Problem Chosen	2023	Team Control Number
F	**MCM/ICM Summary Sheet**	**2309571**

Summary

Expanding climate crisis, lightning-speed growth in pollution, rising risk of global warming–all of these trends suggest that environmental sustainability should become the primary goal for any human activity in the future. In order to better reflect the performance of each country in terms of its climate and environmental status, economists proposed a new way to calculate the Gross Domestic Product (GDP)–Green GDP (GGDP), which takes environmental factors into consideration. In our research, we analyzed and evaluated the GGDP method, and proposed a possible solution for countries to adopt.

Firstly, our team examined different GGDP calculation methods and selected the most comprehensive and universal GGDP formula for further study. By observing the formula, we realized that there might be a relationship between GDP and each environmental factor. In order to understand their relationships, our team constructed a Polynomial Regression Model (PRM). To verify our model is valid, we found the data from ten countries in the past twenty years, and by using RStudio, we found that each environmental factor affects GDP in different ways, and the change from GDP to GGDP has a much less impact on developed countries than on developing countries.

We then studied how each factor affects the GDP and GGDP. We then noticed that not all environmental factors are not specifically relevant to climate mitigation, so we believe an adjusted GGDP formula would be able to more accurately reflect the impact on climate. From our PRM model, we learned that CO2 emission is a more important factor in climate, while solid waste might be less relevant to climate change. Therefore, we adjust the original GGDP formula by assigning different weights to these factors. Also, by considering the difference between developed and developing countries, we take different possible policies into consideration.

To achieve this goal, we constructed a three-layer Adjusted Climate-Focused GGDP Model (ACF) by using Analytic Hierarchy Process- Entropy weight method (AHP-EWM) Analysis. The result suggested that developing countries are in general more negatively affected by the change from GDP to GGDP, but they can achieve an optimal GGDP when they adopt moderate environmental and climate policies, i.e. prioritize both climate mitigation and economic growth. On the other hand, developed countries do not need to change their policies, because they were barely affected by the change from GDP to GGDP.

In the end, we applied our findings from both models to China and compared the estimated GGDP with its actual GDP from 2001 to 2020. Our team found that the result of our model matched the actual GDP growth trend and growth rate of China, and we attempted to explain our findings.

Keywords: Green GDP (GGDP); Polynomial Regression Model (PRM); Adjusted Climate-Focused GGDP Model (ACF);

1 Introduction

1.1 Background

Gross Domestic Product (GDP), defined as "the monetary measure of all finished goods and services produced in a country over a given period of time" (What Is Gross Domestic Product?, n.d.), is one of the most crucial and frequently used indicators to reflect the performance of an economy and predict the future economic growth of a country. Typically, GDP in a country is calculated by the governmental agency of a country, following a standard international method, and therefore GDP can also be used to make international comparisons of economic performance among countries according to the GDP (BOYLE & RATHBURN, 2022).

However, GDP does reveal all economic activities of a country, and neither it does reflect some other important factors that impact a country's economy. For example, The development of the manufacturing industry and the consequential economic growth of a country can be reflected by the GDP growth, but this development at the expense of environmental health would not be revealed by the GDP. The graph below that is obtained through RStudio demonstrates different levels of CO2 emissions between countries across the world during the past decade.

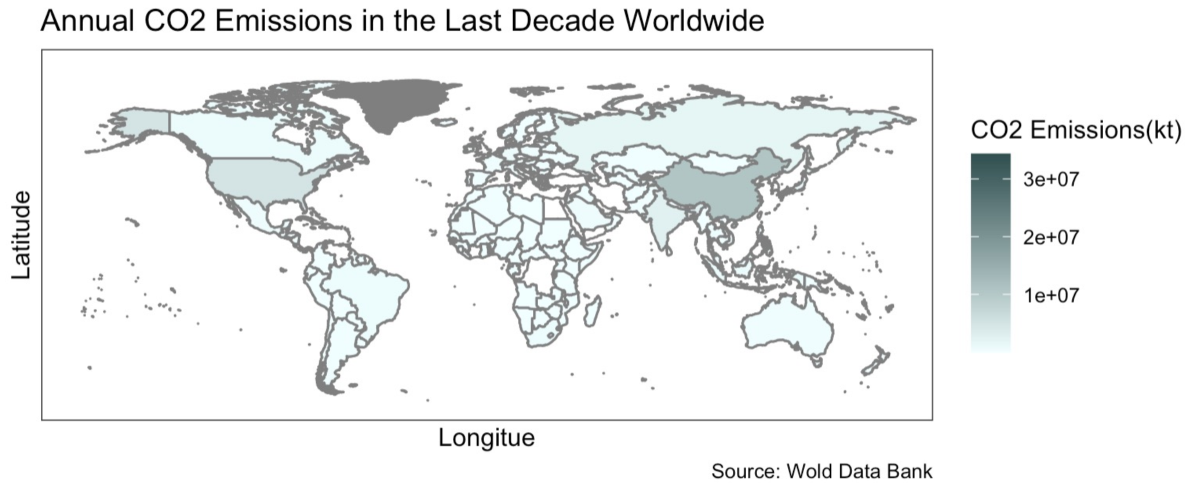

Figure 1.1: Average Annual CO2 Emissions Worldwide

As the climate and environmental issues are getting more severe globally, it is time to consider how to incorporate environmental factors into the development of an economy. In recent years, many economists proposed an alternative method–the "Green" GDP (GGDP), which takes environmental factors and sustainability into consideration.

1.2 Research Questions Re-stated

According to the requirements, we break down our research questions into the following parts:

a) What is a valid GGDP calculation formula that can apply to all countries?

b) How is climate mitigation impacted globally if the current method of calculating GDP is substituted by a new GGDP formula?

c) How do we evaluate the GGDP formula?

d) How do we predict the development of a country if GGDP replaces the current GDP?

1.3 Research Overview

In our research, we plan to answer questions by taking the following steps:

1) We find a generic formula or equation for calculating the GGDP proposed by economists, and determine what environmental/climate factors are included in this equation other than the current GDP value.

2) We use the **Polynomial Regression Model** (PRM) to find out the relationship between the current GDP value and each environmental factor in the equation, and then try to model the relationship between GDP and GGDP.

3) Based on our findings from PRM and the GGDP formula we found, we further explore the impact of GGDP on the climate by using the hierarchy analysis method to construct an **Adjusted Climate-Focused (ACF) GGDP** formula.

4) By using the ACF formula, we find the optimal GGDP of countries. Then, we evaluate the changes and determine how the economy and climate would be impacted by these changes.

5) We apply our findings to a country, and discuss how the change from GDP to GGDP (our ACF formula of GGDP) would impact this country, and what policies the government of this country could make to improve both the economic and the environmental health.

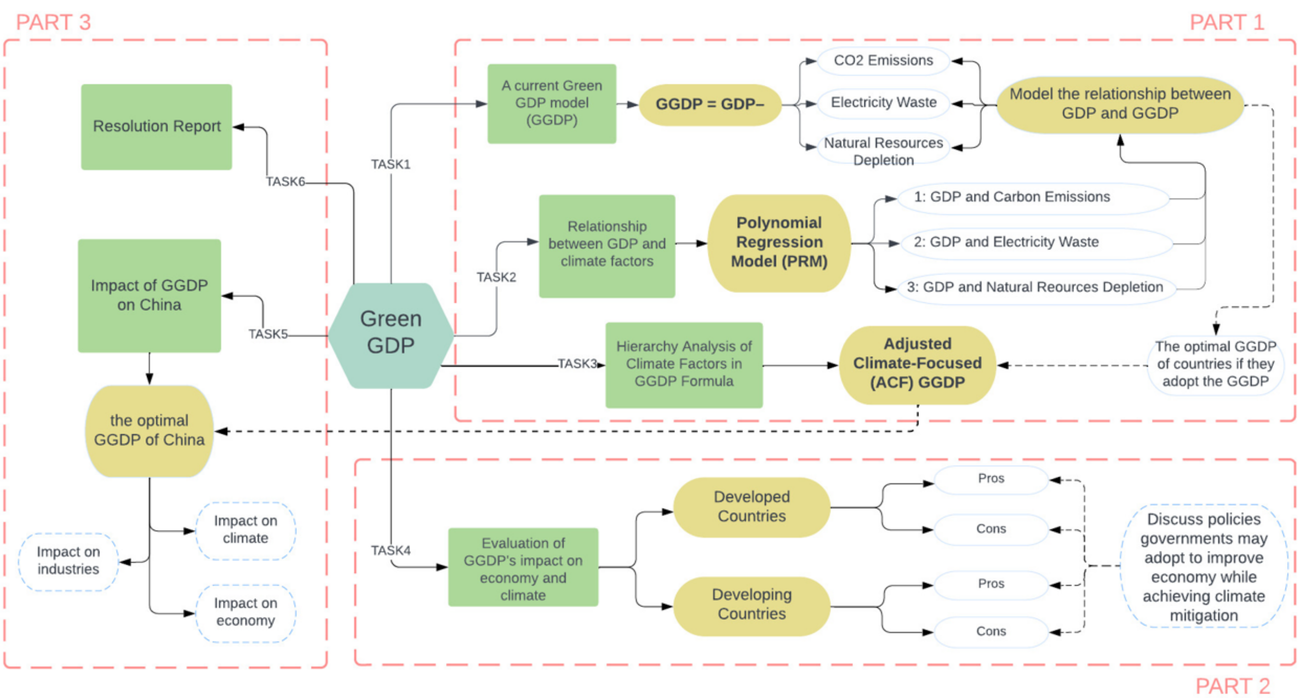

Figure 1.2: Overview of Our Work

2 Methodology

2.1 GGDP Formula

A typical method to calculate GGDP is to deduct the environmental or climate cost from the current GDP. As early as 1994, economist Kirk Hamilton proposed this idea (Hamilton, 1994). In the past 30 years, economists managed to find a better way to estimate the value of environmental factors. Our team found that Stjepanović et al. proposed a GGDP formula in 2017, which takes the three most important and universal environmental and climate factors into consideration, including the costs of carbon dioxide (CO2) emission, the opportunity costs of electricity waste, and the depletion of natural resource (NRD) (Stjepanović et al., 2017).

According to their estimation, the costs of CO2 emissions in a country can be calculated by multiplying the total amount of CO2 emissions by the current average carbon market price. The data on electricity waste was inaccessible, however, they found an alternative way to calculate the total waste of electrical energy: since the generation of electricity requires other sources, they could find the total amount of electricity wasted by finding the relationship between other sources and electrical energy. In their findings, the ratio of solid waste and electrical energy is about 74 (i.e. 1 tonne of waste would result in 74 kWh of electrical energy waste).

Then, multiplying the total electricity wasted by the average electricity price, they estimated the opportunity costs of wasted electrical energy as well. The calculation of NRD is less intuitive because there are so many different types of natural resources. However, they found that forest, energy, and mineral depletion are most relevant to environmental health, so they converted the value of these depleted natural resources into a percentage of the Gross National Income (GNI) of a country. Therefore, the formula is written as

$$GreenGDP = GDP - (KtCO_2 * PCDM) - (Twaste * 74kWh * Pelect) - (\frac{NRD}{100} * \%GNI)$$

2.2 Model Setup

2.2.1 Polynomial Regression Model

It takes two steps to find out the relationship between GGDP and GDP. First, by observing the GGDP formula, we see that GGDP is impacted by both original GDP and environmental factors. Therefore, we first find out the relationship between the original GDP and each factor, and then we are able to find the relationship between GDP and GGDP.

In order to find the relationship between GDP and each environmental factor, as well as between GDP and GGDP, we decide to construct a Polynomial Regression Model (PRM). The reason we chose this model is that PRM is a powerful analysis of the relationship between the independent and dependent variables (Ostertagová, 2012). Since we are studying the relationship between GDP and every single environmental factor respectively, PRM is our first choice. Also, it is important that PRM is not constrained at a certain level of polynomial degree, as we did not know the complexity of the relationship between GDP and environmental factors beforehand.

2.2.2 Adjusted Climate-Focused GGDP Model

Our team noticed that the GGDP formula proposed by Stjepanović et al. did not reflect the impact of each environmental factor on climate, and we believe that such adjustment is necessary to better answer the question. Therefore, based on our result from the previous step, we use hierarchy analysis to adjust the importance of three environmental factors in the GGDP formula. The Adjusted Climate-Focused GGDP Model (ACF Model) helps us to determine how a country is affected if GDP is replaced by GGDP.

The reason we use hierarchy analysis is that it is well-structured while straightforward in terms of the analysis of inter-relations among complex factors (Ricardo Viana, 2010). Since we are unknown of the impact of each environmental factor on climate, nor do we know the impact of different environmental policies on climate mitigation, hierarchy analysis can help us determine the weight of each factor when we calculate the GGDP in terms of climate impact specifically.

2.3 Variables

Parameter	Description
B_i	The coefficient of B to the power of i for i = 0, 1, 3, …, n, n∈ Real numbers for polynomial regression
MSE	Mean Squared Error for polynomial regression
SSE	Sum of Squares for Error for polynomial regression
y	The the arithmetic mean of our variable Y, amount of CO_2 emission for adjusted R^2 equation
R^2	The percentage of variation of in the amount of CO_2 emission for adjusted R^2 equation
k	Number of variables for adjusted R^2 equation
n	Number of observations for polynomial regression
λ	Coefficient of difference
W_α	Weight under subjective weight
W_β	Weight under objective weight
C.I	Coincidence Indicator
R.I	Random Coincidence Index

3 Polynomial-Regression Model

3.1 Assumption

In order to evaluate the global impact on climate mitigation for countries after they adopt GGDP as an alternative measurement for a country's economic health condition, we need to first predict the action that different countries might take after replacing GDP with GGDP. We believe it is reasonable to assume that all countries would attempt to maximize their GGDP value once the GDP is replaced by GGDP, based on the fact that all countries are trying hard to increase their GDP values in the real world. Also, since we know that there are only three major environmental factors, CO2 emission, NRD, and electrical energy waste (total solid waste), that may potentially impact GGDP, we consequently assume a country may take three types of actions to increase GGDP: by reducing CO2 emission, NRD, or total solid waste.

3.2 Potential Problems for Estimating the GGDP

According to the GGDP formula, we know when the GDP of a country is fixed, if the values of three independent environmental variables are decreased, the GGDP will accordingly increase. However, we also know that these independent variables such as CO2 emissions are often highly correlated with GDP in reality. For example, the manufacturing industry contributes to approximately 21% of global CO2 emissions (Sutaria, 2020), but meanwhile, the output from the manufacturing industry is a major component of GDP in many developing countries such as China (27.4% of GDP in 2022) (China GDP From Industry, n.d.).

In other words, it means when a country tries to constrain the total amount of CO2 emission by cutting down the relevant industries to increase the GGDP, it is likely that the GDP value would be hurt as well, and this makes it hard to determine whether certain policies taken by one country will lead to an increase in GGDP or not. If we can derive the relationship between GDP and the three additional environmental variables in the GGDP model, we could then determine the effect of different policies for increasing GGDP qualitatively and quantitively, find the optimal policies, and then estimate the impact of the optimal policies. Therefore, we first use PRM to find the relationship between GDP and each of the three variables.

3.3 Method

We realize that it is unrealistic to predict the relationship between GDP and environmental variables of a future time. In order to find these relationships, we conduct three separate polynomial regressions by using the data of ten countries over the past 20 years (from 2001 to 2020), including annual GDP, annual CO2 emissions, total solid waste, and NRD percentage (The World Bank, n.d.).

In the polynomial regressions, we regress the dependent variables(CO2, NRD, Total Waste) on the independent variable GDP separately with different powers (Ostertagová, 2012). Take CO2 emission as an example, the one-variable polynomial regression of CO2 on GDP can be expressed as:

$$GDP = B_0 + B_1 * CO_2 + B_2 * {CO_2}^2 + B_3 * {CO_2}^3 + \cdots + B_k * {CO_2}^k + e$$

where k stands for the degree of the polynomial.

The mean squared error (MSE) is an unbiased estimator of the variance σ^2 of the random error term and is defined in the equation:

$$MSE = \frac{SSE}{df_E} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-(k+1)}$$

R^2 measures the percentage of variation in the amount of CO2 emission explained by GDP. It is an important measure of how well the regression model fits the data. It is computed through the following formula

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2}$$

where SST is the total sum of squares and y is the arithmetic mean of the Y variable, which in our case stands for the amount of CO2 emission. In order to avoid overfitting issues, we will use adjusted R^2 of the model to determine the goodness of the fit. Adjusted R^2 is defined as follows:

$$R^{*2} = R^2 - \frac{(1 - R^2)\,k}{n - (k+1)}$$

It is noteworthy that we purposely include both developing and developed countries in our dataset when modeling in case there are different trends and relationships between countries with different level of development. After building the models, we derive (mean squared error)MSE, Adjusted R squared, and p-value for each model to measure the accuracy, effectiveness, and validity of our models. We fit the model with different powers and pick the one that produces the best accuracy(in our case polynomial regression with power 2). We also plot our regression lines on original data to better illustrate and interpret the underlying trends. From RStudio, we obtain the following results.

3.4 Result and Interpretation

3.4.1 GDP and CO2 Emissions

According to Figures 3.1 and 3.2, the relationship between GDP and CO2 emissions varies across different countries, but there are three types of relationships in general. First, China and India show a very strong positive correlation between GDP and CO2 emission, indicating that with the increase in GDP value, the amount of CO2 emission also increases. For example, the GDP of China increases from less than 3 trillion dollars to approximately 15 trillion dollars over 20 years, and the number of CO2 emissions also largely increases from about 3000 million tons in 2001 to over 10,500 million tons in 2020.

Brazil shows a much weaker positive correlation, as the GDP increases, the number of CO2 emissions slightly increases.

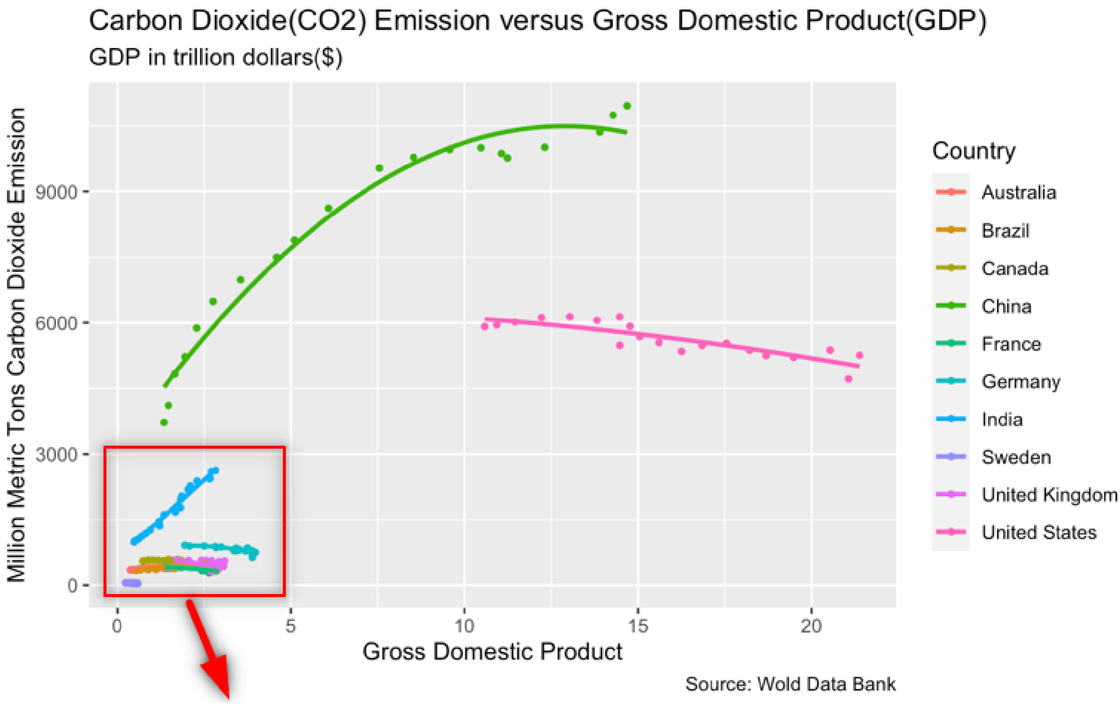

Figure 3.1: Relationship Between CO2 and GDP, 10 countries

The second type of relationship is that as the GDP increases, the CO2 emission amount does not change. Canada is the only country that exhibits this trend: as the GDP of Canada increases, the CO2 emission amount stays at the same level over the past 20 years, which means that there is no correlation between Canada's GDP and its CO2 emission. The last type of relationship summarizes the trend of the rest countries, including Australia, France, Germany, Sweden, the United Kingdom, and the United States.

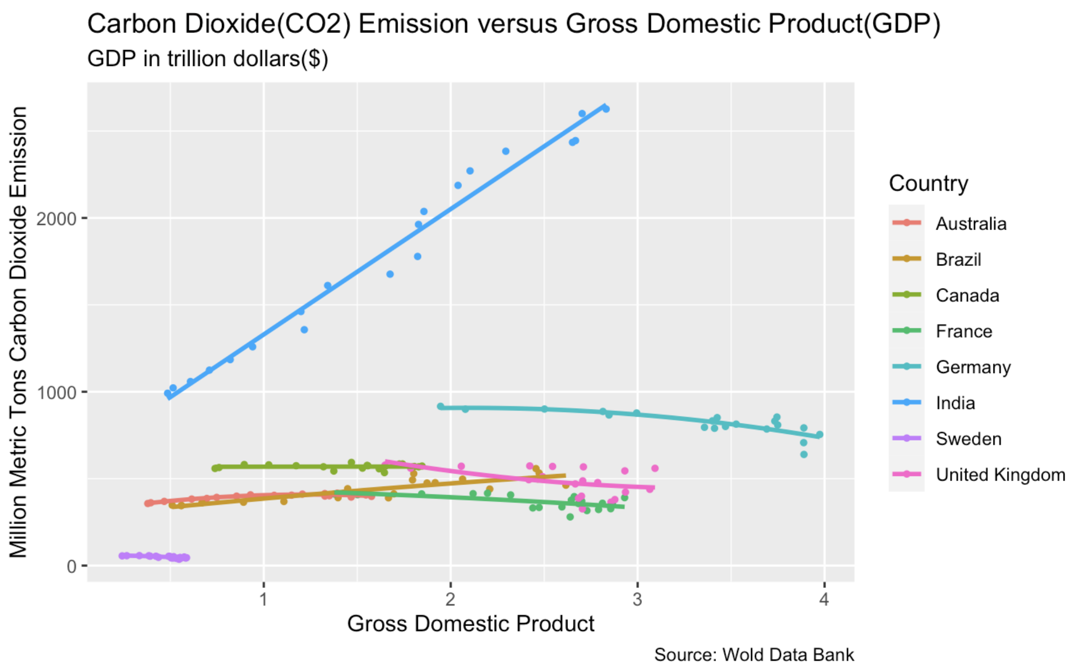

Figure 3.2: the Relationship Between CO2 and GDP, excluding China and the United States

From the figures, we see a weak negative correlation between the GDP and CO2 emission amount, which tells that as the GDP increased, the CO2 emission decreased. We are surprised to see that the growth of GDP in some countries is not directly proportional to the growth of CO2 emissions, as we assumed that the development of industries would also result in an increase in CO2 emissions. We found a possible explanation in a study done by Cederborg & Snöbohm in 2016–the Environmental Kuznets Curve (EKC). They pointed out that since the level of industrialization varies across countries, the dependence on industrial-heavy production also varies among countries. Developed countries have achieved a high level of industrialization in the past, so they can rely much less on industrial-heavy production which causes pollution, such as chemical production. On the other hand, developing countries have no choice but to rely on industrial-heavy productions.

Therefore, for developing countries, the more they invested in industrial-heavy productions, the more likely the GDP will increase, with the increase of CO2 emission amount simultaneously; while developed countries have a strong motivation to replace industrial-heavy production with less polluted high-technological production, and therefore there GDP would not be negatively impacted by CO2 emission reduction. However, at the time when a developing country turns into a developed country, it will naturally follow the path of developed countries, which means it will also start phasing out industrial-heavy productions. This is verified by the result in figure 3.1, where the CO2 emission of China exhibited a turning point. With the coefficients of the polynomial regression models that we build, we observe different impacts on the emission of CO2 by increasing or decreasing GDP, which implies that the expected climate mitigation effect of adopting GGDP also varies across countries with different levels of development.

3.4.2 GDP and Electrical Energy Waste

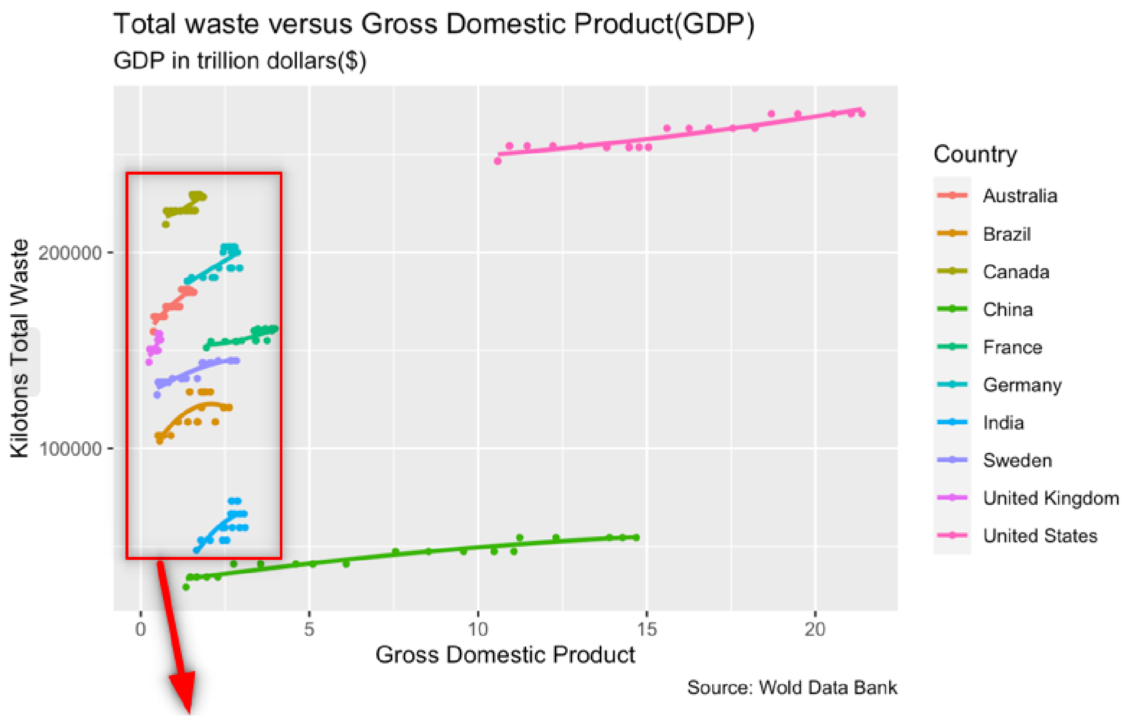

Figure 3.3: the Relationship Between GDP and Total Waste (Electrical Energy), 10 countries

We can tell from the result that as the GDP increased, the amount of solid waste also increased. Figures 3.3 and 3.4 show a positive correlation between the GDP value and the solid waste amount of each country. Specifically, China has the largest total amount of solid waste for each of the past twenty years, and a more positive correlation between GDP value and the solid waste amount in China compared to other countries, suggesting that China has a faster increase in the solid waste amount in the past twenty years as well. On the other hand, the rest of the countries displayed a much more mild increase in solid waste over the past twenty years. For example, the increase of solid waste in China increased by over 45% from 2001 to 2020, while that number was merely 5% in the United States.

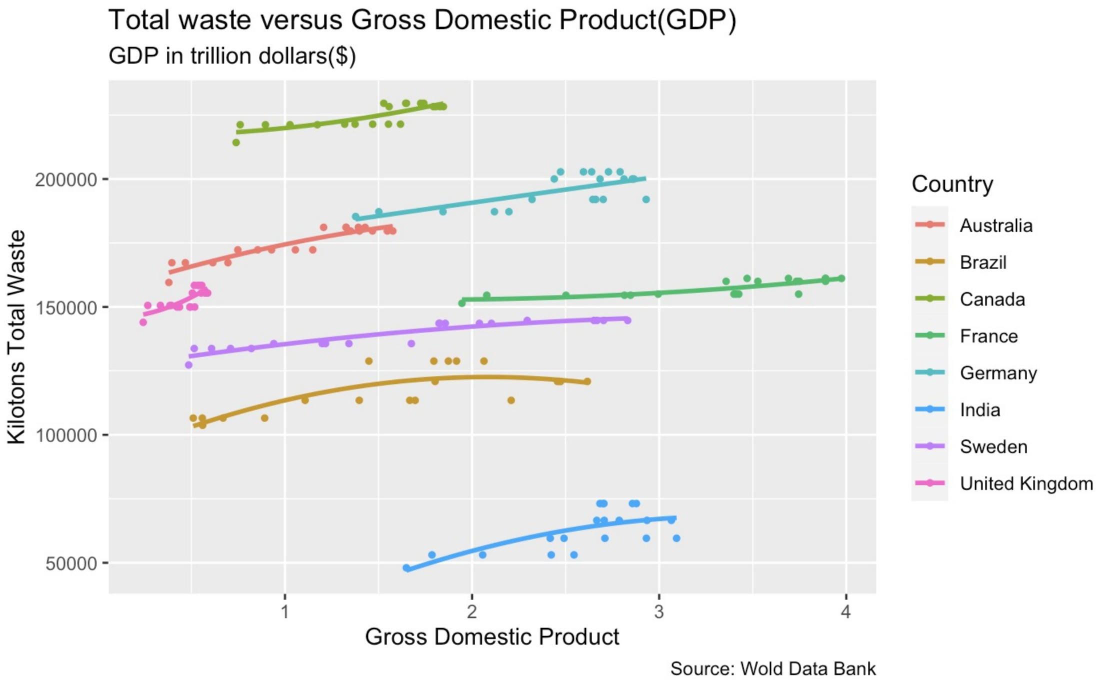

Figure 3.4: the Relationship Between GDP and Total Waste (Electrical Energy), excluding China and the United States

We believe this result is reasonable, because it is not likely that a country had a huge jump or decrease in total waste amount without a large increase or decrease in human population over a short period of time. Furthermore, when solid waste is converted into electrical energy wasted, this explanation still holds, as electricity usage and waste are not expected to exhibit an abrupt turning point or a large fluctuation if there was no such change in population in a country.

3.4.3 GDP and NRD

The relationship between GDP and NRD varies across countries, but we observed three different results. First, the relationship between GDP and NRD in some countries suggests no relationship between the increase in GDP and the depletion of natural resources. This includes France, Germany, the United Kingdom, Sweden, the United States, and Brazil. As Figures 3.5 and 3.6 show, we see a flat straight line in each country. Another type of relationship between GDP and NRD is that as the GDP increases, NRD decreases. Canada is the only country that exhibits this trend: as the GDP of Canada increased over the past twenty years, NRD decreased to less than one-fifth of the NRD in 2001.

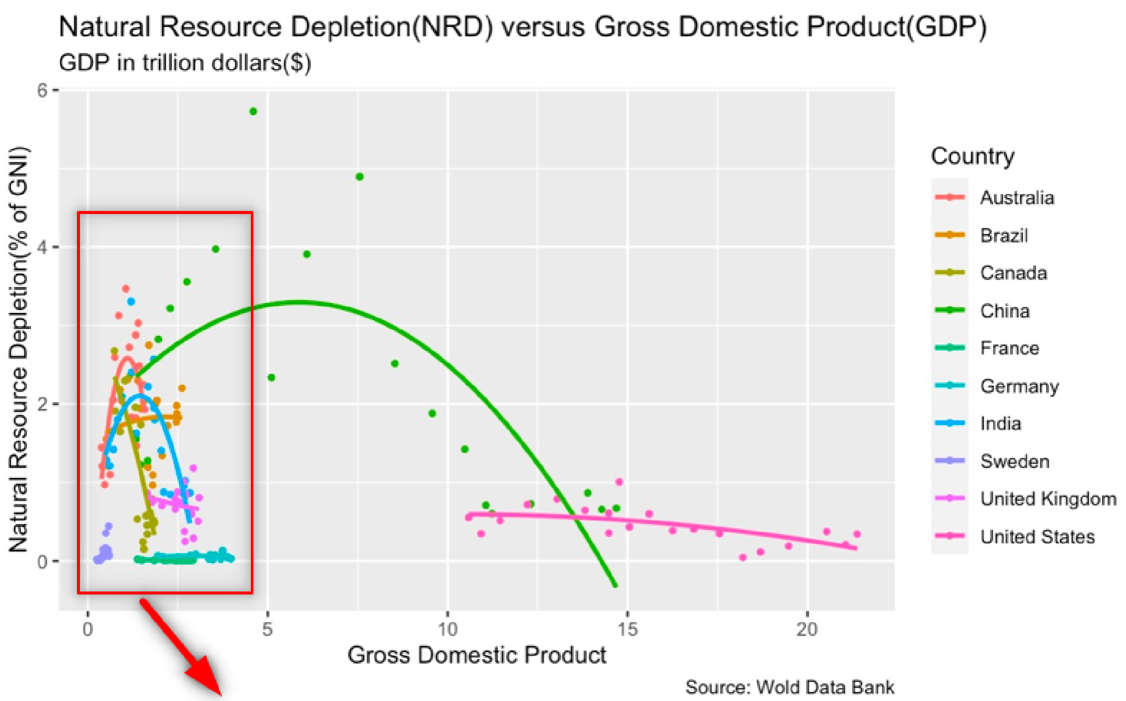

Figure 3.5: the Relationship Between GDP and NRD, 10 countries

The last type of relationship summarizes the trend of China, Australia, and India. From the figures, we see a concave-down curve in each country, which tells that as the GDP increased, NRD also increased. However, to a certain point, NRD reached a maximum point and then it started to decrease.

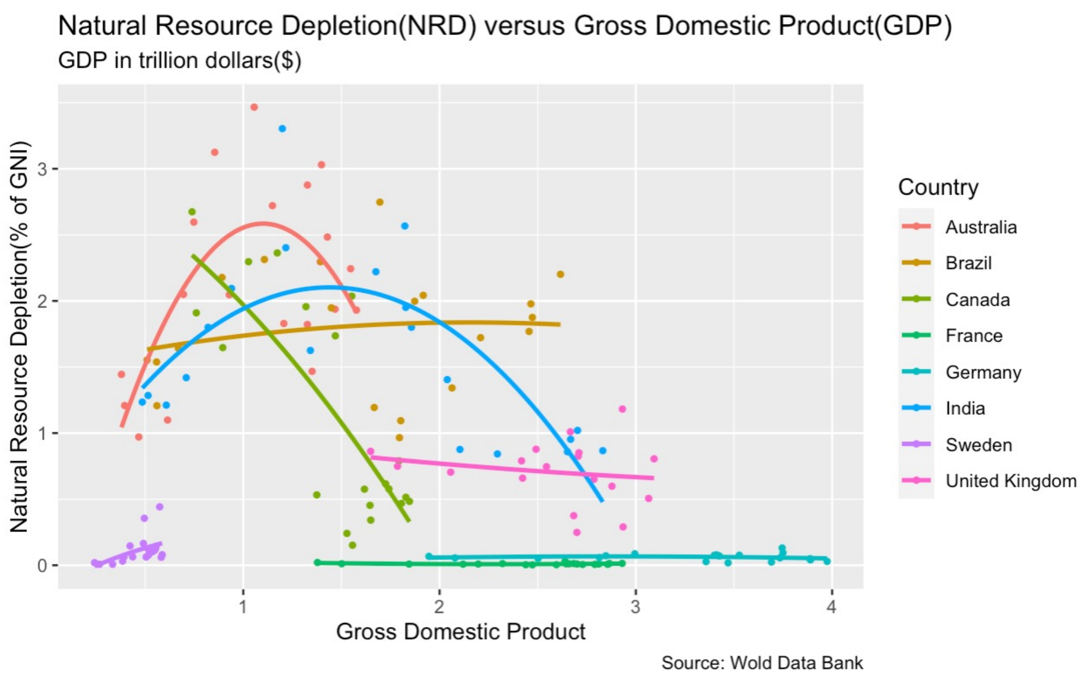

Figure 3.6: the Relationship Between GDP and NRD, excluding China and the United States

We believe the interpretation of the relationship between GDP and NRD in these 10 countries is much similar to the explanation of the Environmental Kuznets Curve mentioned above: when a developing country turns into a developed country, it would start to phase out the industries which have more negative impact on environments and try to replace these industries with more sustainable and eco-friendly industries. Therefore, it is very likely that our result displays countries at different points on the Environmental Kuznets Curve–a concave-down curve may suggest that a developing country is turning into a developed country, while a flat straight line implies a developed country.

3.5 Discussion and Next Step

Based on our findings through Polynomial Regression Model, we can confirm that there is a relationship between GDP and each environmental factor. However, we also realize that it does not suggest all three environmental factors should be equally weighted when we calculate the GGDP of a country. The first reason is that some factors, such as solid waste amount, are barely impacted by GDP growth. Hence, we want to adjust the original GGDP formula proposed by Stjepanović et al., to make it more accurately reflect the impact of GGDP on climate specifically.

Also, we specifically included both developing and developed countries when we were selecting ten countries, to see if there was any difference between developing and developed countries in terms of the relationship between GDP and each environmental factor. The result supports the fact that there is a clear difference between developing and developed countries in terms of these relationships. However, not all relationships exhibited such differences. For example, the relationship between GDP and total solid waste or GDP and NRD is not really differentiated in developing and developed countries.

Overall, we believe that we should consider CO2 emission as a more important factor of climate change than the other two environmental factors in the GGDP formula. Therefore, we decide to use a more complex model to adjust the original GGDP formula to better reflect how GGDP may impact global climate mitigation.

4 Adjusted Climate-Focused GGDP Model

4.1 Assumptions

In our previous step, we constructed a Polynomial Regression Model to find the multivariate characteristics between GDP and environmental factors, and we concluded that the GGDP formula needs to be adjusted. In the Methodology part, our team proposed an assumption that a country may adopt different policies to cope with the change from GGDP to GDP in order to increase the GGDP value. We continue our assumption here, and we further assume that a country may adopt three different types of policies: an aggressive environmental policy, a moderate policy, and a traditional economic policy (Wang et al., 2017).

We introduce the Adjusted Climate-Focused (ACF) GGDP Model here. Based on this model, we can obtain the optimal GGDP of a country when they adopt different policies and predict how different policies would impact the value of optimal GGDP. We continue to expect that the optimal GGDP would vary across different countries (Ricardo Viana, 2010).

Also, it is important that we observed two distinctive patterns among ten countries in the relationship between GDP and each environmental factor in the previous section. For example, for developing countries like China, CO2 emissions and total waste are positively correlated with GDP, and this suggests there might exist an optimal point, i.e. an optimal strategy for developing countries when they try to maximize their GGDP value. Thus, we could build models to find this optimal point.

However, for developed countries such as the United States, the annual CO2 emission has been decreasing for years, which suggests a good performance in terms of environmental sustainability. Therefore, we can say that these three environmental factors may not be strongly negative-correlated to GDP. This implies that the adoption of GGDP will have little effect on dveloped countries' actual GGDP value or their places in GGDP ranking. Therefore, we assume the actions of developed countries towards the adoption of GGDP is highly subjective and unable to be quantified. Thus, we will mainly focus on developing countries in this section.

4.2 Structure

We select five indicators and three factors for analysis by using the analytic hierarchy process(**AHP**) and Entropy weight method(**EWM**) with three criterion layers:

<table>
<tr><th>Goal</th><th>Criteria</th><th>Sub-criteria</th><th>Plan</th><th>Alternatives</th></tr>
<tr><td rowspan="5">GGDP Model</td><td rowspan="2">A1 CO_2 Emission</td><td>C1 Population</td><td rowspan="2">P1 Agressive</td><td rowspan="5">N_i
$i \in N$
Preset alternatives nations</td></tr>
<tr><td>C2 Price for raw material</td></tr>
<tr><td rowspan="2">A2 NRD</td><td>C3 Resource</td><td rowspan="2">P2 Mordate</td></tr>
<tr><td>C4 Development Degree</td></tr>
<tr><td>A3 Electricity Waste</td><td>C5 Industry</td><td>P3 Mild</td></tr>
</table>

Figure 4.1: Indicators and Factors for AHP Analysis

In this AHP analysis, our goal is to find the optimal ACF GGDP of a country. We hereby introduce 3 considerations:

1) Criteria: This is from the original GGDP formula, as these three factors are the only environmental/climate factors considered when calculating the GGDP.

2) Sub-criteria: We also realize that there are so many other sub-factors affecting the global climate, so we select the 5 most important factors, according to the United Nations (United Nations Development Programme, n.d.).

3) Plan: As we discussed above, we expect countries to take different environmental policies in order to increase the GGDP value.

AHP is just based on our subjective judgment to determine the weight of each indicator, so we need an objective method EWM to reflect that decision-makers attach importance to different indicators, and there will be a certain weight contrary to the actual indicators. The internal statistical rules and authoritative values among index data should be considered in the weight allocation of indicators. In this way, index weighting is more just, the internal unity of subjective and objective is realized, and the evaluation results are more real and scientific.

4.3 First-Layer AHP- EWM Analysis: Sub-criteria

4.3.1 Variables

We first define each indicator above:

C1: Population: A fundamental prerequisite of any human activity is the population. The population includes all citizens, temporary residents, or permanently settled aliens in a country. This indicator measures the impact on criteria by different population sizes. The population of a country is estimated by counting the annual changes in population resulting from births, deaths, and migration.

C2: Price for raw materials: A lot of raw materials are crucial for both production and environmental health. For example, mineral resource is a component of NRD, and it is also very important in the manufacturing industry. This indicator measures the total cost of several most important raw materials that could meanwhile potentially harm environmental health, including coal, oil, nuclear energy, metal, etc.

C3: Resource: This indicator includes all natural resources such as land, which is viewed as both the site of production and the source of raw materials.

C4: Development Degree: As we have mentioned previously, developing and developed countries are different in terms of economic development and many other aspects. This indicator measures the difference between developing and developed countries.

C5:Indusrty: This indicator further measures the degree of industrialization and urbanization of a country. Since countries are at various stages of economic development, we expect countries to have different potentials to affect the weight of criteria factors.

4.3.2 Implementation

Now we do a hierarchical single sort from the sub-criteria level to rank each of the indicators by the previous analysis tendency standard to calculate the weight value of the important order of all nodes associated with this level:

Criteria	C1	C2	3	C4	C5
C1	1	1/3	1/3	3	3
C2	3	1	1/3	3	5
C3	3	2	1	5	6
C4	1/3	1/3	1/5	1	3
C5	1/3	1/5	1/6	1/3	1

We then use the square root to determine the geometric mean of each row of the matrix, by referring to the general formula. Let A denotes the matrix above to calculate the weight value,

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & & & \\ \vdots & & \ddots & \\ a_{n1} & & & a_{nn} \end{bmatrix}, \quad \mathbf{w}_i^0 = \frac{(\prod_{j=1}^{n} a_{ij})^{\frac{1}{n}}}{\sum_{i=1}^{n}(\prod_{j=1}^{n} a_{i,j})^{\frac{1}{n}}}, n = 1, 2, \cdots, n$$

Then normalize each column of the judgment matrix, and take the new matrix to calculate the arithmetical average of the rows W0i (Lay et al., 2018), which is used to calculate C.R followed by:

$$C.R. = \frac{\frac{1}{n}\sum_{i=1}^{n}\frac{Aw_i^0}{W_i^0} - n}{R.I. * (n-1)}$$

By substituting all data into Matlab, we got the result I = 0.0876 < 0.1, which passed the consistency test. To visualize the weight value of the important order of all nodes associated, we produce a cluster barplot:

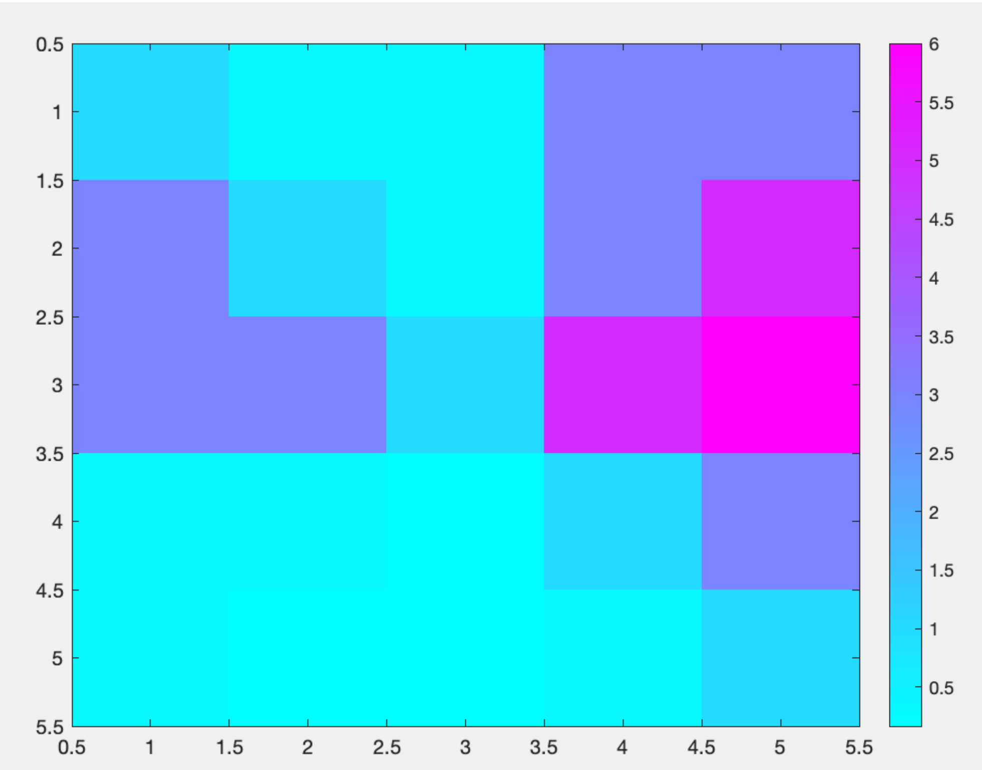

Figure 4.3: Weight Value for Indicators

From the cluster barplot above, we can easily observe that the intersection of C3 and C5 have the most weight value, indicated by the deepest color, which means resource and industry have a very strong importance impact on GGDP. And we also got the engine vector W_α for sub-criteria, where $W_\alpha = (0.153, 0.264, 0.452, 0.087, 0.048)^T$.

In the next step, we create 5 matrices, and each matrix corresponds to the relationship between the sub-criteria (C layer) and the upper-level criteria (A layer). We have the total hierarchical ranking of layer C for i factor in layer A are following by

$$C_n = a_1c_{n1} + a_2c_{n2} + a_3c_{n3} + ... + a_mc_{nm}$$

The result of layer A comparison matrix between layer A and layer C:

$$C1 = \begin{bmatrix} 1 & 2 & 5 \\ \frac{1}{2} & 1 & 3 \\ \frac{1}{5} & \frac{1}{3} & 1 \end{bmatrix} \quad C2 = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{5} \\ 3 & 1 & \frac{1}{2} \\ 5 & 2 & 1 \end{bmatrix} \quad C3 = \begin{bmatrix} 1 & 7 & 3 \\ \frac{1}{7} & 1 & \frac{1}{5} \\ \frac{1}{3} & 5 & 1 \end{bmatrix}$$

$$C4 = \begin{bmatrix} 1 & \frac{1}{7} & \frac{1}{5} \\ 7 & 1 & 2 \\ 5 & \frac{1}{2} & 1 \end{bmatrix} \quad C5 = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ 2 & 1 & 2 \\ 2 & \frac{1}{2} & 1 \end{bmatrix}$$

After each single sort matrix passes the consistency test, we then use EWM according to index variability to determine the objective weight (Guo et al., 2014). Firstly, from the criteria level normalize each of the indicators, we can differentiate the factor for positive indicator (C1, C2 and C5) by the following formula, where x_{ij} represents the weight of each subcriterion to the upper criterion:

$$x'_{ij} = \frac{X_{ij} - \min(X_{1j}, X_{nj}, \cdots, X_{nj})}{\max(X_{1j}, X_{nj}, \cdots, X_{nj}) - \min(X_{1j}, X_{nj}, \cdots, X_{nj})}$$

and inverse indicator(C3 and C4) by (Guo et al., 2014):

$$x'_{ij} = \frac{\max(X_{1j}, X_{nj}, \cdots, X_{nj}) - X_{ij}}{\max(X_{1j}, X_{nj}, \cdots, X_{nj}) - \min(X_{1j}, X_{nj}, \cdots, X_{nj})}$$

By obtaining the ratio of each index under the influence factors, we can calculate the information entropy of each index, and obtain the weight obtained by EWM through the information entropy calculation, we record the weight for W_β.

$$W_j = \frac{\sqrt{\alpha_j \beta_j}}{\sum_{j=1}^{n} \sqrt{\alpha_j \beta_j}}$$

By combining the weights obtained by the above two methods, we can get the final weight of the combination index W_j = (0.122, 0.273, 0.328, 0.125, 0.152).

4.4 Second-Layer AHP Analysis: Criteria

Following the previous step, continue to create comparison matrices for the three factors at the criteria level.

4.4.1 Variables

1) P1 (Aggressive): Some governments may prioritize environmental factors over economic development and try their best to reduce CO2 emissions, electricity waste, and

NRD in order to increase the value of GGDP. This indicator measures the impact of such aggressive environmental policies on GGDP.

2) P2 (Moderate): Some countries may also take environmental factors seriously, but they may still prioritize both economic growth and climate mitigation simultaneously, This indicator measures the impact of moderate policies on GGDP.

3) P3 (Mild): We also anticipate that some countries may not care about the impact of environmental factors on GGDP at all, and this indicator measures the potential impact of such traditional economic policies.

4.4.2 Implementation

In the second-layer AHP analysis, we repeat the hierarchical single sort from the criteria level to rank each of the factors. Through summation progress, we get the following histogram plot, which shows us the weight of each factor we should take when we calculate the GGDP of a country. It is worth noting that our result indicates CO2 Emissions as the most important factor, as the weight of the CO2 emission, 0.426, is the highest among all three factors. The weight of electricity waste is 0.321, less than the weight of CO2 Emission, but more than the weight of NRD, 0.253, suggesting that electricity waste is a more important factor compared to NRD, but it is less important than CO2 Emissions.

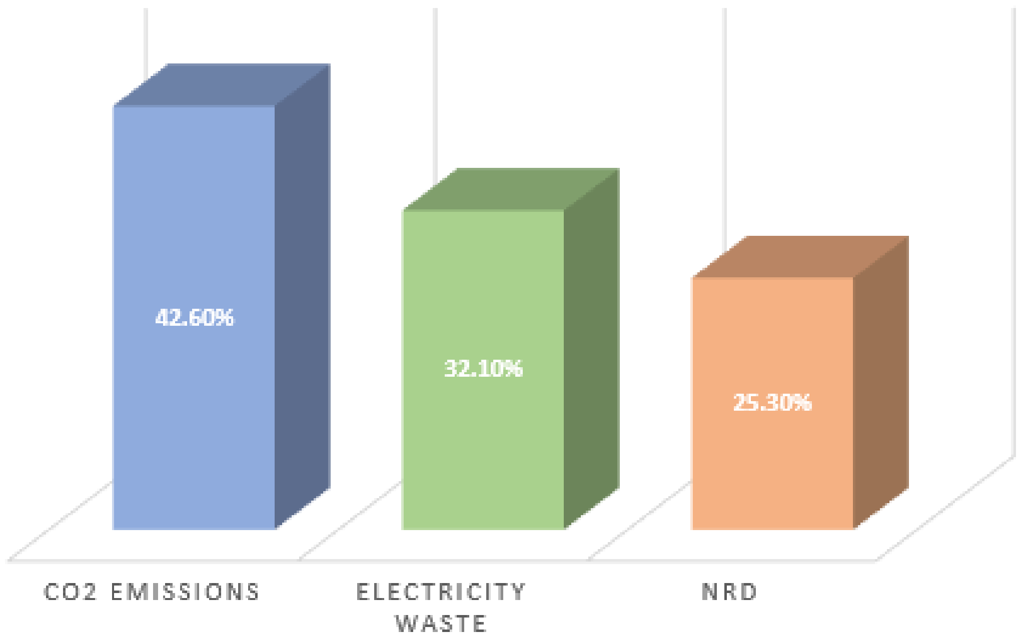

Figure 4.4: Weight Value for Indicators

4.5 Result

In the last step, we combine the result from both the first-layer analysis and the second-layer analysis, by multiplying and summing the weight calculated from both analysis, for example, the final weight of policy 1, denoted as FW of P1, is calculated by

$$FW of P1 = 0.426 * 0.581 + 0.253 * 0.117 + 0.321 * 0.102 = 0.31$$

Based on this result, we continue to create three matrices corresponding to the relationship between the criteria (A layer) and the upper-level plan (P layer). The following combined weight vector shows:

$W^{(3)}$	0.426	0.253	0.321
$W^{(4)}$	0.581	0.309	0.109
	0.117	0.264	0.617
	0.102	0.619	0.279
$W^{(combined)}$	0.310	0.397	0.293

Figure 4.5: Table of Combined Weight Vector

According to Figure 4.5, the last row is the final weight of each policy. The value of the final weight indicates the importance of that policy on climate mitigation. Since P2 > P1 > P3, we, therefore, adopt the Moderate environmental policy as our optimal decision for developing countries when calculating their Adjusted Climate-Focused GGDP. In other words, this result shows that after adopting GGDP, assuming countries will take all effort to maximize their GGDP, they will choose to take the Moderate environmental policies to achieve their goal. The expected global impacts of those policies on climate mitigation can be directly calculated by the following formula:

$$EGI = GGDP_{acf}^{optimal} - GGDP_{acf}^{original}$$

where $GGDP_{acf}^{original}$ stands for the adjusted GGDP value of a country at one year if the country takes no action at all after adopting GGDP measure methods. $GGDP_{acf}^{optimal}$ stands for the adjusted GGDP value of a country at one year if it takes its optimal environmental policies to increase its adjusted GGDP value.

5 Discussion

5.1 Pros and Cons of Adjusted GGDP

After deriving the weightings for the Adjusted GGDP formula from the AHP analysis and calculating the optimal Adjusted GGDP value, we observe a significant improvement in a developing country's impact on climate mitigation. In other words, adopting GGDP will motivate them to take moderate environmental policies to increase their GGDP values. Therefore, we can see that for developing countries, the positive EGI value, which stands for the difference between the optimal Adjusted GGDP value and the original Adjusted GGDP value, demonstrates the positive effect of adopting GGDP in terms of climate impact. For developed countries, since from our polynomial regression analysis in the previous sections we observe little or no positive correlation between GDP and the three major variables in the GGDP formula, we believe GGDP value for developed countries remains at a high level and thus we assume they will not necessarily take any major policies because of the change of measure method. Therefore, is worth mentioning that we assume the positive effect of GGDP in climate mitigation in developed countries is not significant in our model. Furthermore, we want to discuss how would different countries be impacted by the ACF GGDP model, both positively and negatively.

5.1.1 Developed Countries

We assumed in Sections 3 and 4 that developed countries and developing countries would be impacted by environmental/climate factors in different ways, and our assumption was verified through both PRM and ACF models. Therefore, the discussion of pros should also be divided into two parts: for developed countries, and for developing countries.

As we found in Section 3, many developed countries had started to decrease their CO2 emissions, as well as tried to constrain the total solid waste to a certain amount, and these actions were due to the fact that they have achieved a higher level of industrialization, so they have a strong motivation to phase out high-polluting industries and shift to more eco-friendly industries. Based on this fact, we would expect the GGDP value or the place of a developed country on the global ranking would not be largely affected in any way, and in fact, they might be beneficial from this calculation, because a lot of developed countries, as we found in Section 3, are leading the actions of reducing CO2 emission. If the change from GDP to GGDP actually took place, they could have a better say when creating a global standard. On the other hand, developed countries are barely affected by this change negatively. For example, they have the option to move their high-polluting factories to those developing countries seeking to increase industrial production. This might be morally controversial, but it is undeniably beneficial for developed countries. Overall, the impact of replacing GDP with GGDP might not be significant at all in reality.

5.1.2 Developing Countries

However, developing countries could be significantly impacted by this change, and our team believes that developing countries may be more negatively affected than positively affected.

The upside of this change is that the change from GDP to GGDP could serve as an incentive to motivate developing countries to adjust their economic structures and meanwhile make policies to constrain the pollution to the environment as well as the harm to the climate. This is beneficial for both developing countries as a whole, and the people of these countries.

However, as we discussed above, developing countries typically have no choice but to develop industrial-heavy productions, and it would inevitably lead to more pollution than service-based productions. If these high-polluting industries were cut down by governments of developing countries, we would very likely see a huge drop in economic growth, despite the positive impact on climate mitigation. Consequently, it would actually take a longer time for developing countries to achieve a high level of industrialization, which means these countries had to suffer from the pollution and environmental damage for an even longer time. People may argue from either side, but our team believes that the result we obtained from both models supports a less aggressive environmental policy for developing countries. In other words, better economic growth might be more important for actual development and GGDP value of developing countries.

5.2 In-depth Analysis on China with Time Series

In the end, we decide to apply all of our findings and assumptions to a specific country, and we selected China because China is the largest developing country in the world, which provides enough information for us to reference. By using RStudio, we calculated the ACF GGDP of China from 2001 to 2020, and made a comparison chart between ACF GGDP and GDP. As figure 5.1 shows, the red line represents the GDP growth from 2001 to 2020; the green line represents the original GGDP growth, calculated by using the formula proposed by Stjepanović et al.; and the blue line represents the optimal GGDP calculated by using our ACF GGDP Model.

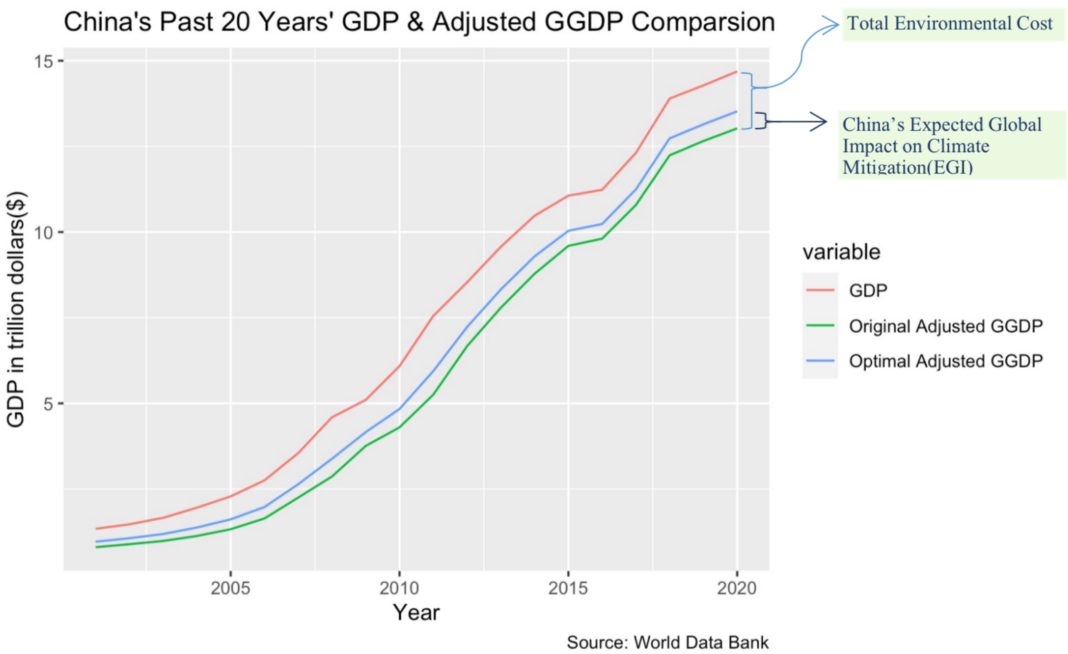

Figure 5.1: China's Past 20 Years' GDP & Adjusted GGDP Comparison

Furthermore, we compared the GDP growth rate with the GGDP growth rate of China from 2001 to 2020, and we see that these two trends are also very similar. As we expected, the growth trend of GGDP is very similar to that of GDP over the past twenty years, except the total GGDP value is a little smaller than the GDP value.

Therefore, we can conclude that the GGDP of China would not be largely negative-affected if China adopted a moderate environmental policy, specifically in terms of the reduction of CO2 emission, NRD, and electrical energy waster. We can predict that as the GGDP of China continues to grow in the future, it will start to slow down as it turns into a developed country, and the cutdown of industrial-heavy productions in China would gradually occur without significant harm to the economy of China.

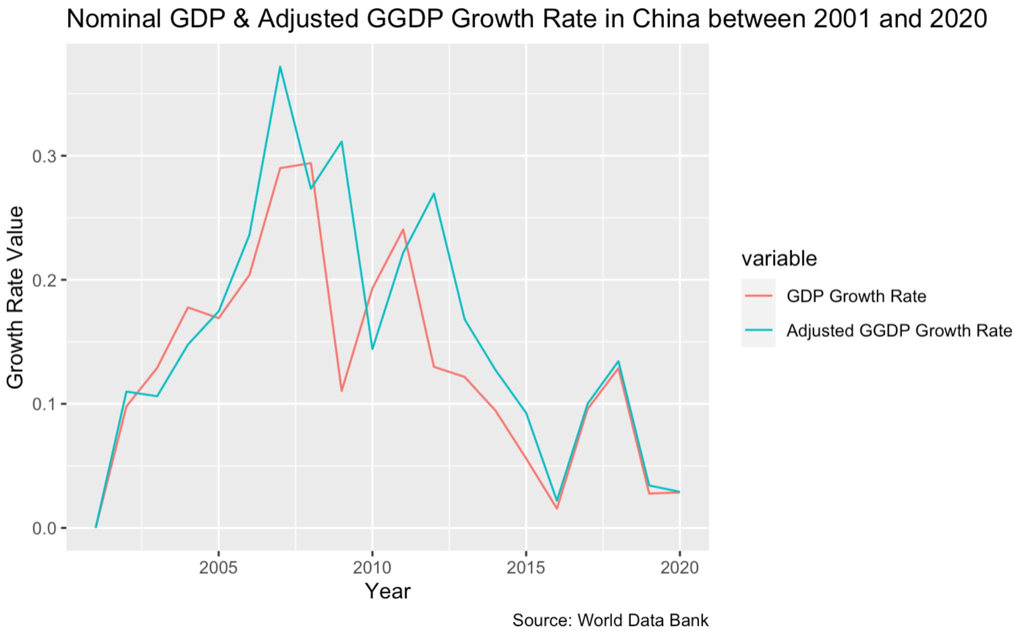

Figure 5.2:Nominal GDP Adjusted GGDP Growth Rate in China between 2001 and 2020

5.3 Strength and Weakness

Strength

1) Reliable data were obtained from official sources. For our PRM model, we collected data from the World Bank to find the result. Therefore, we are confident that our result from PRM is reliable and unlikely to have factual errors.

2) Sufficient theoretical preparations are made before we construct models. For the ACF GGDP model, we used a three-layer analysis to prevent the possibility that a single factor takes too much weight in the overall structure. We believe we successfully prevented such errors and ensured that the weight of each factor is within a reasonable range respectively.

Weakness and Improvement

1) Our first weakness is the classification of countries is too general. Even though we have discussed developing and developed countries separately, we think we can do a more in-depth classification when we study the relationship between GDP and environmental/climate factors.

2) We did not have an opportunity to do more layers of analysis when we construct the ACF GGDP model. For example, we proposed that population is a sub-factor impacting the climate and GGDP. In the next step, we may further consider factors associated with each sub-factors, such as the health conditions of the population, the cost of filtering greenhouse gas, etc.

3) Problems with the knock-on effects of environmental impacts are difficult to estimate, and there may be many potential costs that have no direct impact that has not been taken into account.

5.4 Conclusion

In conclusion, our team researched the possibility of change from GDP to GGDP and the consequential impact on global climate mitigation by using complex mathematical and statistical models. The result of our findings supports the conclusion that a change from GDP to GGDP is viable.

In our future research, we decide to further study the impact of each individual factors we included in the ACF model, to provide more in-depth results of the impact of GGDP on global climate and environment.

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7 A Policy Recommendation

Dear world leaders:

I hope this letter finds you all well. We are a research team from the United States, and we are excited to have this opportunity to bring awareness to an important agenda of all human-being: sustainable development and climate mitigation.

We are delighted to see that global economic growth was faster than ever over the past century. However, a side-effect of economic development, the harm to the environment and climate, was largely overlooked. Due to the impact of the increasing global climate crisis such as severe effects, we believe it is time to take action to change the status quo, and based on our recent research, our team believes that a great start is to change from our current GDP calculation to a new method of calculating GDP, which includes the impact of environmental and climate factors, and we call it Green GDP (GGDP). As an environmental production research team, we are entrusted by the United Nations Development Programme with seeking an optimal model to calculate Green GDP. And in the new GDP criteria, nations can better balance economic growth and climate mitigation.

In our research, we found that a country does not need to take any aggressive environmental policy to largely improve its performance on environmental protection and climate mitigation–a moderate environmental and climate policy would enable a country to reach its optimal GGDP over a short period of time. With it said, developing countries may have to undergo a period of hard time because the cut down of industrial-heavy productions may cause some short-term negative effect. However, we want to assure you that this change would not largely affect the economic growth of your countries, and from a long-term perspective, we believe this is the best solution for the development of your countries.

We firmly believe that climate mitigation and sustainable development require the effort of all nations, and we are optimistic to see all countries would be benefited from this change from GDP to GGDP in the future.

Best Regards,

Team 2309571