Using Synergy Approach To investigate the developmental trends of Solar Energy

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Abstract. In recent years, electricity generation using solar energy has become a popular trend. At present, the solar energy output value of China, the United States (US), and the European Union (EU28) together account for more than 70% of the total global output value; therefore, these nations have a significant influence on future development of solar energy technologies. In this study, we analyzed data, including those for patents; key technology; output value; trade surpluses (deficits); research and development (R&D) funds and manpower; energy density, and publications in journals, and collected data related to solar energy use in these countries to analyze trends in its use by applying the synergy theory. The subsystems investigated include the industry, government, and academic, and the study period was 2005–2015. We also integrated resources and linked application statuses to track applications by the considered subsystems.

The following results were obtained at the end of this study:

(1) Development of solar energy use technology has slowed down in the EU28, is growing in China, and has plateaued in the US. In terms of trends in synergy, the EU28 showed growth up to 2013, after which a rapid decline was observed; an overall growth trend was observed in China; and a plateau in the US was noted in the US after 2011.

(2) Overall, variations in these trends reduced across the industry subsystems affecting decision-making in companies. Overall investment in research and development (R&D) by the government has plateaued. There appeared to be a growth in the academic subsystems, with the number of studies on solar energy increasing.

(3) Patents and published journal articles indicate that, in the EU28, research on key technology for solar energy use has been dominated by theory. However, in China and the US, research is mainly focused on the application of such technology.
The observed trends for solar energy technologies in the study areas. However, the environment for the solar energy use can change; it is recommended that future research take market considerations into account to better understand the trends in the development of solar energy technologies.

1. Introduction
In recent years, issues regarding solar power generation have gradually become the focus of global research attention. The current total solar energy output value of China, the United States (US), and the European Union (EU28) together constitute more than 70% of the total global output value[1-2]. To enhance the competitive power, the industry applies for patents for development results, the government invests in research funding and manpower, and the academic community publishes research results in journals. We also integrated resources and linked application statuses to track applications by the considered subsystems, and collected data related to solar energy use in these countries to analyze trends.

This study focuses on China, the United States, and the European Union as research areas, based on the synergy theory approach. The study period is from 2005 to 2015. The research scope is limited to an analysis of the subsystems of industry, government, and the academia, and data were collected from the World Intellectual Property Organization (WIPO), Organisation for Economic Co-operation and Development (OECD), and Web of Science®, respectively.

2. Technologies Utilized in Solar Energy
The development of clean energy sources became a global trend after the Second Industrial Revolution. Improvements in the energy conversion efficiency can produce benefits such as lowered greenhouse gas emissions, safe energy, and an improved energy supply [3]. The most important issues related to solar energy are the low efficiency of conversions and energy storage capacity. However, the methods currently available to resolve these issues are insufficient [4]; the most popular key solar technologies involve techniques such as “light concentration,” “Förster energy transfer,” “conductive materials,” “plasmons,” “nanoantennas,” and “quantum energy transport.” Research on the key solar energy technologies have tended towards the goal of improving the efficiency of solar energy [5]. Light concentration improves the focus density of solar cells and can result in increases in the conversion efficiency per unit area [6-8]. The plasmonic effect plays a very important role in increasing local solar power density and thus in efficient solar cell conversion [9-10]. Traditional solar cells absorb visible light during the day but not at night; however, nanoantennas can absorb radiation energy from mid-infrared light and can thus be used both during the day and at night, when their surroundings continue to radiate infrared light. Thus, they can improve the efficiency of solar energy conversion by prolonging the time for which devices utilizing solar power can be used [11].

Manipulating the resistance of solar cells can also improve conversion efficiency. Transparent conductive films are low-resistance materials that generally improve the conductivity and transparency of the devices; however, they need to be very thin [12]. In 1982, Professor Arakawa Taehoon, director of the Nano-Quantum Information Electronics Research Organization at the University of Tokyo, pioneered the concept of quantum dots. The current conversion efficiency for solar cells using polycrystalline silicon is about 15%; however, those employing monocrystalline silicon offer a conversion efficiency of 20%. Although the use of crystalline silicon has increased efficiency, the latter is still less than the level desired. Quantum and coherent energy transfer methods, e.g., Förster energy transfer, are key technologies expected to lead to increase the absorption of solar energy [13-20]. These studies suggest that the use of light concentration, nanoantennas, conductive materials, quantum dot technologies, plasmons, and Förster energy transfer methods can improve solar energy absorption. They also suggest that the future direction for research should be based on such considerations.

Other paragraphs are indented (BodytextIndented style).
3. Basic Equations

Our approach uses the synergy theory proposed by the German physicist Hermann Haken in 1974. [21-22] We combined statistics with dynamics to integrate applications between systems and determine the causal relationships among factors with the aim to explore the interactions between industry, government, and the academia.

The theory can be expressed as the following basic formulas:

\[
\frac{du}{dt} = -KU + g (I, G, A) + F 
\]

(1)

\[
\frac{du}{dt} = -K_1 U + g_1 (I, G, A) + F_1 
\]

(2)

\[
\frac{du}{dt} = -K_2 U + g_2 (I, G, A) + F_2 
\]

(3)

\[
\frac{du}{dt} = -K_3 U + g_3 (I, G, A) + F_3 
\]

(4)

where:

- \( t \): time;
- \( K \): coefficient describing the relationship between the rate of change and the original state;
- \( K_1, K_2, K_3 \): coefficients describing the relationships between the rates of change in I, G, and A, respectively and the original state;
- \( U \): uncorrected degree of synergy;
- \( g \): effect of the subsystem synergy on the development of collaborative systems;
- \( g_1, g_2, g_3 \): impact of the synergy of the three subsystems on E, R, and P, respectively;
- \( I \): industry subsystem;
- \( G \): government subsystem;
- \( A \): academia subsystem;
- \( F \): constant external force;
- \( F_1, F_2, F_3 \): constant external force in individual subsystems;

According to Equation (1), the synergy between the application status trajectories of the three subsystems I (industry subsystem), G (government subsystem), and A (academic subsystem) show that they can be integrated. By analogy, Equations (2), (3), and (4) represent the synergy between the application trajectories of the EU28, China, and the US over the years.

Let \( S = \{S_1, S_2, \ldots, S_j, \ldots, S_n\} \) and \( j = 1, 2, \ldots, n \), where the set of order parameters in the subsystem is \( S_j, e_j = \{e_{j1}, \ldots, e_{ji}, \ldots, e_{jm}\}, i \in [1, m]; e_{ij} \in [\beta_{ji}, \alpha_{ji}] \).

\( \alpha_{ji} \): the limit value of the system order parameter \( e_{ji} \);  
\( \beta_{ji} \): the limit value of the system order parameter \( e_{ji} \).

The order degree \( u_{ji} \) can be determined as follows:

\[
u_{ji}(e_{ji}) = \left\{ \begin{array}{ll}
\frac{(e_{ji} - \beta_{ji})}{(\alpha_{ji} - \beta_{ji})} & \text{if } e_{ji} \leq \alpha_{ji} \\
\frac{(\alpha_{ji} - e_{ji})}{(\alpha_{ji} - \beta_{ji})} & \text{if } e_{ji} > \alpha_{ji}
\end{array} \right.
\]

(5)

where \( u_j(e_j) \in [0, 1] \).

\[
u_j(e_{ji}) = \sum_{i=1}^{m} \lambda_i u_i(e_{ji}), \lambda \geq 0, \sum_{i=1}^{m} \lambda_i = 1
\]

(6)

As shown in Equation (6), the following model formula is used:
$u_j(e_{ij})$ is the order degree of subsystem $S_j$, given $u_j(e_{ij}) \in [0,1]$

$\lambda_i$ is the weight of $e_{ii}$

$u_j^0(e_{ij})$ is the subsystem order value, for example $t_1$, expressed as $u_j^1(e_{ij})$. Then,

$$U = \theta \times \prod_{i=1}^{n} |u_j^1(e_j) - u_j^0(e_j)|$$

where

$$\theta = \frac{\min_j [u_j^1(e_j) - u_j^0(e_j)]}{\min_j [u_j^1(e_j) - u_j^0(e_j)]}$$

among them, $u_j^1(e_j) - u_j^0(e_j) \neq 0$

4. Developments in Solar Energy Technology in Industry, Government, and Academia

This study uses the World Intellectual Property Organization (WIPO) as the basis for an investigation data of solar cell patents. All journals can be obtained from the Web of Science® database. Research and development funding sources were determined from data taken from the Organization for Economic Co-operation and Development (OECD) database on research funding statistics.

4.1 The European Union (EU28)

The number of solar energy patent applications remained generally stable in the EU28 from 2005 to 2008 (see Figure 1). The number of the approved solar patents show that the top three technologies in this market involved the use of “light concentration,” “plasmons”, and “conductive materials.” The top three research fields, based on the number of papers published on solar energy, are “conductive materials,” “light concentration,” and “nanoantennas.”

![Figure 1](image)

Figure 1. Trends in the number of (a) patents and (b) key solar technology patents filed, (c) journal articles published and (d) key journal articles, related to solar technology, for the EU28 countries from 2005 to 2015.

4.2 China

From 2005 to 2015, the Chinese government invested a lot of money on scientific research, patents, and journal papers, as shown in Figure 2. Based on the number of approved solar patents, the top three technologies of the interest during this time period were “nanoantennas,” “conductive materials,” and “quantum energy transport.” The top three research fields, based on the number of papers published on solar technology, were “conductive materials,”
“nanoantennas,” and “light concentration.”

Figure 2. Trends in the number of (a) patents and (b) key solar technology patents filed, (c) journal articles published and (d) key journal articles, related to solar technology in China from 2005 to 2015.

4.3 The United States

In the US, the number of patents related to solar technology first showed an increasing trend and then began trending downwards in 2012; this had an indirect relationship with the input for research funding, as shown in Figure 3. Based on the number of the approved patents for solar technology, the top three technologies under investigation were “conductive materials,” “nanoantennas,” and “quantum energy transport.” The top three research fields, based on the number of papers published on published solar technology, are “conductive materials,” “light concentration,” and “nanoantennas.”

Figure 3. Trends in the number of (a) patents and (b) key solar technology patents filed, (c) journal articles published and (d) key journal articles, related to solar technology in the United States from 2005 to 2015.

5. Results and Discussion

This study attempted to integrate and present data on the current status of the solar energy technology industry, related government policy, and academia, and to speculate on future trends and provide strategic advice, using big data operations. Until 2011, the synergy between the EU28, China, and the US showed steady growth, with the EU28 ahead of the other two countries (Figure 4). In 2013, there was a divergence in this trend; discovery continued to grow in China, plateaued in the US, and declined in the EU28.
The trends in the subsystems of industry, government, and academia can be described as follows (see Figure 5):

For industry, the EU28 had a steady growth in the period 2005–2009 but began to decline sharply after a turning point in 2013 (Figure 5(a)). The reasons for this could be a sharp decrease in solar output (the 2012 value was half of the preceding year); a sharp decrease in the trade surplus (deficit) in 2015, when it was one quarter of that in 2011; and a decrease in the number of patents issued in the same year, which was one-eighth that in 2011. In 2009, 2012, and 2014, China experienced a decline in market volatility owing to a slight decline in output and a trade surplus (deficit). The US market enjoyed growth in 2009 before experiencing a shock from 2009 to 2013 and then a slowdown owing to a decrease in the number of patents approved.

The patents, output, and trade surplus (deficits) invested in by the industry over the years responded to changes in the industrial environment of a particular country. When the EU28 suffered an economic decline; the US economy declined steadily as well and when the Chinese market increased and then slowed down, a corresponding diminishing trend was noted in the industrial environment. Companies need to make steady decisions carefully considering the trends in industry, government, and academia.

In terms of government subsystems, the EU28 experienced growth during the period 2005–2012, after which it gradually declined (Figure 5(b)) because the budget for government R&D expenditures decreased annually after 2012. 2005–2012 marked a period of rapid growth in China followed by a plateau after 2013, the latter again owing to a levelling-out in the budget for government R&D expenditure and government R&D manpower. The US experienced a shock during the period 2007–2011, with the budget for government R&D expenditure changing only slightly annually 2007 to 2011, before stabilizing in 2012 and remaining level since then.

The R&D expenditure and manpower that governments have invested in solar energy technology over the years has reflected the state of investment in R&D in the country. Overall trends, and therefore the intensity of government investments in R&D on solar energy technology, were flat for the period of interest for this study.

In terms of the academia subsystems, the EU28 enjoyed growth from 2005 to 2013 and a decreasing trend after 2014, as shown by the slight decline in the number of journal publications after that time. However, there was a rapid growth in China from 2012 to 2014 owing to a spike in the number of journal articles published. From 2005 to 2013, there was growth in the US; however, this gradually reached a plateau after 2014 as the trend in the number of journal articles published after 2014 flattened.
The number of journal articles published over the years reflects the state of research in a country; as the overall trend increases, there is an implied increase in research output.

![Graphs showing trends for industry, government, and academia subsystems.](image)

**Figure 5** Trends noted for the order of the degrees of synergy for (a) industry, (b) government, and (c) academia subsystems, related to solar energy technology in the EU28, US, and China.

The trends in the key technologies related to solar energy discussed in section 4.1–4.3, applicable to solar-powered devices and classified by country (Figure 6), show that developments related to solar-based thermal technology was better in the EU28, whereas China and the US fared better in terms of solar photovoltaic technology. The key technologies related to solar energy will affect the trend in development of solar energy technologies in these countries.

![Graphs showing trends for EU28, China, and US.](image)

**Figure 6**. Trends related to solar photovoltaic heat mixing, general solar photovoltaics, and solar thermal technologies in (a) the EU28, (b) China, and (c) the United States. [24]

6. Conclusion

In summary, the results of this study show that a rise in the development or improvement of key technologies related to solar energy does affect the development of devices and research in the area. The EU28 dominate the field of theoretical studies, in terms of patents filed and journal articles published whereas China and the US are engaged mainly in applying key technologies.

Our research also showed that:

(1) In terms of trends in synergy, the EU28 showed growth up to 2013, after which there was a rapid drop. This could be attributed to the fact that, solar energy output value; patents; and import and export values for the region fell sharply after 2013. An overall growth trend was seen in China; after 2011, there was a plateau in the trend for the US, due mainly to small fluctuations in solar energy output value, patents, and a trade surplus (deficit).
(2) The degree of the change in the trends was, overall, downward for the industry subsystem, although the EU28, China, and the US showed diverging trends in 2013; the former did however affect the decisions taken by companies. For the government subsystem, overall trends were flat; therefore, trends for investment in R&D were flat. The academia subsystem exhibited a growing trend, as the annual production of journal articles increased and, as a result, the number of studies undertaken on solar energy also increased.

This study shows that, in terms of trends for solar energy technologies, the EU28 is in recession, China is growing, and the US has plateaued. In the industry subsystems, there has been a continuous downward trend continues since the divergence described in this paper. This may affect corporate decision-making; however, the environment for the solar energy industry can change, it is recommended that future research take market considerations into account, so that it can better understand the trends in the development of solar energy.

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