Green Tech Race in the Solar Supply Chain:

Tracking Innovation

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Author's Note

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Abstract

This paper aims to build a conceptual block for a comprehensive index – what I might call Green Innovation Index – to track innovation in green technologies, particularly in the solar industry with a focus on the US and China. The increased role of the state in green transition is more crucial than any other time before to achieve leadership in future industries and tackle climate breakdown. Despite the urgency, tracking green technology innovation has not been an attainable goal due to the absence of a consistent, comprehensive index. I expect the Green Innovation Index will serve as a bedrock for my dissertation which aims to connect three dots between green technology innovation, state intervention in the form of industrial policy, and US-China rivalry.

Keyword: green industrial policy, innovation strategies, US-China rivalry, solar industry

Section I: Ever-intensifying Green Technology Race

When US President Biden signed the Inflation Reduction Act (IRA) - the biggest climate spending package in US history – into law, it immediately provoked heated debates on whether the country, the premier capitalist powerhouse, has come around to take the path of state intervention through subsidisation and industrial policy, under the guise of fiscal policy.[1] The IRA will invest $369 billion into clean energy to build a domestic clean tech manufacturing sector designed to displace China as the key supplier of critical equipment for solar, wind and batteries.[2] The US IRA provoked another game of economic self-interest and protectionism among major trading nations. France and Germany developed new subsidy measures that could include requiring European manufacturers to use home-grown products or clean technologies for them to qualify for EU subsidies.[3] That is a concept French President Macron has called "Buy European". China has also taken an aggressive step. It poured $381 billion of public and private investment into clean energy in 2021, which outstrips North America by $146 billion.[4] It does look familiar to us, giving a deja-vu of Trump's trade war; but what is different about this time is that climate change, not an economic rationale, provoked the self-interest and ever-intensifying competition.

This acceleration in the green tech race is not just a collective race against the climate emergency. It is a race on to invent, produce and deploy green technologies on a massive scale. It is a "green industrial revolution" in which all stakeholders compete against each other for leadership in green technologies and future industries (Park & Tiberghien, 2022). Using a

[1] https://euobserver.com/opinion/156488
[2] https://www.politico.com/news/2022/08/20/china-clean-energy-ira-climate-00052684
[3] https://www.politico.eu/article/ursula-von-der-leyen-joe-biden-trade-europe-first-brussels-gets-ready-to-dump-its-free-trade-ideals/
[4] https://www.iea.org/data-and-statistics/data-product/world-energy-investment-2022-datafile

classical industrial policy to facilitate economic growth is often seen in emerging countries; however, proactive government support to stimulate green growth is also often seen in even countries with established technology industries to give domestic manufacturers an edge against the foreign competition (Stokes, 2013). Now all are rushing into one race.

Conceptually, this green tech race has set in motion a paradigm shift from market fundamentalism to state activism, challenging the long-standing primacy of the laissez-faire economic model (Capri, 2020). Market fundamentalism is no longer seen as capable of delivering a green transition in time to avoid the climate emergency and to one up in the time-sensitive technology race (Park & Tiberghien, 2022). The notion is that the nation that wins this competition will be the nation that leads the global economy in the 21st century (Nahm, 2021); conversely, once a country is lost to its foreign competition, the odds of reclaiming it are vanishingly small.[5] This dire situation indicates that it is not just a question of inventing new technology to tackle climate breakdown – it is a way to attract manufacturers and their supporting industries back to home. This new way of thinking is now tilting countries toward state activism by rejuvenating the old and new tools of industrial policy to speed up innovation in renewable energy and manufacturing products using such technologies.

Some scholars see parallels between the era of rapid economic growth in postwar East Asia and the current period of investments in renewable energy, notably in the wind and solar industries (Esarey, Haddad, Lewis, & Stevan, 2020; Nahm, 2021). Winning such competition requires large public funding to build domestic industry. Proficiency both in innovation and production is needed to achieve and maintain technological lead (Berger, 2013; Nahm, 2021).

[5] https://www.politico.com/news/magazine/2022/08/01/industrial-policy-comeback-00048799

The nature of emerging technologies – high risk and high uncertainty – makes the role of government more crucial than any time before. The "entrepreneurial" governments are needed in funding and supporting early-stage, high-risk research and development (R&D) for which uncertainty discourages corporates (Mazzucato, 2015).

Despite the urgency in taking one up in the green tech race, international organizations and institutions have pointed out major obstacles in tracking energy innovation required for a timely evaluation of where we are standing and what we have achieved (IEA, 2020, 2022b; Kruse, Dechezleprêtre, Saffar, & Robert, 2022). Without appropriate evaluation, it is even harder to figure out where more financial resources should be allocated and where weakness comes up. Moreover, with the rejuvenated enthusiasm for state activism, the current scholarship tends to merely stress "what is good or bad industrial policy", mostly in the context of the US-China rivalry (DiPippo, Mazzocco, & Kennedy, 2022; Hochstetler, 2020).

Black-and-white thinking on government intervention, however, does not give us much about what countries have been doing. It only reinforces the myth that a market-driven model has utterly failed and thus should imitate a state-controlled pathway. One of the stylized facts concerning the role of government in the green tech race is that the US is a market-driven model, while China is a prototype of a state-led approach. Revived enthusiasm toward industrial policy among American policymakers and entrepreneurs has been agitating for the US government to play a much bigger role in countering China's mercantilist system. They call for more proactive "visible hands" of the government in green technology innovation, a battlefield for dominance over the future of the global economy.[6]

[6] https://www.politico.com/news/magazine/2022/08/01/industrial-policy-comeback-00048799

Although a government is called for a more aggressive role to achieve climate and innovation goals, missing from this dichotomous point of view is a discussion on the *nature* and *character* of government intervention. The green tech race is far from being state intervention versus non-intervention. It is about the extent to which the state is more or less present and proactive in the innovation process (Weiss, 2014).

With that in mind, my dissertation aims to connect three dots between green technology innovation, US-China rivalry and state intervention in the market. The much-needed first step for this goal is to identify where countries are similar and different in the context of green technology innovation. To do so, I seek to create what I might call Green Innovation Index with two dimensions – one is on innovation outcome and the other on policy interventions. The Index is expected to give a better insight into a different type of government intervention in green tech, and thus answer the following questions. Are we seeing a new type of government intervention in emerging industries? Or is it another iteration of postwar industrial policy as we have seen in history? Placing a government's goal to build innovative domestic industries within the context of green transitioning economy, I argue that the green transition necessitates both a new understanding of technological innovation and a recasting of state-business relations.

Empirically, I will focus on the solar photovoltaic industry. First, it is the most available and cheapest renewable energy technology. The average cost of solar energy per MWh is $36, while the figure is $38 for wind, $75 for geothermal, and $114 for biomass.[7] According to the IEA forecast, global renewable energy is set to grow by 60% from 2020 levels to over 4,800 gigawatts by 2026. Solar has the biggest potential for its cheap cost. Second, the solar industry has evolved since the reorganization of the global economy. Contrary to legacy industries such

[7] https://www.visualcapitalist.com/what-are-the-five-major-types-of-renewable-energy/

as computer, semiconductor, or auto industries whose origin long traces back to the Cold War military competition between the US and the Soviet Union. Many key technologies in these legacy industries were initially developed for military purposes and later commercialized. Quite in the contrast, firms that produced solar panels did not reach economies of scale until the early 2000s (Nahm, 2021; Nemet, 2019). It enables us to separate the effects of globalization on legacy industries from the development of new industries. For regional focus, I will focus on the US and China, as they represent the two distinct economy models – market-driven and state-led –, respectively. This distinction is important given that one of the ultimate questions that I seek to answer is whether the US and China are fundamentally different in supporting green technology innovation. Moreover, both take the biggest share in the global solar market, which makes them the most representative case in the solar value chain.

With this overarching scheme, the remainder of this paper will proceed as follow. In the next section, I survey the current discussion on the scope and definition of green industrial policy and the nexus between the energy innovation system and the role of government from diverse angles. The third section presents Green Innovation Index and elaborates on each dimension with the cases of the US and China. The current empirical focus lies on the solar industry, but the index is expected to use for cross-country comparison in green technologies such as electric vehicles or batteries. Since this report is still at conceptualizing stage, the last section summarizes the discussion and presents a future research plan for my dissertation.

Section II: The Nexus between the State and Green Energy Innovation

Green Industrial Policy as a Strategic Intervention in the Innovation Game

The creation of innovative domestic industries has long captured the attention of policymakers both in emerging and advanced economies. In the postwar era, the government in East Asian economies employed strategic intervention to encourage domestic enterprises to catch up with the innovative, incumbent firms in global industries. The state picked winners and channelled support to select industrial groups with the use of preferential financial resources (Chang, 2008). Through a mix of public funding and private efforts, Korean and Japanese conglomerates achieved global competitiveness in electronics, automobiles, and semiconductors (Amsden, 2001; Johnson, 1982). Although not uncontested, the role of industrial policy in the East Asian developmental states is considered crucial not only in economic growth but also in the innovation game (Krugman, 1994; WB 1993; Nahm, 2021).

According to Rodrik (2014), green growth is defined as a trajectory of economic development that is based on the sustainable use of non-renewable sources and that fully internalizes environmental costs related to climate change. Green growth requires *innovative* technologies that would lower costs in green transition and help achieve material progress under that path. Industrial policy can play a key role in achieving these objectives. Built on the definition of classical industrial policy referring to "state initiatives whose primary goal is to increase economic output through changes to the composition of domestic economic activity", green industrial policy is defined as "intentional efforts to build specific industries in the green economy" (Allan, Lewis, & Oatley, 2021; Nahm, 2021).

This definition presents three key pillars in government support in the renewable energy industry.[8] First, policies need to be implemented by *a government* itself or *at the direction of a government* or by any *public body* (e.g., state-owned enterprises or state-owned banks). Second, it is a strategic policy that entails a government's *intentionality* to tilt the direction of growth toward a low-carbon economy and to tackle climate breakdown. Third, government support involves *specificity* to accelerate the development and growth of green industries with the use of strategic allocation of resources. In this sense, some market-driven mechanisms could be interpreted as green industrial policies if they were designed in a targeted manner to push a *specific* industry (e.g., auto, electricity sector, etc.) toward environmental goals. However, it can be safely said that there is an academic consensus on the difficulties in establishing tight analytical boundaries around green industrial policy (Allan et al., 2021).

Not exclusively, examples of green industrial policy include public investments (e.g., loans, grants, subsidies, government procurement and rebates), fiscal and financial incentives (e.g., feed-in tariffs or renewable portfolio standards), tax incentives, environmental regulations or standards, and policy supports designed to facilitate the development of environmental technologies (IEA, 2020; Lewis, 2021; Mazzucato, 2021c).[9] In terms of the scope of green industrial policy, Nahm (2021) makes a clear point that (green) industrial policies differ from science or technology policy that prioritizes purely scientific discovery *without* short-term economic objectives. They also differ from energy policies that focus on the domestic energy

[8] My Green Innovation Index will follow this three-pillar rule in determining what is to be included or not in the policy pool.

[9] Unlike other scholars, Lewis (2021) confines her definition of green industrial policy to "industrial support measures" which is distinguished from "deployment measures". The former encompasses trade policies such as import/export bans, quotas, trade remedies (i.e., anti-dumping and countervailing measures), import tariffs, and non-tariff measures. Unlike Lewis, this paper puts trade measures aside and confines the scope of green industrial policy to domestic policy instruments.

mix *without* emphasizing the creation of industries engaged in the development of clean energy technologies (Nahm, 2021). Following this distinction, this paper also primarily focuses on strategic policies assuming a linear relationship starting from basic scientific discovery to commercialization eventually leading to mass production and industrial development.

The Nexus between the State and the Market in Green Technologies

There are three avenues of research on green technology innovation. The first domain focuses on the extent to which a government intervenes in innovation cycle. In advanced and developing economies, public support for innovation in green industries rested on the assumption that the invention of new technologies would attract industrial activities beyond innovation itself; environmentally friendly technologies ranging from renewable energy generation to transportation are advantageous from a national standpoint (Nahm, 2021; Steer, 2013). This assumption justifies government support required for technological innovation, ranging from the large public investment in basic research to the establishment of manufacturing facilities as well as large numbers of suppliers to bring innovation from the laboratory to market.

In the spectrum of the role of government in clean energy innovation, one extreme can be represented by economist perspective. From a neo-liberal point of view, green industrial policy is a response to a set of market failures – failure to fully capture R&D positive spillovers by the original investors and failure to internalize the risks of climate change (Rodrik, 2014). These market failures all contribute to leaving private returns to green technological developments well below those to society as a whole, leading to a free rider or no private investment in technological innovation (Allan et al., 2021). Specifically, economists' traditional skepticism of industrial policy lies in two forms. Asymmetric information between the private and public sectors hinders the government from “picking winners” to be supported. Moreover, government support likely invites rent-seeking and political manipulation by incumbent firms or lobbyists, driving policy-making decisions driven by political motives rather than economic ones (Mazzucato, 2015; Rodrik, 2014). On the neoliberal view, due to these intrinsic market failures, the legitimate realms of state intervention are only limited to areas such as defense, public health, and clean air. The problem of collective actions – free riding – hinders private actors and markets from achieving a universally desired societal outcome, leading to inherent failures of cooperation. Therefore, confining government intervention to these areas involves little long-term risk (Berger, 2021).

However, supporters, even some from the economists’ camp, argue that asymmetric information and political manipulation are not special to green industrial policy. Historically, government support and public funds have played a key role in the development of key industries such as telecommunication, GPS, semiconductor, computing and biotechnology or so in the US (Block & Keller, 2001;)Campbell, 2014; Mazzucato, 2013). Given its indispensable role in putting one’s economy on low-carbon growth and in determining the pace of the energy transition, green industrial policy is now perceived as a proactive intervention to address problems in strategic situations a country faces.

Empirically, the dominant presence of green industrial policies both in emerging and advanced countries involves a major shift in the perspective of international organizations which previously discouraged state intervention; the United National Industrial Development Organization (UNIDO) advised some African countries and China to develop green industrial policy “action plans” and to see them “as a practical way to shape sustainable economies” (Meckling & Allan, 2020). The “Green Economy” framework by the United Nations

Environment Programme (UNEP) represented South Korea's and China's green investments as models. Similarly, it resonates "paradigm shift from cost-minimizing to opportunity seizing" and "from a focus on emissions to a focus on technologies" (Schmidt & Sewerin, 2017). This initiative was not the cause of this conceptual shift; it reflected changes set in motion by green industrial policy (Allan et al., 2021).

The second avenue of research focuses on the political economy of green technological change. Large R&D support led to cost reduction and an increase in the deployment of green energy technologies. Inevitably, this change brings resistance from fossil fuel-based industries facing a cut in the fossil fuel subsidies and strengthened environmental standards that will harm their corporate benefits. Climate action with green industrial policy can break carbon lock-in by broadening the coalition for change (Kelsey & Meckling, 2018; Meckling & Nahm, 2018). In general, the contest between green industrial policy and fossil fuel-based industry has set the pace of change in much of Asia and middle-income economies (Nahm & Urpelainen, 2021)(Gao et al., 2021). As China's coal power sector has shown, opposition to the state's ambitious goals to decarbonize might come from within the state itself as state-owned coal plants and government agencies with substantial investments in such firms strive to block policies that will likely reduce the value of their assets (Nahm & Urpelainen, 2021).

The increased role of the state – both action and inaction – marks a break with the liberal compromise of the postwar era (Allan et al., 2021; Bernstein, 2001). Since the Kyoto Protocol, state actions were dominated by market-based actions such as carbon pricing in regional carbon markets. Indeed, industrial policies entrenched and expanded the role of fossil fuels in the economy. State inactions were structured by the political power of fossil fuels and subsidies that made fuel cheap and society increasingly dependent on the internal combustion engine (Oatley, 2021). As China's green industrial policies transformed the market for renewable energy technologies, state action is needed to invest in infrastructure, drive innovation, and create new industries (Meckling & Allan, 2020).

The last avenue – the scholarship of the National Innovation System - has emphasized the influence of different constellations of domestic actors on the types of innovation (Nelson, 1993). From this point of view, instead of using a global level, the national characteristic conditions micro-level behavior on how firms and individuals interact to produce a distinct national system. They put a strong emphasis on knowledge creation and spillover (Nemet, 2019). Built on the concept of "Innovation System", the family of Energy Technology Innovation System studies makes a distinction from the linear model of innovation in which scientific discovery leads to useful innovation and pays more attention to feedback between innovation stages through technology-push and demand-pull (Gallagher et al., 2012). Despite a heavy dependence on distinct national profiles in explaining different innovation outcomes across countries, the presence of the state is least acknowledged in this group of scholars.

Most renewable energy studies rarely touch on the use of green industrial policy, while industrial policy literature tends to overly hold a zero-sum assumption and ask for a stronger intervention as a cure-all. However, several questions remain unanswered. How renewable energy industries are being supported? Why are some types of green industrial policies adopted over others? What has been the most effective mechanism in which a government and a corporatist sector bring an innovative outcome? A myriad of snapshot-like analysis exists primarily looking at the recent trends in wind turbines, solar PV, and electric vehicles. However, as IEA 2020 Tracking Innovation report points out, we need a consistent and comprehensive tool to evaluate a pathway each country has followed in an overall innovation cycle.

Section III: Green Innovation Index - Policy Instruments and Innovation Outcome

This section involves conceptual works to create a new index, Green Innovation Index, designed to track both innovation outcomes and policy instruments. It covers policies of key countries in the solar industry with a strong focus on the US and China. The period of the analysis is between 2000-2022, as major renewable energy technologies such as solar and wind did not make a remarkable position until the 2000s.

Why is a New Index Needed and What is It?

Despite the importance of maintaining and increasing clean energy R&D support with a long-term vision to stimulate innovation, in many cases, green technologies would face instability and fluctuation in public support. It is primarily because time lags between inputs (e.g., R&D support, fiscal policy and market instruments) and outputs (e.g., patents, knowledge spillovers, lower costs and higher efficiencies) often an obscure correlation between policy changes and innovation outcomes in markets and society (IEA, 2020). Moreover, by its nature, the energy innovation journey is complex, lengthy, uncertain, and often fails. On top of those endogenous factors, it depends on exogenous factors such as past policy choices, macroeconomic conditions, infrastructure and the political economy of a given country, history, and social norms (IEA, 2020). All add to the necessity of developing and adopting a set of metrics to track green tech innovation and to answer the following questions. How does the country compare with its international peers? Which combination of policies has the highest impact? What is the mainstream policy to support innovation? By creating a comprehensive index, this paper aims to build a bedrock for cross-country comparison.

Green Innovation Index consists of two parts – green energy innovation outcome and policy instruments. Literature on energy innovation systems places innovation processes within a broader system of institutions, technological progress, policies and resources, and time and space (IEA, 2020). Actors ranging from firms (e.g., manufacturers, energy suppliers and users) to policymakers are embedded in the broad innovation ecosystem (Grubler & Wilson, 2014). The incentives that drive choices made by these actors in supporting and adopting technologies are formed by more than static cost-benefit analysis (Rodrik, 2014). The incentives include: institutional structure, policies, prior investments, endowed resources, positioning in industrial value chains, market expectations, and government-business relations.

In crafting the key pillars in the innovation outcome index, I followed the IEA's definition of "technology innovation" which refers to "the process of generating ideas for new products or production processes and guiding their development all the way from the lab to their mainstream diffusion into their market" (IEA, 2020). Instead of zooming in on one or two specific segments such as an invention or mass production of new technologies, this definition suggests that the overarching innovation journey should be considered. Likewise, IEA 2020 Tracking Innovation report identifies four main stages of development for emerging technologies: prototype, demonstration (first commercial-scale example, knowledge transfer), early adoption (niche markets and economies of scale) and maturity. Specifically, on the global solar industry, Nemet's comprehensive study on the leadership change in the market reveals that scientific discovery, niche market, demand-pull policies, and disruptive production were all contributing factors (Nemet, 2019). Although all the existing classifications hold promising, I found the necessity to separate what drives innovation (i.e., policy instruments) from what we have achieved so far (i.e., innovation outcome).

Table 1. Green Energy Innovation Outcome Index

Level of analysis	Dimensions	Measurements
Domestic	1. Economic benefits from scientific discovery and R&D support	1-a. Patent activities (in absolute terms and the share of the global patent activities)
		1-b. Cost reduction in such technologies (in five segments in the solar supply chain)
	2. Commercialization and mass production	2-a. Manufacturing (in absolute terms, the share of GDP, the share in the global market)
		2-b. Installed capacity (in absolute terms, the share of GDP, the share in the global market)
International	3. Trade	3-a. Export of such technologies (in five segments in the solar supply chain) 3-b. Market share

Table 1 shows that three dimensions are categorized into two different levels of analysis: domestic and international. First, scientific discovery is where an innovation journey starts. In the solar sector, the development of the first practical solar cell by AT&T's Bell Laboratory in the US initiated the modest beginning of the modern solar PV industry (Nemet, 2019). From a perspective of policy intervention, outcomes of scientific discovery should be separated from pure scientific progress without economic objectives. Also, a scientific discovery which refers to a stage before reaching sufficient maturity for commercial application should be distinguished from its consequential industrial growth and national competitiveness (Nahm, 2021). Therefore, my index confines the scope of scientific discovery to practical application with commercial purposes.

One possible indicator to measure the economic benefit of scientific discovery is the number of patents being filed and granted in the green energy sector.[10] Patent, as an indicator of technological innovation, shows a key link between successful inventive activities and

[10] Major transnational patenting offices include the US Patent and Trademark Office, the European Patent Office (EPO), the Japanese Patent Office, or the China National Intellectual Property Administration (IEA, 2020).

commercial markets (Shubbak, 2019). United States maintained its global leadership in the solar PV industry from the 1940s until the mid-1980s. Its highest R&D budget in 1980 and comprehensive program such as the Block Buy (1975-1985) had a positive influence on the trajectory of the solar industry (Nemet, 2019). For example, between 1954 and 2004, 14 out of the 20 most important breakthroughs were in 1974-1981, almost all of which were in the US (Green, 2005). From 1957 to 1993, out of 39 patents, 23 breakthroughs were in solar PV technology more than half of which were developed in the period when the US federal government and relevant institutions, such as the Energy Research and Development Administration (ERDA) or Social and Environmental Research Institute (SERI), proactively supported R&D activities (Nemet & Husmann, 2012).[11]

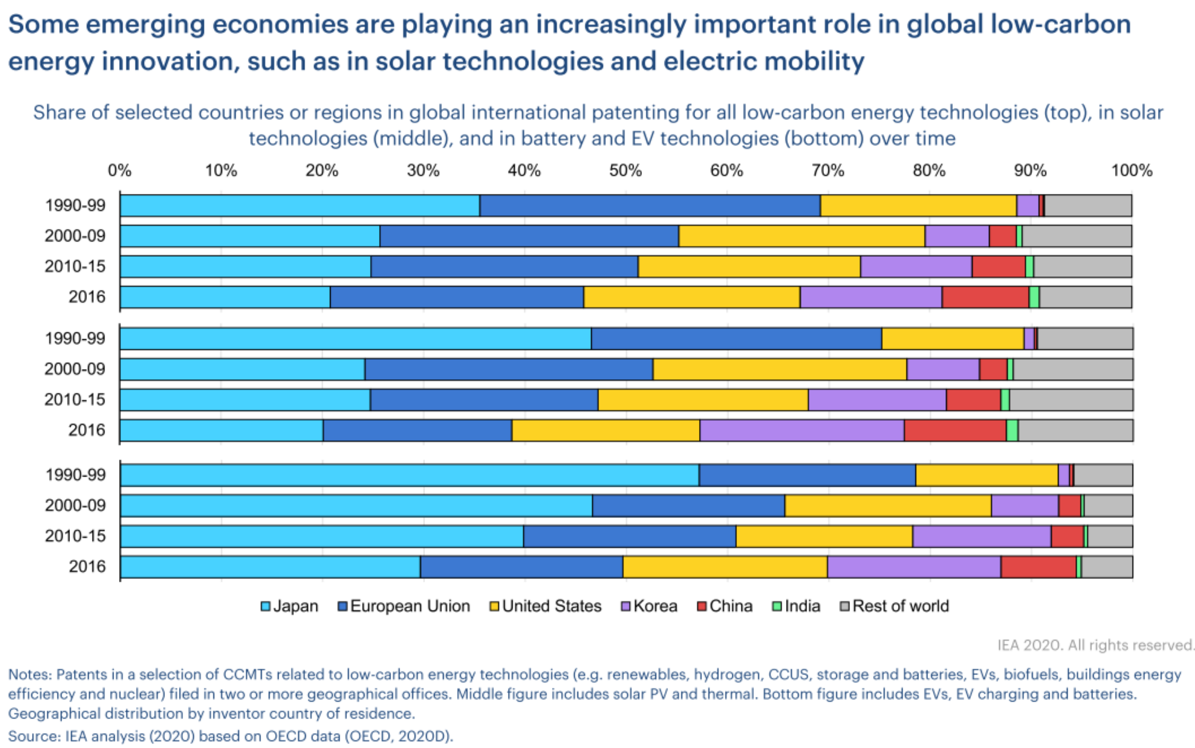
On China's side, it maintained a humble position between 1995 and 1999 when the country did not pay much attention to the solar industry. The average was nine patent filings per year (Shubbak, 2019). In the period of 2005-09, along with the nation's first overarching renewable energy law passed and the local governments' proactive support to encourage R&D activities within local economies, China overtook the US in 2005, Korea in 2010, and Japan in 2011, in terms of the accumulated number of priority filings (Shubbak, 2019). Graph 1 presents the overall trend that emerging countries have an increasing share in the global patenting activities in all low-carbon technologies, solar, and battery & electric vehicle over time.

Relatedly, there is a good consensus that public funding or the governments' R&D support is crucial in innovation outcomes. Cost reductions in technologies can show how much

[11] Improved efficiency can be another good indicator to measure scientific discovery. For example, module efficiency improved from 5% to 15% by 1985 (Nemet, 2019). However, due to limited data and difficulties in estimating improved efficiency in all segments of the solar value chain, I decided to put aside the efficiency indicator out of the outcome index.

economic benefits R&D support for scientific discovery has made. Solar module costs dropped dramatically by a factor of five between 1974 and 1981, the era when the US "technology-push" support hit its peak (Nemet, 2019). The drop was the second fastest pace of cost reductions in solar PV history, exceeded only by a slightly faster fall in the post-2010 period. The cost reductions were seen as a result of the R&D program combined with a relatively modest government procurement (Nemet, 2019).

Graph 1. Share of Key Countries in Global International Patenting Activities (IEA, 2020)



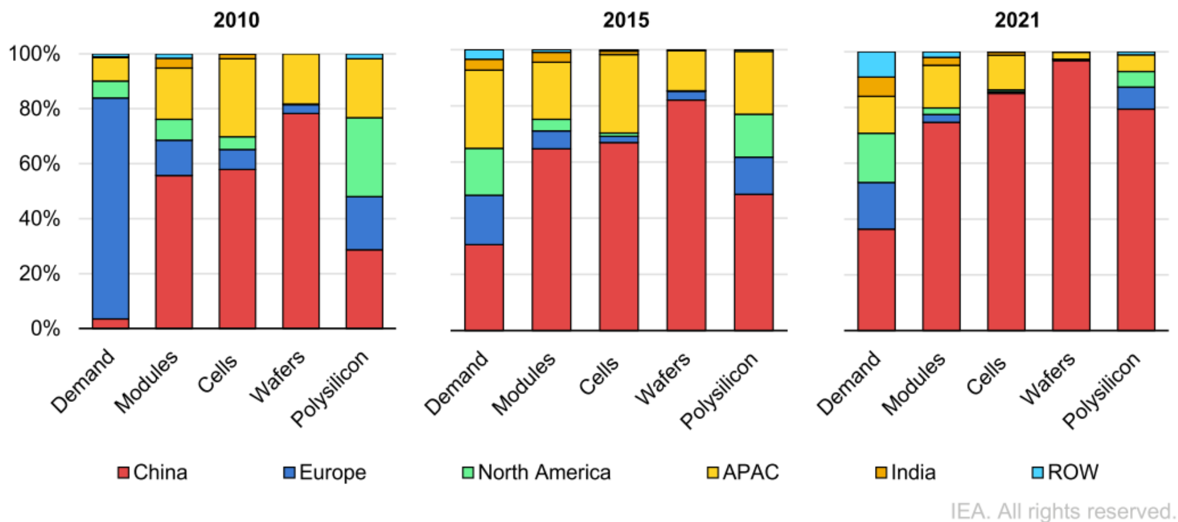
Second, commercialization and mass production is the stage where scientific discovery and public support for R&D activities are brought to market. Not all "innovative" ideas and initial applications can reach this stage. Technological innovation often requires the establishment of manufacturing facilities on a massive scale and large numbers of suppliers who could successfully bring products (with patents) from the laboratory to market (Berger, 2013; Nahm, 2021).

Commercialization and mass production is measured by two indicators – manufacturing capabilities and installed capacity both in absolute and relative terms. These indicators will allow us to compare which country dominates the manufacturing stage in the value chain. There are four key stages in the main manufacturing process for solar PV: polysilicon, ingot, wafer, cell, and panel/module (IEA, 2022a). Manufacturing capabilities and installed capacity in each segment will be measured in the Outcome Index.

As Graph 2 shows, China maintains its leading position in the manufacturing capacity of wafers, cells, and modules between 2010 and 2021. In all stages, China's share in the globally installed capacity exceeds 80%; especially for wafers, no rivalry with China exists. Unlike its dominant position in the R&D support for scientific discovery, the US does not have an impactful position in manufacturing. For cells and modules, Viet Nam, Malaysia and Thailand have considerable manufacturing capacity (IEA, 2022). Germany continues to be a major supplier of polysilicon, while the US and Japan possess significant capacity with a focus on the production of semiconductor-grade products (IEA, 2022). Graph 3 also confirms China's monopoly in solar PV production. The country is responsible for 70% of production in 2021, up from 50% in 2010. The records of other countries with high module assembly capacity are humble – the US (4%), Germany (1%), and India (1%).

Graph 2. Solar PV Manufacturing Capacity by Country and Region, 2010-2021 (IEA, 2022)

Solar PV manufacturing capacity by country and region, 2010-2021

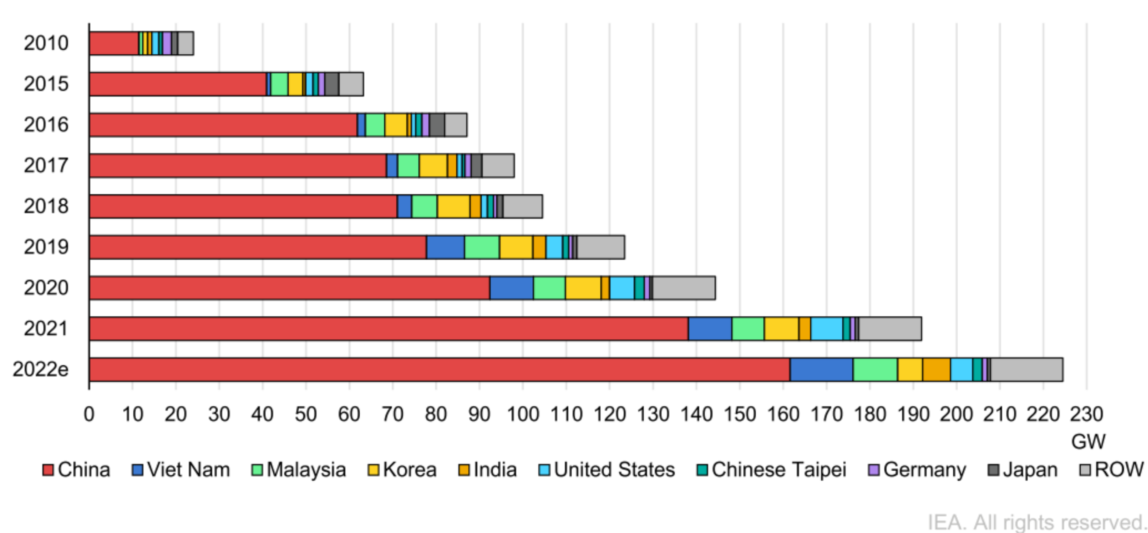


Notes: APAC = Asia-Pacific region excluding India. ROW = rest of world.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

Graph 3. Global Solar PV Module Production by Countries, 2010-2022 (IEA, 2022)

Global solar PV module production, 2010-2022



Notes: ROW = rest of world. Values for 2022 are estimates.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

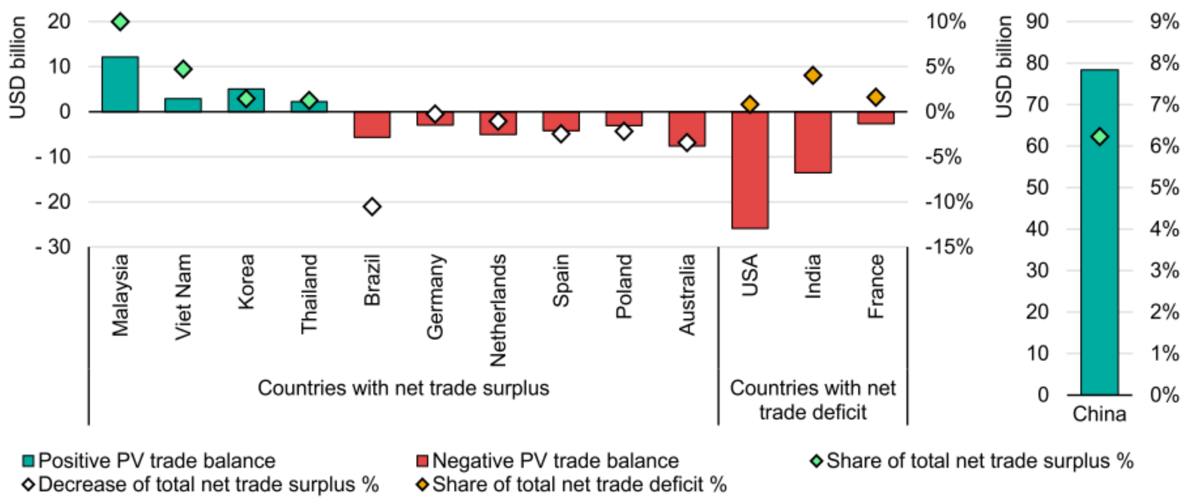
The third dimension, at the international level, to measure an innovation outcome is the trade balance. Green technologies that are exported abroad and thus are gaining market share are likely to be seen as the outcome of the innovative competitiveness of the exporting country. Likewise, those that are losing market share may be seen as less innovative. When it comes to the trade balance, China again proves its consolidated position as exports of wafers, cells, and modules; an average of over 6% of the country's trade surplus between 2017-2021 (Graph 4). The US witnessed trade deficits of 1% in solar PV in the same period, while the figure for France was 2% and 4% for India, respectively.

Market share in the solar PV reveals that leadership in the solar manufacturing market has shifted from Europe, the US and Japan to China since the Global Financial Crisis.[12] Measured by the market shares by the top ten companies in the solar sector, China accounts for 50%, give or take, followed by Korea, Chinese Taipei and Japan (IEA, 2022). It is a stark contrast to 2008 when the top ten solar PV equipment manufacturers accounted for 90% of the global market, operating in only four countries – Germany, the US, Switzerland and Japan (Graph 5).

[12] If we expand the time scope to the pre-GFC period, the leadership has shifted from the US (in the 1950s-70s), Japan (in the 1980s), Germany (2000s), and China (post-2010s).

Graph 4. Trade Balances in the Solar PV Value Chain, 2017-2021 (IEA, 2022)

Cumulative PV-grade polysilicon, wafer, cell and module trade balances, and national net trade balances in goods and services for major PV exporters and importers, 2017-2021

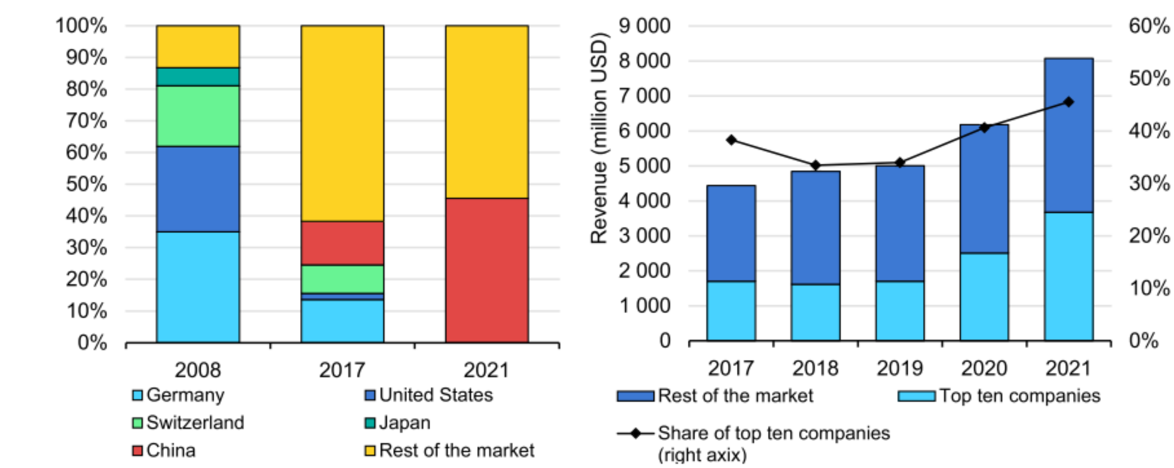


Notes: CAB = current account balance

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink, UN Comtrade, OECD and World Bank.

Graph 5. Top Ten Companies Shares of PV Manufacturing Equipment (IEA, 2022)

Top ten companies' shares of PV manufacturing equipment revenue



Source: IEA analysis based on KDB (2010) and QYResearch (2022).

Policy Instruments Variables

The second part of my Green Innovation Index pays attention to policy instruments designed to support and expedite a transition to a low-carbon economy. Despite plenty of different names such as Green New Deal or Green Deal, the underlying message is more than clear; the green transition is not just about renewable energy; it is about a new type of growth strategy (Mazzucato, 2021a). To put it differently, it is an industrial strategy for tackling climate breakdown while trying to catch a chance to one up in future industries. This new growth strategy has led to rethink the role of government in the economy from a mere 'enabler' or a 'stifler' of innovation to becoming the engine of innovation (Mazzucato, 2021b).

Drawing on Mazzucato's idea of 'entrepreneurial' risk-taking government in launching specific 'green' technologies, I developed Green Industrial Policy Index (Mazzucato, 2015) (see Table 2). Quite in contrast to market fundamentalism, the basic idea underneath the GIP Index is that if the government leaves the market to sort out problems it will likely lead to a lethargic green transition pace. Because innovation is highly uncertain and takes a long time, what is required – more required than in a general innovation cycle – is the willingness and ability of economic agents to take on *risk* and *uncertainty*. Governments are the only actors capable of creating the early and risky investment and of underwriting a massive scale of investments needed, of providing multiple actors with a clear vision of where the society heads, and of coordinating stakeholders with different interests in a way they can pursue the common goal of decarbonization. For that matter, markets are advised to be created and shaped by the '*visible hand'* of the state (Mazzucato, 2015).

The full range of levers is available to governments. Table 2 summarizes four dimensions of green industrial policy and corresponding motivations, different types of government roles, and measurements. Following the classifications in the existing scholarship, the first two dimensions are supply- and demand-side interventions (Allan et al., 2021; Campbell, 2014; IEA, 2020, 2022a; Lewis, 2021; Mazzucato, 2016; Meckling & Nahm, 2019; Nahm, 2021; Nemet, 2019; Shubbak, 2019). The third and fourth dimensions pay attention to a government's comprehensive role as a guiding star and a coordinator for the green innovation system.

Table 2. Green Industrial Policy Index

Dimensions of policy instruments	**Motivations**	**The role of government**	**Measurements**
1/ supply-side intervention	1-a. Stimulating scientific discovery	1-a. Risk-taker	R&D support
	1-b. Enabling investment	1-b. Investor of first resort	Investment Tax Credit (ITC), loans, grants, subsidies for investment, patient capital (funding by public institutions).
	1-c. Boosting manufacturing/ deployment	1-c. Deployment supporter	Renewable Standard Portfolio, Feed-in Tariff, Net-metering, Production Tax Credit (PTC)
2/ demand-side intervention	Boosting consumption	2-a. Market creator	Government procurement, Tax incentives (e.g., for retail consumption or residential use)
3/ Objectives & Plans & Targets	Providing a clear direction, setting a long-term goal, mitigating uncertainty	3-a. Orchestra conductor	Overarching government laws, programs, and executive orders, Detailed legal/administrative actions
4/ Institutional channels for collaboration & coordination	Helping effective interaction for timely feedback and renegotiation	4-a. Coordinator	Public-private partnership

First, supply-side interventions are focused on how energy is generated with specific renewable energy technologies and distributed by supporting the development and deployment of such technologies. Thus, three core motivations are playing underneath; to support scientific discovery; to enable investments to bring the innovation outcome to market, and to boost manufacturing and deployment at a massive scale. In doing so, a government does not restrain its role to ‘last resort’ or at best ‘fixer of market failure’. Emphasis on more basic research requires a government to take the lead as a risk-taker. Supports can be given in the form of either direct funding (e.g., R&D projects or grants) or indirect aid (e.g., tax breaks for private R&D) to mitigate the higher risks at the demonstration stage (i.e., valley of death) (IEA, 2020). In 2015, 25 countries or regions committed to doubling clean energy R&D spending under the Mission Innovation initiative (MI, 2017). Mostly, countries have a comprehensive project which includes a long-term R&D support plan. For example, the 1974 Sunshine Project in Japan allocated a total $150 million per year (20% of the entire project budget) to solar equipment and procurement.

In China, the core technology R&D programs started from the National Basic Research Programme (so-called 863 Program in 1986 and 973 Program in 1997 directed USD 3 billion between 2001-2005) designed to support applied research in enterprises or start-ups such as Suntech and Goldwind (Campbell, 2014; Shubbak, 2019). Since the beginning of the solar industry, the US has continued its proactive financial support: the Energy Reorganization Act of 1974 to present, Project Independence with USD 1.7 billion in solar PV R&D until 1981, the solar PV R&D Act of 1978 with USD 1.5 billion for commercialization, the Energy Policy Act of 2005, the American Recovery and Reinvestment Act of 2009, and the most recently announced Inflation Reduction Act of 2022 (Campbell, 2014; IEA, 2022a; Stokes & Breetz, 2018). Japan and Korea have crafted their own versions of “green new deal” with an investment of $18 billion and $135 billion for R&D in green technology, respectively (Park & Tiberghien, 2022).

Investment in renewable energy is one of the strongest gears in supply-side policy intervention. Consistent and clear signals to the market can reduce uncertainty, attracting more business actors to engage in clean technology innovation. Among other enabling-investment measures, patient capital is crucial in creating the 'catalytic' early and risky investment (Mazzucato, 2015). For most venture capital funds, it is too great to tolerate the financial risk of supporting a firm until it can mass produce and reach economies of scale. State-funded investment or finance through 'development banks' can be a good example (Mazzucato, 2015). The strength of development banks lies in their more risk-taking role; they can take more risks than commercial banks would do since development banks are not required to pay dividends to private stakeholders (Fried et al., 2012). As the key source of funding for green energy projects, development banks committed more than USD 100 billion in 2012, compared to 76.8 billion in 2010 and 36.8 billion in 2007 (Mazzucato, 2015).

Plenty of measures are available to boost manufacturing and deployment of green technologies. Once an innovation outcome is brought to market, an unprecedented scale of deployment is needed to meet climate and growth goals. This demands a major additional expansion in manufacturing capacity (Berger, 2013). Examples are not exhaustive but include: renewable portfolio standard (RPS), Feed-in Tariff (FiT), net-metering, production tax credit, below-market-priced electricity and/or land use, etc. Many countries are relying on FiT and RPS to support their green industries. As of 2014, 60 countries use FiT which is a good way to boost manufacturing, as a government creates long-term financial encouragement for renewable energy by ensuring a fixed price guarantee for developers (Lim & Cho, 2017). Germany's FiT in the solar industry has received worldwide acclaim as it transformed the country into a solar leader in the 2000s; the policy quadrupled the solar PV market and boosted manufacturing of solar equipment (Mazzucato, 2021; Nemet, 2019).

Second, demand-side policies are mainly designed to boost consumption. A government aims to affect domestic energy demand patterns by setting up renewable energy targets, incentivizing product development and helping emerging technologies reach consumers (IEA, 2020; Mazzucato, 2021). It can stimulate eco-friendly generated electricity both in the form of direct intervention (e.g., government procurement) and/or indirect policy (e.g., tax breaks for retail consumption, and incentives for residential purposes). In doing so, government serves as a market creator.

Even before a market reaches maturity, a government's role as a market creator stands out. By establishing a sheltered or "niche" market in which new products do not face full competition with incumbent technologies, the risk of investing in the first manufacturing plants or production facilities can be lowered enough to attract financing (Bennett, 2019; IEA, 2020). The niche market was one of the contributing factors to the growth of the Japanese solar industry. When Japan had yet achieved its solar leadership in the 1980s, consumer electronics provided smaller markets with a higher willingness to pay, which allowed solar PV producers to target real applications at prices without subsidies (Nemet, 2019). After surviving a nascent stage, key conglomerates such as Sharp, Sanyo, and Kyocera scaled up along with the combination of the government's R&D support and subsidizing installations, becoming the world's major PV manufacturers in the early 2000s (Nemet, 2019; Watanabe et al., 2000).

The third dimension entails a guiding role of government in making clear objectives, setting a long-term goal, and, in doing so, mitigating uncertainty. Examples of policy instruments encompass general renewable energy-related laws, legal actions or executive orders specifically targeting a clean energy sector, government programmes, incentives, and plans/targets. Again, a mission-oriented government jumps into the center of the innovation arena and exerts its risk-taking role to guide all relevant actors for the common goal of the green transition. However, a government's role does not stay as a mere risk-taker or uncertainty-mitigator; given that a government's leadership is much needed in all steps in the innovation cycle - but not within an arm's length -, I associate this type of role with an orchestra conductor who is expected to set the tempo, execute clear preparations and beats, control the interpretation and pacing the music, and listen carefully to shape the sound of an ensemble.

Patterns vary across countries. German's Energeiwende has received much acclaim as a successful case which provides a society with clear targets for green transition (i.e., phasing out nuclear power by 2022 and coal by 2038) and one simple goal for all economic actors including business sectors and researchers (Mazzucato, 2021). The US has traditionally relied on market forces and tax incentives to encourage the deployment of new technologies. Although being debatable, some scholars found that individual states have renewable energy mandates, but no federal law exists to drive an overarching development of renewable energy (Campbell, 2014). In a quite contrast, Five-year Plans in China have presented the whole economy's explicit goals and targets for where the country tries to head. Not only for solar, but also wind energy, biomass, and hydropower, China has set up a targeted annual deployment every five years. For solar PV, the figure dramatically grew from 0.07 GW in 2005 to 50 GW in 2020; a similar pattern in the wind shows a more than 150 times increase in the deployment target from 1.26 GW in 2005 to 200 GW in 2020 (Campbell, 2014).

The Chinese central government's motivations for solar PV were diverse over time. In the 1970s, security-wise concerns dominated the motivations, while poverty alleviation was driving in the 1980s-90s. It was not until after 2009-2010 that a growth strategy combined with environmental concerns surfaced. Although the presence of the state did not precede private entrepreneurship, mostly driven by Suntech, once the state appears in the scene, it played a critical role in enabling the thriving solar industry with a variety of relevant laws and programmes. In 2009, the Amendment of Renewable Energy Law, originally passed in 2005, required electricity grid companies to buy all the electricity produced by renewable energy generators (Shubbak, 2019). In the same year, the decision of the State Council on Accelerating the Fostering and Development of Strategic Emerging Industries named solar PV as one of the seven industries to be championed. Golden Sun Demonstration Programme offered an additional 50% of subsidy for a domestic solar market and on-grid systems with projects of 300 MW capacity in service for a minimum of 20 years. In 2012, a specific FYP for Solar PV Industry was announced in line with the 12^{th} FYP (2011-2015) (Hochestetler, 2020). Combined with R&D support and demand-side policies, the Chinese central government sent business sectors a clear signal that the solar industry will remain the country's key strategic industry with targets and goals within a timeframe.

Last but not least, institutional channels for collaboration and coordination should be counted. To measure this dimension, I will use public-private partnerships and research-business consortia as indicators. In the US, the Defense Advanced Research Projects Agency (DARPA) has been often cited as a good example. Key to DARPA's model is the perfect example of why it is wrong to think that the government is simply there to de-risk private risk-takers (Mazzucato, 2021b). It was a model for organization innovation inside the public sector with public officials holding embedded autonomy and deep knowledge of the technological, social, and industrial context. Likewise, public-private consortia were also a driving force in the Japanese solar industry, especially when the market was not fully blown. In the 1980s-90s, the Japanese Photovoltaic Energy Association (JPEA) provided nascent legitimacy for the notion that PV could be an industry on its own rather than a minor input to established industries (Nemet, 2019). Sharp and Sanyo were closely involved with the Ministry of International Trade and Industry

(MITI), and this corporatist government approach created a channel in which government, business, and research institutes actively exchange feedback. By doing so, shared expectations among participations about future deployment levels and prices survived the core PV technologies until the market grew at a massive scale.

Future Research Plan and Expected Contribution

This paper surveyed theoretical discussion on the nexus between the state and the market in green technology innovation. Trying to connect three dots between the role of the state, green innovation, and US-China rivalry, my dissertation tries to answer if the US and China are fundamentally different in their green tech strategies. As a starting point, this paper creates Green Innovation Index on two variables - innovation outcome and policy instruments. Data collection on both the dependent variable and independent variables is underway. Some variables can be measured with quantifiable data, while others need to be converted into a categorial variable. A full dataset will be submitted to the statistics department to participate in a student-led quantitative consulting project. The scoreboard on the US and China will be available once the preliminary data analysis is completed. It will allow me not only to grasp an overall trend but to identify any outliers or abnormal pattern which is not visible with the current snap-shot approaches. By doing so, I hope my dissertation can contribute to disentangling a causal mechanism underlying the green tech race which seems to have brought an industrial policy to strike back and only exacerbated self-interest, inward attempts of countries to go solo in the green value chain.

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