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Shifting scientific power in solar research: the spectacular rise of China in emerging photovoltaics

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China is the undisputed leader in the industrialization and commercialization of crystalline silicon photovoltaic (PV) cells – the most widespread solar technology – and a cornerstone of the global energy transition. In this work, we analyze the global scientific output published in peer-reviewed journals on emerging PV technologies, namely dye-sensitized solar cells (DSSC), organic photovoltaics (OPV), and perovskite solar cells – promising but less mature alternatives for future solar electricity generation. Our bibliometric analysis reveals that China has progressively assumed a leading role in this research area. In 2024 alone, Chinese researchers accounted for 31% of global publications in emerging PV, compared to only 5% from the United States. The "China Initiative," launched by the US administration in 2018, significantly disrupted US-China collaborations and prompted China to establish new strategic partnerships with other nations. It also catalyzed the development of greater autonomy among Chinese scientists. Notably, China's scientific leadership now extends beyond sheer volume of publications; it also leads in terms of quality, as evidenced by its growing presence in high-impact journals and increasing citation rates. Without substantial and sustained investments in emerging PV research, both Europe and the United States risk falling irreversibly behind in the global race for next-generation solar innovation.

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Broader context

Emerging photovoltaic technologies like perovskite, organic, and dye-sensitized solar cells are key to diversifying and advancing solar energy. Our analysis shows that China now leads global research in this field, both in volume and quality, following strategic shifts triggered by US-China tensions. Contrary to its goals, the first Trump administration China Initiative did not curb China's rise in science but instead accelerated its autonomy and global reorientation. This underscores the need for renewed investment and open collaboration if the US and Europe wish to remain competitive in next-generation solar innovation.

Introduction

China has acquired an impressive technological leadership in many areas.[1] According to the Australian Strategic Policy Institute, China is the absolute leader in 57 of the 64 technologies identified as "critical".[2] This is especially the case for solar photovoltaic technologies, where data gathered by ASPI indicate that China's high-value scientific output would even be 4 times greater in volume than that of the United States of America (USA).[3] Yet China holds a dominant position in the industrialization and marketing of photovoltaic equipment. According to the International Energy Agency (IEA), over 80% of commercialized solar cells are today produced in China, resulting in the asphyxiation of Western competitors over the last 20 years. These cells are mostly based on the dominant solar photovoltaic semiconductor: crystalline silicon.[4] China holds 95% of this raw material world-wide production. This solar technology is today the most mature and widely deployed in the world.

Admitting that one can't win a technological battle by betting on the technologies of the past, we'll focus our study here on the so-called "emerging" solar photovoltaic (PV) technologies, those that have the potential to progressively replace the crystalline silicon (c-Si) technology. Compared to mature traditional silicon solar, these emerging technologies hold indeed the promise of higher efficiency, lower costs, and improved scalability, thus accelerating the transition to sustainable energy while minimizing environmental impacts. Emerging PV technologies, including dye-sensitized solar cells (DSSC), organic photovoltaics (OPV) and perovskite solar cells (PSC), have garnered significant attention from the scientific community in

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recent decades. These technologies offer simplified manufacturing processes and the potential for novel applications, contributing to the decentralization of PV production to combat global warming and facilitate the energy transition. Their ability to rapidly compete with mainstream crystalline silicon PV panels remains debatable today. Indeed their Technological Readiness Level (TRL) is unclear and varies from TRL 4 to TRL 8 depending on the final application.[5] It is too early to tell. However, emerging PV technologies already hold promises for specific lightweight/flexible/semi-transparent applications where c-Si is impractical. Some of these materials and approaches can also be combined with crystalline silicon in tandem architectures for enhanced power generation with targets above 350 W_p/m^2 while the best commercially available silicon modules are currently in the range of 230 W_p/m^2.

These emerging cells are a technological challenge for this sector, as are other emerging technologies in artificial intelligence, telecommunications, hydrogen, semiconductors, *etc*.... The United States is leading the way with initiatives designed to "curb" China's technological advance. The "China Initiative" is one such initiative. It was introduced between November 2018 and February 2022 by the US Department of Justice under the first Trump administration. It comprises a series of measures designed officially to track down Chinese espionage in research and industry, but also to discourage if not even ban scientific collaborations deemed the most sensitive with China. With the return of Trump and his promotion of protectionism in all its forms, an assessment of an initiative put in place under his former mandate to curb China's technological advance can already be made. The aim of this article is to assess the impact of the "China Initiative" on scientific research on emerging solar photovoltaic. We will answer the following questions: Has China's access to scientific resources been affected by this "American shock"†? Has China gained in its scientific autonomy ?

To address these questions, we analyzed China's scientific production using data from Elsevier's Scopus database. We developed specific textual queries for each of the three emerging solar cell technologies mentioned earlier, allowing us to identify relevant articles published between 2000 and 2024 (details of the queries are provided in the SI).

First, this data enabled us to compare China's scientific output with that of other leading countries actively researching these topics. Second, we examined China's scientific autonomy in this field by analyzing the evolution of its research output in collaboration with foreign partners. To this end, we introduced a qualitative dimension by studying China's contribution to the most influential articles, defined as those belonging to the Top 10% most cited publications. We assessed China's position within these high-impact publications on a global scale, as well as its ability to produce high quality scientific contributions.

† This "American shock" refers to the term "China shock" put forward in the literature[11] to analyse the impact of Chinese exports on American manufacturing employment. Here, we transpose this analysis to the shock that the China Initiative set up by Trump's US government in November 2018 could have on PV research and innovation.

China, leading scientific research in emerging photovoltaics

Research in emerging PV technologies has been analyzed based on statistics of published scientific articles in peer-reviewed international journals, utilizing data obtained through Scopus. Fig. 1 represents the number of publications in recent years dealing with the three major emerging PV technologies. The most impressive is concerning hybrid perovskite solar cells (PSC) which have witnessed explosive growth over the last decade and represent the most active field of research today in emerging photovoltaics, with a significant increase in publications and a steep learning curve. In 2024, 5529 publications were published on this hybrid perovskite solar topic which is a significant figure. Dye sensitized solar cells (DSSC), the earliest emerging PV technology discovered in 1991, has experienced a decline in research output since 2014, certainly due to the emergence of perovskites attracting the attention of DSSC's experts towards the promising hybrid perovskite materials. Organic photovoltaics (OPV) has known a period of growth of interest until 2014, similar to DSSC. However, while DSSC's field is declining from 2665 articles in 2014 to 1179 articles in 2024, the OPV field has stabilized over the last decade with over 2000 publications per year since then. The inset of Fig. 1 shows the share of major countries in the historical contributions on these three emerging PV technologies. China is absolutely leading with 28% of publications. Even more interesting is to examine the leadership evolution over the recent years. In 2024 only, China is leading with 31% of publications in these emerging PV fields while the USA is far behind, responsible for only 5%. In 2023 only, Chinese research accounts for 2438 articles on PSC, 173 articles on DSSC and 1085 articles on OPV. For comparison, the USA accounts for 407, 71 and 148 articles respectively (see Fig. 2).

Fig. 2 shows the major contributing countries from 2000 to 2023. In 2007, China became first concerning DSSC surpassing

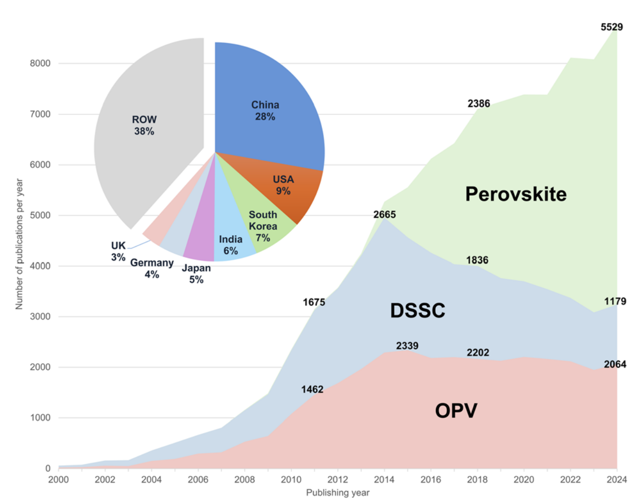

Fig. 1 Annual global scientific publications in peer-reviewed international journals related to the three main emerging photovoltaic technologies: perovskite, DSSC, and OPV. The inset shows the historical share of publications for the leading countries.

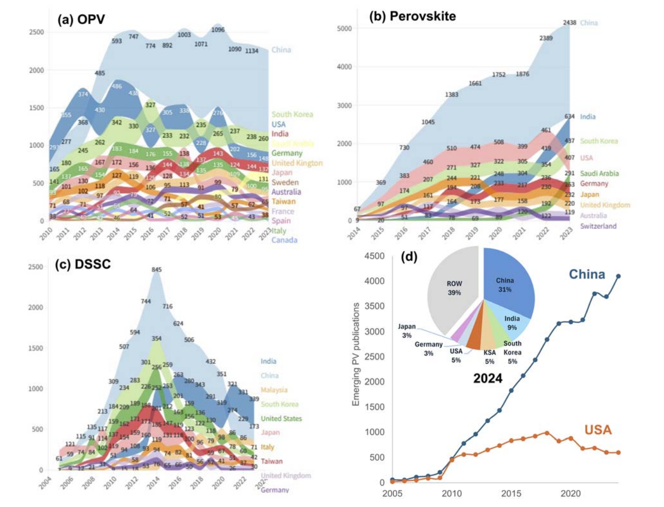

Fig. 2 (a–c) Evolution of annual scientific output by country for the three main emerging PV technologies: OPV, perovskite, and DSSC. Values are expressed as the number of peer-reviewed articles published per year. (d) Annual publication trends in emerging PV research for China and the USA. The inset shows the distribution of national contributions in 2024.

Japan. At the peak of global scientific interest on DSSC in 2014, Chinese researchers published 845 articles followed by South Korea (354) and the USA (256). After the emergence of PSC in 2014, many countries such as South Korea and USA for example have significantly reduced their research efforts on DSSC mostly because experts were switching on to the PSC topic. Such a global tendency has led to an overall reduction of research on DSSC. Interestingly, the only countries who kept growing efforts on DSSC are India and Malaysia. India recently surpassed China since 2021 as top contributing country on DSSC.

Organic photovoltaics (OPV), introduced in 1995 has attracted the attention of the scientific community in a very comparable way as for DSSC (Fig. 1). Simultaneously, from 2000 to 2014, the number of published items increased and very similarly for both DSSC and OPV. At that time, when crystalline silicon solar modules were expensive, both technologies attracted scientists with the promise of building a potential novel cost-competitive PV technology. OPV peaked in 2015 with 2339 published articles, a level of scientific production which was considered as enormous at the time. This was not imagining the perovskite frenzy to come. After 2015, and certainly because of perovskites, the OPVs interest stagnated. The OPV field is still highly active with a stable rate of publication above 2000 articles per year. Interesting is to note that OPV major actors have changed over the years (Fig. 2). This technology was born in the USA at the University of California of Santa Barbara in 1995 in particular thanks to Prof. Alan Heeger, Chemistry Nobel Prize laureate in 2000. The USA have naturally led the race on OPV for a while until 2012 with 374 articles accounting for 22.2% of OPV scientific production. After a peak of 486 articles in 2014, USA's efforts dropped gradually down to 148 articles in 2023 racing at the third place behind China and South Korea. There are multiple factors to explain the reduced interest of Americans on OPV. Of course, again, the perovskite emergence was responsible for many groups switching subjects. Also, many institutes have witnessed the difficulties to raise funds for OPV research after the bankruptcy in May 2012 of the first OPV company, Konarka, founded in 2001 in the USA.[6] OPV research funding was also diminished at government agencies (DOE and NSF) following policies profiting to other subjects like for example artificial intelligence, machine learning, quantum materials and computing. Additionally, it is interesting to note there might be a discipline related story behind OPV leadership evolution. To manufacture an OPV solar cell, and to improve it, one needs materials from Chemistry, mostly organic chemistry, to be understood, processed, characterized and embedded into devices related to Physics aspects. Interesting to mention the OPV leadership of the USA was not sufficiently based on materials and chemistry. It was mostly related to device physics. On the contrary, China focused its efforts on chemistry in particular. By doing so, China has emerged as a leading innovator in organic semiconductors, the key component, driving advancements in OPV technology. Today, China is clearly leading the OPV field accounting for more than half of the global OPV publications with a stable publication rate (approx. 1100 articles per year during the last decade).

Perovskite solar cells represent today the most active emerging solar field of research with a still increasing production rate. The pace of research is unprecedented with a total production worldwide of more than 31 000 articles within the last 10 years. In 2024 only, 5529 articles were published (Fig. 1). Approximately half of the perovskite production arises from China. Such a global effort witnesses the promises of perovskites: a high efficiency solar cell based on abundant, non-strategic, cost-effective materials potentially low-cost to process. However, despite impressive recent achievements in perovskite solar cells, challenges related to stability, scalability, toxicity, and environmental impact persist, necessitating ongoing research efforts prior to wide deployment of this technology.

Tandem solar cells combining hybrid perovskite absorbers with crystalline silicon show promise for improved module power conversion efficiency while using mostly the existing advanced manufacturing processes of the actual silicon industry. Less studied today, this tandem structure is however very promising, enabling the manufacture of PV modules with existing fabs to be only slightly upgraded. Naturally, according to the leading position of China on current silicon-based PV manufacturing, China has been able to address this subject rapidly. China is leading the Si/PSC tandem field with 169 articles. Interesting is to note Germany's efforts (133 articles) surpassing USA's contribution (67 articles) to compete with China in this area. Germany's position here may be correlated with the fact it is currently hosting the first industrial facility of the firm Oxford PV near Berlin very much focused on these tandem products and because Germany was the leader and hosts a solid industrial European base for traditional silicon solar before China's supremacy. Despite the enormous expected impact of this tandem technology, the volume of publicly published articles on perovskite/silicon multi junction cells remains relatively modest to date, with a total of 623 articles among which 134 articles published in 2023. The potential of these tandem cells is impressive, with power conversion efficiencies projected to reach over 45%,[7] twice the efficiency of actual roof-top solar systems. Longi, a leading Chinese c-Si solar manufacturer, has already set a remarkable lab record surpassing 34%.[8] Now comes the question of scalability, social acceptance and reliability before such products are deployed on roofs. The level of complexity to perform research on such advanced tandem solar cells is high and requires high investments. Therefore, it is difficult for academic players at university levels to compete with established solar industrial players, most of which are in China.

In terms of scientific publications in emerging PV solar cell technologies, China publishes the most papers in perovskite and OPV. Publications in DSCCs have decreased, but this decline seems to be linked to the emergence of perovskite-based cells and not to the "China Initiative". The dominant position that China has forged in the past in the field of crystalline silicon is now well set to continue in emerging technologies and does not appear to be challenged by the US initiative.

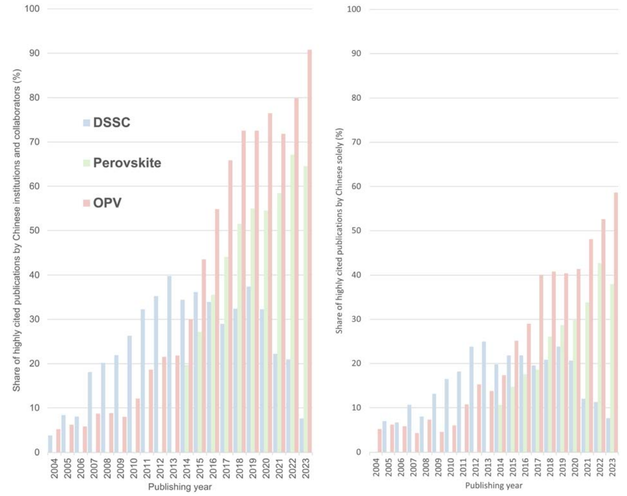

Fig. 3 China's contribution to the Top 10% most cited articles – Total and independent. Unit: "Percentage of global top 10% most cited articles authored by Chinese researchers", based on the average annual number of citations per article.

Is China scientifically autonomous?

Relying on bibliometric data, the 2025 Nobel laureate in Economic Sciences, Philippe Aghion, and coworkers questioned the persistence of Chinese innovation's dependence in general on the USA.[9] Further estimates by Aghion *et al.* indeed highlight a strong persistence in the volume and even more so in the quality of Chinese scientific production with respect to the USA.[10] These studies emphasize the importance of Chinese collaborative research with the West in general and the USA in particular. This non-cooperative US strategy on scientific research implemented in 2018 seems to have "borne fruit" as Aghion *et al.* estimate that Chinese research productivity has decreased by an average of 12% in publications in top journals—although the impact on lower-quality publications is also visible, but significantly less. It is worth noting that on the American side, the restrictions on collaborations with China have not had a significant visible effect on the productivity of American researchers. These results suggest that Chinese scientific research has not yet achieved a degree of autonomy comparable to that of American research. What is the situation in the field of emerging photovoltaics?

Concerning emerging PV technologies, China's research efforts have been characterized by extensive collaborations with various countries. By far, the USA was the largest collaborator of China. Fig. 3 illustrates the main collaborators of Chinese researchers for the three emerging PV topics at stake here. Collaborations with the USA have significantly decreased since the 2018 "China Initiative" launched by the Trump administration. It is particularly evident on PSC and OPV. For both, the number of co-authored articles peaked in 2018 before dropping drastically. It is interesting to note the subsequent acceleration of collaborations between China and other countries to compensate for the lost collaborations with the USA. It is particularly the case with South Korea and Germany (Fig. 3). China has absorbed this American shock by favoring scientific collaborations with non-American researchers.

Overall, China emerges as the leading country in emerging solar research, leveraging quality collaborations with major countries. There are today more impactful articles authored by China in recent years in prestigious journals. And many of these are more authored solely by China indicating its growing autonomy in PV research (Fig. 4). For example, concerning OPV, before 2011, China was involved in less than 20% of the highly cited articles. In 2018, China co-authored 73% of the highly cited OPV studies published in prestigious journals and 41% were solely authored by China. In 2023, 91% of OPV impactful publications were co-authored by China, and 59% were solely authored by China. Similar trends apply on PSC for which China

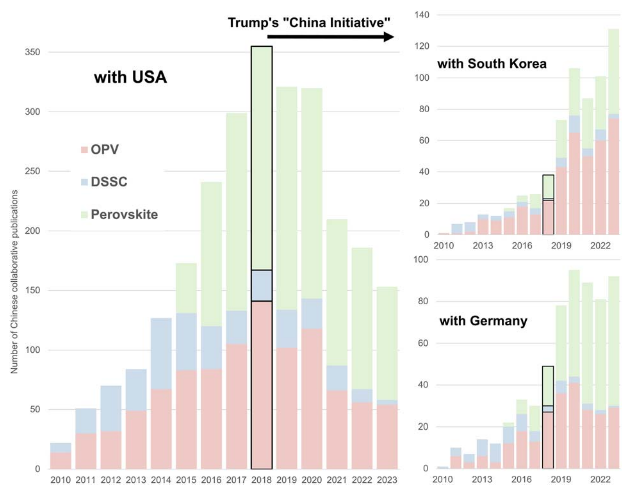

Fig. 4 Scientific collaborations of Chinese researchers with Top partners: USA, South Korea and Germany. Unit: Number of Chinese collaborative articles per year.

is co-authoring 65% of impactful research in 2023 and 58% is non collaborative. Not only China is quantitatively leading emerging solar research, it is indisputable that China is also leading qualitatively. The quantity and the quality of articles produced by Chinese researchers is therefore not declining, despite Trump's "China Initiative" and the drop in scientific collaborations with the USA.

Conclusions

For those who haven't realized it yet, it is time to break away from the illusion that fundamental research in China lags behind that of the West or is, at the very least, still primarily focused on developing technologies already well mastered industrially by the country rather than pursuing future-oriented or breakthrough technologies. Our analysis shows that Chinese dominance is not merely volumetric; it is increasingly becoming qualitative as well. The "China Initiative" did not have the expected effect of curbing Chinese scientific research. China was able to absorb this shock, notably by fostering cooperation with other partners and developing its internal resources. The Chinese government's innovation plans are a step in the right direction in terms of developing indigenous innovation. Combined with the strength of China's photovoltaic (PV) industry, this could quickly give Chinese firms an irreversible competitive advantage in emerging PV solar cell technologies.

It is evident that the China Initiative in 2018 has not had any significant impact on the quality of Chinese research in the field of emerging PV solar cells. The return of US President Donald Trump seems to foreshadow a new hardening of relations with China. Given the limited results of the "China Initiative" and the critical energy stakes surrounding solar cells, the US administration and, more broadly, the governments of Western countries should resist the temptation to intensify their non-cooperative strategies with China for several reasons. Firstly, an open technological war with one of the leaders would inevitably result in a collective loss for the world. Science is a global public good. Any action that hinders the dissemination and production of research is likely to slow technological progress. Secondly, and directly related, with the growing imperatives of combating climate change and accelerating the energy transition, collaborative research, strategic investments, and international partnerships are essential for realizing the full potential of solar energy innovations in creating a sustainable and resilient global energy ecosystem. Any action that could delay or increase the cost of the energy transition would run counter to these imperatives. Finally, there is the risk for the West, by concentrating its PV research (and other related fields) on disruptive technologies, of disconnecting fundamental research from industrial production and underestimating the role of policy in supporting the development of new technologies. The trajectory of China's PV industry since the 2000s teaches us, among other things, that the spread of new technologies depends crucially on policies, economies of scale and learning that take place in industry, not only in academic laboratories. However, to corroborate with the 2025 Nobel laureate in Economic Sciences, Philippe Aghion's opinion, it is perhaps time for the West to invest massively into teaching and innovation in low-TRL disruptive technical directions.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data used in this article were gathered from Scopus database, with searching strategy details provided in the supplementary information (SI). Supplementary information: methodology and queries. See DOI: https://doi.org/10.1039/d5el00101c.

Notes and references

1 A. Bergeaud and C. Verluise, *London School of Economics, CEP Discussion Paper*, 2022, vol. 1876, p. 62.
2 Australian Strategic Policy Institute, *Australian Strategic Policy Institute Limited Annual Report*, 2024, vol. 142.
3 J. Gaida, J. Wong-Leung, S. Robin and D. Cave, *ASPI's Critical Technology Tracker: the Global Race for Future Power, Policy Brief, Report*, 2023, vol. 69.
4 International Energy Agency, *Special Rep Ort on Solar PV Global Supply Chains*, IEA, 2022, vol. 126.
5 Ü. I. Biçer and F. C. Krebs, *Adv. Energy Mater.*, 2025, e02426.
6 *Advanced Science News*, Wiley, 6 June 2012 https://www.advancedsciencenews.com/konarka-technologies-files-for-chapter-7-bankruptcy-protection/.
7 M. H. Futscher and B. Ehrler, *ACS Energy Lett.*, 2016, **1**(4), 863.
8 Longi Press Release16 April 2024, https://www.longi.com/en/news/silicon-perovskite-tandem-solar-cells-new-world-efficiency/.
9 P. Aghion, C. Antonin, L. Paluskiewicz, D. Strömberg, X. Sun, R. Wargon and K. Westin, *POID Working Papers 073, Centre for Economic Performance*, LSE, 2023.
10 P. Aghion, C. Antonin, L. Paluskiewicz, D. Strömberg, R. Wargon and K. Westin, *CEPR Discussion Paper*, 2024, p. 1936.
11 (*a*) D. H. Autor, D. Dorn and G. H. Hanson, *Am. Econ. Rev.*, 2013, **103**, 2121–2168; (*b*) D. H. Autor, D. Dorn and G. H. Hanson, *Annu. Rev. Econ.*, 2016, **8**, 205; (*c*) D. H. Autor, D. Dorn and G. H. Hanson, *NBER Working Paper*, 2021, vol. 81, p. 29401; (*d*) D. Acemoglu, D. H. Autor, D. Dorn, G. Hanson and B. Price, *J. Labor Econ.*, 2016, **34**, S141–S198.