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Impact of NILM-based energy efficiency on environmental degradation and kuznets hypothesis analysis

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ABSTRACT

Nonintrusive load monitoring (NILM) breaks down the aggregated electrical consumption data into individual appliances. The feedback of disaggregated data to the consumers enables awareness and behaviour change to conserve electricity, consequently reducing CO_2 emissions to the environment. However, the limited literature regarding the impact of NILM and Kuznets hypothesis (EKC) analysis on CO_2 emissions reduction has restricted policymakers in developing effective mitigation measures. This work aims to assess the impact of NILM-based based energy efficiency (EE) on environmental improvement. The combined approach of scenario simulation and EKC analysis was adopted to gauge the effectiveness of NILM that leads to sustainable development. The monotonically increase relationship between environmental degradation and economic growth in Malaysia without peaking beyond 2030 implies that the current mitigation measures and policies imposed may not effectively cope with the future power demands for sustainable development. NILM-based EE measures could be a great potential for reducing CO_2 emissions by 10.2%. The inverted-U curves and reduced turning points of environmental degradation from the income level of USD 20,063.36 to USD 16,305.19. Therefore, NILM approach can accelerate sustainable development with lower environmental deterioration. The work may beneficial to policymakers to analyse the impact and effectiveness of mitigation measures quantitatively.

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1. INTRODUCTION

Economic growth needs sustainable development with a balance between economic development and environmental conservation [1]. It is principally to maximize the benefits of economic development while minimizing or at least slowing down the environmental degradation without compromising the benefits of future generations. However, economic growth and environmental degradation could often be conflicting [2]. Since the 1980s, Malaysia has gained rapid industrialization with population growth. Therefore, the escalating electricity demand causes environmental degradation as the economy grows. As reported, the electricity consumption marked 13,152 ktoe in 2018, which is 4.33% higher than in 2017 [3]. Of which both residential (21.2%) and commercial (32.3%) sectors contribute 53% of electricity consumption in Malaysia [4] and 60% electricity in the world [4].

However, economic growth and resource consumption have caused CO_2 emissions with environmental deterioration [5]. Sustainable development needs strategic planning of policies and measures to mitigate greenhouse gases (GHG) emissions. For instance, United Nations Framework Convention on Climate Change Conference (UNFCCC) has mandated the action taken by governments to reduce CO_2 emissions for a sustainable and low-carbon society [6]. Furthermore, the fifth assessment report (AR5) of the intergovernmental panel on climate change (IPCC) affirmed that the acceleration of global warming due to CO_2 emissions from anthropogenic activities [7].

As pledged to UNFCCC, Malaysia needs to reduce 45% GHG emissions in terms of carbon intensity by 2030, relative to the 2005 level. Numerous mitigation policies have been implemented, including energy efficiencies (EE) and renewable energy (RE). Load monitoring approaches can obtain detailed electricity consumption data in the building sector. Nonintrusive load monitoring (NILM) is a cost-effective approach of detecting of the aggregated data from smart meters and inferring the disaggregated appliance consumption [8], [9]. Many use cases of NILM supporting the EE measures include the itemized and breakdown consumption information, demand-side management (DSM/DR) and peak load shaving, to name a few. The studies estimate that 20% of electricity consumption could be conserved [4], [10] NILM has opened up electricity conservation opportunities through consumers' awareness and behaviour change to shrink the release of CO_2 emissions to the environment [11].

Various approaches forecast CO_2 emissions from different contexts such as industrial sectors, provincial-level and national level, to assist policymakers in coping with the future environmental trend. Numerous predictive models, such as the IPAT model, STIRPAT model, and environmental kuznets curve (EKC) hypothesis, are studied to forecast environment degradation and environment-economic growth nexus [12]. As initiated by Crossman *et al*. [13], the EKC hypothesis is then revised by Roberts *et al*. [14] with an inverted U-curve relationship between CO_2 emissions and economic development, as depicted in Figure 1. There are three stages of economic development, i.e. (1) pre-industrial and (2) post-industrial, represented by developing countries and developed countries, and (3) industrial economies as the transition stage with a turning point [15].

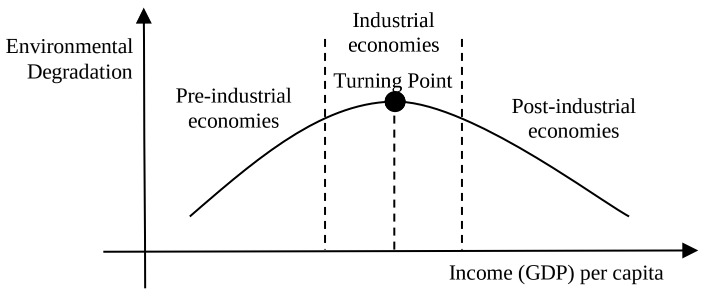

Figure 1. Inverted U-shaped curve of EKC hypothesis

EKC became a hot research topic among scholars [16]-[18], as policymakers potentially use the EKC curve and turning point as empirical evidence for sustainable development planning. In view of the current escalating trend of CO_2 emissions without peaking and the pledge of COP21 for environmental protection, Malaysia has implemented numerous mitigation policies and measures. Therefore, it is crucial to assess the effectiveness of the mitigation measures of CO_2 emissions reduction. However, the limited literature regarding the impact of NILM-based EE and EKC analysis on CO_2 emissions reduction has restricted policymakers from developing strategic planning and effective measures. Few studies in the literature are confined only to the scope of using NILM-based EE measures to conserve electricity consumption [19]-[21], but without quantifying its impact on CO_2 emissions.

To the best of our knowledge, the combined approach of scenario simulation and EKC hypothesis test to study the impact of the NILM-based EE measure on environment degradation is relatively unexplored among the researchers. The scenario simulation allows the adjustment of variables used for different “what if” scenarios to analyse and assess the target policy or measure. On the other hand, the EKC hypothesis is used to position the nation’s economic development stage with a turning point for monitoring and evaluating the effectiveness of policies or measures. NILM-based EE is a potential measure for its impact on environmental degradation by reducing electricity consumption. In the following parts of this study, sections 2 and 3 discuss the methodology and analysis of results, respectively, followed by conclusions.

2. RESEARCH METHOD

This work has proposed a combined scenario simulation and EKC hypothesis approach to quantify the impact of NILM-based EE measures on environmental improvement. The annual time series data of the identified predictor variables from technological innovations, demographic and socioeconomic are used to derive the statistical-based predictive models in this study. The regression models are used to forecast CO_2 emissions. Secondly, scenario simulation is conducted to evaluate the impact of NILM on environmental degradation in 2019-2030 based on EKC analysis. The software used includes python and microsoft excel with data analysis. Figure 2 depicts the procedure in this work.

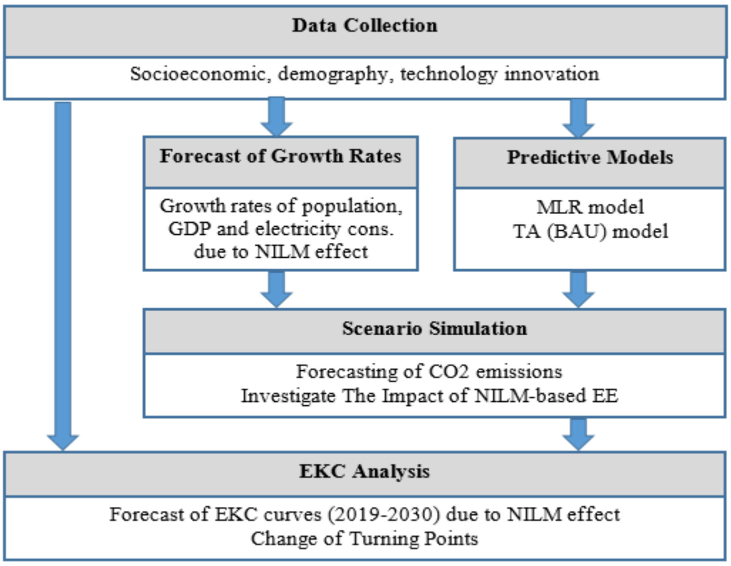

Figure 2. The procedure of the forecasting process

2.1. Data collection

In this work, annual time series data of 1996 to 2018 were adopted from world bank open data [22] and Malaysia energy commission [23]. The total CO_2 and per-capita CO_2 emissions are adopted as the responding variables. The identified predictors include electricity consumption (per-capita in kWh), GDP, FDI net inflows, R&D expenditure, Fossil generation and RE generation. The dataset is pre-processed with a normality test and stepwise regression modelling.

2.2. Predictive models of CO_2 emissions

The regression-based predictive models of CO_2 emissions are derived in this study with the identified predictors. Multiple linear regression (MLR) and trend analysis (TA) models have been developed and eventually validated to forecast CO_2 emissions. A detailed description of the modelling procedure can be found in the authors' paper [24].

2.3. Empirical study of EKC hypothesis in Malaysia

EKC hypothesis is adopted to analyse the current status and forecast Malaysia's nexus relationship between economic development and environmental degradation. Consequently, it evaluates the effectiveness of mitigation policies and measures for strategic planning. Several works used a similar approach to evaluate renewable energy and tourism impact on environmental degradation [25], [26]. This study uses the forecasted CO_2 emissions from the scenario simulation to quantify the impact of NILM-based EE measures in terms of emissions saving, EKC curve and the turning point for sustainable development. The nexus relationship is modelled by the modified-form model [27]. Therefore, the Malaysia EKC model can be re-written as:

$$CO2.PC = B_0 + B_1 GDP.PC + B_2 GDP.PC^2 + B_3 GDP.PC^3 + \varepsilon_{it} \quad (1)$$

Where $CO2.PC$ is CO_2 emissions (per capita); $GDP.PC$ *is* GDP (per capita); B_0 is constant; B_1~B_3 are the explanatory variables' coefficients; and ε is the standard error term. The general model of (1) is used to test several forms of environment-economic development relationships include linear, quadratic and cubic functions, as listed in Table 1.

Table 1. Environment-economic development relationship for EKC hypothesis

	B_1	B_2	B_3	Relationship
1	0	0	0	Flat pattern or no relationship
2	> 0	0	0	Monotonic increase relationship (linear)
3	< 0	0	0	Monotonic decrease relationship (linear)
4	> 0	< 0	0	Inverted-U-shaped relationship (quadratic) The turning point TP of EKC is obtained as $-B_1/2B_2$
5	< 0	> 0	0	U-shaped relationship (quadratic)
6	> 0	< 0	> 0	N-shaped relationship (cubic)
7	< 0	> 0	< 0	Opposite to the N-shaped (cubic)

3. RESULTS AND DISCUSSION

3.1. Predictive modelling results

Figure 3 shows the generated report of regression estimation results by graphical user interface (GUI) software written in Python. The predictors of both per-capita GDP and per-capita kWh show strong evidence against the null hypothesis ($i.e. H_0$: $B_0 = B_1 = B_2 = B_3 = 0$) which have positive correlations with CO_2 emissions. The coefficient of determination adjusted R2 is 0.959 signifies that the identified predictors could explain 95.9% variation in CO_2 emissions. From the t-statistic result, p-values of 0.004 and 0.0000 for GDP.PC and kWh.PC predictors have confirmed their significance to the model. Furthermore, the model's goodness-of-fit is confirmed by the *Prob (F-statistic)* value of 4.85e-15 (<0.05). The relationship is translated into MLR model (2) by using the regression coefficients.

```
==============================================================================
Dep. Variable:                CO2(kt)   R-squared:                       0.963
Model:                            OLS   Adj. R-squared:                  0.959
Method:                 Least Squares   F-statistic:                     260.1
Date:                Mon, 05 Apr 2021   Prob (F-statistic):           4.85e-15
Time:                        14:41:12   Log-Likelihood:                -242.61
No. Observations:                  23   AIC:                             491.2
Df Residuals:                      20   BIC:                             494.6
Df Model:                           2
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       7612.9400   1.14e+04      0.670      0.511   -1.61e+04    3.13e+04
GDP.PC         5.7859      1.799      3.216      0.004       2.033       9.539
kWh.PC        39.2966      6.351      6.188      0.000      26.050      52.544
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Figure 3. Generated results of regression estimation

$$CO2(kt) = 7612.94 + 5.7859\, GDP.PC + 39.30\, kWh.PC \quad (2)$$

For the TA model, an adjusted R2 of 0.985 also signifies that the identified predictors could explain 98.5% variation in CO_2 emissions. The t-test result has confirmed both *year* and *year*^{2} are significant to the model. The relationship is translated into a polynomial regression (3).

$$CO2(kt) = 83449 + 10497\, Year - 133.93\, Year2 \quad (3)$$

3.2. Scenario simulations

To evaluate the impact of NILM-based EE, Malaysia's CO_2 emissions of 2019-2030 are predicted by using (2) with the forecasted GDP and electricity consumption. Based on the relevant policies and research institutions, the variable growth rates are derived from world bank data, international monetary fund (IMF) report [28] and world energy markets observatory (WEMO) 2017 report [29]. Table 2 shows five scenario settings used in the scenario simulations. Scenario 1 serves as the baseline scenario or business-as-usual (BAU), which employed the TA predictive model to forecast the CO_2 emissions from 2019-2030 without considering any improvement in electricity conservation. On the other hand, scenarios 2-5 adopted the MLR model in section 3.1 to forecast CO_2 emissions due to the NILM effect of reduced electricity consumption at different rates imposed, on top of the 4.8% base rate of annual growth increment.

Table 2. Scenario settings of Malaysia

Scenario	The setting of growth rate Population	 GDP	 Electricity consumption
1.	The predicted CO_2 emission by trend analysis (TA) or BAU scenario.		
2.	Use predicted data from World Bank Data.	Use a 4.8% growth rate. (Estimated rate by IMF)	Baseline (+4.8%) with a reduction of 2% of electricity consumption
3.			Baseline with 5% reduction
4.			Baseline with 8% reduction
5.			Baseline with 12% reduction

* To forecast CO_2 emissions for 2019-2030, scenario 1 uses the TA model while scenarios 2-5 use the MLR model

By scenario simulation, the result highlights the significance of NILM-based EE on reducing CO_2 emissions in Malaysia. A 12% electricity consumption reduction from NILM shrinks 10.2% (or 315852 kt) of CO_2 emissions than the BAU model (351739 kt). Therefore, NILM and its use cases can effectively improve environmental degradation and financial saving.

3.3. NILM impact based on EKC analysis in Malaysia (1996-2030)

To analyse the impact of NILM (reduced electricity consumption) and the long-run relationship between CO_2 emissions and its economic growth (1996-2030), the EKC model test of the linear, quadratic and cubic functions used to fit with the coefficient of determination R2, t-statistic and F-statistic. The forecasted data of CO_2 emissions is obtained from the scenario simulation in Section 3.2. The empirical results are shown in Table 3.

Table 3. Hypothesis tests of EKC model in Malaysia (1996-2030)

Scenario	Type of function	Expression of the function (with p-values of T-test of predictors)	R2	Prob (F-statistic)	Type of the curve
Scenario 1 - BAU	Linear	$CO2.PC = 4.619 + 0.309\ GDP.PC$ (0.000) (0.000)	0.887	2.03e-17	Monotonically increasing
	Quadratic	$CO2.PC = 3.716 + 0.507\ GDP.PC - 0.008\ GDP.PC^2$ (0.000) (0.000) (0.133)	0.915	9.76e-18	
	Cubic	$CO2.PC = 1.808 + 1.268\ GDP.PC - 0.093\ GDP.PC^2 + 0.003\ GDP.PC^3$ (0.104) (0.004) (0.050) (0.093)	0.914	3.45e-17	
Scenario 2 - 2% red. in kWh	Linear	$CO2.PC = 4.562 + 0.309\ GDP.PC$ (0.000) (0.000)	0.887	2.03e-17	Inverted-U curve found.
	Quadratic	$CO2.PC = 3.564 + 0.571\ GDP.PC - 0.014\ GDP.PC^2$ (0.000) (0.000) (0.006)	0.908	9.76e-18	Potential TP =USD 20063.36
	Cubic	$CO2.PC = 1.808 + 1.268\ GDP.PC - 0.093\ GDP.PC^2 + 0.003\ GDP.PC^3$ (0.104) (0.004) (0.050) (0.093)	0.914	8.85e-05	
Scenario 3 - 5% red. in kWh	Linear	$CO2.PC = 4.64 + 0.296\ GDP.PC$ (0.000) (0.000)	0.875	1.10e-16	Inverted-U curve found.
	Quadratic	$CO2.PC = 3.548 + 0.582\ GDP.PC - 0.016\ GDP.PC^2$ (0.000) (0.000) (0.003)	0.902	2.60e-17	Potential TP =USD 18759.39
	Cubic	$CO2.PC = 1.555 + 1.372\ GDP.PC - 0.105\ GDP.PC^2 + 0.003\ GDP.PC^3$ (0.151) (0.002) (0.026) (0.053)	0.911	5.63e-17	
Scenario 4 - 8% red. in kWh	Linear	$CO2.PC = 4.709 + 0.283\ GDP.PC$ (0.000) (0.000)	0.858	8.90e-16	Inverted-U curve found.
	Quadratic	$CO2.PC = 3.531 + 0.592\ GDP.PC - 0.017\ GDP.PC^2$ (0.000) (0.000) (0.002)	0.893	1.07e-16	Potential TP =USD 17619.66
	Cubic	$CO2.PC = 1.295 + 1.479\ GDP.PC - 0.117\ GDP.PC^2 + 0.003\ GDP.PC^3$ (0.226) (0.001) (0.130) (0.030)	0.906	1.35e-16	
Scenario 5 - 12% red. in kWh	Linear	$CO2.PC = 4.813 + 0.264\ GDP.PC$ (0.000) (0.000)	0.827	2.51e-14	Inverted-U curve found.
	Quadratic	$CO2.PC = 3.507 + 0.607\ GDP.PC - 0.019\ GDP.PC^2$ (0.000) (0.000) (0.001)	0.875	1.40e-15	Potential TP =USD 16305.19
	Cubic	$CO2.PC = 0.934 + 1.628\ GDP.PC - 0.134\ GDP.PC^2 + 0.004\ GDP.PC^3$ (0.384) (0.000) (0.005) (0.14)	0.894	8.47e-16	

Note: The values in parenthesis are p-values (t-statistic), at a 5% significance level.

Based on Table 3, the EKC curve functions for different scenarios sets are identified. Figure 4 depicts the NILM impact on environmental degradation in Malaysia (1996-2030) from the perspective of the

EKC hypothesis. Scenario 1 (BAU setting) has been tested with different functions, i.e. linear, quadratic, and cubic. It is empirically identified BAU scenario has a monotonically increase relationship. Neither inverted-U curve nor turning point found with an increasing trend of CO_2 emissions without peaking. The phenomenon can be explained that Malaysia's current mitigation measures and policies may not effectively cope with the future demand for sustainable development. Hence, the policymakers should devise strategic planning of environmental improvement as earlier as possible.

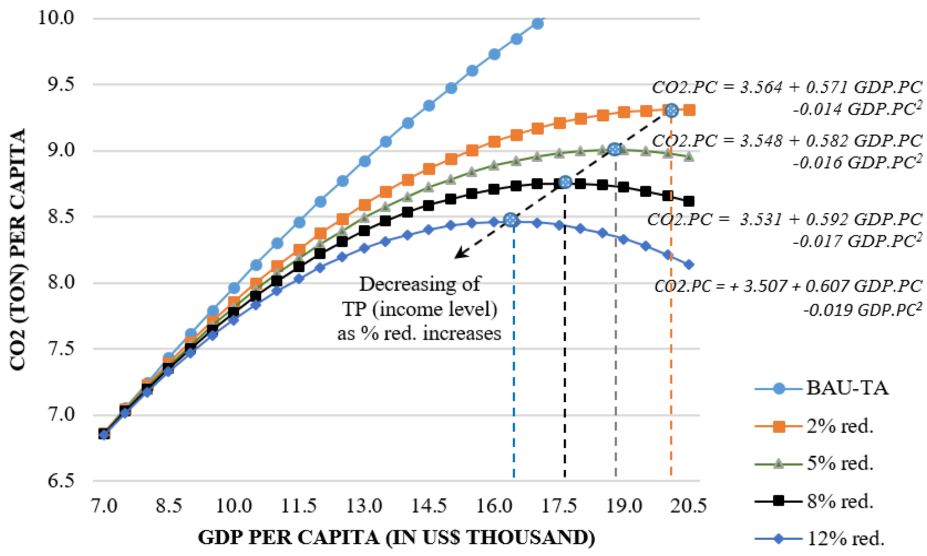

Figure 4. Impact of NILM from the perspective of EKC hypothesis

As one of the potential approaches to mitigate environmental degradation, it is crucial to quantitatively assess the impact of NILM-based EE measures by conducting the scenario simulation and the hypothesis test on the EKC model. As shown in Figure 4, Scenario 2 of NILM-based EE with a 2% reduction of electricity consumption imposed, inverted-U curve and turning point are found as empirical evidence of EKC. The turning point is identified as USD 20,063.36 and implies that there would be environmental improvement once the GDP per-cap level is improved. The evaluation continued with Scenario 3-5 by gradually increasing the reduction rate of electricity consumption and the EKC hypothesis test conducted. All the scenarios with NILM-based EE found compliance to the EKC model's inverted-U curve. The turning point is significantly reduced to USD 16,305.19 at a 12% reduction in electricity consumption. The empirical result is well-supported by several works [30], [31] that the developing countries could attain higher levels of economic growth at a lower environmental cost by "tunnelling" through the EKC curve with a better sustainable development path [32].

4. CONCLUSION

Strategic planning of policies and environmental measures is vital to the policymakers for sustainable development. The quantitative analysis of the impact of NILM-based EE measure with the EKC hypothesis is presented. It is the first attempt to quantitatively analyse its impact on environmental degradation from the EKC hypothesis perspective. The significance of this work is as; i) the NILM-based measure could reduce CO_2 emissions by 10.2% compared with the BAU model, ii) the BAU scenario simulation of Malaysia 2019-2030 found a monotonically increase relationship between environmental degradation and economic growth. It implies that the current mitigation measures and policies imposed may not be effective enough to cope with the future power demands for sustainable development. Hence, the policymakers should restructure the strategic planning of environmental improvement as earlier as possible, iii) the inverted-U curves show that the turning points of environmental degradation have been reduced from the income level from USD 20,063.36 to USD 16,305.19 with the increment of reduction rates in electricity consumption. It implied NILM-based EE measures could accelerate sustainable development with lower environmental deterioration, iv) the shift or decreasing trend of turning point levels of GDP income implies that an effective policy can "tunnel through" the EKC curve with lower environmental deterioration.

Consequently, these results may help policymakers devise and evaluate the strategic planning of policies and measures that ensures a balance between economic growth and environmental degradation. Other measures such as renewable energy, taxes, and policies can be further studied in the proposed analytical framework for future improvement.

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