

Research on Path Optimization of Industrial Energy Technology Innovation under the Constraint of "Dual Control" Goals: A Case Study of Bengbu City, Anhui Province

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Abstract

The fundamental reason why China has become the country with the largest global carbon emissions is that energy and its related industrial systems mainly rely on fossil resources. To this end, promoting the energy structure and related industrial systems from high carbon to low-carbon green development in a scientific and orderly manner will help achieve the "dual carbon" goals and support China's high-quality and sustainable development. Among them, technological innovation plays a crucial role. Under the dual carbon goal, Bengbu explores energy technology innovation - developing copper indium gallium selenium thin film solar power generation systems, providing new development ideas for reducing building carbon emissions and achieving friendly interaction between buildings and the power grid. This article will explore the feasibility of adjusting the energy structure through technological innovation to achieve carbon emissions peak and carbon neutrality goals, and then use multi-attribute decision-making models and other methods to explore the optimal path to achieve the "dual control" goal of emissions reduction. Based on life cycle assessment, the trade-off effect of renewable energy, economy, and environment will be explored. Finally, the inductive summary method is used to provide reference opinions for the formulation of follow-up policies to optimize energy structure and how to achieve green and low-carbon development.

Keywords

Building emission reduction, Energy structure, technological innovation life cycle.

1. Introduction

China's energy consumption system has the characteristics of high carbon and high coal systems. With the continuous increase in demand for energy and electricity, carbon dioxide emissions have entered a stage of large-scale and high growth. Since the proposal of the "dual carbon" goal, how to orderly promote energy reform while ensuring the timely growth of the national economy has become a new challenge facing the people of the whole country. The White Paper on China's Energy Development in the New Era points out that it is necessary to strengthen breakthroughs in cutting-edge technologies for efficient energy conversion, storage, and utilization, while maintaining stable energy supply, and build a clean, low-carbon, safe, and efficient energy system. Therefore, exploring the impact of energy structure adjustment on carbon emissions is of great significance [1].

Many previous studies have predicted and analyzed whether China's carbon reduction targets can be achieved. Some studies have comprehensively considered factors such as economic growth, energy intensity, industrial structure, and urbanization, predicting that China will

achieve peak carbon emissions between 2030 and 2035. However, whether changes in energy structure will have an impact on peak carbon emissions has not been thoroughly studied. Shaohua Wang et al. used path analysis to calculate the impact of energy structure on carbon intensity, and the results showed that energy consumption structure is the main driving factor for carbon intensity growth [3].

Although there has been good progress in research on carbon reduction targets, existing research also has the following limitations: few studies have taken the "dual control" target as the research object, most of which are single indicators or combine carbon peaking with carbon neutrality.

In summary, this study attempts to explore the optimal path to achieve the "dual control" goal of emission reduction, providing reference opinions for the formulation of follow-up policies to optimize energy structure and how to better achieve green and low-carbon development. In addition, this article will focus on copper indium gallium selenium solar film modules and use life cycle assessment to explore the hidden energy, environmental, and economic trade-offs generated in the life cycle of solar power. This will provide policy makers with a systematic renewable energy power planning approach from a life cycle perspective.

2. Data sources

Data sources: Energy Outlook (2017) from the US Energy Information Agency (EIA), National Bureau of Statistics, China Statistical Yearbook, 14th Five Year Plan for Modern Energy Systems, Environmental Impact Assessment Report on Kaisheng Photovoltaic (Weihai) Co., Ltd.'s Annual Production of 300 MW Copper Indium Gallium Selenium Thin Film Battery Module Project, 2022 Urban Construction Statistical Yearbook, etc.

3. Explore the optimal path for the "Dual Control" goal of carbon reduction

3.1. Scenario design

3.1.1. Economic development status

Referring to the Energy Outlook (2017) by the US Energy Information Agency (EIA), China's future economic development is designed into three scenarios:

- 1) Rapid development: China's average annual economic growth rate from 2017 to 2030 is 5.3%.
- 2) Medium speed development: From 2017 to 2030, China's economic growth rate was 4.9%.
- 3) Low speed development: From 2017 to 2030, China's economic growth rate was 4.6%.

3.1.2. Energy structure scenario

1) Policy constraint scenarios

The policy constraint scenario is to adjust the energy structure under natural conditions (using grey prediction models) to meet policy requirements. In order to alleviate the pressure of carbon reduction, China has successively proposed the planning goals of 20% of non fossil energy to primary energy consumption by 2025 and 25% of non fossil energy to primary energy consumption by 2030 in terms of energy consumption structure.

2) Scenario of minimum energy production cost

The scenario of minimizing energy production costs involves adding up the consumption and carbon emission costs of each energy source to minimize their sum. Using Matlab software for planning and solving, taking the minimum value of the objective function.

3.2. Result Analysis

3.2.1. Energy structure prediction results

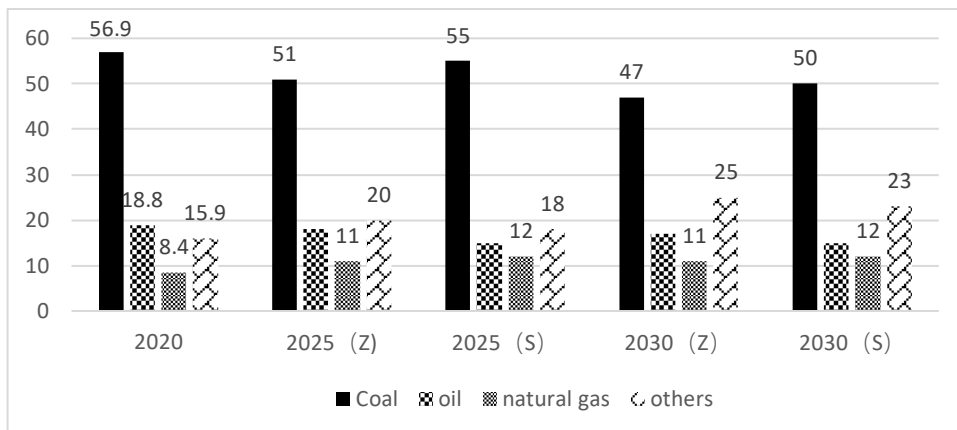


Figure 1: Energy structure prediction

The results show that from 2020 to 2030, China's energy consumption structure is still dominated by coal, but the proportion of coal consumption shows a downward trend in both scenarios, with a significant decrease in the scenario under policy constraints. In addition, the proportion of natural gas and other energy sources has increased. Therefore, the trend of China's future energy structure is to increase the proportion of natural gas and other energy consumption, gradually breaking away from dependence on coal.

3.2.2. Feasibility of China achieving peak carbon emissions targets

1) Carbon emission measurement methods

$$CE = \sum EC_i \times EF_i \times \frac{44}{12} \tag{1}$$

$$CI = CE / GDP$$

2) Results

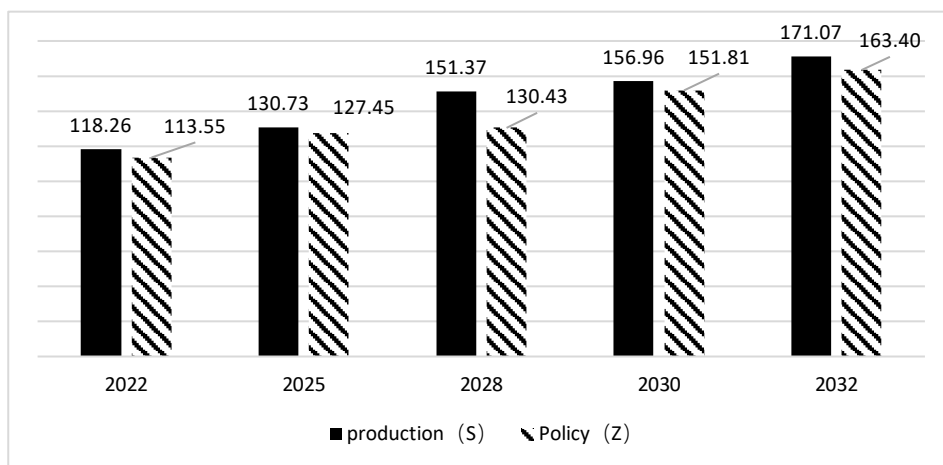


Figure 2: China's carbon emissions under rapid economic development

From the above figures, it can be seen that no matter how the economy develops, all scenarios have not reached the goal of peaking carbon emissions before 2030, and carbon emissions are increasing every year. Among them, in the latter two economic scenarios, carbon emissions will reach a short-term peak from 2025 to 2028, but there will be a significant increase afterwards, which obviously does not meet the requirements of carbon peak. Therefore, it is worth our in-depth thinking on how to control carbon emissions in the later stage and no longer increase. In addition, under the three economic development conditions, the carbon emissions under the

energy production cost scenario are higher than those under policy constraints. To some extent, it indicates a certain conflict between cost and environment.

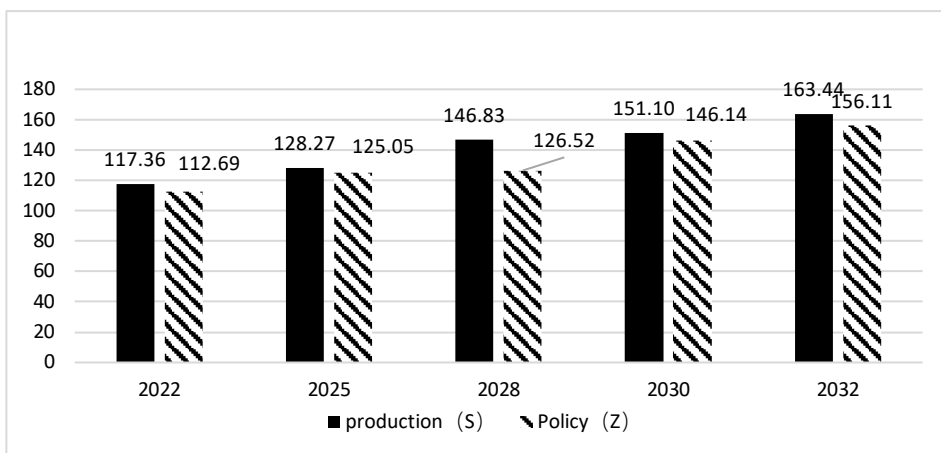


Figure 3: China's carbon emissions under moderate economic development

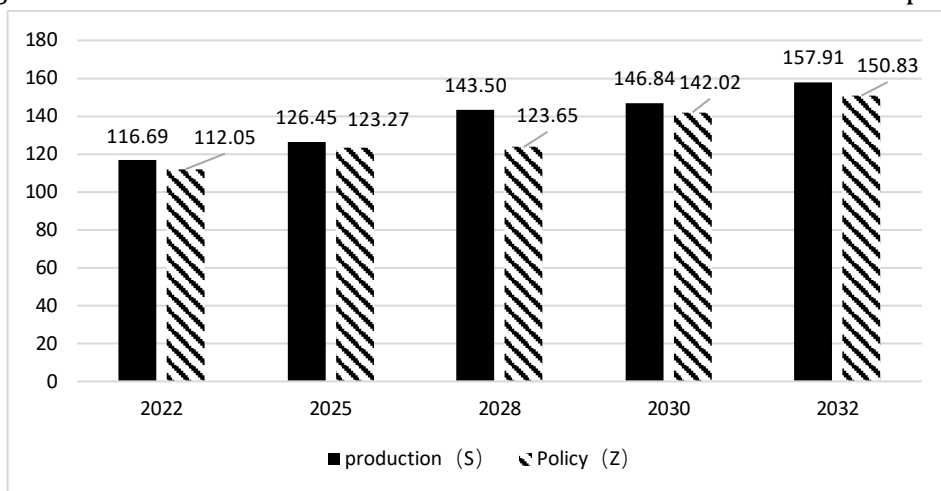


Figure 4: China's carbon emissions under low-speed economic development

3.2.3. Feasibility analysis of China's achievement of carbon intensity targets in different contexts

According to relevant data, the carbon intensity targets for 2025 and 2030 are: an 18% decrease in carbon intensity by 2025 compared to 2020, and a decrease of approximately 32% in carbon intensity by 2030 (GDP calculated at constant prices in 2020). The calculated decrease in carbon intensity for each scenario in 2025 and 2030 is shown in the following figure.

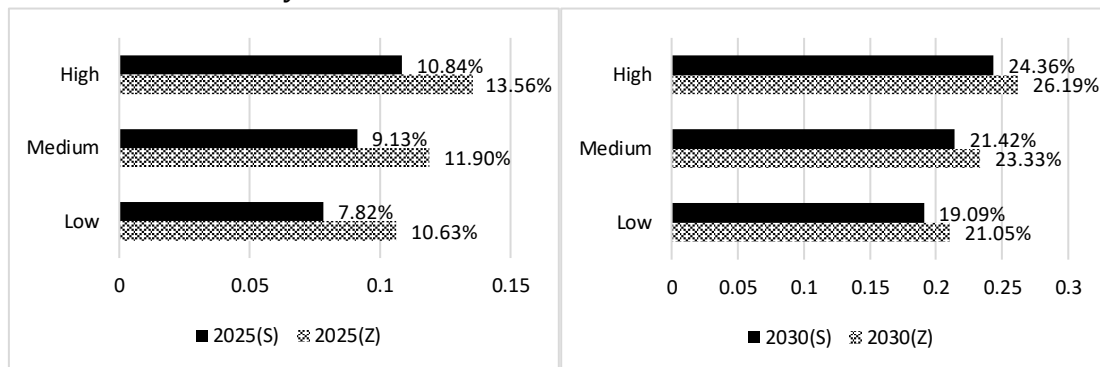


Figure 5: The decrease in carbon intensity for each scenario in 2025 and 2030

According to the results, regardless of the economic development situation, the energy structure in both scenarios can achieve the carbon intensity target. The decrease in carbon

intensity under energy production costs is greater than that under policy constraints. It is worth noting that the degree of carbon intensity decline is positively proportional to the state of economic development. Under the condition of low-speed economic development, the decrease in carbon intensity is the smallest. In the 2025 policy constraint scenario, the decrease in carbon intensity is only slightly higher than the 2025 carbon intensity target.

3.2.4. Exploring the optimal path for achieving "Dual Control" goals

In response to the "dual control" goal of carbon emissions reduction, this article selects four evaluation indicators: energy intensity, total consumption, carbon emissions, and completion of carbon intensity targets, and uses a multi-attribute decision-making model to explore the optimal path.

$$A = W \cdot R = \sum W_j R_i \tag{2}$$

In the formula, R_i ($=1, 2, 3, 4$) respectively represent energy intensity, total energy consumption, completion and degree of carbon intensity targets, and total CO2 emissions; W_j represents the weight coefficient. According to the different focuses on carbon reduction targets, this article sets the weights of various indicators as follows.

Table 1: Weight settings

Indicator	no preference	preference intensity	preference total
W_1	1/4	1/3	1/6
W_2	1/4	1/6	1/3
W_3	1/4	1/3	1/6
W_4	1/4	1/6	1/3

The formula for processing the relevant data to eliminate dimensional differences between positive and negative indicators is as follow,

$$B = \frac{\min(A_{ij})}{A_{ij}}$$

$$D = \frac{A_{ij}}{\max(A_{ij})} \tag{3}$$

Substitute the standardized indicator values into the above equation to obtain the comprehensive index of each combination scenario that simultaneously achieves the carbon reduction "Dual Control" goal.

Table 2: Composite index

Scene	High				Medium				Low			
	2025		2030		2025		2030		2025		2030	
	Z	S	Z	S	Z	S	Z	S	Z	S	Z	S
No	0.881	0.877	0.714	0.722	0.894	0.884	0.715	0.720	0.908	0.892	0.719	0.721
Intensity	0.852	0.851	0.692	0.707	0.863	0.854	0.683	0.695	0.877	0.860	0.681	0.689
Total	0.910	0.903	0.736	0.737	0.925	0.914	0.747	0.745	0.939	0.924	0.757	0.754

The results show that under no preference control, the scenario with the highest comprehensive index is economic low speed policy constraint, followed by economic medium speed policy constraint. Firstly, from a practical perspective, a low-speed economic situation is not conducive to social stability. Secondly, the index obtained from the scenario of economic

medium speed policy constraint is only slightly lower than the "optimal" choice, so this article takes "economic medium speed policy constraint" as the optimal path under the condition of no preference.

Under both preference intensity control and preference total control, the scenario with the highest comprehensive index is consistent with the results under no preference control.

In summary, regardless of the type of control, the scenario of "economic moderate speed policy constraints" is the optimal path to achieve emission reduction goals. However, there is still uncertainty about whether the carbon emission peak target can be achieved before 2030, and more optimal methods still need to be explored.

4. Life cycle assessment of solar thin films

4.1. Life cycle boundaries of solar photovoltaic power generation systems

Photovoltaic power generation is the use of solar cells to directly convert solar energy into electricity. Its life cycle boundary includes the production stage, transportation and construction stage, operation stage, and recycling stage. According to IOS standards, processes with unclear process level, inability to obtain data lists, and a contribution of less than 1% to carbon emissions results are not considered. Due to the fact that the production stage of the solar photovoltaic power generation life cycle is the main stage of energy consumption and material consumption, we will focus on introducing the energy consumption, material usage process, and environmental impact of the production stage [5]. Taking the CIGS thin-film solar cell modules produced by Kaisheng Photovoltaic Materials Co., Ltd. as an example, the details are as follow,

The production process of copper indium gallium selenium thin film solar cell modules can be divided into two stages: battery manufacturing and module packaging.

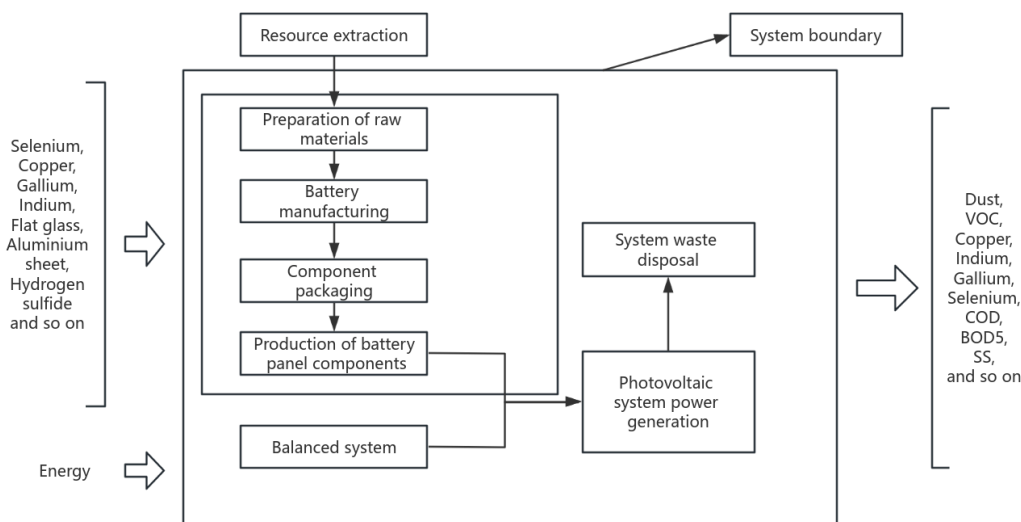


Figure6: Life cycle system boundary

4.2. Cases and Data

Bengbu City, Anhui Province is located in the inland area of central and eastern China, with a total area of 5952 square kilometers. It is situated in the northeast of Anhui Province and the middle reaches of the Huai River. The total annual solar radiation is 119.1 kilo calories per square centimeter, and among the urban construction land area, residential land is 50.41 square kilometers. In this article, it is planned to occupy 20% of residential land and promote the application of thin-film solar power generation systems. Propose a battery life of 10 years

for solar panels and compare it with the carbon emissions and costs of standard coal to explore the coupling analysis of energy, environment, and economy.

Table3: Basic information of photovoltaic modules

Basic information of photovoltaic modules	
Outer Dimensions	1587*664mm ²
power	140Wp/Pcs
thickness	38mm
weight	16kg
Type	CIGS battery
Cover Glass	3.2mm tempered glass
Power generation glass	2.1mm semi tempered glass
Module efficiency	≥15.2%
Component area	1.05m ²
Effective area of components	0.95m ²

4.3. LCA explorer

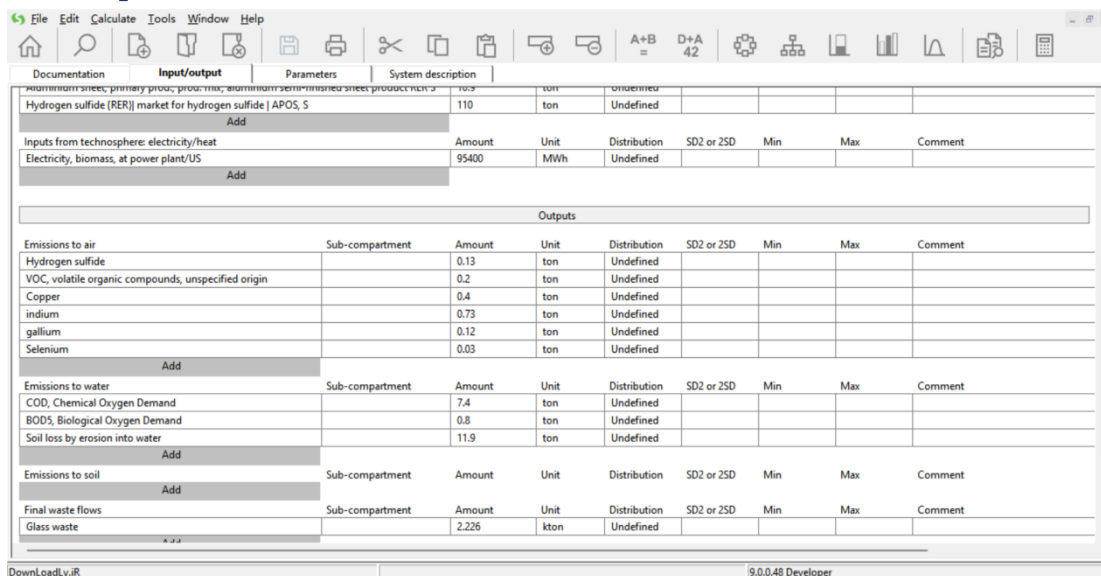


Figure7: Establish a life cycle assessment process

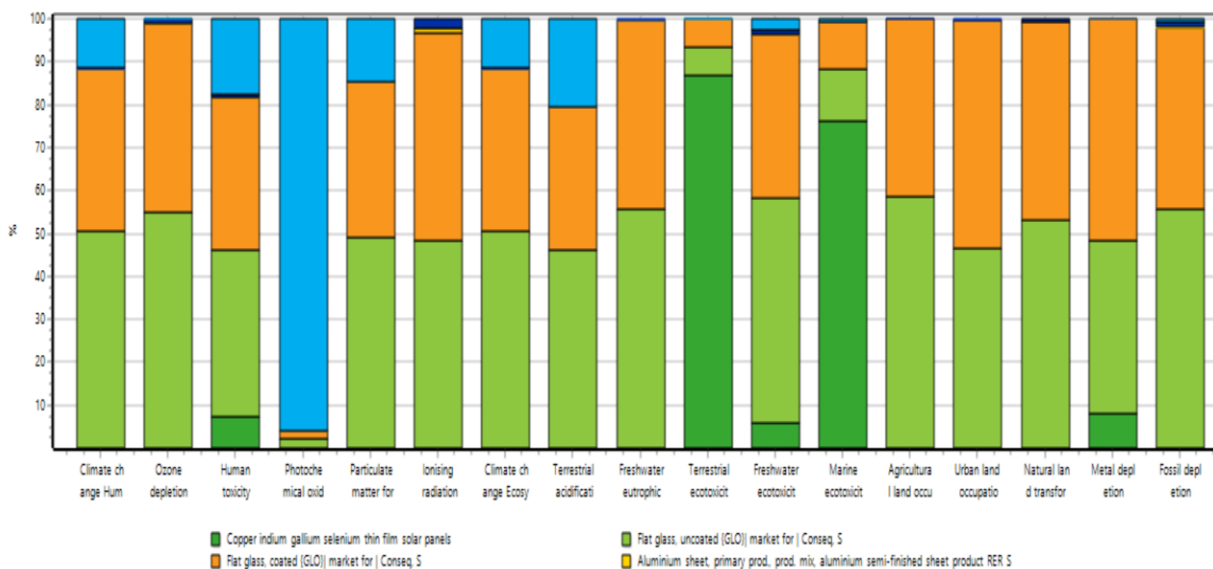
1)In Simapro software, the IPCC 2013 GWP 100a method was used to conduct a life cycle assessment of the production stage of copper indium gallium selenium thin film solar modules using Ecoinvent 3-allocation at point of substitution system, and obtain GWP values. A thin film solar module has a GWP value of 17.9 kg CO₂ eq.

Se	impact category	unit	Total	Copper indium gallium selenium thin film solar panels	Flat glass, uncoated (GLO) market for Conseq. S	Flat glass, coated (GLO) market for Conseq. S	Aluminium sheet, primary prod., prod. mix, aluminium	Hydrogen sulfide (RE market for hydrogen
<input checked="" type="checkbox"/>	IPCC GWP 100a	kg CO ₂ eq	17.9	x	9.11	6.74	0.0165	0.0338

Figure8: Running results

2)In Simapro software, the ReCiPe Endpoint (H) method was used to conduct a life cycle assessment of the production stage of copper indium gallium selenium thin film solar modules using Ecoinvent 3-allocation at point of substitution system. The results are as follows,

Se	Impact category	Unit	Total	Copper indium gallium selenium thin film solar panels	Flat glass, uncoated (GLO) market for Conseq, S	Flat glass, coated (GLO) market for Conseq, S	Aluminium sheet, primary prod. mix, aluminium	Hydrogen sulfide (RE market for hydrogen
<input checked="" type="checkbox"/>	Climate change Human Health	DALY	2.49E-5	x	1.26E-5	9.37E-6	2.3E-8	4.55E-8
<input checked="" type="checkbox"/>	Ozone depletion	DALY	3.05E-9	x	1.68E-9	1.34E-9	3.21E-12	3.02E-11
<input checked="" type="checkbox"/>	Human toxicity	DALY	1.14E-6	8.56E-8	4.41E-7	4.1E-7	8.52E-10	4.57E-9
<input checked="" type="checkbox"/>	Photochemical oxidant formation	DALY	7.31E-8	x	1.64E-9	1.22E-9	1.25E-12	5.44E-12
<input checked="" type="checkbox"/>	Particulate matter formation	DALY	1.75E-5	x	8.6E-6	6.3E-6	7.13E-9	1.64E-8
<input checked="" type="checkbox"/>	Ionising radiation	DALY	3.45E-9	x	1.67E-9	1.68E-9	3.61E-11	7.53E-11
<input checked="" type="checkbox"/>	Climate change Ecosystems	species.yr	1.41E-7	x	7.16E-8	5.31E-8	1.3E-10	2.58E-10
<input checked="" type="checkbox"/>	Terrestrial acidification	species.yr	9.67E-10	x	4.48E-10	3.2E-10	3.74E-13	1.1E-12
<input checked="" type="checkbox"/>	Freshwater eutrophication	species.yr	7.17E-11	x	4E-11	3.16E-11	1.48E-15	1.32E-13
<input checked="" type="checkbox"/>	Terrestrial ecotoxicity	species.yr	1.13E-9	9.82E-10	7.31E-11	7.56E-11	5.57E-14	9.21E-13
<input checked="" type="checkbox"/>	Freshwater ecotoxicity	species.yr	1.67E-11	9.86E-13	8.74E-12	6.3E-12	3.03E-15	2.17E-13
<input checked="" type="checkbox"/>	Marine ecotoxicity	species.yr	1.18E-11	9.03E-12	1.4E-12	1.3E-12	6.71E-16	1.99E-14
<input checked="" type="checkbox"/>	Agricultural land occupation	species.yr	6.04E-8	x	3.54E-8	2.5E-8	x	2.3E-11
<input checked="" type="checkbox"/>	Urban land occupation	species.yr	3.69E-9	x	1.72E-9	1.97E-9	x	7.37E-12
<input checked="" type="checkbox"/>	Natural land transformation	species.yr	4.88E-9	x	2.59E-9	2.25E-9	x	4.06E-11
<input checked="" type="checkbox"/>	Metal depletion	\$	0.198	0.0161	0.08	0.102	2.26E-6	0.000225
<input checked="" type="checkbox"/>	Fossil depletion	\$	0.689	x	0.383	0.292	0.000637	0.00778



Method: ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/A / Characterization / Excluding infrastructure processes / Excluding long-term emissions
Analyzing 16 kg 'Copper indium gallium selenium thin film solar panels'

Figure9: Running results

As shown in the figure, the environmental impact generated by a solar panel is very small, with only metal depletion (kg Fe eq) and fossil depletion (kg oil eq) having larger values of 0.198 and 0.689, respectively. Other environmental indicators such as climate change and ozone depletion are relatively small.

4.4. Result Analysis

After calculation, it can be concluded that the daily radiation in Bengbu City is 3.792 kWh. Due to the battery life of solar cells, the total power generation calculated using the equivalent daily radiation method is 19.19 billion kWh. To generate the same amount of electricity, it is necessary to burn 2.36 million tons of standard coal and emit 6.136 million tons of carbon dioxide. Compared to burning coal, using solar thin film modules can reduce emissions of 5.964 million tons of carbon dioxide, but the cost is nearly 1 billion yuan higher. Based on this, we can find that there are contradictions and conflicts between energy, environment, and economy. How to balance the relationship between the three is an urgent problem that we need to solve. During the calculation process, we found that improving the conversion efficiency of solar photovoltaic cells can effectively reduce the price of carbon dioxide. This requires enterprises to increase their innovation efforts, continuously break through the series of technological

bottlenecks in thin film components, and contribute to the early realization of the "dual carbon" goal.

5. Suggestions

This article proposes the following policy recommendations:

Firstly, while promoting green, low-carbon, and sustainable development, it is necessary to ensure the stable operation of the economy. The results indicate that under the condition of rapid economic development, carbon emissions are the highest. Under the condition of low-speed economic development, carbon emissions are relatively low. The two are positively correlated to a certain extent. But the economy and environment should promote each other and develop harmoniously. While advocating environmental protection, the country also needs to consider the normal operation of the economy.

Secondly, adhere to policy guidance and continuously strengthen the endogenous driving force for promoting green and low-carbon development. The results show that national policy factors play an important role in influencing changes in the energy structure. Therefore, the government should actively formulate and improve relevant policies and regulations to implement more clear and precise low-carbon policies, and stimulate new drivers of green growth in the whole society.

Thirdly, solve the problem from the source and strictly control the total energy consumption. The results indicate that it is uncertain whether the carbon peak target can be achieved before 2030. There is an inseparable relationship between carbon emissions and energy consumption. Therefore, while optimizing the energy structure, energy consumption should also be controlled at an appropriate level.

Fourthly, encourage enterprises to use technological innovation to solve the difficulties of low-carbon transformation in traditional industries, and inject new vitality into green and low-carbon development. Enterprises should seize opportunities, actively respond to national policies, adhere to innovation driven approaches, continuously break through relevant technological challenges, and promote green and low-carbon transformation. At the same time, this can to some extent alleviate the contradiction and conflict between energy, environment, and economy.

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