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Principles, development, and utilization of silicon-based solar cell

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Abstract. Photovoltaic technology is a technology that uses the photoelectric conversion properties of semiconductor materials to convert solar energy into electricity. Photovoltaic technology is a kind of renewable energy technology that does not produce pollution and greenhouse gas emissions and has many application prospects. According to data, from 1985 to 2017, the cumulative total installed photovoltaic capacity globally exceeded 400 GW and is expected to grow in the next few years. Photovoltaic technology has become an essential part of renewable energy worldwide. Photovoltaic cells are the core equipment of photovoltaic technology. There are mainly monocrystalline silicon, polysilicon, amorphous silicon, organic solar cells, and other types. Among them, monocrystalline silicon photovoltaic cells have high photoelectric conversion efficiency, but high cost, mainly used in high-end applications; Polysilicon photovoltaic cells are cost-effective and used primarily in large-scale photovoltaic power station construction; Photovoltaic technology can also be used in mobile chargers, solar streetlights, solar pumps, and other aspects. In addition, photovoltaic technology also has a wide range of application prospects in urban rail transit, automobiles, robots, and other fields also appear. Although photovoltaic technology has many advantages, there are still some problems, such as panel cost, reliability, stability, and storage of photovoltaic power generation. Solving these problems requires continuous upgrading and development of technology. With the progress of technology and the support of policies, it is believed that photovoltaic technology will continue to develop and make more significant contributions to global energy transformation and sustainable development.

Keywords: Photovoltaics, Production, Application, Cost, Environment.

1. Introduction

Photovoltaic technology refers to the direct conversion of light energy generated by solar radiation into electrical power. It utilizes by far the most abundant energy available on the planet, with the net solar input to the earth being nearly 6,000 times more than the fossil and nuclear fuels currently used by humanity [1]. Photovoltaic cells are based on the photovoltaic effect of semiconductor materials to generate electricity and, combined with the cell manufacturing process, are rapidly becoming a core component of photovoltaic technology.

The future development direction of the photovoltaic industry includes the following aspects:

(1) Improve the efficiency of photovoltaic modules. At present, the conversion efficiency of polycrystalline silicon photovoltaic modules has broken through 20%, and the conversion efficiency of monocrystal silicon photovoltaic modules is also gradually improving. In the future, the efficiency of photovoltaic modules can be enhanced through continuous promotion of research to achieve higher power generation.

(2) Reduce the cost of photovoltaic modules. The cost of photovoltaic modules is mainly concentrated on silicon wafers and production costs. In the future, the cost of photovoltaic modules can be significantly reduced through technological progress and large-scale production.

(3) Innovative photovoltaic application fields. In addition to being widely used in electricity, photovoltaics can be applied in construction, transportation, etc. In the future, we can constantly innovate the application fields of photovoltaic and expand the development space of the photovoltaic industry.

(4) Develop new photovoltaic technologies. In addition to traditional silicon-based solar cells, future photovoltaic technologies will likely include organic solar cells, perovskite solar cells, and other emerging technologies. In the future, the photovoltaic industry can continue to develop and promote new technology to expand the industry's development prospects.

The first generation of solar cells is the longest-developed and most mature generation of cells in terms of the preparation process. From the development of monocrystalline silicon solar cells to the present, despite the various problems experienced with the raw material silicon, it is still the primary material for solar cells today, and its proportion accounts for about 90% of the entire solar cell. This paper focuses on the first generation of solar cells.

2. Development History

The history of solar photovoltaic cells dates back to the early 19th century. In 1839, French scientist Edmond Becquerel discovered the photovoltaic effect, which occurs when a light on certain materials produces an electric current. In 1853, American scientists Willoughby Smith and Joseph Biham found that selenium could convert light into electric energy, inspiring further exploration of the technology.

In the early 20th century, German scientist Ferdinand Braun discovered that silicon had photoconductive properties and could convert light into electric energy, laying the foundation for photovoltaic cell technology. In 1954, Bell Labs in the United States produced the first high-efficiency, low-cost solar cell, the "Bell Solar Battery."

1973 the first oil crisis occurred, leading to a global energy crisis and increased interest in alternative energy sources. The solar photovoltaic cell became one of the most promising alternative energy sources, and by the 1980s, it had become a mature industry.

From the 1950s development to today, the first generation of solar cells' efficiency has reached 15-25% (the theoretical efficiency limit of 29%) [2]. Due to the high cost of silicon, there is limited room to further improve the efficiency, so the second generation of thin film type solar cells, represented by new structures (laminated structure) of the third generation of solar cells, gradually on the stage of history. Their emergence aims to reduce production costs and improve energy conversion efficiency continuously. The solar cell classification system has been formed [3]. (see Figure 1)

However, the first generation of solar cells is still the subject of this paper because it is the basis for the development of all solar cells. From 2006 to 2012, the number of documents published on silicon solar cells surged to about 1,500(see Figure 2), and the number of related articles published was nearly

20,000, with the penetration of disciplines including applied economics, electrical engineering, chemical engineering, mechanical engineering, etc. Although the rise of new materials such as second and third-generation solar cells has led to a decline in research on traditional silicon solar cells in recent years, they are still the direction for which many scholars are studying [4].

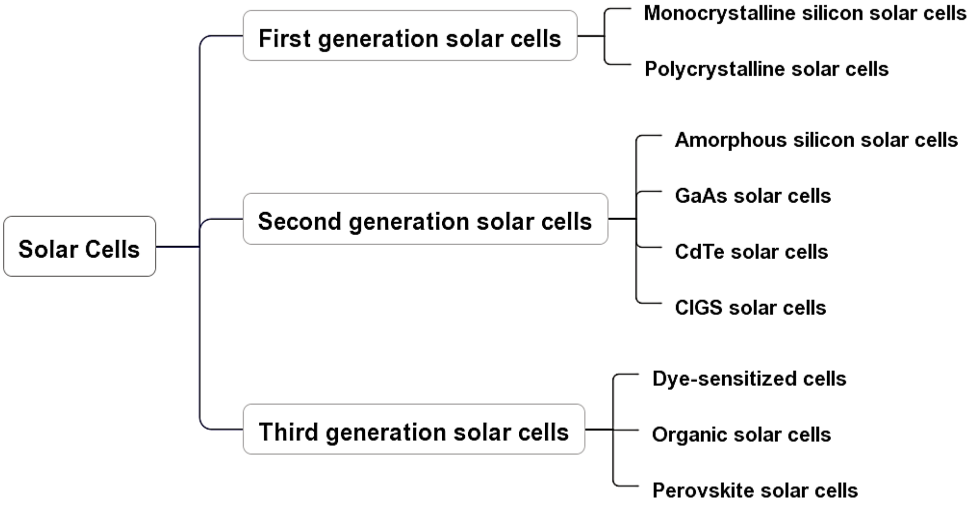

Figure 1. Diagram of the solar cell classification [5].

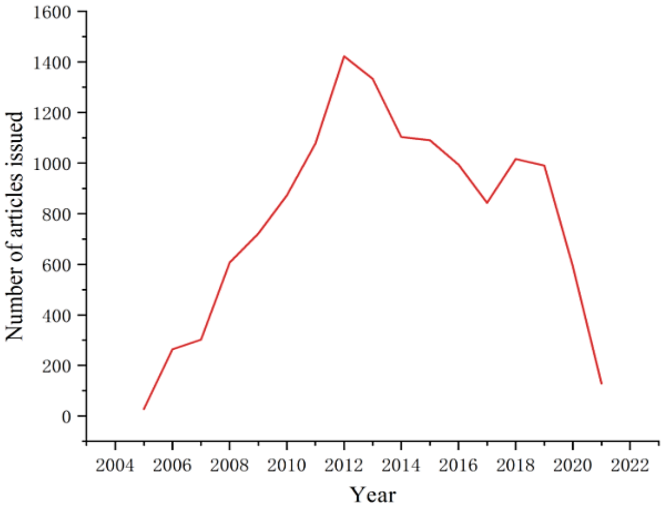

Figure 2. Statistics on the number of articles published by year.

3. Physical principles

3.1. Basic semiconductor concept

The band theory is the basic theory describing the electronic properties of semiconductor materials. In a semiconductor, the energy distribution of electrons is divided into two regions: the conduction band and the valence band. The conduction band is empty at room temperature, while electrons occupy the valence band. When external energy or an electric field is applied, electrons can be excited from the valence band to the conduction band, forming a current.

The energy difference between the conduction and valence bands is called the bandgap or energy gap. The bandgap determines the conductivity and photoelectric properties of the semiconductor material. The smaller the bandgap, the easier the semiconductor is to be excited into a conductive state.

When the energy of a photon is equal to the bandgap of the semiconductor, it can be absorbed, promoting electrons from the valence band to the conduction band and generating a photocurrent. The following figure provides a visual illustration of the relationship between these three concepts(see Figure 3)

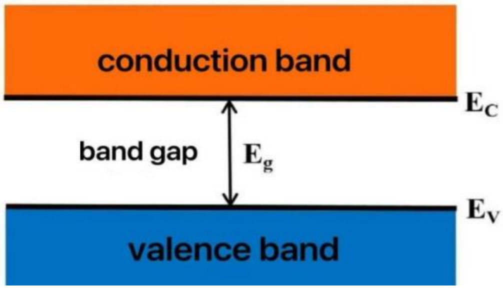

Figure 3. Schematic diagram of basic semiconductor concepts.

3.2. The formation of p-n junctions

A p-n junction is a typical semiconductor device formed by connecting a p-type and n-type semiconductor material. In a p-type semiconductor, impurity atoms create holes that can be filled by nearby electrons, forming positively charged regions. In an n-type semiconductor, impurity atoms provide additional free electrons, developing negatively charged areas. When a p-type and an n-type semiconductor are joined, the electrons from the two regions diffuse, forming a junction electric field. Holes and free electrons near the junction recombine, creating a structure that can control the flow of electric current, known as a p-n junction.

The diffusion of holes and electrons combines with other spots and electrons, thus creating an electric field at the junction, preventing their distribution and forming a dynamic balance.

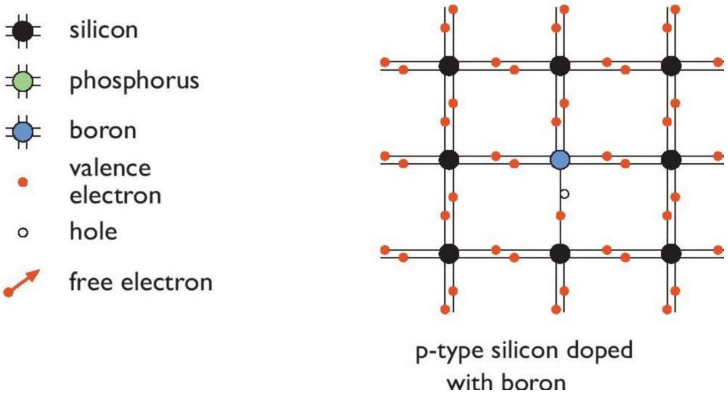

Figure 4. Diagram of p-type silicon doped with boron [6].

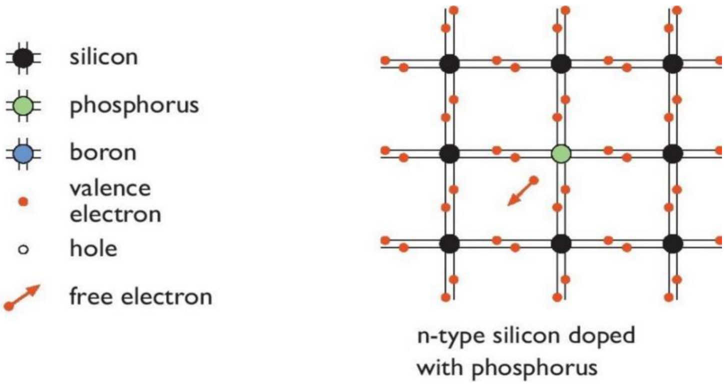

Figure 5. Diagram of n-type silicon doped with phosphorus [6].

3.3. Photovoltaic effect

The photovoltaic effect can be observed in the p-n junction of a semiconductor. When photons strike the p-n hub, their energy is absorbed by the electrons in the semiconductor, which get excited into the conduction band. Near the p-n junction, there is a built-in electric field due to the non-uniform distribution of charges, which causes the moving electrons from the p-type region to be hindered by force and to aggregate near the n-type region. This generates a short-circuit current, which creates a voltage and current across an external load. This phenomenon is known as the photovoltaic effect of the p-n junction and is widely utilized in solar cells for converting solar radiation into electrical power.

4. Production process

4.1. From sand to monocrystalline silicon solar cells

The production of monocrystalline silicon involves melting the silicon feedstock in a crucible under high temperatures and carefully controlling the cooling process to grow a single large crystal. The crystal is then sliced into wafers, which are further processed to remove impurities and form the basis for solar cells. The process typically involves several steps of chemical treatment, cleaning, polishing, and etching to ensure high purity and uniformity in each wafer. Monocrystalline silicon production requires precise temperature, pressure, and chemical composition control to achieve high efficiency and consistent quality [7].

4.2. Purification

The purification of monocrystalline silicon involves removing impurities such as boron, phosphorus, and oxygen from the silicon crystals. The process usually includes zone refining, chemical vapor deposition, and diffusion. Zone refining uses a thermally induced traveling liquid zone to segregate and remove impurities. At the same time, chemical vapor deposition applies chemical reactions to deposit pure silicon layers onto the surface of the crystal. Diffusion involves diffusing contaminants into the surface of the crystal and then annealing it to achieve a desired level of purity. Each step requires precise control of temperature, gas composition, and other variables to achieve high efficiency and purity of the silicon material.

The diagram below shows the flow chart of the Siemens reduction method [8]:

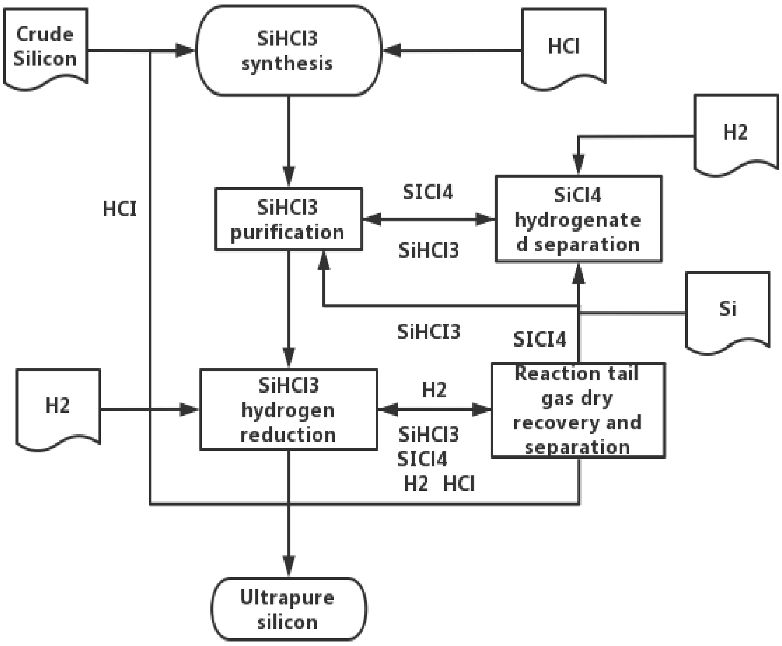

Figure 6. Siemens reduction method flow chart.

4.3. Washing and fleece making

After the monocrystalline silicon preparation, the wafers' surfaces need to undergo washing and texturing processes to remove impurities and form a hydrophobic anti-reflective coating, which enhances the conversion efficiency of solar cells. The washing process usually takes place in a series of metal trays using high-purity chemicals and water to clean, rinse, and dry the surface of the silicon wafer. The silicon wafer is etched in an acid solution to remove impurities and create microscopic pits during the texturing process. These pits help improve the surface's anti-reflective properties while forming a layer of anti-reflective coating with an appropriate thickness. These steps and techniques play a crucial role in the performance and efficiency of monocrystalline silicon solar cells. The chemical reaction equation for the corrosion process is:

$$Si + 2NaOH + H_2O \rightarrow Na_2SiO_3 + 2H_2 \uparrow \tag{1}$$

4.4. Preparation of anti-reflection coating and Electrodes

The performance and efficiency of monocrystalline silicon solar cells depend significantly on the quality and characteristics of their anti-reflective coatings and electrodes. The preparation of an anti-reflective coating typically involves depositing a multilayer film of materials, such as physical vapor deposition or chemical vapor deposition, on the surface of the wafer. For electrode preparation, a metal film such as aluminum, silver, or copper is typically deposited on the surface of the silicon to improve its electrical conductivity. The processes require careful attention to uniformity and adhesion of the coating. New materials and methods continue to be developed to enhance the quality of monocrystalline silicon solar cells.

4.5. Battery Processing and Assembly

The processing and assembly of monocrystalline silicon solar cells is a crucial part of manufacturing, determining whether the processed monocrystalline silicon can be turned into a functional solar cell. First, the cell is wire-bonded, bonding small silver wires to the electrodes to enhance electrical flow. Then, the processed partition is mounted on a conductive substrate before being coated with an adhesive and subjected to a high-temperature and high-pressure lamination process. Finally, the cells are arranged according to specific requirements and interconnected to form a complete solar module [9]. This process involves precise alignment, creating electrical connections between the cells, and ensuring uniformity and quality in the assembly process. The assembly quality directly affects the final solar panel's performance, efficiency, and longevity. As technology advances, new materials and methods continue to be developed to enhance further the quality and efficiency of monocrystalline silicon solar cells.

5. The application of solar cells

Solar cells have become one of the leading representatives of renewable energy and are widely used in various fields.

5.1. Residential and commercial buildings

panels are installed on roofs, walls, and other locations to directly supply energy to the house by converting solar energy. They can also be connected to the grid to provide excess electricity to different places, reducing reliance on fossil fuels.

Solar panels have proved to be a significant renewable energy source in residential and commercial buildings. They can be built right into the house's structure or added afterward. Residential units are smaller and designed to generate enough energy to meet the needs of individual households. In contrast, commercial units are much larger, creating more power for entire buildings.

5.2. Remote Area Power Supply

Solar panels can be installed in remote areas to power the local electricity grid. This application can help improve the quality of life in poverty-stricken areas. For remote area power supply, solar panels are handy for providing power in areas with little or no electrical infrastructure. Where building a traditional grid is either difficult or prohibitively expensive, solar panels can provide a reliable power source for homes and businesses [10].

5.3. Transportation and Vehicles

Solar panels can be installed on vehicles to provide energy for electric cars, bicycles, and ships, reducing reliance on traditional fuels. In transportation and cars, solar panels are becoming increasingly important. Many are now used on boats to generate power, helping to reduce fuel consumption and enhance energy efficiency. Electric cars and bicycles can also be fitted with solar panels, creating leverage and extending their range [11].

5.4. Electronic device chargers

Solar panels can conveniently charge electronic devices such as phones and tablets. Electronic device chargers represent a relatively small but essential application for solar cells. A growing number of solar-powered phone chargers, tablets, and other devices are hitting the market, giving consumers a flexible and eco-friendly alternative to traditional power sources [12].

In conclusion, solar cells are an increasingly important renewable energy source in many applications. As technology continues to improve, solar cells will become even more efficient, cost-effective, and versatile, helping to meet the growing demand for clean energy worldwide.

6. Impact of solar energy

The impact of solar energy can be discussed in three aspects: environment, economy, and society.

6.1. Environmental Aspect

Solar energy is a clean and renewable energy source, and its power generation process does not produce harmful gases such as carbon dioxide, nitrogen oxide, and sulfur oxide [13]. It does not pollute water or land; compared to fossil fuels, it significantly reduces pollution and environmental hazards. Using solar power can effectively reduce the use of fossil fuels, decrease carbon emissions, protect the environment, and preserve ecosystems. Also, solar power can reduce the reliance on fossil fuel mining and lower its risk to energy security and resource depletion.

6.2. Economic Aspect

Solar energy can bring economic benefits. Firstly, using solar energy can help businesses and households reduce energy costs. Solar power operation costs become much lower because it needs almost no fuel to generate power. Moreover, it creates employment opportunities in the solar industry, contributing to economic development. More and more people are using solar energy in fields such as solar water heaters, solar panels, and chargers, thus creating job opportunities. It has also provided an opportunity to optimize the economic structure, improve competitiveness, and develop sustainable solutions. As a result, the manufacturing process technology and performance of photovoltaic cells have gradually grown by leaps and bounds, and the cost of photovoltaic power generation has decreased year by year, with prices tending to be affordable.

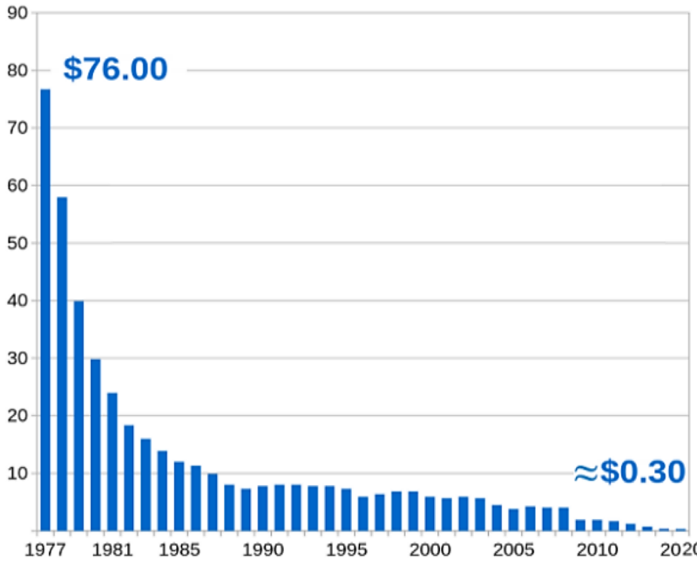

Figure 7. Price history of silicon solar cells.

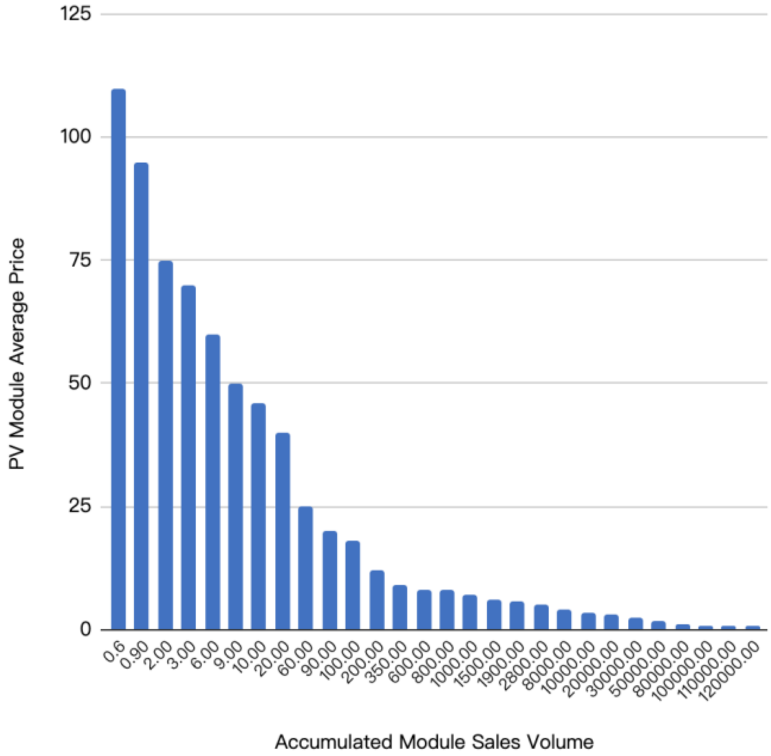

Figure 8. The average price of a Photovoltaic module against the accumulated module sales volume.

6.3. Social Aspect

The development of the solar industry can bring about social transformation. Firstly, solar power can help reduce energy poverty, allowing more people to access clean and sustainable energy [14]. Secondly, it changes the existing economic structure and promotes transformations and upgrades, which improve a country's green competitiveness. Developing solar energy industries can also reduce energy waste and emissions, which can help achieve global energy conservation [15].

7. Conclusion

However, solar energy also faces a series of challenges. For instance, solar energy has lower energy density, which requires a larger surface area to capture the sun's energy, which limits mass-scale application in certain areas. Weather conditions such as strong winds, snow, overcast skies, and time factors like seasons also affect energy output. The local climate, solar radiation, and building orientation also affect energy output.

In conclusion, the impact of solar energy is significant in environmental, economic, and social aspects. Gradually developing solar energy industries can promote the transformation of energy systems, combating global warming, climate change, and ecological destruction, shaping new models of technological progress and economic development, and enhancing a society's overall competitiveness and sustainable development capacity [16].

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