GGDP Calculation and Application based on Shadow Prices

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Abstract. As global climate and environmental issues continue to increase, Green Gross Domestic Product (GGDP) has become a more suitable indicator of economic health and development than Gross Domestic Product (GDP). This paper proposes a new climate-environment cost-based GGDP model in macro form, using shadow price that is more economically sound than existing GGDP models. We also introduce a new method called relation chain analysis to export the GGDP model to micro form. Our mathematical analysis predicts a positive impact of using our model on the global economy and climate.

Keywords: GDP , GGDP , climate environmental costs, shadow prices, climate mitigation

1 Introduction

GDP(**Table 1**) accounting has always been an important indicator of the health and development of a country or region's economy.[13]

However, one of the main architects of GDP recommended from the beginning not to use GDP as a measure of social welfare (Kuznets, 1934[1]). In recent years, with economic and industrialization, many environmental problems have become more prominent and people have to spend extra money or resources to maintain or improve environmental problems such as climate and ecology. GDP accounting does not take these into account, and there is now a greater awareness of the shortcomings of using GDP alone as an indicator of economic health and development.

Many new indicators have emerged to replace GDP as a measure of the health and devel- opment of a country or region, and GGDP is one of the highly competitive new indicators to account for economic health and development.

1)Our work can be summarized as follows:

After reviewing a large amount of GGDP-related literature[2][3][4][5][6], the GGDP model based on climate-environment costs (Wang F, et al. 2020[7]) was selected

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as the base model (Section 3.1); the serious shortcomings of some existing climate-environment cost models were pointed out, and a model based on shadow prices of climate-environment costs was established (Section 3.2). Then we proposed our macro GGDP model(Section 3.3).

2) Through theoretical analysis, two lemma related to GDP and human energy extraction were obtained (Section 4.1); combined with the lemma, two independent root variables implicit in the GGDP model were discovered with the help of relational chain analysis tools: renewable energy extraction and non-renewable energy extraction (Section 4.2), and all variables in the GGDP model were fitted with the independent root variables through regression analysis. The analytical equations of GGDP and the two independent root variables were finally obtained, making quantitative analysis possible (Section 4.3); Then we proposed our micro GGDP model(Section 4.4).

3) Based on the analytical equations, it was found that using GGDP as an indicator of economic health would be beneficial to improving the global climate environment ,pointing out that it is worthwhile to use GGDP instead of GDP(Section 5.1). Analyzed the possible resistance to promoting the use of GGDP indicators in terms of both social factors and data access factors (Section 5.2).

Data availability: The datasets generated and/or analysed during the current study are available in the GGDP-data repository,
https://github.com/BestAnHongjun/GGDP-data.

2 Notations and shadow prices

Table 1. Explanation of all letter symbols in this paper.

Symbol	Explanation
EXT	Total Energy Extraction.
EXTre	Total Renewable Energy Extraction.
EXTno	Total non-renewable energy extraction.
A	Upper bound of renewable energy extraction.
B	Upper bound of non-renewable energy extraction.
GDP	Gross Domestic Product.
GDPp	Current GDP.
GDPf	Future GDP.
CEC	Climate Environmental Costs.
CECp	Current climate environmental cost.
CECf	Future climate environmental cost.
r	Discount rate (economics).
SP	Shadow Price(CO2).
TE	Total Emission (CO2).
R2	Linear correlation coefficient (regression analysis).
F	Significance test results (regression analysis).
P	Significance (regression analysis).
VIF	Severity of multicollinearity (regression analysis).
$f(\cdot)$, $f'(\cdot)$, $g(\cdot)$	Generalized functional relationship.

Table 2. Conversion results of shadow prices[16].

Year	2005	2007	2010	2012	2015	2017
Shadow Price (dollars/kgCO2)	0.5685	0.7110	0.9660	1.1130	1.2060	1.4685

3 Macro GGDP Model

3.1 Basic Model

There are many ways to calculate green gross domestic product (GGDP), but their core is very similar. Taking the green GDP(Table 3) model proposed by Xi'an Jiaotong University as a reference example (Wang F, et al., 2020[7]), we define the basic GGDP model as follows:

$$GGDP = GDP - CEC \tag{1}$$

In the Formula (1), GDP is the gross domestic product and CEC represents the climate environmental cost.

Table 3. The total amount of oil, coal, gas and non-renewable energy extracted[10][11][12].

Year	Oil (GWh)	Coal (GWh)	Gas (GWh)	EXTno (GWh)	Year	Oil (GWh)	Coal (GWh)	Gas (GWh)	EXTno (GWh)
2000	1.2 ×105	1.5 × 107	2.6 ×107	4.2 ×107	2011	1.4 ×107	2.6 ×107	3.6 ×107	6.2 ×107
2001	1.2 ×105	1.6 ×107	2.7 ×107	4.3 ×107	2012	1.4 ×107	2.6 ×107	3.6 ×107	6.3 ×107
2002	1.2 ×105	1.6 ×107	2.7 ×107	4.4 ×107	2013	1.4 ×107	2.6 ×107	6.4 ×107	6.4 ×107
2003	1.3 ×105	1.7 ×107	2.8 ×107	4.6 ×107	2014	1.5 ×107	2.6 ×107	3.7 ×107	6.4 ×107
2004	1.3 ×105	1.8 ×107	2.9 ×107	4.8 ×107	2015	1.5 ×107	2.5 ×107	3.8 ×107	6.4 ×107
2005	1.3 ×105	2.0 ×107	3.0 ×107	5.0 ×107	2016	1.5 ×107	2.4 ×107	3.9 ×107	6.3 ×107
2006	1.4 ×105	2.1 ×107	3.1 ×107	5.2 ×107	2017	1.5 ×107	2.5 ×107	4.0 ×107	6.5 ×107
2007	1.4 ×105	2.2 ×107	3.2 ×107	5.4 ×107	2018	1.6 ×107	2.5 ×107	4.2 ×107	6.8 ×107
2008	1.4 ×105	2.2 ×107	3.3 ×107	5.6 ×107	2019	1.6 ×107	2.6 ×107	4.4 ×107	7.1 ×107
2009	1.3 ×105	2.3 ×107	3.2 ×107	5.6 ×107	2020	1.5 ×107	2.5 ×107	4.2 ×107	6.8 ×107
2010	1.4 ×105	2.4 ×107	3.5 ×107	5.9 ×107					

Table 4. The calculation results of global energy extraction[15][16][17].

Year	EXTre (PWh)	EXTno (PWh)	EXT (PWh)	Year	EXTre (PWh)	EXTno (PWh)	EXT (PWh)
2010	1.96	59.67	61.63	2016	2.67	63.52	66.19
2011	2.09	62.32	64.41	2017	2.81	65.88	68.69
2012	2.19	63.40	65.60	2018	2.94	68.71	71.65

2013	2.32	64.23	66.55	2019	3.03	70.96	74.00
2014	2.44	64.52	66.96	2020	3.23	68.33	71.56
2015	2.55	64.11	66.66				

3.2 Climate Environmental Costs(CEC)

3.2.1 Fatal flaws in some existing CEC-like models.

Some scholars have focused on the loss of local future ecological value due to ecological damage after resource extraction, and have quantified these losses in monetary terms as CEC, which is later subtracted from GDP. These individuals may have the right idea, but there are some shortcomings.

First of all, the prediction of the future ecological value of the loss is difficult to determine, i.e., different degrees of environmental damage in different areas will cause different value losses and can be analyzed only in specific situations, and the accounting has certain technical difficulties and is not universally applicable. At the same time, the direct subtraction of the ecological value of future depletion, expressed in monetary terms, from the GDP of the real present contradicts the financial concept of the time value of money. This is due to the presence of inflation and other effects that cause the value of future money to be more likely than not equal to the current value. It should be discounted to the present using some discount rate, and this discounted value should be subtracted from current GDP to obtain the realistic environmental cost.

We assume that the total GDP of the current year is GDPp and the total GGDP of the current year is GGDPp. Using some expertise, we estimate the total value of the future damage caused by our current actions as CECf , the duration of this environmental and ecological damage is N years, and the value of the damage caused each year i is CECfi , with the discount rate set to r. If we use the formula in 4.2 directly, we get the following equation:

$$GGDPp = GDPp - CECf \tag{2}$$

However, in the presence of relevant factors such as inflation or deflation, the present value of money is often not equal to the future value, which means that the present GDPp does not directly subtract the future CECf . Therefore, we should discount the CECf in the above equation to the present using the discount rate r. Let this value be CECp , and we have:

$$CEC_p = \sum_{i=1}^{N} \frac{CEC_{f_i}}{(1+r)^i} \tag{3}$$

Thus, the CECp we obtain should be an ideal value that can be directly added to or subtracted from GDPp. However, r is affected by many factors such as inflation, deflation and economic policies, and its estimation is itself a financial puzzle; in addition, CECf1 , CECf2 and CECf3 represent the value of the losses caused by our current behavior in each of the following three years, and the value for each time period is difficult to determine because it requires much knowledge of biology and economics.

3.2.2 Shadow prices.

In order to avoid the above problems, the concept of shadow price of environmental resources will be introduced in this paper for the accounting of CEC. Shadow prices are prices determined according to certain principles that reflect the true economic value of inputs and outputs, the supply and demand situation in the market, the degree of resource scarcity, and the rational allocation of resources, taking into account the degree of resource scarcity and the demand for final products in a certain optimal state of the social economy (Wu X, et al. 2015[8]). Because of its uniqueness, we can directly measure depleted ecological costs in terms of unit prices of environmental costs, and because shadow prices are fixed for each type of resource, they are universally applicable(Table 2).

3.3 Our Macro GGDP Model

It has been argued that factors such as wastewater discharge, solid waste discharge, solid waste storage, fossil energy consumption, and water consumption have a high global environmental impact (Wang F, et al., 2020[7]) and should be included in the Green GDP evaluation system. We agree with this view, but in the context of the actual needs of this question, we need to estimate the expected global impact of climate mitigation, and therefore include solid waste emissions and fossil energy consumption, which have a direct impact on climate mitigation, as primary considerations, and leave the rest of the factors out of consideration for the time being.

At the macro level, solid waste emissions, fossil energy consumption, etc. will eventually be mainly reflected in the emissions of greenhouse gases, mainly carbon dioxide. Starting from CO2 gas emissions, we construct a simple equation for calculating the climate environmental cost.

$$CEC = \varepsilon 1 \cdot SP \cdot TE \tag{4}$$

In the work equation, SP represents the shadow price of carbon dioxide gas and TE represents the total emissions of carbon dioxide gas. And $|\varepsilon 1| = 1$ is a balancing factor to eliminate the magnitude and balancethe order of magnitude relationship between CEC and GDP.

In summary, the Macro GGDP Model can be defined as:

$$GGDP = GDP - \varepsilon 1 \cdot SP \cdot TE \tag{5}$$

4 Micro GGDP Model

4.1 Lemmas

Lemma 1 (Strong linear correlation between GDP and total global energy extraction) . Energy is an important factor influencing GDP growth. Combined with historical data, Dataset 1[9] gives the global total GDP by year, Table 3 and Table 4 gives the global total energy extraction data (EXT) by year, and linear regression analysis based on the Polynomial Regression method can prove that GDP and

EXT have strong linear correlation. Table 5 gives the analysis results of linear regression, Equation (6) gives the equation of the linear relationship between GDP and EXT, and **Fig. 1.** Graph of GDP vs. EXT function. gives the image of the function of GDP and EXT.

$$GDP = -36.155 + 1.698EXT \tag{6}$$

Table 5. Results of linear regression analysis of GDP and EXT. R^2 is the linear correlation coefficient, F is the significance test result, P indicates significance, and V IF is the degree of multicollinearity.

Parameters	R^2	F	P	V IF
Value	0.953	184.365	< 0.01	1
Reference Value	1.0	-	< 0.05	< 5

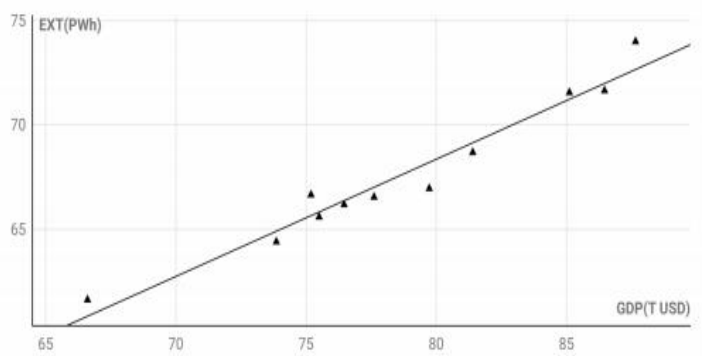

Fig. 1. Graph of GDP vs. EXT function.

Lemma 2 (Boundness of human extractable energy). Whether it is the extraction of renewable energy or non-renewable energy, due to the level of human science and technology and the theoretical upper limit, the total amount of energy that can be extracted by humans has an upper limit:

$$\begin{aligned} \mathrm{EXT_{re}} &\leq \mathrm{A} \\ \mathrm{EXT_{no}} &\leq \mathrm{B} \end{aligned} \tag{7}$$

Clearly, the total amount of energy extracted by humans is non-negative, so there is a lower boundness:

$$\begin{aligned} \mathrm{EXT_{re}} &\geq 0 \\ \mathrm{EXT_{no}} &\geq 0 \end{aligned} \tag{8}$$

4.2 Relationship chain analysis

In Section 3.3, we introduced the Macro GGDP Model(Formula (5)). However, It is difficult to perform a quantitative analysis because of the interaction relationship between the variables GDP , SP and TE. Therefore, in this subsection, we will perform a relational chain analysis for each variable and try to identify the most basic independent variables that affect the change in each variable in **Fig. 2**. The total energy extraction is one of the important factors affecting the change of GDP. Therefore, if we assume that the demographic factors, political factors, and other relevant reasonable factors at the macro level are essentially constant. Non-renewable energy sources are mainly fossil energy sources, which are characterized by their direct ecological and climatic impact when they are used. It should be emphasized that electrical energy is a vague concept. If electricity is produced by thermal and other means, it should be classified as non-renewable energy; if it is produced by wind, solar and other means, it is renewable energy.

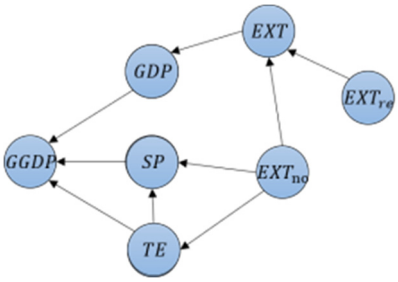

Fig. 2. Relational network of variables.

From this, we use the relational chain analysis tool to find the root independent variable that determines GDDP: the total amount of renewable and non-renewable energy extraction.

4.3 Verifying and Adjusting Relationships

4.3.1 Adjusting shadow prices as a function of the amount of non-renewable resources extracted Linear regression analysis is performed using Ridge regression to obtain the following results in Table 6. .

Table 6. Table of results from the linear regression analysis of shadow prices and non- renewable resource extraction.

Parameters	R2	F	P	V IF
Value	0.944	67.366	< 0.01	1
Reference Value	1.0	-	< 0.05	< 5

The shadow price is shown to have a strong linear correlation with the amount of non-renewable resources extracted, and the fitted linear relationship is:

$$SP = -2.222 + 0.054EXTno \tag{9}$$

4.3.2 Adjusting global CO2 emissions as a function of non-renewable resource extraction Linear regression analysis was performed using Least Absolute Shrinkage and Selection Operator regression to obtain the following results in Table 7.

Table 7. Table of results from linear regression analysis of global CO2 and non- renewable resource extraction[14]

Parameters	R2	F	P	V IF
Value	0.942	2217.635	< 0.01	1
Reference Value	1.0	-	< 0.05	< 5

The total emissions is shown to have a strong linear correlation with the amount of non-renewable resources extracted, and the fitted linear relationship is:

$$TE = -4.4 + 4.661EXTno \tag{10}$$

4.3.3 Validating Relationships

Combining equations (5), (6), (9) and (10), the GGDP equation is derived as:

$$\begin{gathered} GGDP = (-36.155 + 1.698(\text{ EXTTe } + \text{ EXTno })) \\ -(-2.222 + 0.054 \text{ EXTno })(-4.4 + 4.661 \text{ EXTno }) \end{gathered} \tag{11}$$

This means GGDP = f(EXTTe , EXTno), so the relational chain analysis is valid.

4.4 Our Micro GGDP Model

By simplifying Equation 11, we can obtain the micro GGDP model, as shown in Equation 12.

$$GGDP = -26.3782 + 1.698EXTTe - 24.6802EXTno - 0.2517EXT^2no \tag{12}$$

5 Social Effects

5.1 Improving Climate, Improving Economy

Using GGDP as a measure of economic development, countries around the world will tend to maximize the level of their GGDP. This process can be modeled using optimization theory:

$$\begin{aligned}\begin{bmatrix}EXT_{re}\\EXT_{re}\end{bmatrix} &= \underset{\substack{0\le EXT_{re}\le A\\0\le EXT_{no}\le B}}{\arg max}\, GGDP\\ &= \underset{\substack{0\le EXT_{re}\le A\\0\le EXT_{no}\le B}}{\arg max}\, 26.3782 + 1.698EXT_{re} - 24.6802EXT_{no} - 0.2517EXT_{no}^2 \quad (13)\\ &= \begin{bmatrix}A\\0\end{bmatrix}, (GGDP_{max} = -26.3782 + 1.698A)\end{aligned}$$

Of course, this is only a theoretical maximum, which is difficult to achieve in real life. However, in order to obtain better indicators of economic development, human social development must move toward the theoretical optimum:

$$\begin{aligned}EXT_{re} &\to A\\ EXT_{no} &\to 0\end{aligned} \quad (14)$$

Then according to the Formula 10:

$$\lim_{EXT_{no}\to 0} TE = 4.4(TE \to TE_{\min}) \quad (15)$$

This will gradually reduce greenhouse gas emissions and improve the global climate.

The greatest value of using GGDP as an indicator of economic health and development is that it can compensate for the shortcomings of GDP in not effectively measuring climate-environment impacts.

If GDP is certain, from Equations (6) and (12):

$$\begin{aligned}EXT &= \frac{GDP+36.155}{1.698}\\ GGDP &= -26.3782 + (GDP + 36.155) - 26.3782EXT_{no} - 0.2517EXT_{no}^2 \quad (16)\\ \frac{dGGDP}{dEXT_{no}} &= -26.3782 - 0.5034EXT_{no} < 0\end{aligned}$$

For a given GDP , GGDP increases with the decrease of EXTno. Using GGDP as an indicator of economic health and development status, we can obtain elements related to climate mitigation, that is, we are able to develop the economy while considering the impact on the climate environment. By adjusting the variables, we can achieve improved climate mitigation without affecting the current GDP. At the same time, this would have an additional benefit. By using GGDP as an indicator of economic health and development in a way that adjusts the variables without affecting the current total GDP , politicians associated with the promotion of GGDP may gain additional political success. For they will find an opportunity - an opportunity to improve the environment without affecting the current total output of the economy. This will help us break down some of the barriers mentioned in Section 5.2 and facilitate the diffusion of GGDP applications.

5.2 Barriers

The first is a direct obstacle. One is the different responsibilities of each unit in the political system, which makes each unit view GGDP from different perspectives, and some units may hinder its promotion because they think GGDP may not bring substantial benefits. The second is the obstruction caused by the political purposes of some politicians. The biggest advantage of promoting the application of GGDP is to obtain long-term benefits after considering and adjusting the relevant indicators. However, it also leads to the possibility of sacrificing some short-term benefits or making it difficult to obtain huge benefits in the short term, and some politicians who are eager to pursue political achievements may be more willing to obstruct its promotion.

The second is an indirect barrier. This barrier arises from the fact that not everyone associated with GGDP promotion has a relevant educational background or sufficient level of education, and that under- standing GGDP requires the integration of many disciplines, such as economics, social sciences, and biology.

Thus, if certain participants related to the promotion of GGDP directly or indirectly oppose, hinder or try to hinder the use of GGDP-related modalities, it will create obstacles to the promotion of GGDP (Hoff J V, et al. 2021[3]).

6 Conclusion

This study is based on the context of intensifying global climate change and increasing environmental and ecological impacts, while GGDP is gradually becoming a more suitable indicator of healthy economic development.

We propose a new macro GGDP model based on the environmental costs of climate, incorporating shadow prices into the model calculations. A relational chain analysis approach is introduced to extend the GGDP model to a micro form.

After analysising，we predicts that our model will have a positive impact on the global economy and climate. By incorporating environmental and climate factors into the measurement of economic development, our GGDP model helps to more accurately reflect the real costs of economic activity on the environment. This approach can reveal the true state of economic development that may be overlooked under GDP models that do not account for environmental impacts.

And it remains valid when applied to a country's GGDP accounting, simply by converting extraction to acquisition.By introducing shadow prices, our model allows the value of environmental factors to be reflected in economic decision-making, providing policymakers with a more powerful tool to more intelligently balance economic growth and environmental protection. The newly introduced chain-of-relationships approach allows our GGDP model to be extended to the micro level, which not only helps to more concretely assess and manage the environmental impacts of economic activities, but also helps policy makers and economic decision makers to be more nuanced in their decision making.

Overall, the new GGDP model we propose is expected to have a positive impact on the global economy and climate, helping to drive the implementation of more sustainable and environmentally friendly economic development strategies.

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