Carbon Abatement Technology, Early Action and GHG Decoupling Strategy

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Abstract

Economic growth decoupling with greenhouse Gas (GHG) emissions have become the new century's most important goals of sustainable development. This study builds up an endogenous growth model to discuss the impact of energy and carbon abatement technology. The main results obtained are as follows: (1) high energy price, although in the short run the impact economic growth will be negative, however, in the long term it can improve the energy structure (using clean energy) and stimulate Carbon Capture and Storage (CCS) technology innovation enabling GHG decoupling with economic growth. (2) Energy emission elasticity (the index of energy cleanliness structure) is the common determinant of economic growth and GHG emissions, an important factor in decoupling, a less than 1 energy emissions elasticity is a necessary condition for weak decoupling, and decrease returns to scale of emission function is the sufficient condition. (3) If the average annual energy intensity declines 2.4%, then Taiwan can achieve absolute decoupling by 2020.

Keyword: Endogenous Growth; Energy Prices; Accumulation of Knowledge

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1. Introduction

For centuries now global warming has become the most important environmental problem. Many governments have responded with countermeasures that can achieve the ultimate goal of absolute decoupling GHG (GHG) emissions with economic growth.[3] This is also a key indicator for investigating the performance of GHG abatement policies and measures (Mielnik et al., 2004; Lee et al, 2006).[4] The three most important tools for GHG emissions decoupling include technological innovation, social behavior change and market mechanism instruments (IPCC, 2007). Other important technological innovation measures that are actively promoted are: (1) the development of energy efficiency standards, encouraging energy-saving technology and energy efficiency; (2) the development of renewable energy, energy self-sufficiency and energy security of supply; (3) the development of alternative energy sources (biomass energy, ethanol and methane, etc.); and new energy (fuel cell and hydrogen) technology that will replace the use of fossil fuels in the transport sector; (4) the development of CO2 capture and storage (CCS) and the re-use of technology to reduce CO2 emissions (IPCC, 2005). There has been a lot of enthusiasm by international organizations in the effective promotion of energy technologies, the International Energy Agency, (IEA, 2011) proposed 25 energy efficiency policy recommendations; the United Nations Framework convention on Climate Change (UNFCCC 2011) seventeenth meeting of states parties, Durban, South Africa discussed CCS in the Clean Development Mechanism (CDM) future projects that can contribute to the commercialization of CCS.[5]

Acquiring the context of scientific and technological progress on decoupling GHGs will help in the formulation of policies (Jaffe et al., 2001).[6] In the past there has

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[3] Economic growth is usually the measurement of Gross Domestic Product (GDP).

[4] OECD Environment Minister's meeting (2001) provided one of the main policy objectives, environmental decoupling. The terminology "decoupling" is used to describe the link between the cut of environmental pollution (environmental bads) and economic growth (economic goods) (OECD, 2002).

[5] It is estimated that CCS technology will be able to reach commercialization by 2020. However, commercialization through the CDM can be joined before.

[6] The science and technology of how to balance economic growth and decrease pollution has already been studied by many scholars (ex., Grandus and Smulders, 1993; Bovenberg and Smulders, 1995); the main distinction between the three basic models (Gradus and Smulders, 1993), are as follows: (1)

been a lot of literatures on discussions of national GHG decoupling and about how to induce GHG abatement technology, such as, through technological innovation and learning by doing to accumulate abatement knowledge, and endogenous technological progress factors (eg. Wigley et al., 1996; Glubler, 1999; Bayoumiet et al., 1999; Goulder and Mathai, 2000; McDonald and Schrattenholzer, 2001; Papathanasiou and Anderson, 2001; Nordhaus, 2002; Rosendahl, 2004; Manne & Richels, 2004; Olson, 2005; Lee et al., 2007; Huang et al., 2007). However, previous researches that focuses mostly on economic incentives encouraging technological innovation tools in countries for pursuing optimum GHG abatement policies, but lack the linkage with economic growth. In Goulder and Schnieder (1999) despite a reference to scientific and technological innovation, discussed the affects to the country's economic output, but did not in-depth analysis of long-term economic growth factor; Huang and Cai (1994) where the first to introduce the endogenous growth model to analyze the impact of pollution abatement expenditure on economic growth, however, they did not discuss the issues of abatement of technological innovation; Moon and Sonn (1996) discussed the use of endogenous growth models of economic growth of a country to pursue the optimum problem of energy expenditure, however, the issue of economic growth impact from energy emit GHG was not discussed, in other words, the GHG decoupling literature, lacked the link with energy technology, economic growth and GHG decoupling, and analysis of policies.

In 2008 Taiwan enacted "Sustainable Energy Policy Guidance " and in 2015 organized its "Fourth National Energy Conference" and developed a national GHG emissions decoupling and economic growth target, i.e. to return GHG emission to 2005 emissions level by 2020, and to the year 2000 GHG emissions level by 2025 by using the following policies and measures to achieve the GHG abatement target, such as (1) Enhancing energy efficiency by 2% per year; (2) Deploying carbon-free renewable energy sources, as total share of power generation to more than 14.8% by 2025; (3) Increasing the use of low-carbon natural gas to achieve more than 25% of

neoclassical model of exogenous technology; (2)AK endogenous growth models (Rebelo, 1991); and (3) human capital model(Lucas, 1988) and so on.

power generation by 2025. However, an evaluation of whether these policies and measures can achieve the national emission abatement targets has not been performed.

As understood from the above literature has not yet distinguished between the energy structure (alternative energy sources), energy efficiency and carbon abatement techniques (such as Carbon Capture and Storage), three carbon abatement technology patterns, combined with endogenous growth model to explore the issue of long-term economic growth of the country. Based on this, this study will establish an endogenous energy growth model, taking into consideration the energy technologies progress, to explore the structure of energy, energy efficiency and carbon sequestration effects of technological progress, thus, this study will use empirical data to assess the effect of energy efficiency as well as clean energy technologies progress on the Taiwan's long-term economic growth decoupling with GHG emissions.

This paper is organized as follows: section 1 is the introduction section 2 establishes the energy consumption and the country's economic growth model, as the baseline scenario analysis. Section 3 explores the issue of energy consumption and GHG gas emissions, discussion on energy efficiency, restructuring of energy and GHGs by doing absolute decoupling. Section 5 Simulation analysis. Section 6 concludes.

2. Energy Economic growth model

2.1 The Utility Function of Temperature Combined with the Damage

In general, the damage caused by the rise of utility is largely based on the interaction of the following three mechanisms: (1) GHG associated with the stock of emissions on the atmosphere (concentration); (2) the accumulation of GHGs is associated with the temperature increase; (3) the temperature will damage the utility function. If the household is also a producer and assume the utility function of each person follow a "Constant Relative Risk Aversion" (CRRA). The combination of the utility function of damage from temperature can be expressed as

$U = (C_t / \phi_t^{\delta})^{1-\sigma} / 1-\sigma$ [7] among them, σ is a relative risk coefficient for consumers ($1/\sigma$ intertemporal elasticity of substitution for consumption), [8] δ for consumers tolerance or sensitivity to temperature, the larger, δ , the temperature rise then it means the greater the disutility;[9] $\phi_t(S_t)$ is damage function which is function of the atmospheric concentration of GHGs (CO_2 concentration) S_t, and $\emptyset_t' > 0$ indicates a higher atmospheric concentration of GHGs; the more severe the GHG effect the greater the damage.

2.2 Production Function and Emissions Function

If economic output, Y_t , capita, K_t , and energy, E_t , being the two input functions,[10] and assuming the production function, $Y_t = AK_t^{\alpha}E_t^{\beta}$, wherein, A is the technology parameter, $0 < A < 1$, and α, β are production parameter, $0 < \alpha, \beta < 1$. Assuming GHG emissions from energy consumption, [11] however, through of government abatement expenditure, G_t , GHGs can be reduced and thereafter, the net GHG emissions function e_t , for $e_t = E_t^{\omega} G_t^{-\gamma}$, whereby, ω, elasticity of emissions for

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[7] For a slightly different traditional literature on how pollution affects the economic well-being of the set, part of the literature of pollution flow way effect (such as Foster, 1973; Gruver, 1976; Gradus and Smulders, 1993), part of the literature in the stock well-being way effect (eg. Luptacik and Schubert, 1982), perhaps the literature while taking stock of the impact the well-being of traffic and setting mode (such as Van der Ploeg and Withagen, 1991). These articles discuss the problems of GHG emissions of global warming, and therefore, the paper stock type is set to affect the economic well-being.

[8] $\sigma = -CU''/U'$, generally, σ reflects the size of preference characteristics of consumers, when σ in many growing literature theory, often assume $\sigma = 1.5$, however, some scholars based on empirical results indicate that in developing countries, consumer, σ , value may be less than 1.

[9] In short, δ , the reaction temperature is used to generate the degree of consumer disutility of indicators.

[10] This article assumes the Cobb-Douglas production function, in accordance with the settings of neoclassical growth theory.

[11] Literature for setting pollution emission patterns are distinguish between two main functions, such as emissions from production (Foster; 1973; Van der Ploeg and Withagen, 1991), or from consumption, production and capital stock of emissions (Luptatacik and Schubert, 1982; Gradus and Smulders, 1993). This article discusses the GHG emissions set by energy consumption.

energy consumption,[12] γ is government expenditure elasticity for abatement,[13] and $\omega, \gamma > 0$, $\boldsymbol{\omega}$, the smaller the value indicates the use of cleaner energy economic structure (such as natural gas or renewable energy), γ , the higher the value indicates that the government will take better abatement techniques, such as CCS, and $\omega \geq \gamma$, implies incomplete abatement technology.

2.3 Capital Accumulation Equation

Assuming the economy has output levels for consumption, C_t , energy expenditure, $P_t E_t$, and government GHG abatement expenditure, G_t , and the remainder in full for investment; the capital accumulation equation is as follows: $\dot{K}_t = Y_t - C_t - P_t E_t - G_t$ where P_t is the relative price of energy to commodities (assuming the price of consumption goods and capital goods are normalized to 1).

2.4 GHG Accumulation Equation

Assuming the environment has self-purification capacity, $b_1 S_t$, then GHG concentration stock accumulation is the difference between the concentration of GHG emissions and environmental self-purification capacity, i.e., $\dot{S}_t = b_0 e_t - b_1 S_t$, where b_0 is the proportion of current emissions accumulations in the atmosphere, b_1 is CO_2 stock decline (decay) ration for the current period.

The economic system optimal decision model is as follows:

$$\underset{\{C_t, E_t\}}{Max} \; PVU = \int_{t=0}^{\infty} \exp(-\rho t)[\frac{(C_t / \phi_t^{\delta})^{1-\sigma} - 1}{1-\sigma}]dt \qquad (1)$$

[12] With power factor, for example, expressed per kilowatt per hour, a few units of CO2 emissions, in 2009 Taiwan had a power factor of 0.636 kg CO_2/degree.

[13] Prevention of government expenditure is not considered in learning by doing effect, and the in the accumulation of knowledge effect, but a subsequent article will discuss the issue.

S.t. $\dot{K}_t = Y_t - C_t - P_t E_t - G_t$ (2a)

$\dot{S}_t = b_0 e_t - b_1 S_t$, $b_0, b_1 > 0$ (2b)

$\phi_t = \phi(S_t)\, \phi'_t > 0$ (2c)

K_0, S_0 Known

This study assumes that energy intensity is $\eta_t = E_t / Y_t$;[14] it is set to a fixed value (Moon and Sonn, 1996), therefore, energy expenditure can be rewritten as $P_t E_t = P_t \eta_t Y_t$, where $P_t \eta_t < 1$ represents the share of energy costs, in addition, assumes a certain percentage of government investment in energy technology innovation outputs, or GHG abatement technology, $G_t = \mu Y_t$, where μ, government spending, accounts for a fixed proportion of output, and $0 < \mu < 1$, assumed fixed, then (2a) can be rewritten as $\dot{K}_t = (1 - P_t \eta - \mu) Y_t - C_t$. The current Hamiltonian function of the above can be as follows:

$$H = \frac{(C_t / \phi_t^{\delta})^{1-\sigma} - 1}{1-\sigma} + \lambda_t \left[(1 - P_t \eta_t - \mu) A K_t^{\alpha} E_t^{\beta} - C_t \right] - \theta_t (b_0 e_t - b_1 S_t)$$

Where λ_t and θ_t are co-state variables or shadow price of consumption and CO_2 emissions respectively. The 1st order condition is as follows:

$$\frac{\partial H}{\partial C} = 0 \Rightarrow C^{-\sigma} \phi^{\delta\sigma - \delta} = \lambda \quad (3a)$$

$$\frac{\partial H}{\partial E} = 0 \Rightarrow \lambda\beta(1 - P\eta - \mu_t) A K^{\alpha} E^{\beta - 1} - \theta\omega b_0 E^{\omega - 1} G^{-\gamma} = 0 \quad (3b)$$

$$\dot{\lambda} = -\frac{\partial H}{\partial K} + \rho\lambda = -\alpha\lambda(1 - P\eta - \mu_t) A K^{\alpha - 1} E^{\beta} + \rho\lambda \quad (3c)$$

$$\dot{\theta} = -\frac{\partial H}{\partial S} + \rho\theta = \delta C^{1-\sigma} \phi^{\sigma\delta - \delta - 1} \phi' - \theta b_1 + \rho\theta \quad (3d)$$

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[14] Its reciprocal is energy productivity, under normal circumstances, the economy and technological progress (learning and innovation effects), energy productivity gains, that represent energy consumption savings (or the tendency of economies of scale), the implied growth rate will be greater that the energy growth rate.

Putting equation (3c) into equation (3d), we get $\frac{\dot{\lambda}}{\lambda} = -\alpha(1-P\eta-\mu)AK^{\alpha-1}E^{\beta}+\rho$; the details of economic (consumption) growth rate are available in appendix I, the long term steady state equilibrium is proven in Appendix II:

$$g_C = \frac{\beta(1-P\eta-\mu)/P\eta-\rho}{\sigma[1+\delta(\sigma-1)\varepsilon_{\phi}(\omega-\gamma)]} \quad (4)$$

Where ε_{ϕ} is GHG damage elasticity ($\varepsilon_{\phi} = \frac{\partial\phi/\phi}{\partial S/S} = \phi'\frac{S}{\phi} > 0$), the right hand side shows the factors affecting economic growth rate, including the intertemporal elasticity of substitution ($1/\sigma$) , GHG damage elasticity ε_{ϕ} , interpemporal time preference rate, ρ , energy production elasticity, β , CO_2 emissions elasticity, ω , CO_2 abatement elasticity, γ , energy intensity (or energy productivity), η , government expenditure and abatement ratio, μ . Therefore, the consideration of the use of energy that produces GHG effects can be found in the symbols of economic growth rate, depending on the combination of many factors, see Table 1. If the economic growth rate is positive (in case 1), this indicates that if the time preference rate is small enough implying that individuals are more concerned about future consumption, if the coefficient of future investment ratio $(1-P\eta-\mu)$ is high (or energy expenditure ratio, $P\eta$, low enough) then there is higher energy productivity (β higher), under equation (4), the numerator is positive; in addition, if the economy of each individual prefer smooth consumption, then the intertemporal elasticity of substitution becomes lower, i.e., $\sigma>1$, if we satisfy the above conditions then the economy achieves positive economic growth rate, $g_C > 0$, the result, in general, is more in line with the status quo in industrialized countries.[15] Case 2 and case 3 implies higher intertemporal elasticity of substitution $\sigma<1$, or that energy

[15] Germany, the UK and the North European countries have presented economic growth and GHG decoupling phenomenon (UNFCCC, 2007).

productivity, β, is low, the economic growth rate is negative, these results can be explained by the situation in developing countries, which notes lower energy productivity, but also considerable importance on current consumption levels, ρ higher, and then each phase of investment ratio $(1-P\eta-\mu)$ is lower; the results will show a negative economic growth phenomenon; in case 3, some developing countries, particularly the more environmental vulnerable, although the rate of time preference is small enough, and each phase of the investment ratio $(1-P\eta-\mu)$ and energy productivity, β, high enough, however, since the intertemporal elasticity of substitution is larger, $\sigma<1$, damage caused by the GHG effects and environmental degradation (ε_ϕ) is larger; if GHG abatement technology is not good enough, i.e., γ is small, the economic growth rate will be negative. The fourth case is more difficult to interpret in the real world therefore they will not be discussed. The proposition one is obtained as follows:

Proposition 1: If the energy productivity is high enough, or energy expenditure ratio is low enough, and more smoothing consumption path (smaller ρ or σ larger), then the economy will show a positive growth.

Table 1: Positive or Negative Impact of the Economic Growth of a Combination of Factors

	$\beta(1-P\eta-\mu)/P\eta>\rho$	$\beta(1-P\eta-\mu)/P\eta<\rho$
$\sigma>1$	Case1： $g_C>0$	Case2： $g_C<0$
$\delta(1-\sigma)\varepsilon_\phi(\omega-\gamma)<-1$	Case3： $g_C<0$	Not Discussed

Next, the discussion of the comparative static results of formula (4) (for detailed derivation see Appendix III), in order to further understand the effects of various factors, the scenario in the case of $g_C>0$, the analytical results are shown in Table 2, it briefly compares its economic significance as follows: the higher GHGs elasticity emissions greater is the harm, thus greater is the impact on climate change, countries affected therefore need to invest more resources in reducing GHG emissions and in adaptation activities, the results will reduce the economic growth rate; if the intertemporal elasticity of substitution is smaller, σ greater, then the higher the rate of time preference which means that individual current consumption will increase and should reduce investment causing a reduction of future capital stock accumulation, and lower economic growth rate; the higher energy productivity it will enhance economic growth rate causing energy prices to increase, this increases the proportion of energy expenditure which then reduces consumption and capital investment giving result to a reduction in the economic growth rate. Energy intensity improvement will be the cause of energy-saving effects, which also represents to increase economic growth rate. GHG abatement expenditure increases the proportion of energy and the crowding out the capital and other productive resources, which will reduce the rate of economic growth. Economic systems that use more clean energy, such as natural gas or renewable energy sources, ω smaller, or that their governments take better immobilization of GHGs, γ larger, reduce GHG emissions, thus reduces the damage caused to the economy, and increases economic growth rate; as consumer tolerance or sensitivity to temperature increases, δ , it indicates that there will be negative effects on consumption, thus causing a lower economic growth rate. From the above analysis we have obtained result I as follows:

Result I: High energy prices and low energy efficiency give result to a negative economic growth. However, if higher energy prices can stimulate the use of clean energy, or the increase of sequestration of GHGs, then it is favorable for economic growth.

Table 2 A Static Comparison Analysis of Economic Growth Rate

Independent Variables (X)	$\partial g_c / \partial X$
ε_ϕ	< 0
σ	< 0
ρ	< 0
β	> 0
P	< 0
η	< 0
μ	< 0
ω	< 0
γ	> 0
δ	< 0

3. **GHG Emission Decoupling with Economic Growth Factors**

Many industrialized countries that currently observe GHG abatement policies,[16] found that even though they invest in efforts for improving the energy structure, and have the GHG abatement action plan,[17] they are still ineffective, what could be the reason? What are the key factors causing the increase in GHG emissions, and why? This questions are the subject of interest of this study, therefore, this section will solve for a steady state that will show GHG abatement under the growth path, and will analyze the impact factors and their correlation with economic growth, as proposed by the GHG decoupling policies. First of all, the net emission function, $e_t = E_t^{\omega} G_t^{-\gamma}$, is

[16] Based on the Kyoto Protocol Annex B countries.

[17] According to the UNFCCC (2008), up to 2006 statistics, if you do not consider the case of countries with economies in transition, only a few industrialized countries such as Germany, Britain, France, the Netherlands, and other countries can meet GHG abatements effectively.

fully differentiated and then substituted into equation (4), the economic growth rate equation, then the equation of growth rate of GHG emissions is obtained:[18]

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

From equation (5), the economic growth rate is an important factor to explain GHG emissions; all factors that affect the rate of economic growth, and also affect the growth of GHG emissions, but the direction of its impact which is the same as $\omega - \gamma > 0$. Decoupling refers to the parallel phenomenon effects of economic growth and GHG emission, i.e., if the economic growth rate is higher than the rate of GHG emissions, then an economic system with a decoupling phenomenon has been achieved.[19] So now we can define the decoupling elasticity of GHG emission, g_e and economic growth rate from equations (5) and (4), resulting in $\varepsilon_{eY} = \frac{g_e}{g_C} = \omega - \gamma > 0$, this shows the current energy structure, GHG emissions from energy decoupling elasticity, ω, or cleanliness of the energy mix, and GHG abatement elasticity, γ, or carbon abatement efficiency; these are the two factors in the net emission function, $e_t = E_t^{\omega} G_t^{-\gamma}$, if it is fixed or increases then there will be a constant or increasing return to scale, that is $\omega - \gamma \geq 1$, an economic growth increase and GHG abatement phenomena appears (Tapio, 2005); however, if the net emission function is decreasing returns to scale, that is $0 < \omega - \gamma < 1$, the economy will show a weak decoupling phenomenon (Tapio, 2005). This paper has obtained Proposition II:

***Proposition II*:** Energy emission elasticity (a clean energy structure) and GHG abatement elasticity (Low carbon efficiency) are important factors in economic

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[18] After the total differentiation of equation 2, $g_e = \omega g_E - \gamma g_G = (\omega - \gamma) g_C$, because in this article we assume that, $g_E = g_G = g_Y$, into equation (4), we can obtain equation (5).

[19] This phenomenon is called weak or relative decoupling; if GHG emissions show a negative growth, it is called strong or absolute decoupling (OECD, 2002; Tapio, 2005).

growth decisions and in decoupling GHG emissions. Energy emissions elasticity less than one, $\omega < 1$, is only a necessary condition for weak decoupling, sufficient conditions are when the net emission function has decreasing returns to scale, $0 < \omega - \gamma < 1$.

The economic meaning of proposition II are described next: If the emission function is constant or increasing returns to scale, it represents that the elasticity of energy emissions is high (or low energy structure cleanliness, such as the use of fossil fuels which causes high GHG emissions), $\omega > 1$, or GHG prevention elasticity or energy efficiency is low enough (there is no use of good enough carbon abatement technology), $\gamma < 1$, this situation is indicative of the GHG abatement dilemma faced by all countries at the present stage.[20] However if we can speed up the restructuring of energy to clean energy sources, such as renewable energy or biomass energy and other alternative energy sources, to replace traditional fossil fuels, and increase the cleanliness of the energy mix that reduces emissions elasticity, making $\omega < 1$, or strengthen the scientific and technological innovation and carbon abatement activities that improve prevention and control of GHG efficiency, improve γ, the economy is expected to achieve, $0 < \omega - \gamma < 1$, a weak decoupling phenomenon, which is at this stage, for best results that international advanced countries can achieve.

4. Absolute Decoupling GHG Policy

The International Energy Agency (IEA 2015) report shows that in order to achieve the long-term abatements goals, i.e. by 2100 stabilize atmospheric concentrations at 450ppm, energy technology strategy planning should be considered; energy efficiency technology contribute 38% abatement effects, carbon capture and storage contributes 13% abatement effects, and nuclear power

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[20] In theory, even though there is energy emissions flexibility, $\omega > 1$, however, if GHG prevention and control technology is good enough, it is possible to achieve $\omega - \gamma < 1$ situation.

generation and technology to contribute 8% abatement effects, which means less GHG decoupling; below we discuss the effect of the breakdown.

4.1 Energy Saving Technology Innovation

Absolute decoupling of GHG, $\omega - \gamma < 0$, is in response to the ultimate goal of global warming,[21], however, the constraints of the above discussed energy technology cannot achieve this goal. Based on this, this section will introduce energy efficiency effects by loose the fixed assumptions of energy intensity function, $\eta = E / Y$, i.e. if the energy intensity decreases with time (or energy productivity increases), the energy intensity function, after taking the natural log, and then total differentiating with time becomes;

$$g_E = g_C + g_\eta \tag{6}$$

Where, $g_\eta < 0$, is the decline rate in energy intensity (represents energy efficiency), similarly net emission, $e_t = E_t^{\omega} G_t^{-\gamma}$, after taking the natural log, and total time differentiating, and rearranging into equation (6) we obtain:

$$\tilde{\varepsilon}_{eY} = \frac{\tilde{g}_e}{\tilde{g}_C} = (\omega - \gamma) - \omega \varepsilon_{\eta Y} \tag{7}$$

Equation (7) considers the promotion of energy efficiency in GHG decoupling elasticity, where $\varepsilon_{\eta Y} = -g_\eta / \tilde{g}_C > 0$ defines the energy intensity elasticity of economic growth, its economic meaning is to capture the economic growth process, the status of energy efficiency, $\varepsilon_{\eta Y}$ being larger, this represents a faster energy efficiency improvement. Equation (7) shows that in the right hand side of the second term is negative, indicating that after considering the effect of energy saving technology, GHG decoupling elasticity can be effectively reduces. If the energy efficiency is high enough then it is consistent with the rate of economic growth,

[21] According to the IPCC 2007 plan, the atmospheric GHG concentration should be stabilized and reach levels of 450ppm by 2100; this can inhibit the temperature not to rice above 2⁰C.

namely $\varepsilon_{\eta Y} \approx 1$, [22] and get $\tilde{\varepsilon}_{eY} < 0$, indicating that the economic system can achieve an absolute decoupling phenomenon. We have obtained result II:

Result II: If the government enhances energy efficiency research and development so that energy efficiency is consistent with the economic growth rate, $\varepsilon_{\eta Y} \approx 1$; the results of GHG absolute decoupling of economic growth is achieved.

4.2 Renewable and Alternative Energy Technology Innovation

Adjustments in clean energy, including renewable and biomass energy structure is also an important GHG decoupling policy, GHG abatement expenditure of government, in addition to direct activities for the abatement of GHGs, while also spending on R&D and innovation activities in renewable and alternative energy sources, namely government spending, will affect energy emission prevention and control flexibility, and the elasticity of the internal energy emission (endogenous), therefore, the net emissions function can be amended as follows:

$$e = E^{\omega(G)} G^{-\gamma} \tag{8}$$

Where ω is function of abatement expenditure of government, taking the natural log of equation (8) and then the total time differential, we obtain:

$$\bar{g}_e = (\omega + \omega\varepsilon_{\omega G} \ln E - \gamma)\bar{g}_C$$

Where $\varepsilon_{\omega G} = (\partial\omega / \partial G)(G / \omega) < 0$ is the government spending on net clean energy technology, its value is negative, indicating that when the value is smaller, the effectiveness of government spending is higher than energy technology, i.e.,

[22] If Taiwan's economic growth rate is 3%, then the rate of energy efficiency can be up to 3%, obtaining $\varepsilon_{\eta Y} \approx 1$.

government spending on technology reduces energy emissions elasticity, this means that improving the energy structure can achieve a good energy level. Therefore, the GHGs decoupling elasticity equation (7) can further be rewritten as:

$$\bar{\varepsilon}_{eY} = \frac{\bar{g}_e}{\bar{g}_C} = (\omega - \gamma) - \omega \left|\varepsilon_{\omega G}\right| \ln E \qquad (9)$$

Equation (9) shows that if the absolute of energy emissions elasticity of government abatement is sufficiently large, for a sufficiently large proportion of clean energy, the economic system will consume more energy, $\ln E$ more, than the use of more clean energy, or $\left|\varepsilon_{\omega G}\right|$ multiplied in $\ln E$, the production of a close economy will have an absolute decoupling results. We now have obtained result III:

Result III: If the government's clean energy structure improvement effect is good enough, and if the energy emissions elasticity and energy consumption (absolute) are close enough to the production rate, i.e. the GHG emissions and economic growth will be the result of an absolute decoupling.

4.3 Early Action and Learning by Doing Effect

Next, considering the abatement expenditure of government has a learning by doing effect, which is GHG abatement behavior with cumulative knowledge (Goulder and Mathai, 2000),[23] can increase abatements effects, therefore equation (8) can be further amended as follows:

$$e = k(G) E^{\omega(G)} G^{-\gamma} \qquad (10)$$

[23] The knowledge accumulation equation is set as follows: : $\dot{H}_t = \alpha H_t + h\Theta(G_t, H_t)$, where representatives of the stock of the knowledge function is influenced by the current cumulative knowledge stock levels, and government budget level, the so called "learning by doing" effect that is placed on the government science and technology expenditure knowledge accumulation function.

where $0 < k(G) < 1$ is the learning parameter representing an abatement knowledge accumulation effect of the expenditure on energy technology by the government, thus increase abatement efficiency, $\partial k / \partial G < 0$,[24] if we define the learning elasticity， $\varepsilon_{kG} = \dfrac{\partial k / k}{\partial G / G} < 0$, we can obtain the emission growth function of "learning by doing " effect as follows:

$$\hat{\varepsilon}_{eY} = \frac{\hat{g}_e}{\hat{g}_C} = (\omega - \gamma) - (\omega |\varepsilon_{\omega G}| \ln E + |\varepsilon_{kG}|) \qquad (11)$$

Equation (11) shows that by taking the efficiency prevention and control consideration we can further reduce the GHG decoupling elasticity, if learning is high enough we can achieve absolute decoupling effects, $\tilde{\varepsilon}_{eY} < 0$. This includes the policy where if the government can carry out GHG abatement activities as soon as possible, early action, and accumulate enough early prevention and knowledge control, thus obtaining better results; this could explain why Germany and Britain and other more active countries reducing GHGs are now able to achieve absolute decoupling results. We have now obtained result IV:

Result IV: When considering GHG abatements has a learning by doing effect which can enhance the effectiveness of GHG abatement, it implies that if the government tries to promote GHG abatement actions early, then it has a potential to achieve GHG emissions decoupling early.

[24]The effect is similar to carbon capture and storage, in that it directly reduces GHG emissions.

5. Energy Technologies and Early Action of GHG Decoupling Simulation

5.1 Unit Root and Co-integration test

This section intends to discuss and analyze the theoretical model with reference to Taiwan's technology-related energy information, such as energy efficiency, etc., and simulate abatement effects of early action. Since GHG emissions, energy consumption, government's energy R&D expenditure and other variables are the property of time series data,[25] and to avoid it is relevant to confirm whether the indicators are stationary or non-stationary and if they are of common co-integration.[26] E-views was used to separately run the unit root test and co-integration test.[27] Augmented Dickey-Fuller (ADF) was used as the test method;[28] test results are shown is table 3. Table 3 shows CO_2 emissions, energy consumption, CO_2 emission abatements and energy-saving technology spending variables are of 1st order stationarity. Next, table 4 present the co-integration test study of CO_2 emissions, energy consumption, CO_2 emission abatements and energy expenditure; the presence of all variables co-integrations can be found, it shows that CO_2 emissions and energy consumption, as well as, CO_2 abatement and energy expenditure enjoy of a long-term stable relationship between them.

[25] CO_2 and energy consumption data was taken from TAIGEM-III in the future CO_2 simulation analysis data (Lee Jian-Ming et al., 2005), energy conservation and energy efficiency and CO_2 abatement management investment amount of information, over the energy research and development results from the Energy Bureau 2007 statistics.

[26] The Engle and Granger (1991) proposed that if the means of two non-stationary time series variables can be combined into a mutual relationship with a function, then you could solve the spurious regression problem.

[27] Refers to test whether two non-stationary state variables can have a linear combination way to become a steady-state variable (a long term relationship).

[28] The DF test is used to confirm the presence of a single root data, and ADF reduce residuals reduced the problem of DF test force, it makes the test results meet the case.

Table 3: Unit root Test

INDEX	DF		1ST		2ST		LAG=1	
	T—value	significant	T—value	significant	T—value	significant	T—value	significant
CO_2 Emissions	-2.043	×	-2.537	×	-2.995	5%	0.929	×
Energy Consumption	-1.535	×	-6.012	10%	-5.838	1%	-3.503	5%
CO_2 Abatements (Tons)	-1.866	×	-2.980	5%	-3.147	5%	-2.856	×
Energy-saving Technology Spending (Millions)	-2.183	×	-2.355	5%	-2.999	5%	-2.226	×

Table 4: Co-Integration Test

INDEX	CORRESPODING TO THE INDEX	T—value	ADF SIGNIFICANCE
CO_2 Emissions	Energy Consumption	-2.275	5%
CO_2 Abatements (Tons)	Energy-saving Technology Spending (Millions)	-2.474	5%

5.2 GHG decoupling Scenario Analysis of Energy-Saving Technology

This section considers a situation where energy efficiency (or energy intensity decreases), we rewrite equation (7), $\tilde{\varepsilon}_{eY} = \frac{\tilde{g}_e}{\tilde{g}_C} = (\omega - \gamma) - \omega \left| \varepsilon_{\eta Y} \right|$, and base on the elasticity of CO2 emissions, $\omega = 0.5648$, see table 5, as well as CO2 elasticity of energy saving technology expenditure, $\gamma = 0.0207$, into equation (7) and set 2005 as the starting year, five kinds of energy intensity (η) years; the rate of decline (g_η) scenarios were -0.4%, -0.9%, -1.4%, -1.9% -0.4%, and -2.4%, cumulative to 2025 energy intensity decrease yearly rate was -8.745%, -19.802%, -33.905% (National Energy Conference Target, 2009), -46.577%, and -52.150%. The simulation results in figure 1 shows, that the energy intensity of only 2.4% annual rate of decline to 2020 can be achieved in the case of absolute decoupling. As for the National Energy Conference 2025 target of reaching a 33% cumulative decline in the rate of energy intensity, the 2025 target could not be absolute decoupling.

The study's objective is to further distinguish the situation of three energy technology innovation actions,[29] see Table 6, situational hypothesis; situation one "early action" is to illustrate to the government as soon as possible to take more aggressive energy technology innovation actions, therefore, acquire a fast upgrade on energy efficiency; situation two "delayed action" represents waiting for technological innovation is better, mature, if they wait then there is a lot of investment energy technology innovation activities (Manne and Richels, 2004), therefore, it is a slow innovation scenario; situation three "accelerated action", it means that the government's R&D innovation has a "learning by doing" effect, causing a rapid increase in energy efficiency year after year.[30]

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[29] Starting in 2009, the target year is 2025.
[30] This study used accelerated energy efficiency to capture learning by doing effect.

The simulation results shown in Figure 2 shows that situation two and three of the situational decoupling effect is insignificant, however, situation three in 2017 after a (cumulative energy intensity decreased to 29.9%), show that the economy can achieve absolute decoupling objectives. The economic meaning is that if the economic system is administered by “early action” policies then enhancing the overall economic system of saving energy and reducing carbon energy (capacity), this is, up the path sustainable development, GHG decoupling may soon reach the goal; “early action” compared to the “delayed action” and “accelerated action” policy is a more advantageous policy.

Table 5: Energy Efficiency Scenarios

Situation	2009-2010	2011-2015	2016-2020	2021-2025	Cumulative Decline Rate
Scenario 1- Early Action	3%	2.5%	2%	1.5%	61.48%
Scenario 2- Delayed Action	1.5%	2%	2.5%	3%	30.56%
Scenario 3- Accelerated Action	1.5%	3%	4%	5%	33.75%

Figure 1: Different Scenarios of GHG Energy Efficiency Decoupling Simulation

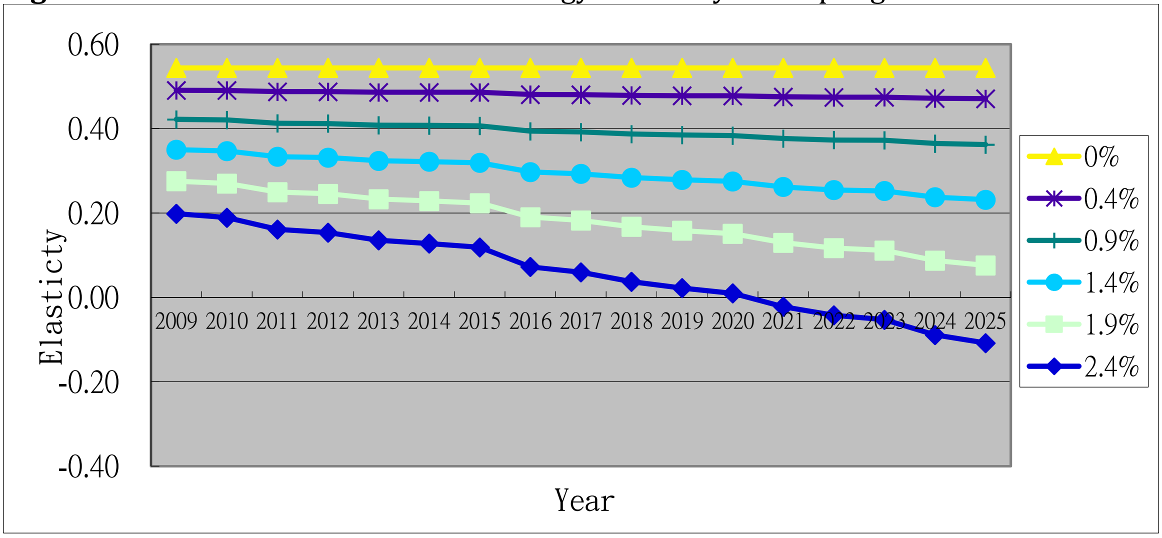
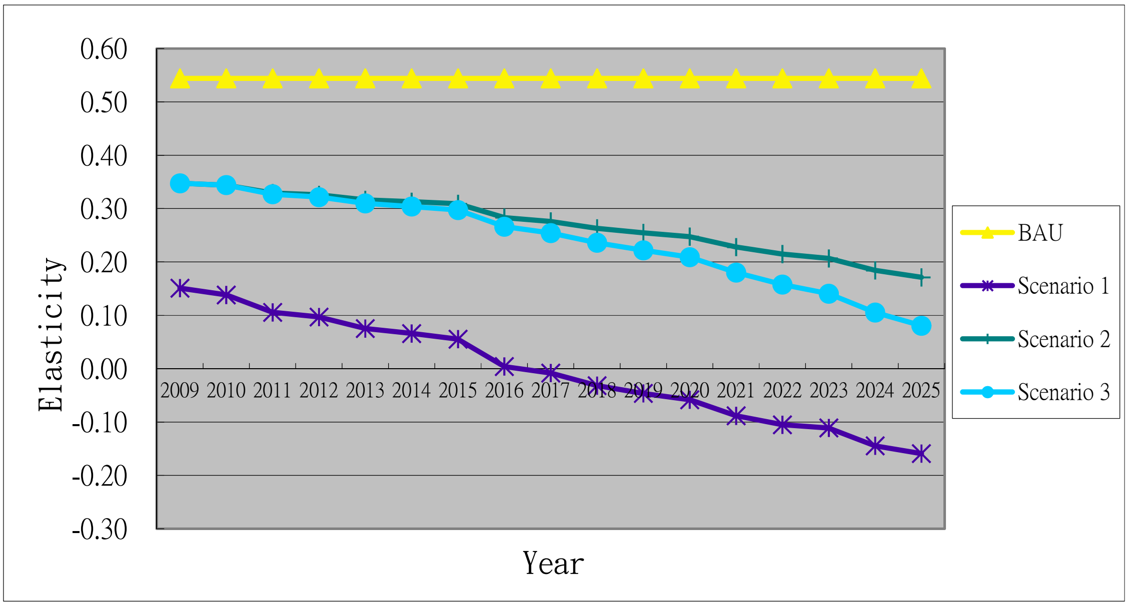


Figure 2: GHGs Innovative Actions of Different Energy Efficiency Decoupling Comparison



6. Conclusion and Recommendations

Economic growth and GHG emissions decoupling has become a national response for the new century, an important GHG abatement policy objective and energy technology development (including energy efficiency, alternative energy and renewable energy technologies), is among the most important driving strategies. The construction of the energy structure at the core of endogenous growth model to explore strategic analysis of energy technology development and GHG decoupling obtained the following results:

- The effect of uncertainty on the economic impact of GHG effects, depends on many factors, including energy productivity, energy expenditure ratio, economic individual intertemporal consumption preferences and other factors, the analysis in this paper can show that as industrialized countries and developing countries are faced with reducing GHG emissions in the economy, the impact effects are different;

- High energy prices and poor energy efficiency of a country's economic growth will be unfavorable, so if there is improvement on the energy structure (the use of clean energy sources), or increase GHG CCS technology it can effectively improve the country's economic growth;
- Energy emissions elasticity (energy cleanliness structure) and GHG prevention elasticity (carbon control efficacy) are common determinants of economic growth and important GHG decoupling factors, but a good clean energy structure still does not ensure economic growth and GHG emissions decoupling, so there is also the need for effective GHG abatement measures (such as CO2 fixing);
- If the government enhances energy efficiency on research and development, so that energy efficiency is close enough to the economic growth rate, or that a low-carbon or carbon-free energy ratio is high enough, it may result in absolute decoupling of GHG emissions;
- Learning by doing really helps to improve the effectiveness of reducing GHG emissions, and implies that government should try to promote GHG abatement actions, we can then achieve results of absolute GHG emissions decoupling at an early stage;
- If the average annual energy intensity declines to 2.4% in 2020, then Taiwan can achieve absolute decoupling of GHGs and economic growth;
- Early action with a superior GHG decoupling policy, and energy –intensity to a cumulative decline rate of 29.9% in 2017 can achieve a GHG decoupling and economic growth phenomenon.

Although this study has examined the relationship between energy prices and economic growth this article does not include endogenous energy prices, that is, there is no establishment of energy markets and energy prices as expected mechanisms, in addition, although "learning by doing" is included in this article it does not consider the effect of energy diffusion technology, this are future further in-depth study of the subject.

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Appendix 1

Energy intensity $\eta_t = \frac{E_t}{Y_t}$, on both sides of the natural logarithm of time and the total differentiation:

$$\frac{d\eta / dt}{\eta} = 0 = \frac{dE / dt}{E} - \frac{dY / dt}{Y} \Rightarrow g_E = g_Y$$

Is of stable sate (steady state), order $\dot{K} = 0$, by formula (2c) we can obtain $C = (1 - P\eta - \mu)Y$, then take natural logarithm on both sides and then total differentiation, to get:

$$\frac{dC / dt}{C} = \frac{dY / dt}{Y} \Rightarrow g_C = g_Y$$

If the returns to scale production function is fixed, $Y = AK^{\alpha} E^{\beta}$, that is $\alpha + \beta = 1$, then the total time differential is as follows:

$$\frac{dY / dt}{Y} = \alpha \frac{dK / dt}{K} + \beta \frac{dE / dt}{E} \Rightarrow g_Y = g_K \Rightarrow g_Y = g_E = g_K$$

then solving for the economic growth rate through equation (3c) we obtain

$\frac{\dot{\lambda}}{\lambda} = -\alpha(1 - P\eta - \mu)AK^{\alpha-1}E^{\beta} + \rho$, but we make $\varepsilon_{\phi} = \frac{\partial\phi / \phi}{\partial S / S} = \phi' \frac{S}{\phi}$, the

$\frac{\dot{S}}{S} = g_C(\omega - \gamma)$, in addition equation (3c) in

$AK^{\alpha-1}E^{\beta} = Y / K = (Y / E)(E / K) = \frac{1}{\eta}(E / K)$, thus solving for a new MRTS

$\frac{MP_K}{MP_E} = \frac{\alpha AK^{\alpha-1}E^{\beta}}{\beta AK^{\alpha}E^{\beta-1}} = \frac{P_K}{P_E} = \frac{1}{P}$, having $E / K = \beta / \alpha P$ we get $AK^{\alpha-1}E^{\beta} = \beta / \alpha P\eta$, so

taking the natural log and total differential of equation (3a) we get:

$-\sigma \frac{\dot{C}}{C} + (\delta\sigma - \delta)\frac{\dot{\phi}}{\phi} = \frac{\dot{\lambda}}{\lambda}$ and solving into the value we get

$-\sigma g_C+(\delta\sigma-\delta)\varepsilon_\phi g_C(\omega-\gamma)=-\alpha(1-P\eta-\mu)\beta/\alpha P\eta+\rho$, then we obtain the growth rate: $g_C=\dfrac{\beta(1-P\eta-\mu)/P\eta-\rho}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]}$

Appendix 2

Stability Analysis

The stability analysis in this paper is of a simplified general model, therefore we rewrite equations (3a) and (3c) as follows:

$$\frac{\partial H}{\partial C}=0\Rightarrow U_C(C,\phi)=\lambda \qquad \text{(B1)}$$

$$\dot{\lambda}=-\frac{\partial H}{\partial K}+\rho\lambda=\lambda[\rho-(1-P\eta-\mu_t)f_K(K,E)] \qquad \text{(B2)}$$

Where U_C is the marginal utility, and f_K is the marginal product of capital. Taking the total time difference of equation (B1) and substituting into (B2), we can then obtain:

$$\dot{C}=\frac{U_C}{U_{CC}}[\rho-(1-P\eta-\mu)f_K]-\frac{U_{C\phi}}{U_{CC}}\phi'\dot{S} \qquad \text{(B3)}$$

Then equation (2c) can be rewritten as follows:

$$\dot{K}_t=Y_t-C_t-P_tE_t-G_t \qquad \text{(B4)}$$

and the steady state $\dot{C}=\dot{K}=\dot{S}=0$, equation (B3) and (B4) can be rewritten as:

$$\rho=(1-P\eta-\mu)f_K] \qquad \text{(B5)}$$

$$C=Y-PE-G \qquad \text{(B6)}$$

In order to solve the economic system's long-term stable equilibrium (Jacobian) we take the differentials of equations (B3) and (B4) and obtain

$$J = \begin{vmatrix} \frac{\partial \dot{K}}{\partial K} & \frac{\partial \dot{K}}{\partial C} \\ \frac{\partial \dot{C}}{\partial K} & \frac{\partial \dot{C}}{\partial C} \end{vmatrix}_{\dot{K}=\dot{C}=0} = \begin{vmatrix} 0 & -1 \\ -\frac{U_C}{U_{CC}}(1-P\eta-\mu) f_{KK} & 0 \end{vmatrix} = \frac{U_C}{U_{CC}}(1-P\eta-\mu) f_{KK} < 0 \quad \text{(B7)}$$

From the above equation, the characteristic root show negative giving the presence of the saddle point.

Appendix 3

Rewriting the economic growth rate in Appendix I to solve the $g_C = \frac{\beta(1-P\eta-\mu)/P\eta-\rho}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]}$ and separate with different independent variables, X, in the economic growth rate g_C comparative static analysis can sort the following table:

INDEPENDENT VARIABLE (X)	$\partial g_c / \partial X$
ε_ϕ	$\frac{\partial g_C}{\partial \varepsilon_\phi} = [\beta(1-P\eta-\mu)/P\eta-\rho] \cdot -\{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]\}^{-2} \cdot (\delta\sigma-\delta)(\omega-\gamma) < 0$
σ	$\frac{\partial g_C}{\partial \sigma} = [\beta(1-P\eta-\mu)/P\eta-\rho] \cdot -\{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]\}^{-2} \cdot (1+2\varepsilon_\phi\delta\sigma\omega-2\varepsilon_\phi\delta\sigma\gamma-\varepsilon_\phi\delta\omega+\varepsilon_\phi\delta\gamma) < 0$
ρ	$\frac{\partial g_C}{\partial \rho} = \frac{-1}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]} < 0$
β	$\frac{\partial g_C}{\partial \beta} = \frac{(1-P\eta-\mu)/P\eta}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]} > 0$
P	$\frac{\partial g_C}{\partial P} = \frac{-\beta(1-\mu)/P^2\eta}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]} < 0$

η	$\frac{\partial g_C}{\partial \eta} = \frac{-\beta(1-\mu)/P\eta^2}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]} < 0$
μ	$\frac{\partial g_C}{\partial \mu} = \frac{-\beta/P\eta}{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]} < 0$
ω	$\frac{\partial g_C}{\partial \omega} = [\beta(1-P\eta-\mu)/P\eta-\rho]\cdot-\{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]\}^{-2} \cdot(\delta\sigma-\delta)\varepsilon_\phi < 0$
γ	$\frac{\partial g_C}{\partial \gamma} = [\beta(1-P\eta-\mu)/P\eta-\rho]\cdot\{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]\}^{-2} \cdot(\delta\sigma-\delta)\varepsilon_\phi > 0$
δ	$\frac{\partial g_C}{\partial \delta} = [\beta(1-P\eta-\mu)/P\eta-\rho]\cdot-\{\sigma[1+(\delta\sigma-\delta)\varepsilon_\phi(\omega-\gamma)]\}^{-2} \cdot(\sigma-1)\varepsilon_\phi(\omega-\gamma) < 0$