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Economic Growth, Carbon Abatement Technology and Decoupling Strategy – The Case of Taiwan

Chien-Ming Lee, Ever Romel Rosalez*

Institute of Natural Resource Management, National Taipei University, Taipei 23741, Taiwan

ABSTRACT

Greenhouse Gas (GHG) emissions decoupling from economic growth are imperative goals for sustainable development. This study combines decoupling index and Log Mean Divisia Index (LMDI) to study which major transformation is required in the way energy is produced, delivered and consumed in order to achieve decoupling in Taiwan. The results indicate that a high-energy price can improve the energy structure by inciting energy efficiency use and result in decoupling CO_2 emissions from economic growth. Targeting CO_2 emissions through early action is the best approach to acquire decoupling. An annual energy intensity decrease of 2.4% is key for Taiwan to achieve absolute decoupling by 2020. The study suggests that the Taiwan government should focus on energy efficiency through investing in clean energy innovation at an early phase. Taiwan should consider national policies that are sensitive to effective economic strategies that enhance research and development and also invest in promoting energy efficiency in the economy-wide.

Keywords: Decoupling; Energy efficiency; Economic growth; Early action; CO_2 emissions.

INTRODUCTION

Economic growth benefits the social structure of the economy and is considered imperative for combating climate change. Economic growth is the focal point in every nation and energy is the elixir; energy is a fundamental input to economic growth. Energy relates to economic growth by being a basic necessity that fuels the daily consumption of an economy (Moe, 2010; Lin, Liu 2012). Economic growth rate rise initially with productive energy expenditures (Moon and Sonn, 1996). The extensive demand for energy is a cause for the constant flow of GHG emissions. The current energy system is highly dependent on fossil fuels, negatively impacting air quality and contributing to emissions. In 2009 fossil fuels accounted for 84% of global GHG emissions, CO_2 constituted to over 90% of those emissions (IEA, 2015). Energy is a fundamental input to economic activity, however a major transformation is required in the way it is produced, delivered and consumed. The relationship between energy-related CO_2 emissions and economic growth has been extensively studied. Jackson (2009); Kallis (2011) and Van den Bergh (2011) examined the relationship from a de-growth perspective, Bildirici and Ersin (2015) and Wang and Tian (2015) studied the effects of energy price on economic growth, Halkos and Tzeremes (2014); Alper and Oguz, (2016) and Correa da Silva *et al.* 2(016) tested the effects that energy sources, such as renewable energy, have on economic growth, Lin *et al.* (2012) by using input-output analysis studied the modeling of economic-based linkage effects of CO_2 emissions from the electricty industry in Taiwan.

Leaders and civil society have mutual agreement on the need for decoupling economic growth from increasing GHG emissions. Decoupling is viewed as the disuniting of the environmental pressure variable from the economic performance variable. The term was first adapted to environmental studies by Zhang (2000) and was later endorsed as an indicator by the OECD (2002) by dividing the concept into relative decoupling and absolute decoupling. Relative decoupling means that economic growth is positive but more than the growth rate of CO_2 emissions. Absolute decoupling is when the growth rate of CO_2 emissions is zero or negative while economic growth is positive. Tapio (2005) further divided decoupling into three major categories: weak, strong and recessive. Decoupling has become an ambitious objective for a successful economic environment amalgamation. An important tool for decoupling is technological innovation which includes: energy efficiency and energy-saving technology, the development of renewable energy and alternative energy sources; biomass energy, ethanol, methane, etc., the development of carbon capture and storage (CCS) and the re-use of technology to acquire CO_2 emissions abatement (IPCC, 2007).

Energy researchers have gradually acknowledged the

* Corresponding author.
Tel.: +02-0970535580
E-mail address: everros@yahoo.com

importance of decoupling. Lin *et al.* (2007) combined the decoupling index with the LMDI method to study the impacts of five factors on CO_2 emissions from highway transportation in four countries, South Korea, Japan, Germany and Taiwan during twenty-two years. De Freitas and Kaneko (2011) focused on the appearance of decoupling from the relationship between economic growth rate and energy consumption in Brazil. Zhang *et al.* (2013) combined the decoupling index with the Log Mean Divisia Index (LMDI) method to analyze the contribution of the factors which influence energy related CO_2 emissions in Jiangsu Province during 1995–2009. Zhang and Da (2015) discovered, through the LMDI method, that economic growth appears to be the main driver of CO_2 emissions increase and that energy intensity decrease combined with cleaning of final energy consumption structure plays an important role in curbing CO_2 emissions in China. More recent studies have found diverse results through a various analytical approaches. Zou *et al.* (2016) used the LMDI method to analyze the relationship between the Chinese household CO_2 emissions and economic growth. By applying quantitative evalution on the relationship between economic development and GHG emissions Chovancova and Vavrek (2016) was found that the V4 countries enjoyed of strong decoupling from 1991–2012. Hang *et al.* (2016) attempted to acquire, by applying a decoupling index decomposition analysis, a deeper understanding of the decoupling relationship between CO_2 emissions and industrial growth. The results show that Taiwan experienced a negative decoupling from 2007–2009 and decoupling from 2009–2013. Their result also suggests a strong role of energy intensity in promoting decoupling. Schandl *et al.* (2016) studied the decoupling of global environmental pressure and economic growth. They adapted a combination of economic and environmental modeling to find out if well-designed policies can reduce energy and primary material use, and carbon emissions. Three policy scenarios were used in the study; business as usual, global carbon price increase, and improved resource input efficiency. The results show that emissions would considerably decrease with an increase in the global carbon price while energy use will continue to grow rapidly under the three scenarios. Chen *et al.* (2017) found out that Macao's economy has experienced four decoupling stages, with a distinct tendency towards strong decoupling, by adopting embodied GHG emissions from 2000 to 2013. Zhao *et al.* (2017) focused on investigating the decoupling effect of economic growth from CO_2 emission through LMDC. The results show that China was facing weak decoupling from 1992–2012, being the result from a decrease in energy intensity or aquiring energy efficiency.

Many distinct methods have been used to express different aspects of decoupling. From the literature we can confirm that there have been limited studies devoted to analyzing decoupling of energy-related CO_2 emissions from economic growth in Taiwan. This research serves as a preliminary study in applying the decoupling index presented by Tapio (2005) and OECD (2002) combined with the LMDI method to examine which use of energy and approach Taiwan should take to achieve absolute decoupling. The purpose of this study is to identify the linkage effect between energy-related CO_2 emissions and economic growth through the decoupling analysis and to analyze the approach behind acquiring absolute decoupling in Taiwan.

According to the IEA (2015) report, Taiwan released 249.66 metric tons of CO_2 in 2014, a 4.4 metric ton increase compared to 2005, ranking 22nd in world emissions. The major factor for the increase is economic growth. Reflecting the global objective of reducing CO_2 emissions in 2015 Taiwan organized its fourth national energy conference and developed a national GHG emissions decoupling objective, to return GHG emission to 2005 level by 2020, and by 2025 return CO_2 emission to the year 2000 level. This target will be achieved by using the following policies and measures; (1) Develop and enhance an annual 2% energy efficiency; (2) deploy carbon-free renewable energy sources as total share of power generation to more than 14.8% by 2025; (3) increase the use of low-carbon natural gas to achieve more than 25% of power generation by 2025.

Taiwan's aim is to achieve economic growth while reducing CO_2 emissions; Taiwan wants to achieve decoupling. To support this goal, this paper intends to analyze the relationship between energy related CO_2 emissions and economic growth and discuss the factors that can influence decoupling. This research can serve as a reference for the Taiwan government when implementing policies that are oriented to achieve their fourth national energy conference objective. This paper is organized as follows: section 1 is the introduction section 2 establishes the energy consumption and the country's economic growth model. Section 3 covers Taiwan's data for the simulation analysis. Section 4 concludes and suggests recommendations.

METHODOLOGY

Energy Economic Growth Model

When dealing with pollution, the damage to the environment caused by consumption's utility increases largely from the interaction of (1) externalities emitted on the atmosphere causing atmospheric concentration; (2) the atmospheric concentration's effects on temperature increase; and (3) temperature increase effects on the utility function. If a producer assumes the utility function of a consumer to be Constant Relative Risk Averse (CRRA) then the combination of the utility function and damage from temperature rise can be expressed as:

$$\int_0^\infty U\left[C(t)\right]e^{-\rho t}dt = \int_t^\infty e^{-\rho t}\frac{\left(C_t / \phi_t^{\delta}\right)^{1-\sigma}-1}{1-\sigma}dt$$

where the rate of time preference and the coefficient of relative risk aversion, $1 - \sigma$ is also the intertemporal elasticity of substitution in consumption, are both positive. δ is consumers tolerance or sensitivity to temperature; a larger δ means greater disutility, $\phi(S_t)$ is the atmospheric concentration of emissions, S_t indicates the increase of emissions effects and $\emptyset_t' > 0$ indicates a higher atmospheric concentration of emissions; the more severe the emissions effect the greater the damage.

Production and Emission Function

The level of production in the economy, $Y_t = AK_t^{\alpha}E_t^{\beta}$, depends on capital service, K_t, and energy, E_t; A denotes the production parameter, $0 < A < 1$, and $0 < \alpha, \beta < 1$ denotes the output elasticity of capital and energy consumption. With consumption expenditure, C_t, energy expenditure, PE_t, and government investment, G_t, the capital accumulation equation is as $\dot{K}_t = Y_t - C_t - PE_t - G_t$. It is assumed that the price of consumer and capital goods are normalized to 1.

Assuming that energy intensity is $\eta_t = E_t/Y_t$; PE_t can be rewritten as $PE_t = P\eta Y_t$, where $P\eta_t < 1$ denotes the share of energy intensity. Additionally we assume a percentage of government investment in outputs, $G_t = \mu Y_t$, where $0 < \mu < 1$ is government spending for a fixed proportion of output. After substitution, capital accumulation can be rewritten as $\dot{K}_t = (1 - P_t\eta_t - \mu_t)Y_t - C_t$.

Through government investment on prevention and control, G_t, emissions can be reduced and we obtain the net emissions function, $e_t = E_t^{\omega}G_t^{-\gamma}$, ω denotes elasticity of emissions from energy; γ is the government expenditure prevention parameter. A smaller ω value indicates the use of cleaner energy such as natural gas or renewable energy. A higher γ value indicates that government will take better prevention and control techniques, such as CCS; $\omega \geq \gamma$ implies full prevention technology is unavailable.

Static Comparative Analysis

The use of a natural resource, such as energy, as a productive input reduces the stock of natural resources; CO_2 emissions increase. The law of motion of CO_2 emissions is $\dot{S}_t = b_0e_t - b_1S_t$, where S_t is the atmospheric concentration, or stock, of CO_2 emissions at time t, b_0 denotes the ratio of emissions to the atmosphere at time t, b_1 is the decay ratio of S_t which expresses the purification of the environment.

The economy chooses time paths for consumption and production that maximizes

$$\int_0^{\infty} U\left[C(t)\right]e^{-\rho t}dt = \int_t^{\infty} e^{-\rho t}\frac{\left(C_t / \phi_t^{\delta}\right)^{1-\sigma} - 1}{1-\sigma}dt \tag{1}$$

where ρ denotes the social rate of time preference, subject to:

$$\dot{K}_t = (1 - P_t\eta_t - \mu_t)Y_t - C_t \tag{2a}$$

$$\dot{S}_t = b_0e_t - b_1S_t,\ b_0, b_0 > 0 \tag{2b}$$

$$\phi_t = \phi(S_t),\ \phi_t' > 0 \tag{2c}$$

K_0, S_0 is given.

Eq. (2b) captures the effect of resource use on environmental quality. Environmental quality affects utility directly and also indirectly through its effect on production and regeneration of the resource. This model can be analyzed using optimal control theory. The current value Hamiltonian function is given by:

$$H = \frac{\left(C_t / \phi_t^{\delta}\right)^{1-\sigma} - 1}{1-\sigma} + \lambda_K\left[\left(1 - P_t\eta_t - \mu_t\right)AE_t^{\alpha}K_t^{\beta} - C_t\right]$$
$$-\theta_S\left(b_oE_t^{\omega}G_t^{-\gamma} - b_1S_t\right)$$

where λ_K and θ_S are co-state variables that can be interpreted as the shadow prices, or marginal values of their respective state variables.

The necessary conditions for an optimal (interior) solution include

$$C^{-\sigma}\phi^{\delta\sigma-\delta} = \lambda_K \tag{3a}$$

$$\lambda_K\beta\left(1 - P_t\eta_t - \mu_t\right)AK_t^{\alpha}E_t^{\beta-1} = \theta_S\omega b_oE_t^{\omega-1}G_t^{-\gamma} \tag{3b}$$

$$\dot{\lambda}_K = -\lambda_K\alpha\left(1 - P_t\eta_t - \mu_t\right)AK_t^{\alpha-1}E_t^{\beta} + \rho\lambda_K \tag{3c}$$

$$\dot{\theta}_S = \delta C^{1-\sigma}\phi^{\delta\sigma-\delta-1}\phi' - \theta_Sb_1 + \rho\theta_S \tag{3d}$$

Eqs. (3a) and (3b) are static efficiency conditions that require the marginal value of the flow of services from an asset to be equal to the marginal value of stock of resources. This ensures that the marginal value of natural resources is the same in all its uses. In this model, the marginal utility of consumption must equal the marginal value of capital and the value of the marginal productivity of energy input must equal the marginal value of natural resource stock.

Eqs. (3b)–(3d) are the dynamic efficiency conditions that require for the rate of return of each asset to equal the rate of discount, thus, each asset earns the same rate of return. Therefore, the rate of return to capital is the capital gain, $\dot{\lambda}_K / \lambda_K$ plus the marginal productivity of capital.

Differentiating Eq. (3a) with respect to time and using Eq. (3c) gives

$$\dot{C} = \frac{U_C}{U_{CC}}\left[\left(\rho - P_t\eta_t - \mu_t\right)AK_t^{-1}E_t^{\beta}\right] - \frac{U_{C\phi}}{U_{CC}}\phi'\dot{S} \tag{4}$$

where $U_C/U_{CC} > 0$ is the elasticity of the marginal utility of consumption. Eq. (4) shows that the ability to substitute capital for natural resources allows for increasing consumption.

Differentiating Eqs. (3a), (3c) and (3d) we get

$$g_C = \frac{\beta\left(1 - P\eta - \mu\right) / P\eta - \rho}{\sigma\left[1 + \left(\delta\sigma - \delta\right)\varepsilon_{\phi}\left(\omega - \gamma\right)\right]} \tag{5}$$

The subscript ε_{ϕ} is the emissions damage elasticity, $\varepsilon_{\phi} = \phi'\dot{\phi}_S / \phi_S > 0$. A higher discount rate, ρ, results in greater consumption and pollution. This effect and simultaneously having low energy productivity will result in a negative economic growth rate, $g_C < 0$. A decreasing relative risk aversion, σ, results in energy investments, $(1 - P_\eta - \mu)$. A concurrent σ and higher energy productivity, β, results in positive economic growth, $g_C > 0$. Since the intertemporal elasticity of substitution is large, $\sigma < 1$, ε_ϕ increases and if the government does not invest enough on emission abatement technology, γ small, economic growth rate will be negative, see Table 1.

Proposition one is obtained as follows:

Proposition I: If energy input is high enough or energy expenditure ratio is low enough the economy will obtain a positive economic growth.

In order to further understand the effects of various factors in scenario $g_C > 0$ we discuss the comparative static results of Eq. (5) as shown in Table 2, (For more detail please see appendix 1).

It briefly compares the economic significance as follows:

- Higher emissions elasticity results in greater damage and impact on the environment. Countries affected therefore need to invest in resources that reduce emissions, thus, reducing the economic growth rate.
- Intertemporal elasticity of substitution greater, $\sigma < 1$, or time preference higher, means that the current consumption will increase, thus, reducing investment and causing capital stock accumulation to decrease and consequently lower the economic growth rate.
- Higher energy productivity will enhance the economic growth rate causing energy prices to increase, consequently increasing energy expenditure ratio, which reduces consumption and capital investment resulting in a decrease in economic growth rate.
- Energy intensity improvements will cause an energy-saving effect, which also represents an increase in the economic growth rate.
- Emissions prevention expenditure increases the proportion of energy, the crowding out of capital, and other productive resources, thus, reducing the rate of economic growth.
- Economic systems that use more clean energy, such as natural gas or renewable energy sources, ω smaller, invest on energy system by reducing consumer and capital investment which then reduces economic growth.
- If government takes better control of emissions, γ larger, they reduce the damage to the economy, thus, increases economic growth rate.
- As consumer tolerance or sensitivity to temperature increases, δ there will be negative effects on consumption causing a decrease in economic growth rate.

From the above analysis we have obtained result I as follows:

Result I: High-energy prices and low energy efficiency results in negative economic growth. However, if higher energy prices improve the energy structure and stimulate the use of clean energy or the increase of low carbon technology then it is favorable for economic growth.

Prevention & Control of GHG Emissions and Economic Growth Factors

Many industrialized countries currently implementing emission abatement policies have found that even though they invest in efforts for improving their energy structure they are still ineffective, what could be the reason, what are the key factors causing emissions to increase, and why. These questions are the focus of this study. This section solves for a steady state that will show emissions abatement under the growth path. Net emissions function, $e_t = E_t^{\omega} G_t^{-\gamma}$, is differentiated and substituted into Eq. (5) and we obtain

$$g_e = g_C(\omega-\gamma) = \frac{(\omega-\gamma)\left[\beta(1-P\eta-\mu)/P\eta-\rho\right]}{\sigma\left[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)\right]} \tag{6}$$

Eq. (6) denotes emissions growth rate. It shows the important factors of economic growth rate and emissions, all factors that affect the rate of economic growth affects the growth of emissions and the direction of its impact is $(\omega - \gamma) > 0$. Differentiating Eq. (5) into Eq. (6) gives us the current energy structure, $\varepsilon_{eY} = g_e/g_C = (\omega - \gamma) > 0$. It shows both energy elasticity, ω , and emissions abatement elasticity, γ. If both factors are constant or increasing we will obtain constant or increasing return to scale, $\omega - \gamma \geq 1$. An economic growth increase and GHG abatement phenomena appears, however, if the net emissions function is decreasing returns to scale, $0 < \omega - \gamma < 1$ the economy will show a weak decoupling phenomenon (OECD, 2002).

Proposition *II* is as follows:

Proposition II: Energy elasticity and GHG emissions abatement elasticity are important factors in economic growth decisions. Energy elasticity less than one, $\omega < 1$, is a necessary condition for an environmental friendly economic growth. The sufficient conditions is having a decreasing returns to scale, $\omega - \gamma < 1$.

The economic significance of proposition II is described as follows;

- A constant or increasing returns to scale, $\omega - \gamma \geq 1$, means that energy elasticity is high or has a low clean energy structure, $\omega > 1$.
- Emissions prevention/control elasticity; or energy efficiency low enough, $\gamma < 1$, is indicative of an emissions abatement dilemma.

Consequently, if the economy can accelerate a substitution reform of traditional fossil fuels for clean energy, $\omega < 1$, or strengthen scientific and technological emissions abatement activities, $\gamma < 1$, the economy is expected to achieve, $0 < \omega - \gamma < 1$.

Table 1. Impact on Economic Growth by a Combination of Factors.

	$(1 - P_\eta - \mu)/\eta\beta > \rho$	$(1 - P_\eta - \mu)/\eta\beta < \rho$
$\sigma > 1$	1: $g_C > 0$	2: $g_C < 0$
$(\delta\sigma - \delta)\varepsilon\phi(\omega - \gamma) < 1$	3: $g_C < 0$	Not Discussed

Table 2. A Static Comparative Analysis of the Economic Growth Rate.

Exogenous Variables X	$\partial g_C/\partial X$
$\varepsilon\phi$	< 0
σ	< 0
ρ	< 0
β	> 0
P	< 0
η	> 0
μ	< 0
ω	< 0
γ	> 0
δ	< 0

Energy Use and Emission Abatement

Absolute decoupling of GHG emissions, $\omega - \gamma < 1$, is in response to the ultimate goal for global warming. However, because of the constraints of energy technology, achieving this goal has been daunting. This section will discuss energy efficiency effects by un-stabilizing the fixed assumptions of the energy intensity function. We assume that energy intensity decreases or energy productivity increases with time, taking the natural log and then total differentiating with time we obtain

$$g_E = g_C + g_\eta \tag{7}$$

where $g_\eta < 0$ is the decline rate of energy intensity or energy efficiency. Similarly, the net emission function after rearranging into Eq. (7) results in

$$\tilde{\epsilon}_{eY} = \tilde{g}_e \big/ \tilde{g}_Y = (\omega - \gamma) - \omega\epsilon_{\eta Y} \tag{8}$$

Eq. (7) considers the promotion of energy efficiency. $\epsilon_{\eta Y} = -g_\eta / \tilde{g}_C > 0$ means the energy intensity elasticity of economic growth. The economic significance is to capture the economic growth process. $\epsilon_{\eta Y}$ larger represents a faster energy efficiency improvement. The second term on the RHS of Eq. (8) is negative and implies that after considering energy efficiency approaches, such as energy saving technology, emissions can be effectively reduced. If energy efficiency is high enough, then it will be steady with the rate of economic growth, $\epsilon_{\eta Y} \approx 1$, and obtain $\tilde{\epsilon}_{eY} < 0$. This indicates that the economy can achieve emissions abatement.

We have obtained result II as follows:

Result II: If the government enhances energy efficiency research and development so that energy efficiency is consistent with economic growth rate, $\epsilon_{\eta Y} \approx 1$, absolute GHG emissions decoupling from economic growth can be achieved.

Energy Efficiency Options and Approaches

Renewables and biomass energy technology are important emission abatement approaches. Government investments in prevention/control and R&D affect both energy input and its by-product; emissions. Therefore, the net emissions function can be modified as

$$e_t = E_t^{\omega(G)} G_t^{-\gamma} \tag{9}$$

$\omega(G)$ denotes government abatement expenditure. After taking the natural log and time differentiating we obtain

$$\bar{g}_e = (\omega + \omega\epsilon_{\omega G} lnE - \gamma) g_C \tag{10}$$

where $\epsilon_{\omega(G)} = (\partial\omega/\partial G)(G/\omega) < 0$ is government investment on clean energy technology. The value is negative, denoting increasing return to scale on government spending. Government spending on clean energy reduces emission's elasticity. This means that improving the energy structure can achieve a good energy level. If government's science and technology spending is sufficiently large then the economy will consume more energy and increase economic growth. Eq. (8) can further be rewritten as

$$\bar{\epsilon}_{eY} = \bar{g}_e \big/ \bar{g}_Y = (\omega - \gamma) - \omega\epsilon_{\omega G} lnE \tag{11}$$

Eq. (11) shows that if the energy absolute elasticity value of government's science and technology spending is sufficiently large for a sufficiently large proportion of the economy then the economy will consume more clean energy, $\epsilon_{\omega G}$, multiplied by ln$E$. Thus, the production of a closed economy will have an absolute decoupling phenomenon.

We now have obtained result III:

Result III: If the government's clean energy approach is good enough while energy elasticity and energy consumption values are close to the production rate then it will result in absolute decoupling.

Early Action and Learning by Doing Effect

The prevention and control of government spending through learning by doing effects is an emissions prevention and control behavior with cumulative knowledge (Goulder and Schneider 1999). Through learning by doing abatement effects can be increased. Eq. (9) can be modifies as follows:

$$e_t = k(G) E_t^{\omega(G)} G_t^{-\gamma} \tag{12}$$

where $0 < k(G) < 1$ is the learning parameter representing abatement knowledge accumulation effect from government expenditure on energy technology. If abatement efficiency is increased, $\partial k/\partial G > 0$, and the learning elasticity defined, $\epsilon_{kG} = \partial k/k/\partial G/G < 0$, we can obtain the emissions growth function for "learning by doing" effect as follows:

$$\hat{\epsilon}_{eY} = \hat{g}_e / \hat{g}_C = (\omega - \gamma) - \omega\epsilon_{\omega G} lnE + \epsilon_{kG} \tag{13}$$

Eq. (13) shows that by considering the efficient prevention and control of emissions we can further reduce the GHG decoupling elasticity. If learning is high enough we can achieve absolute decoupling effects, $\tilde{\epsilon}_{eY} < 0$. This includes policies where government can carry out GHG emissions abatement activities as soon as possible, early action. Thus, accumulating enough knowledge in the early prevention and control of emissions and obtain better results.

We have now obtained result IV:

Result IV: Considering emissions through early action can enhance effective abatement. This implies that governments should promote emissions abatement through early action.

RESULTS AND DISCUSSION

Taiwan's energy sector has been largely driven by economic and political forces, which have had a profound impact on energy policies. When considering Taiwan's energy policy it is best to consider four different periods: The first, 2009–2010, being a period of catastrophic disaster; typhoon Morako impacted Taiwan in 2009 leaving hundred dead and a colossal of financial damages surpassing US$3 billion; the second period, 2011–2015, follows the democratic reelection of President Ma in 2012; the third period, 2016–2020, begins with the year of the first female president to win elections; the fourth period covers 2021–2025.

Data Collection

The main purpose of this paper is to show how and through which approach Taiwan can achieve decoupling. The research period starts in 1999 and ends in 2025. CO_2 is used as the emissions variable and is measured in metric tons, GDP is measured in Yuan, final energy consumption is measured in kiloliters of oil equivalent, and government abatement investment is measured in Yuan. All the data comes from the Taiwan Energy Bureau Website.

Simulation Analysis

This section considers decoupling through energy efficiency or energy intensity decrease. According to the energy intensity statistics of Taiwan for the last two decades, 1995–2015, there are various annual energy intensity gains in each of five year periods; –0.37% (1995–2000), –0.021% (2001–2005), –2.67% (2006–2010), and –2.23% (2011–2015) (Bureau of Energy, 2016, see appendix 2). We assume five scenarios of energy intensity rate of decline, g_η; –0.4%, –0.9%, –1.4%, –1.9%, and –2.4% respectively. We note that the assumptions of the energy intensity rates of decline for this paper is less than the largest absolute value, 2.67%, and greater than the smallest absolute value, 0.021% given by the Bureau of Energy.

Considering Eq. (8), through regression we obtain the coefficients of the net emissions function as ω = 0.5648 and γ = 0.0207 respectively. While considering the energy intensity assumptions and setting 2005 as the base year cumulative to 2025, further substitution into Eq. (8) results in g_η becoming –8.75%, –19.80%, –33.91%, –46.58%, and –62.12%. Plotting the results converts into Fig. 1, which shows that Taiwan can achieve absolute decoupling by 2020 through an annual energy intensity decrease of 2.4%.

The second objective of this paper is to decide, through energy technology innovation, which decoupling approach Taiwan should consider. A three decoupling approach is assumed as follows; situation one, early action – means that government should take aggressive energy technology innovation actions at an early stage, this implies that there should be more energy innovation efforts at the early stage; situation two, delayed action – states that waiting for technological innovation is better and saves entrepreneurial investment activities; situation three, accelerated action – means that the government's science and technology innovation has a "learning by doing" effect, causing a rapid increase in energy efficiency year after year (Manne and Richels, 2004). Each approach is given an outset g_η of 3%, 1.5%, and 1.5% respectively, early action is assumed to have a 0.5% decrease, delayed action an increase of 0.5%, and accelerated action a proportional increase from 2009–2015 and consequently a 1% increase after 2015 through to 2025. Substituting into Eq. (8) and setting 2009 as the outset year cumulative to 2025, g_η becomes –61.48%, –30.56%, and –33.75%, see Table 3. In Table 3 we see that early action has the largest emission decline rate with 61.48%. This means that government must approach emissions immediately by investing in innovative low CO_2 emission energy.

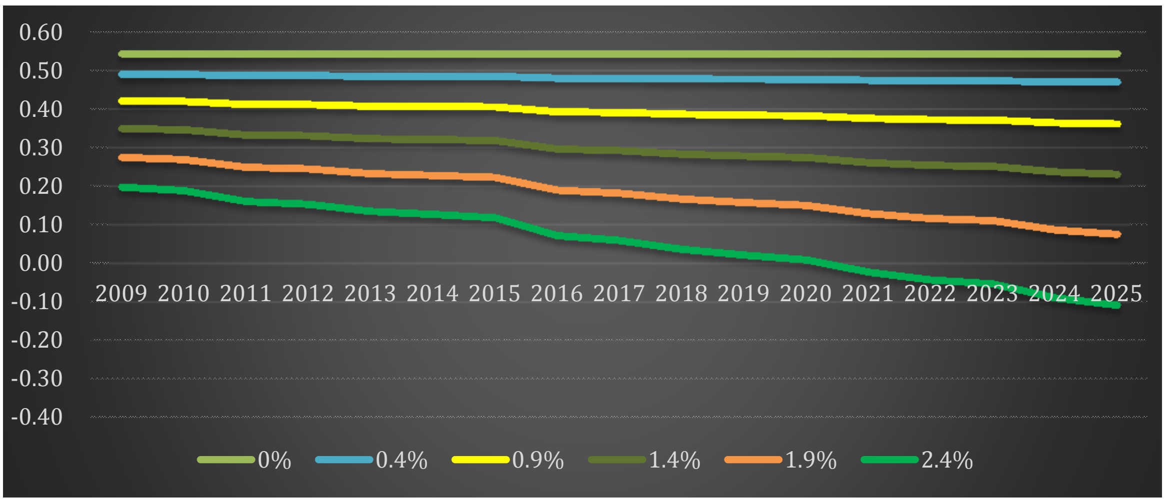

Fig. 1. Energy Efficiency Decoupling Simulation.

Table 3. Decoupling Approach**.**

Scenarios	2009–2010	2011–2015	2016–2020	2021–2025	Decline Rate
Early Action (Scenario 1)	3%	2.5%	2%	1.5%	61.48%
Delayed Action (Scenario 2)	1.5%	2%	2.5%	3%	30.56%
Accelerated Action (Scenario 3)	1.5%	3%	4%	5%	33.75%

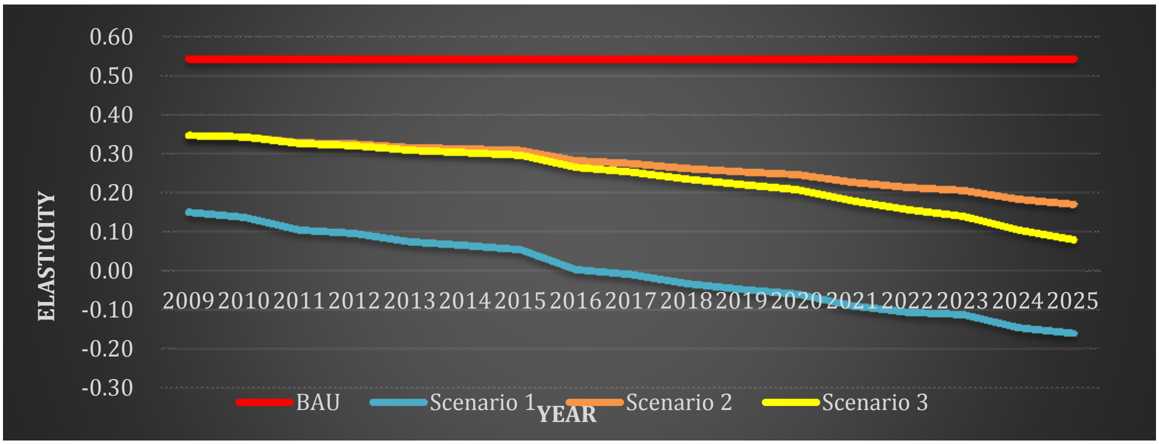

Fig. 2. Decoupling Approach through Energy Efficiency.

Furthermore, Fig. 2 shows that delayed action and accelerated action are insignificant; cannot obtain absolute decoupling. However, early action utters that in 2017, after cumulative energy intensity decreases by 29.9%, Taiwan achieves absolute decoupling. This means that the approach government must take, for achieving absolute decoupling, is that of investing in innovative clean energy technology and CO_2 emissions abatement activities at an early stage. Government should create policies that enhances energy saving and reduces energy intensity at an early stage.

CONCLUSIONS

GHG emissions are a public externality that has encapsulating global attention. Governments and academia around the world have increasingly focused their attention on emissions abatement and have incorporated research that helps in the formulation of emissions abatement policies that can achieve decoupling. Policies targeting energy innovation development objectives are among the most important driving strategies for reducing GHG emissions. However, what energy use and approach can achieve efficient emission reduction and decoupling has not been studied. This study analyzed, by using an endogenous growth model, the decoupling effect of energy related CO_2 emissions from economic growth and the approach needed to achieve absolute decoupling in Taiwan. The analysis shows that both economic growth and GHG emissions depend on many factors including energy productivity, energy expenditure ratio and high-energy prices. Poor energy efficiency, i.e., high-energy intensity, is not favorable for decoupling.

The study points out that an annual 2.4% decline rate in energy intensity is the threshold value to achieve absolute decoupling by 2020. According to the performance of energy efficiency improvement in the last two decades, this is a practical or achievable value in Taiwan. However, it is difficult to keep emission abatement without energy efficiency policy and measures.

In 2015, global intensity improved by three times the average of the last decade, i.e., from –0.5% (2003–2013) increasing to –1.8% but, intensity gains need to increase to 2.6% to achieve our climate goals (IEA, 2016). Comparing to the report of the IEA (2016), it seems acceptable that Taiwan can achieve absolute decoupling by 2020 through an annual 2.4% energy intensity decrease. Thus, Taiwan can acquire absolute decoupling by shifting the energy structure towards lower carbon intensity and by enhancing energy efficiency through early action. Taiwan should further consider national policies that are sensitive to effective economic strategies that enhance R&D oriented towards promoting energy efficiency in the economy-wide.

High-energy price is critical in decoupling CO_2 emissions from economic growth. Energy prices in Taiwan are relatively lower than in OECD countries. Therefore, how high the price of energy is sufficient for decoupling in Taiwan? In addition, how much more GHG reductions can be achieved by promoting energy efficiency or energy saving in the industry sector in Taiwan? These are other important issue, and we suggest a further empirical study in the future.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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