetric adjusting process among time series variables.

Evidence from this paper rejects the null hypothesis of linear co-integration either in the collocation between GDP and aggregate energy use or with several categories of energy consumption, which is consistent with the findings of Lee and Chang (2005) and Lee and Chang (2007). The threshold co-integration model confirms the non-linear long-run equilibrium relationship between GDP and disaggregated energy consumption in Taiwan. There exist significantly asymmetric dynamic adjusting processes between macroeconomic and energy variables in Taiwan, implying important policy features. The energy-inefficient periods in which energy consumption grows faster than GDP can be captured when disaggregated energy consumptions exceed a certain threshold level. Policy-makers should create an effective energy policy system to improve energy efficiency under disequilibrium regime, especially in which energy consumption may grow faster than GDP expands.

Developed and developing economies are facing the challenge of sustainable energy. Energy demand-side management is a possibly tool to entail actions that influence the quantity or patterns of energy consumed by end-users such as actions targeting reduction of peak demand when energy-supply systems are constrained. EDSM activities ideally could bring the supply and demand closer to a perceived optimum in the market.

To promote greater energy efficiency, Taiwan's policy makers need to implement some strategies in energy markets. First, the energy market in Taiwan generally belongs to monopolies due to the policy regulations and law restrictions. Compared to neighboring East Asian economies such as Japan and South Korea, energy prices in Taiwan are relatively much lower, hence worsening its energy efficiency and producing environmental over-pollution. To raise the energy efficiency and cut down the production costs, the government should liberalize the energy market, impose carbon taxes, and the energy-savings be consciousness of both industries and consumers through the propagation and education. Second, investment in co-generation (i.e., simultaneously generate both electricity and useful heat) is a feasible scheme to stimulate the power users to install the co-generation system which helps reduce the load of power utilities. By the end of July in 2007, the installed power capacity of co-generation reached 2.75MWs (million of watts) by at least 64 companies. Therefore, to encourage users to install co-generation systems, the government should provide firms with tax deduction, favorable financing terms, and favorable rates for them to sell extra co-generated power. Third, the government should apply the capacity management to reduce peak load levels, for example, the seasonal price discrimination and peak load shifting of electricity. Fourth, a niche for energy development in Taiwan is to explore green (or renewable) energy, including waterpower, wind power, solar power energy, geothermal energy, and biomass energy, due to the suitable environment and advanced agriculture. Based on the planning of Taiwan's Bureau of Energy, Ministry of Economic Affairs, by 2010 renewable energy should account for no less than 10% of electric capacity. Taiwan's dependency of imported energy was up to 97.85% in 2005. Although enhancing the biomass energy has an import substitution effect on the energy supply side, it is still controversial whether or not it can improve the energy efficiency. Finally, developing an effective energy demand-side management system can help restrain the growth of energy consumption and hence improve energy efficiency.

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