Science and Technology Trends
Greenhouse Gas Reduction and Climate Change

Greenhouse Gas Reduction Options: Towards a Climate Control Roadmap for Malaysia

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1. Introduction

It is generally acknowledged that greenhouse gas (GHGs) emissions into the atmosphere is the prime cause of climate related seasonal variations in temperature across planet (IPCC, 2007, 2011; Hansen et al., 2006; Nordhaus, 2008; Stern, 2007), which if allowed unabated shall destroy human civilization. Among the consequences of such a deleterious development is rising temperatures. Mean global atmospheric temperature rose by 14.1 °C over the period 1900-2015 (NASA, 2015). While projections on climate change have continued to grow, there is mounting evidence that climatic damage as a consequence of human activity is increasing the globe's vulnerability (Aldy, Barrett, & Stavins, 2003; Beckerman & Hepburn, 2007; Carter et al., 2006; Füssel, Toth, van Minnen, & Kaspar, 2003; JRC, 2013). Although global warming, particularly its potential speed and degree is still disputed as climatic consequences are affected by periods, country-based specificities (Keith, 2000; Kelly & Kolstad, 1999; Schimmelpfennig, 1996), that mean temperatures and sea water levels are rising is undeniable (Stern, 2007; IPCC, 2007; Bonfils et al., 2008; McKibbin & Wilcoxen, 2002; Nordhaus, 2001; Oreskes, 2004).

The direct impact of temperature rise and global warming are associated with climate change, including the deprivation of natural possessions, harm to national infrastructures and surroundings, health hazards facing humans, and devastation to the global economy (Al-Amin & Leal Filho, 2014). Current projections of climate change and global warming identify the significance of environmental eminence and sustainable economic development, which has encouraged efforts to set up an equilibrium between environmental excellence and economic expansion. Governments recognize this information and that is why 195 members of the United Nations signed the Paris Declaration in 2015 to cap temperature rise to 1.5 over the period 2010-2100 (UNFCCC, 2015). Thus, it is apparent that if existing human activity is left unregulated, temperatures would rise over the next century to between 3.0 °C and 4.0 °C, which almost certainly will elevate the earth's vulnerability to climatic catastrophes (Carter et al., 2006; IPCC, 2007; Nordhaus, 2008; Weitzman, 2007).

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However, several countries are struggling to introduce and maintain a vigorous balance between ecological order and sustainable economic development. These countries require the right instruments for economic investigation to envisage, prepare, and evaluate alternative methods taking account of their specificities, as well as the funds to execute them (Nordhaus, 2008; Stern, 2007)[1]. Indeed, developing countries are lagging behind in putting together strategies to meet sustainable climate emission thresholds, and hence, have not managed to follow the stiff milestones required to meet the goals of the Paris Declaration (UNFCCC, 2015), which include carbon cutbacks, and substitution of fossil fuels with renewable sources of energy, and introduction of backstop technologies.

Being an upper middle income country, Malaysia is no exception. While the INDC was developed through participatory process under an inter-ministerial/agencies working group, which brought 20 national policies in the remit, the stakeholder consultation group realized that there exists major barriers over their implementation, including high costs and capacity constraints. Malaysia developed "A Roadmap of Emissions Intensity Reduction in Malaysia in 2014," which outlined opportunities across various sectors to meet the reduction target of 45% emissions intensity reduction of GDP as contained in the 11th Malaysia Plan. The major challenges facing the country are: unclear technology cost, fragmented institutional framework, LULUCF legacy status related to peat-land management, and the weak national adaptation plan. The country is under pressure to incorporate climate mitigation strategies into development, viz., in energy, industrial processes, water, waste management and agriculture (INDC, 2015).

Nevertheless, it is important to recognise that effective governance of climate mitigation is critical to meet the government's ambition to meet its INDC targets. Moreover, Malaysia is considered a leader among the developing countries in meeting development targets. Malaysia's total GHG emissions represent about 0.6% of global emissions in 2011. The emission intensity per GDP was 0.41 tCO_2eq/RM1000 for that year, which requires a reduction of about 23% from 2005 values (INDC, 2015). The total GHG emissions, including removals by LULUCF sinks is about 0.05% of global emissions. Through public and private sector initiatives, the country prioritising allocation of financial resources for the implementation of climate change programmes as since the Ninth Malaysia Plan (2006-2010), Malaysia has started initiatives to increase the share of use of non-fossil fuel energy. The climate-related policies are nationally implemented along with national priorities such as poverty eradication, improving quality of life and development.

While there is concern over climate change, including the surfacing of limits to growth arguments that claim that the world cannot absorb too much of economic expansion (which was originally advanced by Meadows et al. (1972)), Stern (2007) and Nordhaus (2008) have given us hope by providing convincing evidence that the solution lies with switching its propellants from environment unfriendly to environment-friendly energy. We analyze the greenhouse gas reduction target and abatement costs in this study under two scenarios compared to the no intervention scenario for Malaysia. The purpose is to offer alternatives that can assist Malaysia meet the objectives of the Paris Declaration, which is to cap temperature rise over the next century to 1.5 °C and follow-up with Marrakech initiatives to meet the emission reduction common strategies by the INDCs.

1 Two major economics of climate change projections are available, both of which are based on global options (Nordhaus, 2008; Stern, 2007).

2. Methodology

This study uses a multidisciplinary top-down dynamic model with a detailed description of the 'Climate and the Ecology' notions combining economic theory and earth science concepts, which is arguably the best method available to model emission changes in an economy at the aggregate level. The modelling starts with a detailed description of climatic variables that are deemed responsible for climate change and environmental damage with a focus on abatement costs, backstop technology, carbon concentration (e.g. ppm[2] under 900) over the next 100 years and temperature cap below 1.5 °C to analyse the long-run climate damage effects[3]. The study model considers three scenarios. The first is the business as usual scenario. The second uses Malaysia's INDC submitted to COP 21 with an update of COP 22 until 2030, and subsequent developments if no additional interventions are made to reduce carbon emissions further. The third scenario focuses on initiatives necessary to cap temperature rise to 1.5 °C over the century. Thus, fundamental variables, such as the rate of social time preference, initial growth rate of backstop technology, level of total factor productivity, marginal atmospheric retention rate, emissions-output ratio, and discount rate are used in order to visualize long-run effects. The model also considers population growth rate, capital stock, fossil fuel stock, and cumulative improvement of energy efficiency.

There are two major 'decision variables' in the 'Climate and the Economy' model that are considered, which represent: (a) rate for physical capital (*K(t)*) accumulation (e.g. equation 1) as a function of investment (*I(t)*) with depreciation rate (δ_k) to substitute with green growth in future, and (b) rate of emissions control in the production function, *Q(t)* (e.g. equation 2) with factor productivity, *A(t)* for GHGs over time with a damage, $\Omega(t)$ and abatement cost, $\Lambda(t)$ functions.

$$K(t) = I(t) + (1-\delta_k)K(t-1) \quad (1)$$

$$Q(t) = \Omega(t)[1-\Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma} \quad (2)$$

The two decision variables are closely linked with temperature limit over time (e.g. equations 3 and 4), carbon-saving and capital accumulation for green financing. Capital accumulation is endogenously determined by optimizing the flow of vulnerability over time and carbon-saving is endogenously linked with the abatement or alternative green technology adoption, and is modelled as reducing the ratio of carbon emission to the production process. Production is determined using CES and CET productivity functions, which takes the form of either carbon-based or non-carbon-based energy in output production ratio over the long run. However, technology substitution and abatement costs will fall over time as a consequence of the switch from carbon-based to non-carbon-based technologies as the conventional energy option would become expensive due to rigorous climatic policies.

$$T_{AT} = T_{AT}(t-1) + \zeta_1\{F(t) - \zeta_2 T_{AT}(t-1) - \zeta_3 T_{AT}(t-1) T_{LO}(t-1)\} \quad (3)$$

$$T_{LO}(t) = T_{LO}(t-1) + \zeta_4\{T_{AT}(t-1) - T_{LO}(t-1)\} \quad (4)$$

The model projects economic growth for Malaysia by considering national growth, investment in capital, marginal damage of climate change, marginal cost of controlling damage, and backstop technologies and abatement costs against related climatic effects and vulnerabilities based on three scenarios, viz., (a) climate change with no abatement (b) climate change under Malaysia's INDC committed to cop until 2030 but no further reduction in carbon emissions, and (c)

2 PPM refers to parts particulate matters.

3 This model runs using mathematical optimization with geometric algebraic modelling system (GAMS) programming.

concentrations below doubling rate over next 100 years targeted at meeting 1.5 °C temperature rise cap over the next century[4].

2.1. Study Area and Adoption of Empirical Downscaling

Malaysia is the study area with climate data obtained from the four locations of Kuching (Sarawak) and Kota Kinabalu (Sabah) in East Malaysia, and Kuantan (Pahang) and Petaling Jaya (Selangor) in West Malaysia (MMD, 2009), which are located at 1°25'0"N and 110°20'0"E, 5°58'50˝N and 116°4'37˝E, 3°48'0"N and 103°20'0"E and 3°5'0"N and 101°39'0"E respectively. The data used in this study abstracts from the global level to the local level through empirical downscaling exercise and applied using a national observational data set to predict the annual cycle of observed (a) temperatures and climate effects, (b) GHGs warming parameters, and (b) large-scale unforeseen climate shocks. The predicted annual cycle is downscaled and adjusted by considering (i) national emission, (ii) net damage, (iii) climate vulnerability, (iv) abatement cost, and (v) emission control[5]. The annual cycle of observed parameters of predicted variables (e.g. climate vulnerabilities with their likely impacts) and predictor variables (e.g. yearly average circulation parameters) are closely followed by the probability of unforeseen climate shocks in future.

2.2. Damage Considerations

The damage estimation in the 'Climate and the Economy' model assumes that climate changes are proportional to the output or national economic production process and polynomial functions of mean temperature fluctuation (e.g. equation 5). Aggregate climate change is a function of damages over time, and hence, it is a function ($\Omega(t)$) of climatic effects and fraction of output, climatic vulnerability parameters ($\psi 1$, $\psi 2$) and fluctuation of mean atmospheric temperatures (°C), TAT(t) from 1990. The climate change is estimated with tangible and intangible losses based on monetary value and the utility function with the GHG emission effects. Thus, moving intangible losses of climate change from the production function to the utility function shall enhance the prospects for sustainable economic growth. Lastly, climate change estimation is evaluated in this study after factoring in the emission reduction schedules contained in Malaysia's INDC for UNFCCC (2015)[6].

$$\Omega(t) = 1/[1+\psi_1 T_{AT}(t)+\psi_2 T_{AT}(t)^2] \quad (5)$$

2.3. The Discount Rate and Social Preference

The 'Climate and the Economy' model uses the neoclassical economic growth theory assumptions where sustainable economic growth is optimized under the constraint of a discount rate (ρ) of 1.5% to translate future costs into present values. The discount rate over time (R(t)) is assessed in the present and future as goods and takes a monetary value (e.g. ringgit Malaysia (MYR)) with a net inflation rate of 3-4 per cent per annum (e.g. equation 6). The model is assumed to have a social preference of sustainable economic growth as defined by a social welfare function that ranks different paths of future growth that are constrained by both climate and economic relationships.

$$R(t) = (1+\rho)^{-t} \quad (6)$$

4 The full details of the modeling equations and procedures are presented in Appendix 1.

5 The scenario assumed that neighbouring countries follow the recommendations on reducing carbon emissions made in COP agendas. Otherwise, the projections will be affected as the environment－being a global common－is permeable, and hence, emissions from the neighbours can diffuse into Malaysia.

6 A separate scenario using existing patterns of production to project climate damage over the period 2010–2105 can be found in Al-Amin et al. (2015).

2.4. Data

Two types of data are used in this study, viz., (a) macroeconomic data, and (b) climate and meteorological data. The macroeconomic data is derived from Malaysia's national accounts, including the Department of Statistics (DOS), and Economic Planning Unit (EPU) (DOS, 2010, 2013a, 2013b; Unit, 2010), while the climate and meteorological data are derived from Malaysia's Metrological Department (MMD) (MMD, 2009; 2015). Macroeconomic data from 2010 to 2015 is used to derive the macro baseline estimation in 2015, while meteorological data is based on two monsoons and four seasons from 1969 to 2007. National temperature fluctuations are derived from historical records from 1969 to 2015 to project changes in GHGs (280–927 parts per million (ppm)) concentrations to derive the climatic baseline 2015 [7].

The study also used for calibration:

(i) temperature fluctuations ranges between 0.8 °C and 1.5 °C

(ii) carbon concentration (CO_2) with a maximum limit of 650 ppm level of variations until 2050

(iii) maximum carbon concentration in upper and lower strata of 950 ppm

(iv) equilibrium temperature impact in the national level of 26 °C

(v) initial lower stratum temperature change of 0.8 °C

(vi) final atmospheric temperature change from 1900

(vii) optimal abatement costs from guidelines defined in IPCC (2007; 2011), Nordhaus (2008) and Stern (2007).

However, some modifications have been made to the data from MMD (2019, 2015), IPCC (2007; 2011), Nordhaus (2008) and Stern Review (2007) to meet the present scope of the study.

3. Results and Findings

This study examined three scenarios on climate change mitigation for Malaysia, namely, (a) baseline case with no climate control interventions (Scenario 1), (b) Malaysian INDC pledged to UNFCCC (2015) until 2030 (Scenario 2)[8], and (c) planned climate control intervention to cap global temperature rise to 1.5 °C over the next century and carbon concentration to a maximum of 650 ppm from the 1990 level (Scenario 3). Figure 1 presents carbon emissions projections by the three scenarios over the years from 2010 to 2100. Scenario 1 indicates a rapid increase in carbon emissions from 188 million toe in 2010 to 248 million toe in 2050 and 419 million toe in 2100 with existing environmental practices (Scenario 1). Carbon emissions would decline from 188 million toe in 2010 to 112 million toe in 2050 and to 83 million toe in 2100 once Malaysia implements its climate change commitments to UNFCCC (2015) (Scenario 2).

The study finds that carbon emissions would fall from 188 million toe in 2010 to 163 million toe in 2050 and to 77 million toe in 2100 under the planned climate control framework (Scenario 3). However, the pace of emission reduction of the second and third scenarios are dissimilar, though the pace of the fall is almost similar. The findings indicate that the final outcomes in carbon emission reduction of scenarios second and third are close,

7 Details of the southwest monsoon and northeast monsoon that influences Malaysia's climate from May to September, and from November to February can be found in Al-Amin and Leal Filho (2014).

8 Malaysia planned to reduce greenhouse gas emissions intensity by 45% by 2030, 35% on an unconditional basis and a further 10% upon receipt of climate finance, technology transfer and capacity building from the developed countries (UNFCCC, 2015). Malaysia contributed 0.62% of global emissions with an average of 6.7 metric tons/person of carbon emission, which raised mean surface temperature by 0.14 to 0.25 °C every 10 years.

Figure 1. Carbon emissions, three scenarios

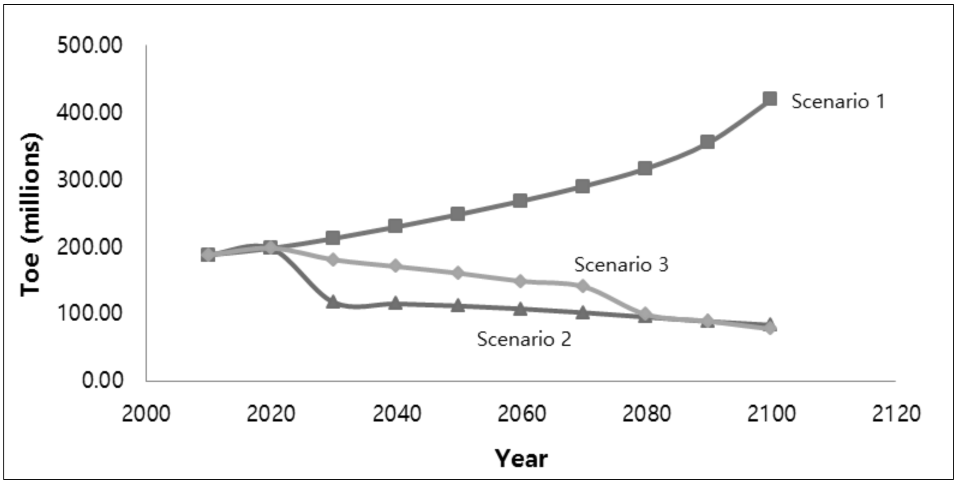
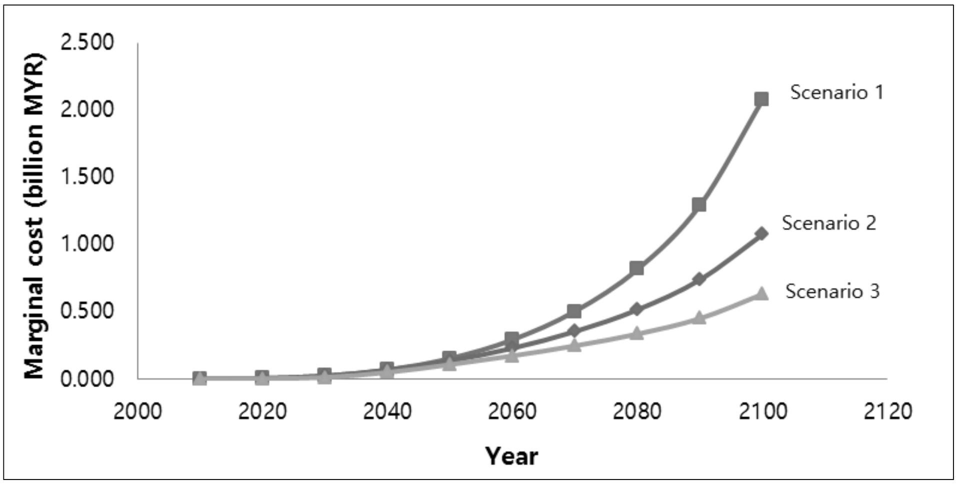


Figure 2. Marginal climate damage cost, three scenarios



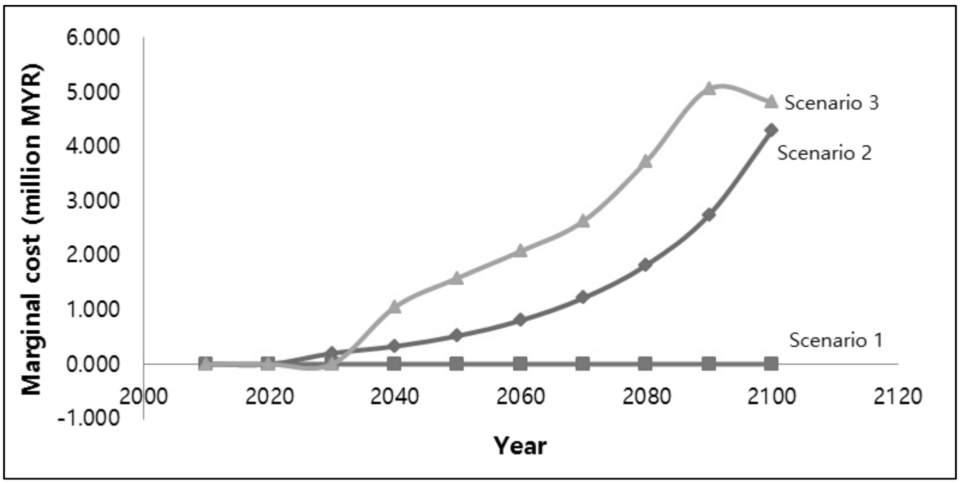
but the nature and emission fluctuations from 2020 to 2035 are quite dissimilar. The second scenario shows better emission reduction outcomes over the period 2030 to 2080, while the third scenario shows better outcomes over the period 2090 to 2100.

To understand better the second and third scenarios, the important sub-components of carbon emission reduction actions under various marginality conditions require evaluation. Figures 2, 3 and 4 present the sub-components of carbon emission reduction actions by marginal damage cost, marginal abatement cost and marginal control rate for the three scenarios over the period 2010-2100. The elasticity of the marginal utility of consumption with a pure rate of social time preference, discount factor, capital stock and investment projections are estimated to capture the relevant and real long-term projections. The marginality findings indicate differences in relative costs trends over the period 2010-2100.

Figure 2 shows marginal climate damage cost of the three scenarios from 2010 to 2100, which is estimated using temperature and carbon concentration cap. The marginal climate damage costs show that at each level of climate action higher additional costs are generated in the second scenario due to additional costs that will have to be borne to reduce of climate damage from 2020 to 2100. The costs in Scenario 2 increase faster than Scenario 3 after 2050 to almost double by 2100. Marginal climate damage cost is the highest in Scenario 1 followed by Scenario 2 and Scenario 3 over the period 2010-2100. The actual climatic damage cost will amount to MYR 14,257 million in Scenario 1, which will fall to MYR 3,789 million in Scenario 2 and MYR 1,407 million in Scenario 3. Thus, the marginal damage cost estimations indicate that the third scenario is more economic than the second scenario, particularly after 2050 onwards.

Figure 3 presents the marginal abatement cost under the three scenarios. The projections in Scenario 2 is based on emissions intensity falling by 45% by 2030 with the assumption that Malaysia will apply the latest greening technology with suitable preferences targeted at emission control with adequate climate change financing for the first 35% reduction in emissions, and capacity building support from the developed countries for the remaining 10% (UNFCCC, 2015). The findings indicate marginal abatement costs and relative outcomes for Scenarios 2 and 3 over the period 2010 to 2100. The marginal abatement cost from 2020 to 2025 and 2100 under Scenarios 2 and 3 are similar. However, the results are quite dissimilar from 2035 to 2090. Importantly, it shows that the abatement cost in Scenario 2 is relatively modest and there is relatively less increase in trend terms compared to Scenario 3. Thus, the marginal abatement costs of Scenario 2 shows the best outcome. The cumulative marginal abatement cost for Scenarios 1, 2 and 3 will be nil, MYR 12 million and MYR 21 million respectively. The total abatement costs[9] for Scenarios 1, 2 and 3 will then be nil, MYR 14,350 million, and MYR 14,645 million.

Figure 3. Marginal abatement costs, three scenarios



9 Total abatement cost is derived by multiplying the marginal abatement cost with cumulative damage measured in toes.

Figure 4. Marginal control rates, three scenarios

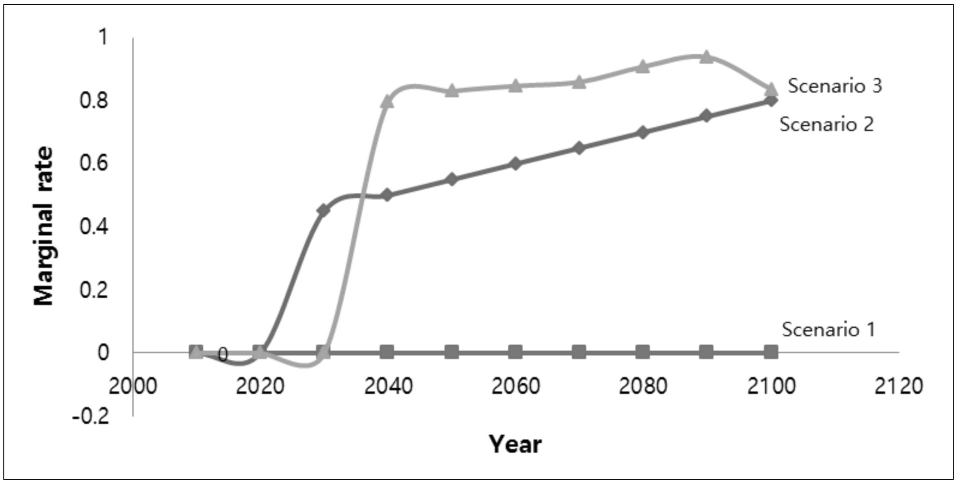


Figure 4 presents the marginal control rate from 2010 to 2100 under the three scenarios. The findings indicate similar marginal control rates in both Scenarios 2 and 3 over the period 2010 and 2100. However, the marginal control rates diverge over time, particularly from 2025 to 2095. Thus, the control rates in scenario is increasing faster than the control rates in Scenario 3 2020 to 2035. However, the control rates in Scenario 3 increase faster than in Scenario 2 from 2035 to 2095. Notably, under the COP 21 proposal carbon emissions would fall gradually and at a faster pace from 2035 to reach the commitment made to UNFCCC by the middle of century. However, the emission scenarios cannot alone indicate the best options, and hence, we examine emission intensities and marginal cost contractions in the next sections.

Figures 5, 6 and 7 present emission intensities under Scenarios 1, 2 and 3, respectively, estimated on the basis of per-capita and per-output estimations over the period 2010 to 2100. The carbon intensity per-output is higher than per-capita. The findings indicate a declining rate over time both for per-capita and per-output basis scenarios in the second scenario. Also, emission intensities per-output shows a more rapid decline compared to emission intensities per-capita scenarios, particularly from 2030 after Malaysia finishes with the implementation of its INDC commitment to UNFCCC. Under Scenario 3, emission intensity for per-output declines faster than emission intensity per-capita. These findings call into question Malaysia's INDC commitment to the UNFCCC given that the measurements used ere on a per-capita basis rather than per-output basis.

This study also considered climate control options by using emission intensities in the economy and limiting the concentration of GHGs by COP emission reduction strategies targeted at averting climate damage over the long run with planned climate control measured as optimal condition. The findings using the emission intensity option and limiting the concentration of GHGs are shown in Figures 8 and 9. The outcomes from the simulations show that emission concentration is expected to rise to a maximum of 899 ppm in scenario 1,850 ppm in Scenario 2, and 851 ppm in Scenario 3. However, carbon concentration is expected to rise to a maximum level of 390 ppm in 2020, 677 ppm in 2050 and 1087 ppm in 2100, 390 ppm in 2020, 677 ppm in 2050 and 881 ppm in 2100 in Scenario 2. The findings indicate similarities in controlling emissions by the end of 2100. However, yearly controlling rates yearly in the period from 2035 to 2080 are more intense in Scenario 3 compared to Scenario 2.

Figure 5. Emission intensity, Scenario 1

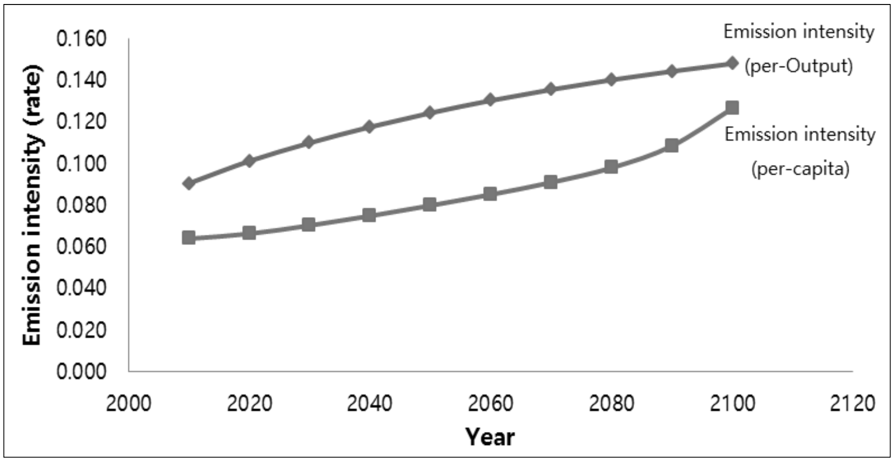


Figure 6. Emission intensity, Scenario 2

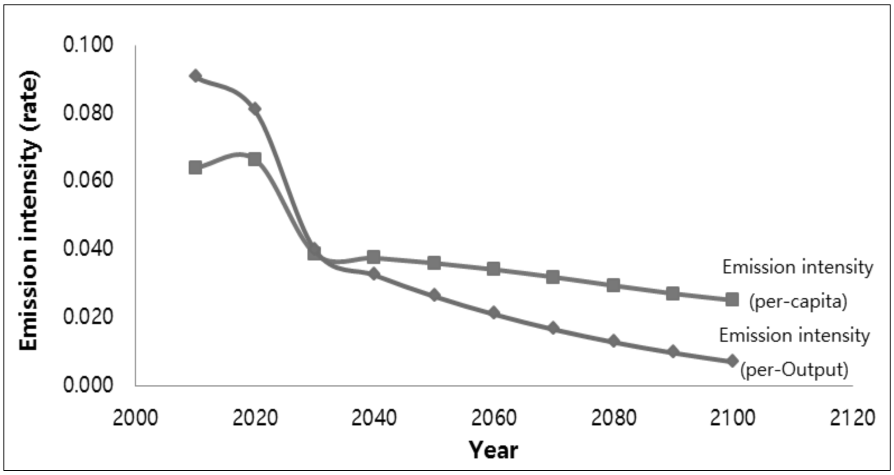


Figure 7. Emission intensity, Scenario 3

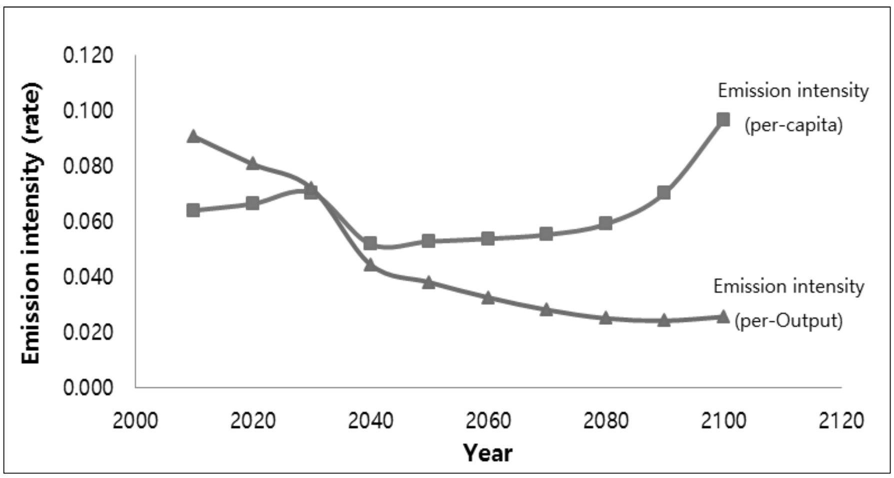


Figure 8. Emission control intensity, three scenarios

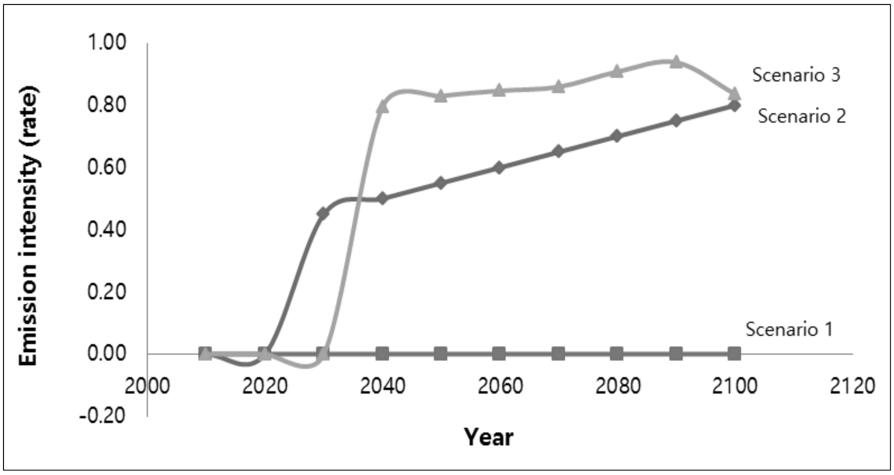
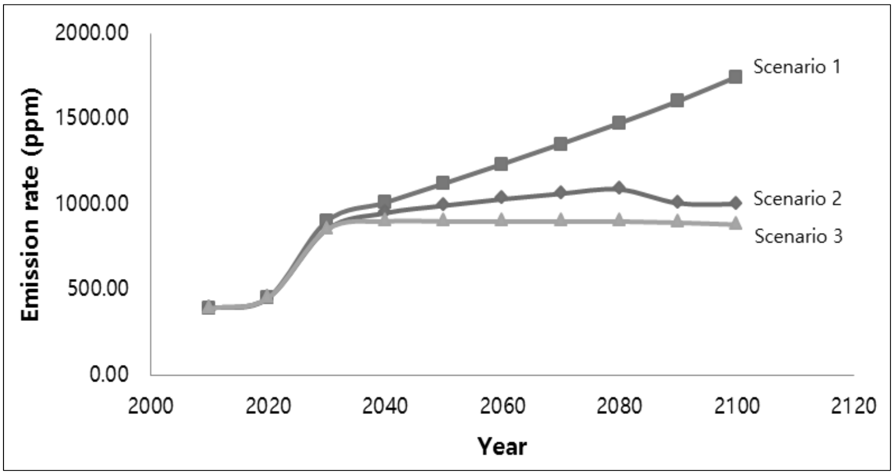


Figure 9. Emission control rates (ppm), three scenarios



Overall, both Scenarios 2 and 3 provide a declining projection trend of emissions over time. However, there are differences in the intensity and pace of emission fluctuations, and abatement costs between the two scenarios. Scenario 3 is the best alternative when the emphasis is on reducing emission intensity, but Scenario 2 shows lower abatement costs. Since the objective is to lower emission intensity efforts must be taken to stimulate the development of backstop technologies, which would inevitably raise the unavoidable abatement costs.

4. Conclusions

This study sought to examine Malaysia's climate mitigation scenarios over the period from 2010 to 2100 based on the existing no intervention scenario and two proposals that have been presented in recent climate policy dialogues, namely, Malaysia's INDC submitted to UNFCCC, planned climate control intervention proposal to cap global temperature rise to 1.5 °C and carbon concentration to a maximum of 650ppm from the 1990 level. On the one hand, the cumulative damage of climatic change over the period 2010-2100 will amount to 2,722 mtoe under the present climate regime (Scenario 1); 1,203 mtoe under Scenario 2, and 699 mtoe under Scenario 3. On the other hand, cumulative carbon concentration over the period 2010-2100 will amount to 11,912 ppm under the present climatic regime, which will fall to 9,714 ppm and 8,592 ppm respectively under Scenarios 2 and 3 respectively. Since the total abatement costs for Scenario 2 of MYR 14,351 million, is close to that of Scenario 3 of MYR 14,645 million, the third proposal is clearly the best. The results are not only important to define Malaysia's climate change mitigation roadmap, but they also offer lessons for other countries seeking to do the same. The findings enhance current knowledge on: (a) setting up long-term national climate change mitigation policies, and (b) plugging gaps in our understanding of impact, (including costs) of the different climate control options.

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APPENDIX I

Mathematical statement of the study model:

$$W = \sum_{t=1}^{T\max} u\left[c(t), l(t)\right]R(t) \quad (1)$$

$$R(t) = (1+\rho)^{-t} \quad (2)$$

$$U\left[c(t), L(t)\right] = l(t)[c(t)^{1-\alpha} / (1-\alpha) \quad (3)$$

$$Q(t) = \Omega(t)[1-\Lambda(t)]A(t)K(t)^{\gamma} L(t)^{1-\gamma} \quad (4)$$

$$\Omega(t) = 1/[1+\Pi_1 T_{AT}(t) + \Pi_2 T_{AT}(t)^2] \quad (5)$$

$$\Lambda(t) = \pi(t)\theta_1(t)\mu(t)^{\theta_2} \quad (6)$$

$$Q(t) = C(t) + I(t) \quad (7)$$

$$C(t) = C(t)/L(t) \quad (8)$$

$$K(t) = I(t) + (1-\delta_k)K(t-1) \quad (9)$$

$$E_{Ind}(t) = \sigma(t)[1-\mu(t)]K(t)^{\lambda} L(t)^{1-\lambda} \quad (10)$$

$$CCum \leq \sum_{t=0}^{T\max} E_{Ind(t)} \quad (11)$$

$$E(t) = E_{Ind}(t) + E_{Land}(t) \quad (12)$$

$$M_{AT}(t) = E(t) + \phi_7 M_{AT}(t-1) + \phi_{11} M_{UP}(t-1) \quad (13)$$

$$M_{UP}(t) = \phi_{11} M_{AT}(t-1) + \phi_{11} M_{UP}(t-1) + \phi_{11} M_{LO}(t-1) \quad (14)$$

$$M_{LO}(t) = \phi_{12} M_{UP}(t-1) + \phi_{12} M_{LO}(t-1) \quad (15)$$

$$F(t) = \eta\left\{\log_2[M_{AT}/M_{AT}(1900]\right\} + F_{EX}(t) \quad (16)$$

$$T_{AT} = T_{AT}(t-1) + \zeta_1\{F(t) - \zeta_2 T_{AT}(t-1) - \zeta_3 T_{AT}(t-1)T_{LO}(t-1)\} \quad (17)$$

$$T_{LO}(t) = T_{LO}(t-1) + \zeta_4\{T_{AT}(t-1) - T_{LO}(t-1)\} \quad (18)$$

$$\prod(t) = \varphi(t)^{1-\theta_2} \quad (19)$$

Variable Definitions and Units (endogenous variables marked as asterisks):

A(t) = total factor productivity (TFP) in units)

**c(t)* = capita consumption of goods and services (RM per person)

**C(t)* = consumption of goods and services (RM)

$E_{Land}(t)$ = emissions of carbon from land use (carbon per period)

*$E_{Ind}(t)$ = industrial carbon emissions (carbon per period)

**E(t)* = total carbon emissions (carbon per period)

**F(t), FEX(t)* = total and exogenous radiative forcing

**I(t)* = investment (RM)

**K(t)* = capital stock (RM)

$L(t)$ = population and labor inputs (number)

*$M_{AT}(t)$, $M_{UP}(t)$, $M_{LO}(t)$ = mass of carbon in reservoir for atmosphere, upper oceans, and lower oceans (carbon, beginning of period)

*$Q(t)$ = net output of goods and services, net abatement and damages (RM)

T = time (decades from 2010–2020, 2021–2030, ...)

*$T_{AT}(t)$, $T_{LO}(t)$ = global mean surface temperature and temperature of lower oceans (°C increase from 1900)

*$U[c(t), L(t)]$ = instantaneous utility function (utility per period)

*W = objective function in present value of utility (utility units)

*$\Lambda(t)$ = abatement-cost function (abatement costs as fraction of world output)

*$\mu(t)$ = emissions-control rate (fraction of uncontrolled emissions)

*$\Omega(t)$ = damage function (climate damages as fraction of world output)

*$\varphi(t)$ = participation rate (fraction of emissions included in policy)

*$\prod(t)$ = participation cost markup (abatement cost with incomplete participation as fraction of abatement cost with complete participation)

*$\sigma(t)$ = ratio of uncontrolled industrial emissions to output

$CCum$ = maximum consumption of fossil fuels (tons of carbon)

γ = elasticity of output with respect to capita (pure number)

δ_k = rate of depreciation of capital (per period)

$R(t)$ = social time preference discount factor (per time period)

T_{max} = length of estimate period for model

η = temperature-forcing parameter (°C per watts per meter squared)

ϕ = parameters of the carbon cycle (flows per period)

σ = pure rate of social time preference (per year)

$\theta_{1....2}$ = parameters of the abatement-cost function

ζ = parameters of climate equations (flows per period)