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Zhang, F., Gallagher, K.S., Myslikova, Z. et al. (3 more authors) (2021) From fossil to low carbon : the evolution of global public energy innovation. WIREs Climate Change. ISSN 1757-7780

https://doi.org/10.1002/wcc.734

Received: 15 September 2020 | Revised: 11 July 2021 | Accepted: 14 July 2021

DOI: 10.1002/wcc.734

WIREs CLIMATE CHANGE WILEY

UPDATE

From fossil to low carbon: The evolution of global public energy innovation

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Funding information
BPBPAE/PAT/50621(5)/63365; National Natural Science Foundation of China, Grant/Award Number: 71721002; Rockefeller Brothers Fund19-635; William and Flora Hewlett Foundation2019-9914; Alfred P. Sloan FoundationG-2021-14173

Edited by Simone Pulver, Domain Editor, and Mike Hulme, Editor-in-Chief

Abstract

A review of global and national energy research, development, and demonstration (RD&D) investments between 2000 and 2018 reveals that global public energy RD&D and cleaner energy RD&D investments dramatically increased, but then plateaued after 2009. In absolute values, nuclear energy has held steady, fossil energy contracted, and clean energy RD&D quadrupled. As a percentage of overall investments, both fossil fuel and nuclear investments contracted during the period. This review compares the energy innovation priorities of the world's largest economies using the metric of public expenditures on energy RD&D. China and India have become important global public investors in energy innovation, now among the top five globally. Priorities set by the Chinese and Indian governments will thus influence new energy technology breakthroughs in the coming years. The US and Chinese governments are now competing for first place in clean energy RD&D, depending on whether or not nuclear and cross-cutting technologies are included. India has dedicated substantial funding to indigenizing nuclear power technologies. Energy RD&D by state-owned enterprises (SOEs) in major emerging economies remains skewed toward fossil fuels and nuclear. Reforming SOE expenditures to move away from fossil fuels could have a major impact on global energy technology trajectories, making a material difference in the quest to decarbonize the energy system.

This article is categorized under:

- TheCarbon Economy and Climate Mitigation > Policies, Instruments, Lifestyles,Behavior

KEYWORDS

energy technology innovation, energy RD&D, public spending, SOEs, indicators

1 | INTRODUCTION

The global energy innovation system is in the midst of a profound transformation as shown in the graphical abstract. Wind and solar energy doubled their share in the global power generation mix between 2015 and 2020, with renewables reaching more than 10% of electricity generation or more in most countries (BP, 2020). Breakthroughs in renewable energy in the 2000s dramatically lowered their costs, rendering coal-fired generation commercially uncompetitive in many key markets (EIA, 2020; Penn, 2020). Yet despite these achievements, investments in fossil fuel technological innovation also resulted in cost reduction, enabling the enhanced recovery of oil and gas from unconventional resources and impeding the shift to low-carbon energy (Calechman, 2016). Many governments continue to support energy research, development, and demonstration (RD&D) investment in fossil fuel technologies either directly or through state-owned enterprises (SOEs). This calls into question the adequacy of government efforts to address the threat of climate change.

This review analyzes government energy innovation priorities and investments to determine how they have changed since 2000. Utilizing a data set constructed by the authors, the study clarifies which countries are making the most significant contributions to the clean energy innovation effort, which are lagging, and why. This study provides an advanced review of new theoretical and empirical developments related to global energy innovation since a 2011 article on this topic was published in this same journal (Gallagher et al., 2011).

We assess global public energy innovation by examining trends in public energy RD&D investments between 2008 and 2018 and through case studies. RD&D investments are an indicator of government effort and intention to shape a country's energy systems in the future. The current paper and the 2011 article (Gallagher et al., 2011) are based on a global integrated database on public energy RD&D investments developed by the Climate Policy Lab of The Fletcher School at Tufts University, building on one previously developed at the Belfer Center at Harvard University (Kempener et al., 2013). All the values reported in this paper are in US$, 2018 prices and purchasing power parity (PPP) in the remaining text unless otherwise stated.

We find that global public investments in energy RD&D are trending cleaner, except for those investments made by SOEs which remain overwhelmingly invested in fossil fuels. Relative newcomers to the global public energy innovation effort, especially China and India (not including their SOEs), have dramatically increased nonfossil energy technology RD&D spending in recent years. India has now joined the top five countries in total public energy RD&D spending, behind the United States and China, briefly outpacing Japan in 2015–2017, due to its large commitment to innovation in advanced nuclear power. The SOEs in China and India continue to prioritize research and development (R&D) in fossil fuels, however, thwarting a comprehensive pivot to nonfossil energy. Given the growth in the magnitude of their efforts, the energy innovation choices made by the Chinese and Indian governments will have an outsized impact on the trajectory for energy technology development in the next three decades as countries attempt to hold global temperatures to 1.5°C and reduce greenhouse gas (GHG) emissions to zero by mid-century. In particular, how governments compel their SOEs to direct energy innovation efforts could make an enormous difference in global public energy innovation spending and outcomes.

Box 1: Key definitions

Clean energy includes energy efficiency, carbon capture, utilization and storage (CCUS), renewables, hydrogen and fuel cells, other power and storage.
Nuclear is reported separately from clean energy.
Nonfossil includes both clean energy (as defined above) and nuclear.
Cross-cutting investments include basic energy research and energy system analysis and can include clean energy investments.
Public investments include those investments made by governments *not* including by state-owned enterprises (SOEs).
SOEs are reported separately from public investments.
For more detail on definitions, see Section 3.

The paper progresses as follows: in Section 2, we review the literature on energy innovation indicators used to measure progress of energy innovation. Section 3 provides the methodology. In Section 4, we quantify public RD&D investments to provide a snapshot of current global innovation. In Section 5, we explore the major countries pursuing energy innovation and the major market, policy and institutional forces driving their innovation efforts. Finally, Section 6 presents major findings and discussion.

2 | SURVEY OF LITERATURE: ENERGY RD&D INVESTMENT INDICATORS, DATA, AND TRENDS

Traditionally, energy technologies have been classified as supply-side energy technologies, meaning those used to bring energy forms to a point of final use, and energy end-use technologies, meaning those applied by users of energy to convert an energy form to a service such as light or motive power. More recently, scholars have expanded the definition of energy technology to include digital-based technologies that can substantially reduce demand-side energy use and environment impacts (Jaffe, 2019, 2020; Popp et al., 2021).

The energy innovation literature defines energy-technology innovation systems (ETIS) as "the set of processes leading to new or improved energy technologies that can augment energy resources; enhance the quality of energy services; and reduce the economic, environmental, or political costs associated with energy supply and use" (Gallagher et al., 2006). It encompasses the RD&D plus deployment of energy technologies, operating within specific contexts and incentive structures. The literature utilizes various indicators of innovation processes and outputs to conduct evaluation of the ETIS. A discussion of these indicators is offered next.

2.1 | Energy innovation performance indicators

Innovation metrics have been developed to measure innovation performance, particularly when there is a need for international comparison (Borup et al., 2013; Grubler et al., 2012; Hu et al., 2018; Kettner et al., 2013; Klitkou et al., 2010; Wilson, 2012). Compared to a single indicator approach, which only provides a limited view of the performance of innovation activities (Tidd & Bessant, 2013), evaluation frameworks with multiple indicators (e.g., the European Innovation Scoreboard) present a more comprehensive picture and are generally believed to better inform policy evaluation and formulation (Carayannis et al., 2018).

Gallagher et al. (2011) summarized the most commonly used quantitative metrics of innovation relating to energy technology, divided into three categories: input metrics, output metrics, and outcome metrics. The process-based input, output, outcome classification of energy innovation metrics (Wilson, 2012) allows for a standard framework to assess innovation processes. RD&D investments are classified as an innovation input in these frameworks.

A broader set of indicators can be used to better measure the effectiveness of policy in driving energy innovation success, such as entrepreneurial activity, market formation, and resource mobilization (Hekkert & Negro, 2009; Miremadi et al., 2018). Other key policy and systematic features of ETIS, such as national context, policy enablers, structural indicators are also important (Kettner et al., 2013; Klitkou et al., 2010). There are also efforts connecting indicators within different stages of an innovation process, including evaluating the success of RD&D spending. A new literature is emerging that enhances these existing frameworks (e.g., Bergek et al., 2008; Hu et al., 2018; Miremadi et al., 2018). Some efforts have successfully combined both process-based and function-based indicators frameworks (Miremadi et al., 2018).

A summary of indicators proposed in existing evaluation frameworks for energy technology innovation is presented in Table 1. Due to the interactions among different functions, there is some overlap among the metrics.

There is no established international common consensus of which indicator or set of indicators is optimal (Borup et al., 2013). Miremadi et al. (2018) finds that most indicators are problematic for assessing ETIS and only 12 indicators meet all the criteria.

In this article, we utilize one indicator, government RD&D investment, because it best reflects the intentions, priorities, and relative effort by governments to change the future trajectories of their countries' energy systems. Public energy RD&D expenditures are also only one of the input metrics that are available on a cross-country basis, although data gaps and ambiguities remain.

TABLE 1 A multidimensional indicator framework for energy technology innovation systems

Functions	Input	Policy indicators	Structural and systemic indicators	Output	Outcome indicators
Knowledge generation	• RD&D projects • Energy RD&D budgets/expenditures (including both public and private)	• RD&D strategies • Research support	• General knowledge base	• Patents • Scientific publishing • Citable documents • H index • # highly cited publications	• New science and engineering • Graduate • PhDs • Learning rates • Process improvements
Knowledge diffusion	• RD&D networks	• Development of communication networks	• University and industry research collaborations • International scientific co-publications per million population • Public–private co-publications • Number of workshops/conferences • Cooperation patterns in RD&D programs • Linkages among stakeholders	• License fees and royalties • Cooperation in R&D projects • Acquisition of knowledge and technology • Co-patent and co-publications • Knowledge-intensive services	• Learning rates • Process improvements • Joint ventures • Foreign direct investments
Guidance of search	• Policy action plans • Shared strategies and roadmaps	• Targets set by governments or industries • Credible political supports	• Debate-meetings/media • Strategy networks • Stakeholder engagement processes	• # press articles raising expectations • Scenarios and foresight projects	
Entrepreneurial activities	• # new entrants • Ratio of energy start-ups to • # new businesses • Incumbents • Share of energy innovative firms of all firms • Entrepreneurial culture • Access to private finance for cleantech start-ups • # of innovative activities • # of diversification activities • # of new MBAs	• Ease of starting a business • Venture capital availability • Sustainable business models • Risk-sharing • Innovative firms supported	• Innovative SMEs collaborating with others • Size of companies	• # technologies commercialized • SMEs introducing product or process innovations • Quantity of new technological products • Experimental application projects • Creative goods exports	• # new businesses created • Production capacity added • Gross-value added • Energy jobs added
Market formation	• High-tech imports	• Public market support • Green tax • Tradable permits	• Resource endowments • Proxies of size • Attractiveness of infrastructure • Domestic market size index	• Market penetration • High-tech exports • Installed capacity	• Economic benefits • Energy/Emissions • Other environment impacts

TABLE 1 (Continued)

Functions	Input	Policy indicators	Structural and systemic indicators	Output	Outcome indicators
		• Incentives and subsidies • Policy processes • Cleantech-friendly government policies • Transparency • Specific tax regimes		• Renewable energy production • Trade of energy technology and equipment • # of niche markets • Environmental standards and certifications	• Environmental performance of energy technologies • Energy jobs created • Equitable access to clean energy • Environmental justice achieved
Resource mobilization	• Investment (including energy RD&D) • Gross expenditure on R&D • Investment in vocational training for industry workers • Domestic credit to private sector • # researchers in R&D per capita • Expenditure on education • Venture capital deals	• Financial source support • Development of innovative financing • Infrastructural support	• ICT access	• Graduates in science and engineering • # plants • Production lines • Product variants • # companies • Turnover	• Employment in knowledge intensive activities • Employment in the energy industry
Creation of legitimacy	• Lobby actions • Regulatory acceptance and integration • Technology support	• Regulatory quality • Intellectual property—protections • Regulatory instruments • Political consistency	• Public opinion on energy technologies		• Executive opinion on environmental regulation • Recognition of benefits

Abbreviations: ICT, information and communication technologies; R&D, research and development; RD&D, research, development, and demonstration; SMEs, small and medium-sized enterprises.
Source: Adapted from Gallagher et al. (2011), Hu et al. (2018), Turk (2017), and Miremadi et al. (2018).

2.2 | Data availability: Existing resources and constraints

Scholars have struggled to compile comprehensive data on energy innovation due to lack of data availability (Bonnet et al., 2019; Dutta et al., 2018; Leon et al., 2018; Popp et al., 2021). Only one-quarter of the indicators examined by Miremadi et al. (2018) are consistently available. Many problems reported by Gallagher et al. (2011) with data availability, accuracy, measuring, and interpreting have persisted. Standardized data remain absent. Access to data on private sector investments in energy RD&D is now available for some countries and firms via the Bloomberg Terminal, but it largely remains spotty or non-existent.

The International Energy Agency's (IEA) Energy Technology RD&D Budget Database tracks government RD&D investment in energy for its 30 member countries. In 2015, Mission Innovation (MI) was established by a group of 24 countries that agreed to accelerate energy innovation in line with the Paris Agreement. As part of MI, member countries agreed to report their annual clean energy RD&D expenditures to the MI Secretariat. Data reporting to the MI Secretariat, including by the United States, have been sporadic. All data reported by MI and the IEA are self-submitted by member countries. The two data sets are distinct and while there is some overlap, definitions and inclusions vary. MI-reported data focus solely on "clean" energy. IEA data include all energy RD&D including fossil energy. The clean energy data submitted by IEA member countries under MI are often a subset of the broader IEA data sets but what is included often depends on the definition of clean energy used by individual countries. For instance, Australia and Canada include nuclear energy RD&D as "clean" energy, while Canada includes some oil, gas, and coal RD&D as clean energy in their MI reports. China is not an IEA member country but is a member of MI. It reports clean coal RD&D as clean energy in its submissions. Some non-IEA MI members do not include a breakdown in their submissions, but rather provide an aggregate clean energy RD&D investment number. In this paper, we try to narrow this data gap between the different data sources by adding more granular time-series RD&D data on clean energy and fossil-fuel sources for all countries.

2.3 | Survey of literature on energy RD&D investments

Government RD&D investments are a key input for energy innovation and thus contribute to the outputs and outcomes of energy innovation. Public investment in RD&D does not immediately produce new or improved technologies. A lag of up to 10 years exists between initial funding and new clean energy academic publications, and more than a decade persists between publication of such articles and the filing of new technology patents (Popp, 2016). Public energy RD&D generates large knowledge spillovers (Dechezlepretre et al., 2013; Noailly & Shestalova, 2017; Popp & Newell, 2012). Peters et al. (2012) argue that it incentivizes domestic innovation but has little spillover effect on foreign innovation, while market-formation policies can influence both. The institutional framework of RD&D institutions also matters (Anadón, 2012).

In the private sector, RD&D spending in the traditional fossil fuel industry reveals a consistently low level of expenditure. Many traditional private energy sector firms still concentrate their RD&D on traditional technologies, broadly reinforcing the existing fossil fuel dominated energy paradigm (Rhodes et al., 2014; Turk, 2017), although recently a few have pivoted to more substantial spending in low-carbon innovation (Shojaeddini et al., 2019). Wiesenthal et al. (2012) show that corporate RD&D investments dominate nonnuclear low-carbon energy research in the European Union (EU). Silicon Valley and Chinese technology giants have also recently entered the field with large new expenditures in battery technology, blockchain, smart metering, energy efficiency software, and artificial intelligence applications for data analytics and automation.

Besides environment externalities and knowledge spillovers that undermine the willingness of private sector in energy RD&D, other factors shape firm-level innovation, including energy liberalization (Jamasb & Pollitt, 2015), energy prices, and the size of energy firms (Noailly & Smeets, 2015).

Public institutions, policies, and financial resources focus on energy-supply technologies more than energy efficiency technologies (Wilson et al., 2012). Some have argued for more allocations to emerging clean energy technologies to avoid "technological lock-in" in the existing single dominant technological design that has emerged in the solar, wind and energy storage technology fields (Sivaram et al., 2018). Public funds could also be channeled into "social technology" (Jamasb & Pollitt, 2015) to improve governance and payment arrangements, the use of information from smart grids/meters, and policy making itself in the face of rising complexity.

One potential concern is that sudden increases in energy RD&D funding might surpass the capacity of research institutes and create efficiency loss per dollar spent but there is no evidence yet (Jamasb & Pollitt, 2015; Popp, 2016).

3 | METHODOLOGY AND DATA COLLECTION

To analyze government efforts to support low-carbon energy innovation, we utilize data collected by the IEA and MI directly from governments and supplement it with data from individual government websites, official government reports, and national science and technology statistical databases. We cleaned the data to create a unified database with consistent definitions, currency conversions, fuel types, and technologies. We supplemented these data with case studies, as described below.

3.1 | Public energy RD&D investments database

Our energy RD&D database covers all member countries of the IEA, plus other major emerging economy countries, and all nations that are signatories of the MI initiative. Because of the size of their energy sectors, we also include Russia and South Africa even though neither is an IEA or MI member. Based on IEA's energy categories, we distinguish nine energy technological categories, including fossil fuels, carbon capture, utilization, and storage (CCUS), nuclear, renewable energy, energy efficiency, hydrogen and fuel cells, other power and storage technologies, cross-cutting technologies (including basic energy research),[1] and unallocated. We crosschecked values and endeavored to fill any gaps (missing years and energy categories) based on various data sources.

We established consistent scientific classification for "clean energy." For the purposes of this paper, we classify CCUS, energy efficiency, renewable energy, hydrogen and fuel cells, other power and energy storage as "clean energy" (Box 1). Other power and energy storage includes electric power conversion, electricity transmission and distribution, and energy storage. Nuclear is reported separately from "clean energy." Nonfossil energy refers to "clean energy" plus nuclear energy. Cross-cutting technologies include basic energy sciences and energy systems analysis and may also include clean energy technologies, but the reporting is inconsistent on a cross-country basis. We use "government" energy RD&D and "public" energy RD&D interchangeably to refer to non-SOE government investments. RD&D by SOEs are reported separately and included in public energy RD&D totals only where specified.

Finally, we use "government spending" and "government investments" interchangeably. We use budget spending/investments when it refers to planned spending by government rather than actual spending. This is important as the data from IEA and MI are budget spending while most of national governments (except India) disclose actual RD&D spending on energy technologies. Only when we aggregate spending number on the global level, we ignore the difference between budget spending versus actual spending. Meanwhile, IEA database includes demonstration while most of non-IEA major economies do not. These underlying data inconsistencies could be one of the data limitations of this study. To ensure precision, we clarify the details of data (e.g., budget spending versus actual spending, including demonstration or not) in the data sources and text.

More detail regarding the data and a snapshot of government energy RD&D in 2018 and energy RD&D by SOEs in 2015 are in Appendix A.

3.2 | Country cases

Seven countries are selected to enable an analysis of their recent RD&D efforts and the major market, policy, and institutional forces that drive trends energy RD&D. These countries are the United States, Germany, Japan, China, India, Mexico, and South Africa. These countries are the largest RD&D investors globally or on their continent. For instance, the United States, China, India, Germany, and Japan are the largest energy RD&D investors globally but Mexico and South Africa are the top energy RD&D investors, respectively, in Latin Mexico and Africa. The seven countries accounted for 57% of global CO_2 emissions[2] in 2014 and 73% of global government energy RD&D spending in 2018.

4 | TRENDS IN GLOBAL PUBLIC ENERGY RD&D INVESTMENTS

4.1 | The landscape of global public energy RD&D investments

Global government energy RD&D spending increased by 138% between 2000 and 2018 (Figure 1), reflecting increasing attention to national security, global competitiveness, and rising environmental and climate concerns. Total government energy RD&D received an extraordinary boost during the financial crisis in 2009 as several governments, including the United States and China, included energy and climate-related RD&D in their stimulus programs. Expenditure then plateaued until 2015 when MI was formed in the context of the global climate change agreement reached in Paris. From 2016 to 2018, government energy RD&D regained momentum and by 2018 nonfossil energy RD&D reached US$19 billion, 1.3 times the 2008 level.

The global public energy RD&D portfolio is decarbonizing. Global public clean energy RD&D in 2018 reached $US12 billion, around 44% of the total. The proportion of public fossil fuel RD&D investments in total peaked in 2009, dropping from 18% in 2009 to only 6% in 2018. The share of nuclear energy RD&D spending decreased to 25% in 2019 compared with 34% in 2008. Both energy efficiency and renewable energy grew to account for 34% of total government energy RD&D in 2018, higher than the share of either fossil fuels or nuclear energy.

The geographical composition of public RD&D investments is also shifting as shown in Figure 2. China has surpassed Japan to become the second largest government RD&D investor. India has surpassed France and Germany to become the third largest investor. In 2018, the Chinese and Indian governments spent US$ 2.8 billion and US$ 2.6 billion in nonfossil fuel energy RD&D, respectively. In clean energy, China surpassed US levels of public investment in 2017 (Figure 2b), not including cross-cutting technologies, which may include clean energy (but are not reported consistently across both countries). If we examine nonfossil fuel energy (clean energy plus nuclear) (Figure 2c), India surpassed Japan in 2015, and now is the third largest investor. It should be noted here that both China's and India's government data do not include demonstration spending. Meanwhile, China's government data are actual spending, while the numbers of the United States, Germany, France, Japan, and India are budget spending.

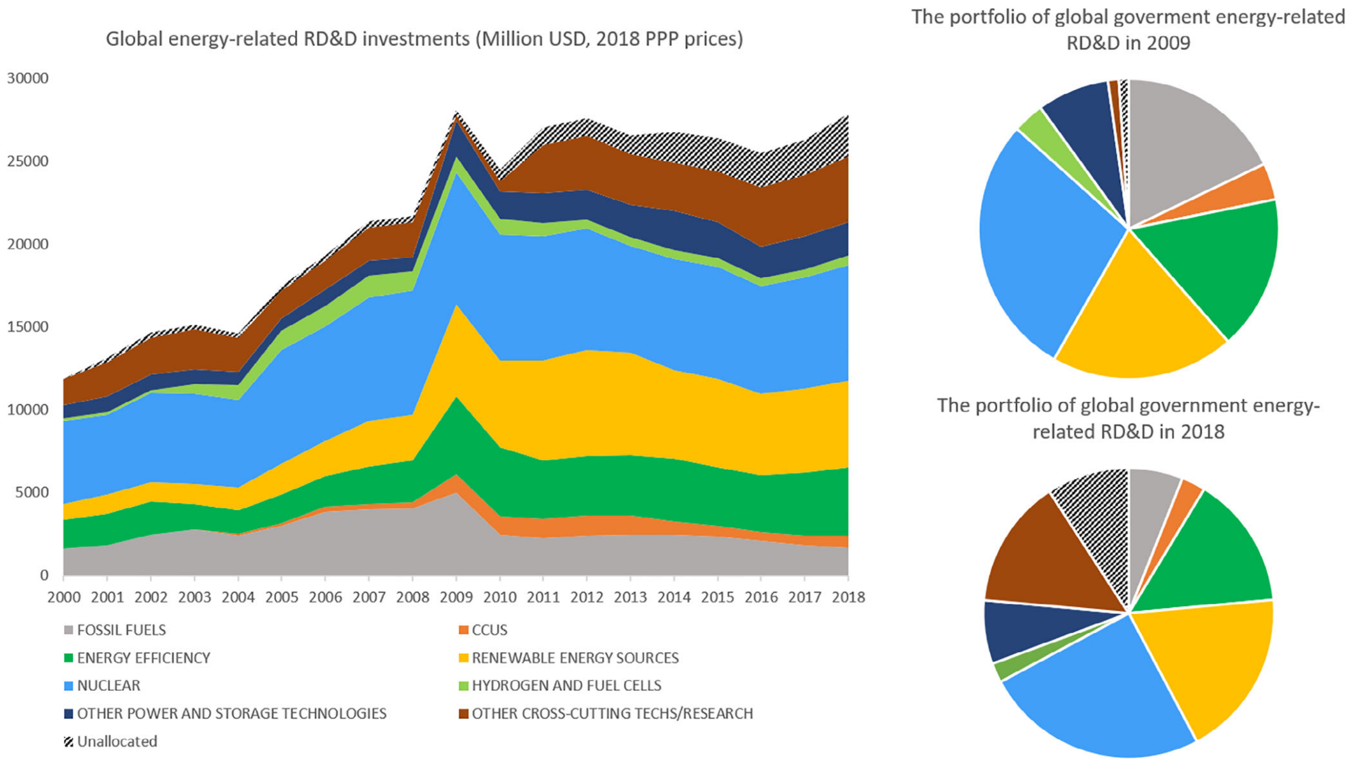

FIGURE 1 Global government energy research, development, and demonstration (RD&D) investments. *Source*: (1) International Energy Agency (IEA) countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation (MI) Country Highlights (fifth MI ministerial 2020). Specifically, China's data are spending data from China Statistical Yearbook on Science and Technology and Bloomberg New Energy Finance (BNEF). India's data are budget spending from annual reports of ministries (such as Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES), Ministry of Coal (MoC), and Department of Atomic Energy) available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). South Africa data are expenditures by government subsidiaries South African National Energy Development Institute (SANEDI) and South African Nuclear Energy Corporation (NECSA). All the data of China, India, Mexico, Brazil, and South Africa do not include demonstration

The United States and China are competing for first place in clean energy government (non-SOE) RD&D whether or not nuclear is included (Figure 2d). China edges the United States out for nonnuclear clean energy. If nuclear is included in "clean," the United States edges China out. "Cross-cutting" technologies could change the clean energy picture considerably because this category may include clean energy, but the two countries do not provide consistent and detailed breakdowns so comparisons are not possible. The United States includes "smart grid" in cross-cutting, for example.

Including the energy RD&D spending of SOEs completely changes the balance of total spending patterns (Figure 3). SOEs are defined as those enterprises that are fully owned by a federal or national government. SOEs from Brazil, Russia, India, Mexico, China, and South Africa spent US$17 billion in energy R&D in 2015. These numbers do not include deployment spending. These numbers do not include demonstration spending in most country cases except in Russia. If these data are included in total national tallies, overall total public energy RD&D spending increases to $US43 billion in 2015. Moreover, inclusion of SOE spending data in global public energy RD&D tallies strongly tilts the

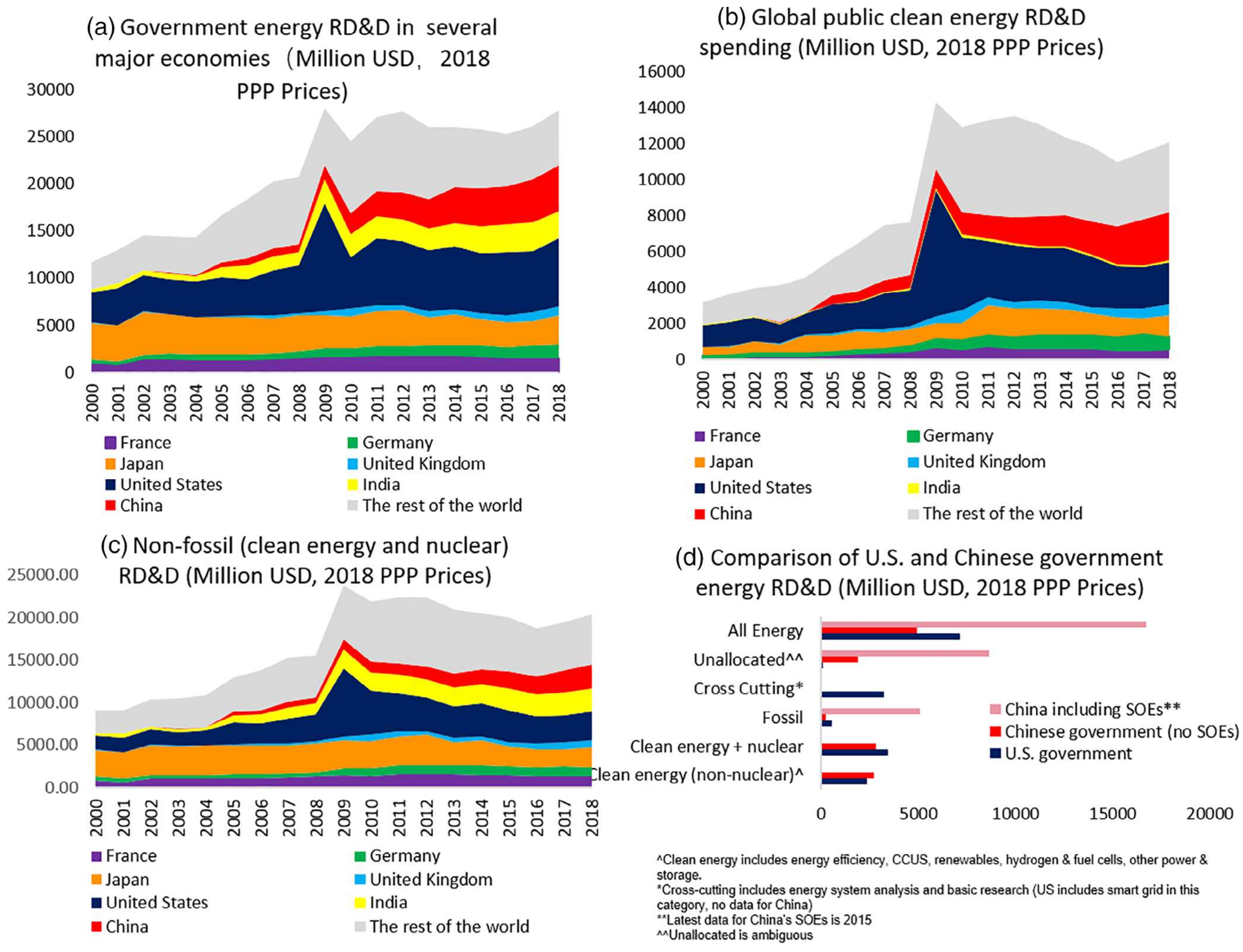

FIGURE 2 Government energy and clean energy research, development, and demonstration (RD&D) in major economies. *Source*: (1) International Energy Agency (IEA) countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation (MI) Country Highlights (fifth MI ministerial 2020). Specifically, China's data are spending data from China Statistical Yearbook on Science and Technology and Bloomberg New Energy Finance (BNEF). India's data are budget spending from annual reports of ministries (such as Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES), Ministry of Coal (MoC) and Department of Atomic Energy) available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). South Africa data are expenditures by government subsidiaries South African National Energy Development Institute (SANEDI) and South African Nuclear Energy Corporation (NECSA). All the data of China, India, Mexico, Brazil, and South Africa do not include demonstration

balance of RD&D world spending toward nuclear and fossil fuels. SOE spending in China and India is substantial, and if included, renders China as the largest total public investor in the energy sector and India the third largest total public investor in the energy sector. One caveat is that SOE RD&D spending is often self-reported and unverified by third parties. In some cases, it is possible that firms may report higher numbers than actual especially if they are pressured by governments to increase their RD&D budgets.

4.2 | Energy RD&D investments

4.2.1 | Fossil fuel and CCUS

Growth in global fossil-fuel government RD&D spending was volatile between 2000 and 2018 (Figure 4). Forty percentage of IEA country fossil fuel government RD&D went to support CCUS in 2018. Excluding CCUS spending from the fossil fuel RD&D investments more clearly reveals a downward trend in the level of global government fossil fuel RD&D, especially since 2009. As of 2018, global non-CCUS fossil energy government RD&D investments had declined to levels last seen in the early 2000s. Two potential explanations for the decline in non-CCUS fossil investments after 2009 are that the transition in 2009 from the Republican George W. Bush administration to the Democratic Barack Obama Administration resulted in a

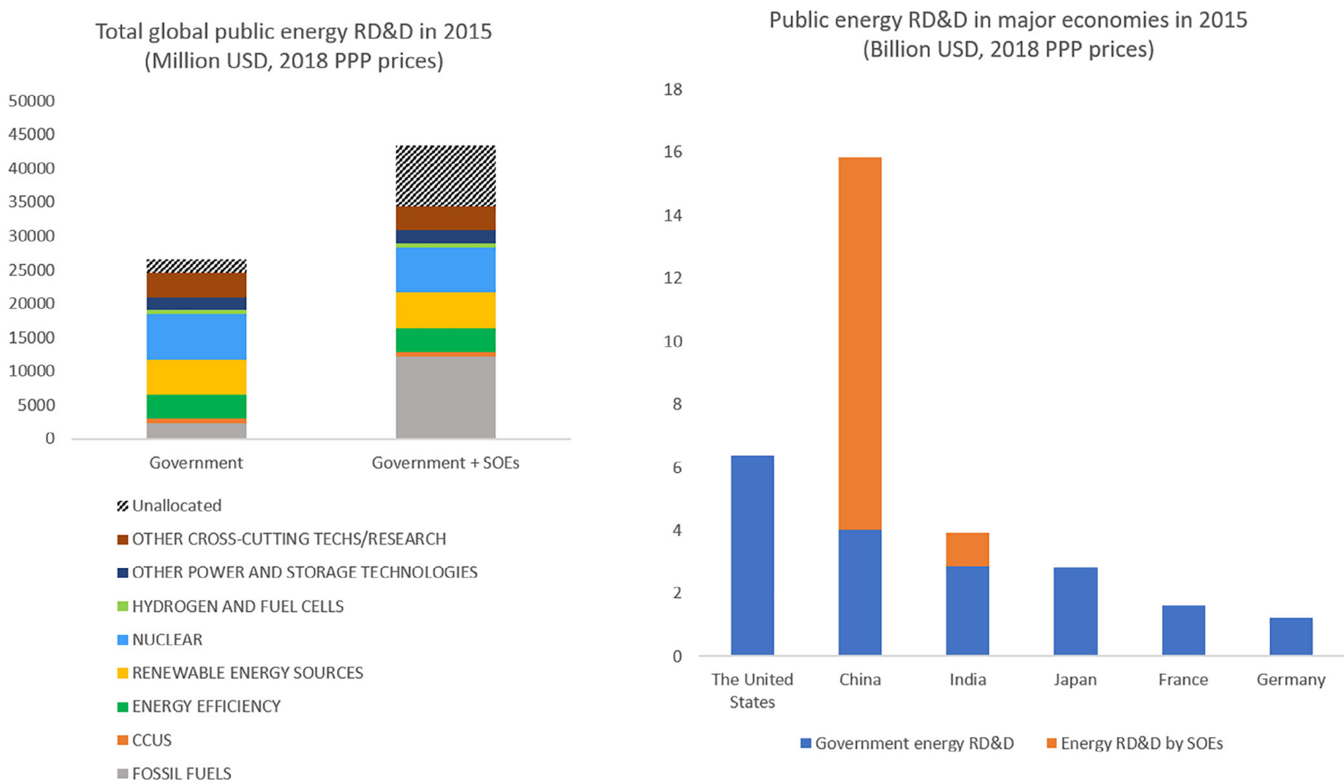

FIGURE 3 Changes in global energy research, development, and demonstration (RD&D) spending after including state-owned enterprises (SOEs). *Source*: The source and notes of government RD&D are the same as Figure 1. Data source of SOEs' RD&D are as follows: (1) China's data are from China Statistical Yearbook on Science and Technology Activities of Industrial Enterprises. (2) India's data are from annual reports of 100% SOEs (including National Hydroelectric Power Corporation (NHPC), National Thermal Power Corporation (NTPC), the Oil Industry Development Board (OIDB), as well as R&D budgets of 100% government owned petroleum companies in India) and partially SOEs, the loans for R&D activities to partially SOEs through OIDB. (3) Mexico's data are from the National Council of Science and Technology (CONACYT) annual reports; (4) Brazil's data are from annual reports of Eletrobras and Petrobras; (5) South Africa's data are from annual reports of Eskom and Sasol. Sasol is included as its major shareholder is the government employee pension fund. (6) Russia's data are from annual reports of state-owned oil, power, and transmission companies, including Gasprom, Bashneft, Lukoil, Russneft, Slavneft, THK-BP, Surgutneftegas, Irkustk, Rosneft, Tatneft, Rosseti, Rosatom. The SOE's R&D data in India are budget spending and all the others are actual spending. All the national data do not include or explicitly include demonstration, except in Russia case

dramatic increase in clean energy RD&D in the United States. Moreover, the 2009 international climate negotiations in Copenhagen caused many countries to consider how to align their innovation policies with a low-carbon future.

The jump in government fossil fuel RD&D in 2009 was mainly driven by the United States but included other large economies as well. All of the largest government investors in fossil fuel RD&D are those abundant in fossil resources (China, India, the United States, Canada, and Mexico). The main investors in CCUS included resource-rich Organisation for Economic Co-operation and Development (OECD) countries including the United States, Canada, and Norway and large energy consumers whose consumption still relies heavy on fossil fuels including Germany and Japan. China and India have large remaining coal reserves and the share of coal in power generation remains higher than 60% (64% in China and 73% in India in 2019) (BP, 2020). For these countries, investing in CCUS could permit carbon mitigation without having to reduce reliance on coal if the cost of CCUS is reduced and geological sequestration is available.

4.2.2 | Nuclear energy technologies

Global public nuclear energy RD&D investments steadily increased in the 2000s, then dropped in the aftermath of the Fukushima nuclear accident in 2011 (Figure 5) by almost US$1.1 billion from 2011 to 2013. India, Japan, the United States, France, and the United Kingdom are the top five nuclear RD&D investors.

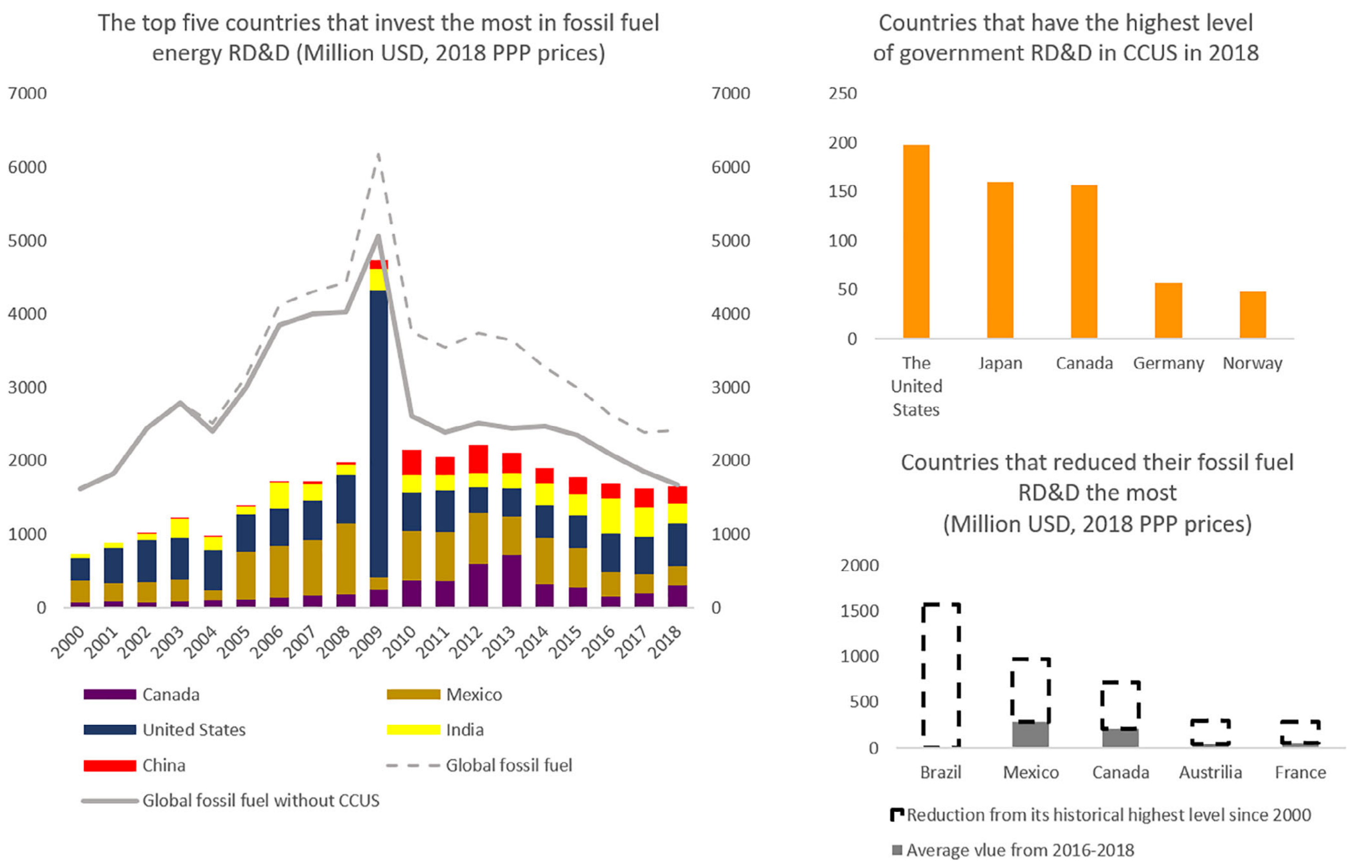

FIGURE 4 Global government fossil fuel energy research, development, and demonstration (RD&D) investments. *Source*: (1) International Energy Agency (IEA) countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation (MI) Country Highlights (fifth MI ministerial 2020). Specifically, China's data are spending data from China Statistical Yearbook on Science and Technology. India's data are budget spending from annual reports of ministries (such as Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES), and Ministry of Coal (MoC)) available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). All the data of China, India, Mexico, and Brazil do not include demonstration

India, China, and the United Kingdom have increased government nuclear RD&D spending in recent years. The Indian government now boasts the largest government expenditure for nuclear RD&D in the world at US$2.6 billion in 2018. United Kingdom and China also substantially increased their government nuclear RD&D, respectively, from US $66 million in 2008 to US$291 million in 2018 and from US$7.4 to US$85 million in 2018.

4.2.3 | Renewable energy and energy efficiency technologies

Since 2012, government renewable RD&D spending has leveled off to about US$5 billion per year, five times the level of government renewable energy RD&D spending in the early 2000s (Figure 6). The top five countries in renewable energy RD&D are China, the United States, Japan, Germany, and France. China surpassed the United States as the largest public contributor to renewable energy RD&D in 2013.

Governments substantially increased their investments in energy efficiency RD&D in the late 2010s when oil prices were rising, but then spending leveled off. The United States was by far the largest investor in energy efficiency RD&D in 2018. Data on energy efficiency RD&D government spending in China, India, and Russia are incomplete. Despite a big increase in total RD&D in 2010s, energy efficiency is still a small portion of government RD&D spending compared to supply-side energy technologies.

4.2.4 | Other energy technologies

Government RD&D investment in hydrogen and fuel cells has experienced a dramatic boom and bust cycle over the last two decades (Figure 7). The greatest interest in hydrogen and fuel cells comes from Japan, the United States, Germany,

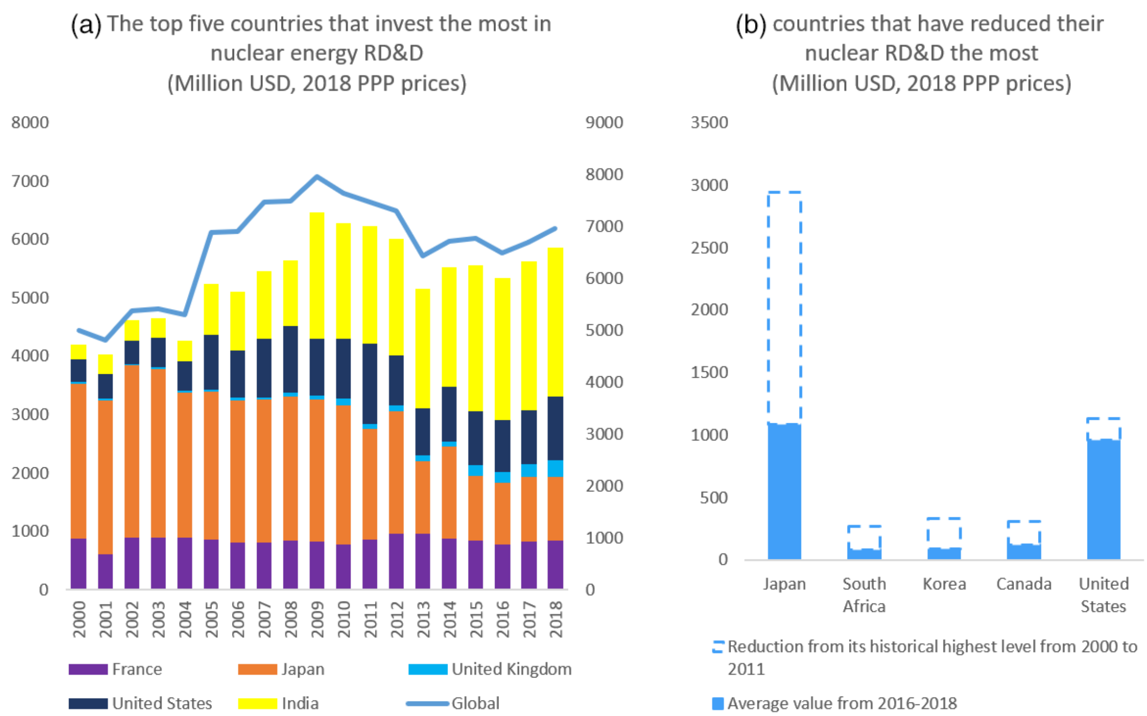

FIGURE 5 Global government nuclear energy research, development, and demonstration (RD&D) investments. *Source*: (1) International Energy Agency (IEA) countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation (MI) Country Highlights (fifth MI ministerial 2020). Specifically, China's data are spending data from China Statistical Yearbook on Science and Technology. India's data are budget spending from annual reports of Department of Atomic Energy available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). South Africa data are expenditures by South African Nuclear Energy Corporation (NECSA). All the data of China, India, Mexico, Brazil, and South Africa do not include demonstration

South Korea, and France. Government spending power and storage technologies accelerated during the 2000s and reached US$2 billion in 2018. After early dominance in the sector, the United States is no longer in the top five government investors in power and storage technologies. China is now the largest RD&D investor, followed by Japan, Germany, South Korea, and the United Kingdom.

During the 2009 financial crisis, there was a sharp cut in government RD&D in cross-cutting energy technologies. Notably, 81% of basic research spending comes from the United States.

4.2.5 | Unallocated energy RD&D

Around $2.6 billion spent by governments is reported as unallocated and it is obviously difficult to determine how these dollars are spent. A large portion of global unallocated spending comes from China. The unallocated energy R&D in China includes petroleum, coking, nuclear fuels processes, manufacture of electrical machinery and equipment, and basic energy R&D through institutions of higher education. It is unclear what is included in unallocated energy RD&D in most other countries.

5 | TRENDS IN MAJOR COUNTRY CASES AND DRIVERS BEHIND THEM

National priorities for energy innovation diverge substantially, influenced by energy resource endowments, costs, markets, technical capabilities, and energy and climate policy policies. The dominant presence of SOEs in most major emerging economies skews RD&D toward fossil and nuclear in those countries while aggressive national policy frameworks for renewable energy deployment is correlated with greater RD&D allocations to renewables.

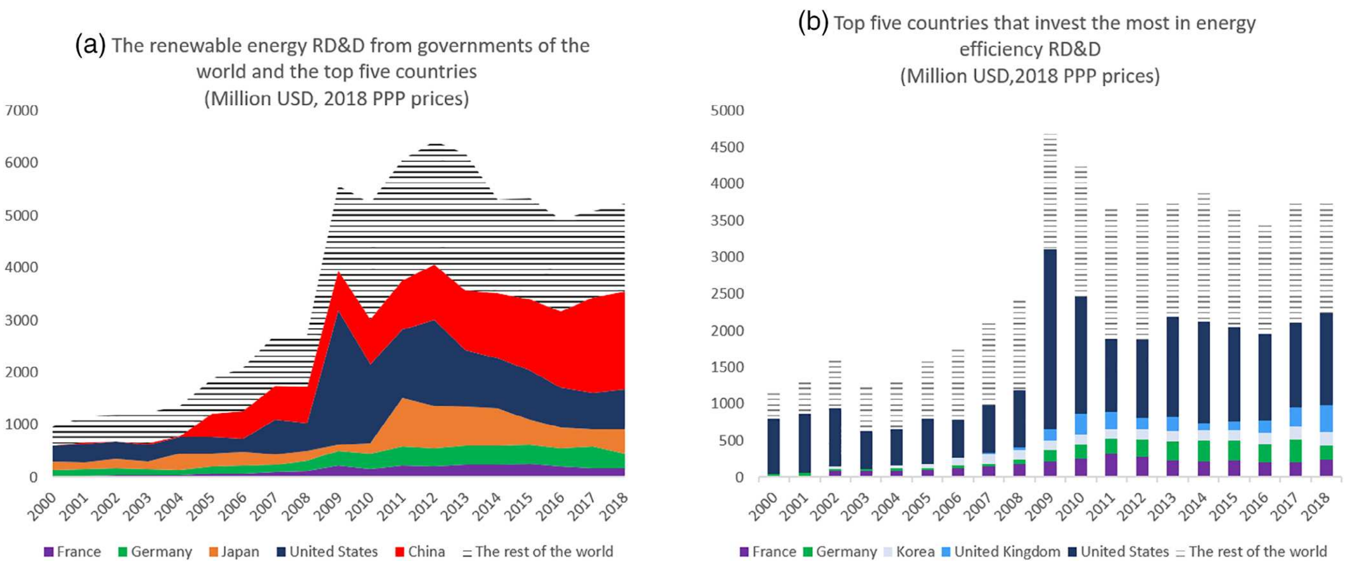

FIGURE 6 Global government renewable energy and energy efficiency research, development, and demonstration (RD&D) investments. *Source*: (1) International Energy Agency (IEA) countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation (MI) Country Highlights (fifth MI ministerial 2020). Specifically, China's renewable energy R&D data are spending data from Bloomberg New Energy Finance database (BNEF). India's data are budget spending from annual reports of ministries (such as Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES)) available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). South Africa data are expenditures by South African National Energy Development Institute (SANEDI). All the data of China, India, Mexico, Brazil, and South Africa do not include demonstration

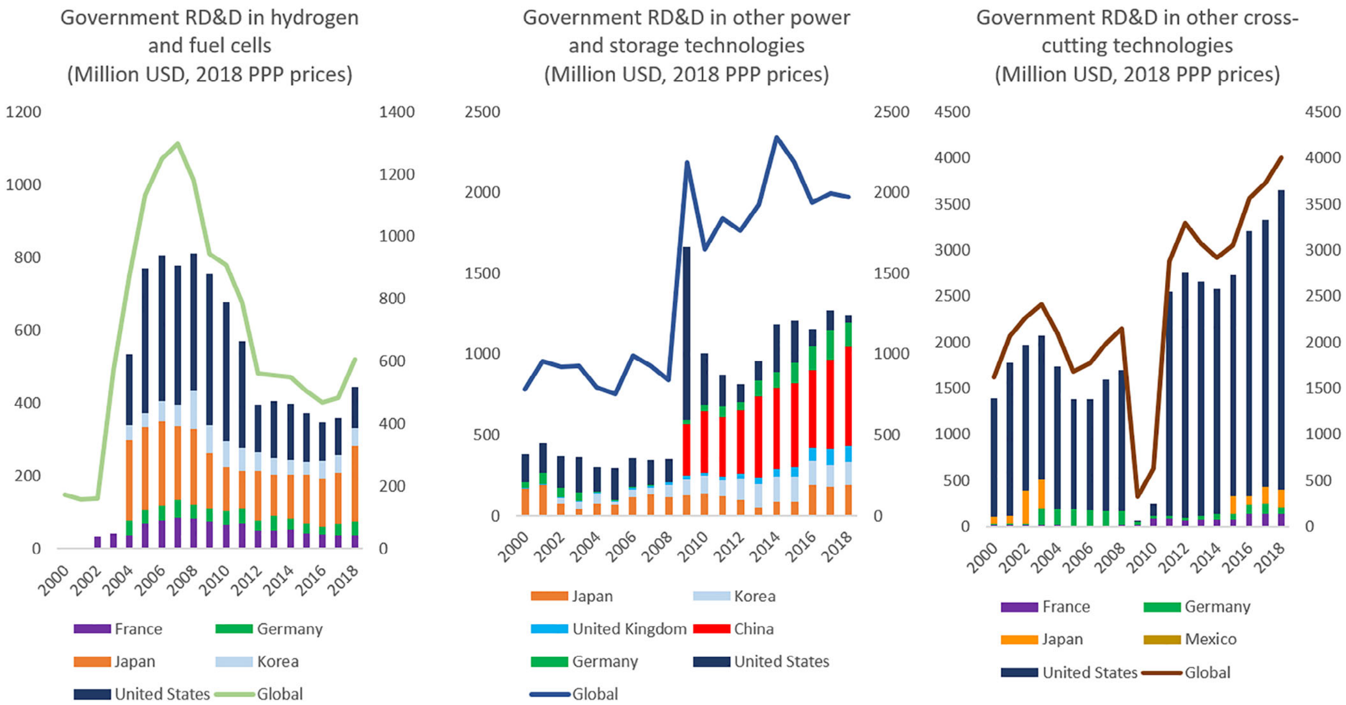

FIGURE 7 Global government research, development, and demonstration (RD&D) in other energy technologies. *Source*: (1) International Energy Agency (IEA) countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation (MI) Country Highlights (fifth MI ministerial 2020). Specifically, China's data are spending data from China Statistical Yearbook on Science and Technology. India's data are budget spending from annual reports of ministries (such as Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES), Ministry of Coal (MoC), and Department of Atomic Energy) available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). South Africa data are expenditures by government subsidiaries South African National Energy Development Institute (SANEDI) and South African Nuclear Energy Corporation (NECSA). All the data of China, India, Mexico, Brazil, and South Africa do not include demonstration

In emerging markets, the political driver to reduce import dependence motivates nonfossil energy RD&D investments. In Europe, political support for climate action is strong supports greater RD&D allocations to clean energy.

5.1 | The United States

When President Trump was elected, many observers expected that the US energy innovation effort would stall due to his lack of support for science, and clean energy specifically. The Trump Administration consistently proposed unprecedented cuts to clean energy RD&D budget, including in financial year 2021, an 81% cut to RD&D for vehicle efficiency, 76% cut to solar, 78% cut to wind, and complete elimination of the Advanced Research Projects Agency-Energy (Gallagher & Anadon, 2020). The US Congress resisted this policy shift, however, and continued to appropriate funds for clean energy RD&D at or above Obama Administration levels in every area except fusion (Figure 8). The only area where the Trump Administration increased energy RD&D was in "advanced energy systems" for coal, which does not include CCUS (DOE, 2020).

Besides political forces, the energy RD&D trends have been influenced by changes in the U.S. energy market. After 2010, wind and solar accounted for more than half of new generating capacity additions and in 2019, US renewable energy consumption surpassed coal consumption for the first time in 130 years (EIA, 2020). For new plants entering service in 2025, onshore wind and solar PV are forecasted to be cheaper than natural gas combined cycle plants even without a tax credit (EIA, 2020). On the demand side, US energy consumption plateaued after 2000 and in 2019, US energy production exceeded consumption for the first time in 62 years (EIA, 2020). Energy efficiency now serves as a vital means for the United States to decarbonize its energy system.

5.2 | Germany

The German government tripled its government energy RD&D budget between 2000 to 2018 with priority given to renewables, energy efficiency, and storage (Figure 9). These budget investments are forecast to continue increase as the Federal Cabinet plans another US$7.58 billion[3] (EUR 6.4 billion) for energy technologies for 2018–2022, which amounts to a 45% increase in funding from the previous period (2013–2017) (Federal Ministry for Economic Affairs and Energy [BMWi], 2018).

Germany's energy RD&D budget reflects the energy transition (or "Energiewende") strategy and domestic climate policies. The federal government aims to increase the share of renewable energy to 65% of gross electricity consumption by 2030, and at least 80% by 2050. Meanwhile, Germany also plans to phase-out nuclear power by 2022, and then end coal-fired power generation by 2038. Government RD&D in fossil fuel is minimal, whereas renewables and energy efficiency account for the majority in 2018. Nuclear energy RD&D still comprises 20% of Germany's government RD&D portfolio, mainly to support nuclear safety, waste disposal and basic science research (IAEA, 2019).

By 2019, renewable energy accounted for 43% of gross electricity consumption. As renewable integration increases in Germany, energy RD&D is shifting from renewable RD&D to systemic integration approaches to the energy transition (BMWi, 2018). Accordingly, other power technologies, storage technologies, and other-cross-cutting technologies have increased and in total accounted for 16% of Germany government energy RD&D.

5.3 | Japan

The composition of Japan's energy supply changed dramatically between 2010 and 2020 (Figure 10). Nuclear power generation steeply dropped between 2010 and 2013, falling from 292.4 TWh in 2010 to 4.5 TWh in 2015 after the 2011

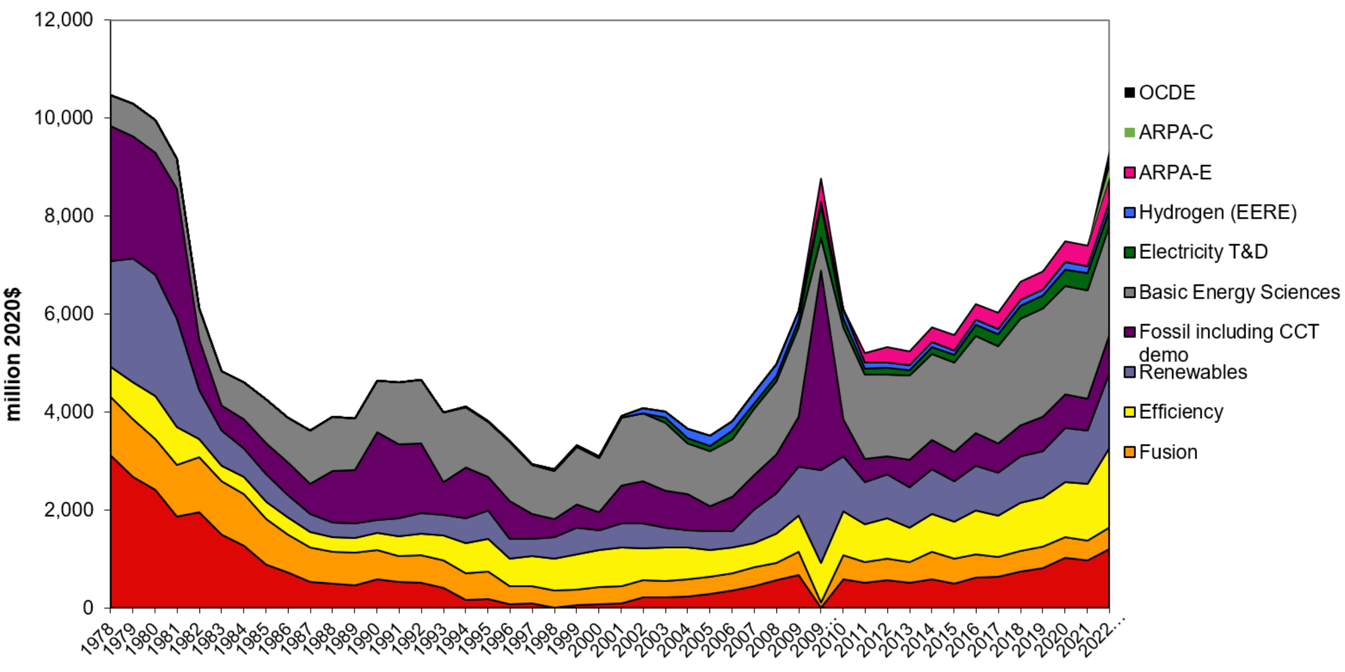

FIGURE 8 Government energy research, development, and demonstration (RD&D) spending in the United States. *Source*: The data are from Gallagher and Anadon (2020); The Fletcher School, Tufts University; Department of Land Economy, University of Cambridge; and Belfer Center for Science and International Affairs, Harvard Kennedy School; July 3, 2020. The data are budget spending data and include demonstration

Fukushima nuclear accident, rising again to 65.6 TwH in 2019 (BP, 2020). Natural gas and coal filled the gap left by the decline in nuclear power. Japan's policies are guided by the 3E + S principles (energy security, economic efficiency, environment, and safety) and have shaped the government's approach to energy RD&D (Government of Japan, 2018).

Japan's RD&D budget for nuclear power in 2018 reflects a reassessment by the government of its energy mix. RD&D budget for nuclear power sharply declined to US$1.1 billion in 2015, thereafter holding steady. On nuclear fusion, Japan has formulated a policy to promote Demonstration of Fusion Reactor design and a roadmap in 2018.

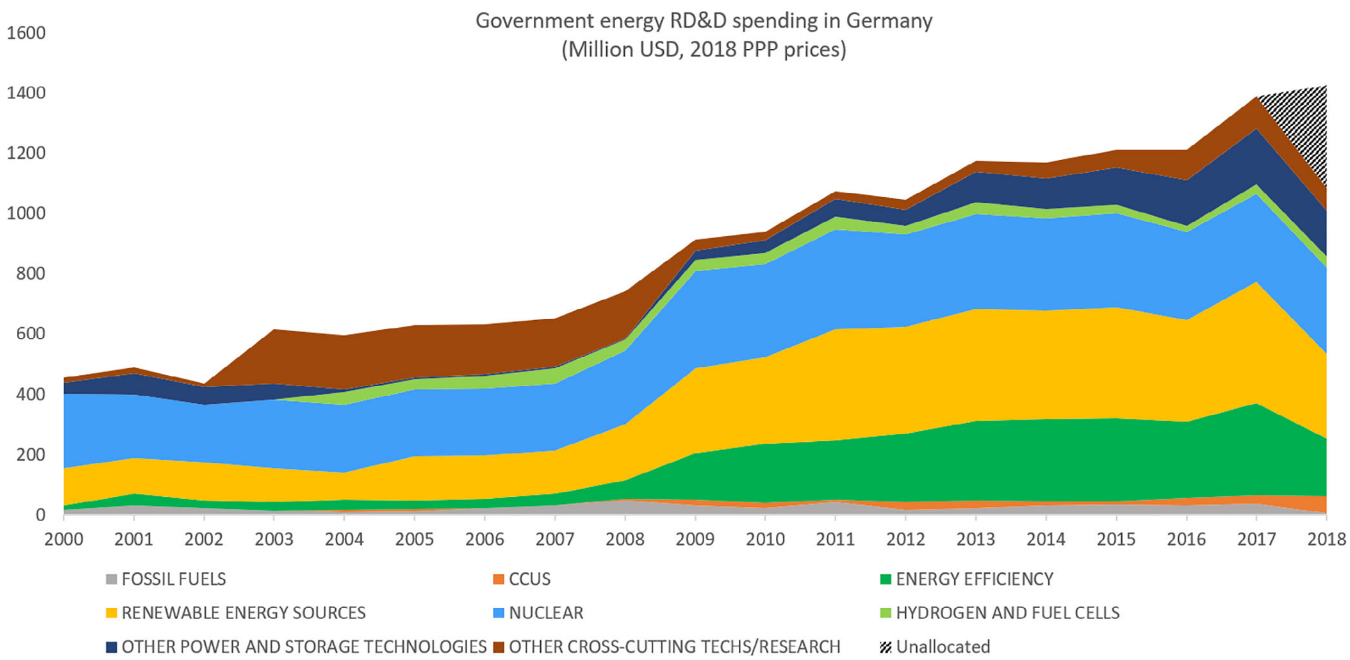

FIGURE 9 Government energy research, development, and demonstration (RD&D) spending in Germany. *Source*: The data are from International Energy Agency (IEA) Energy Technology RD&D Budget Database. They are budget spending and include demonstration

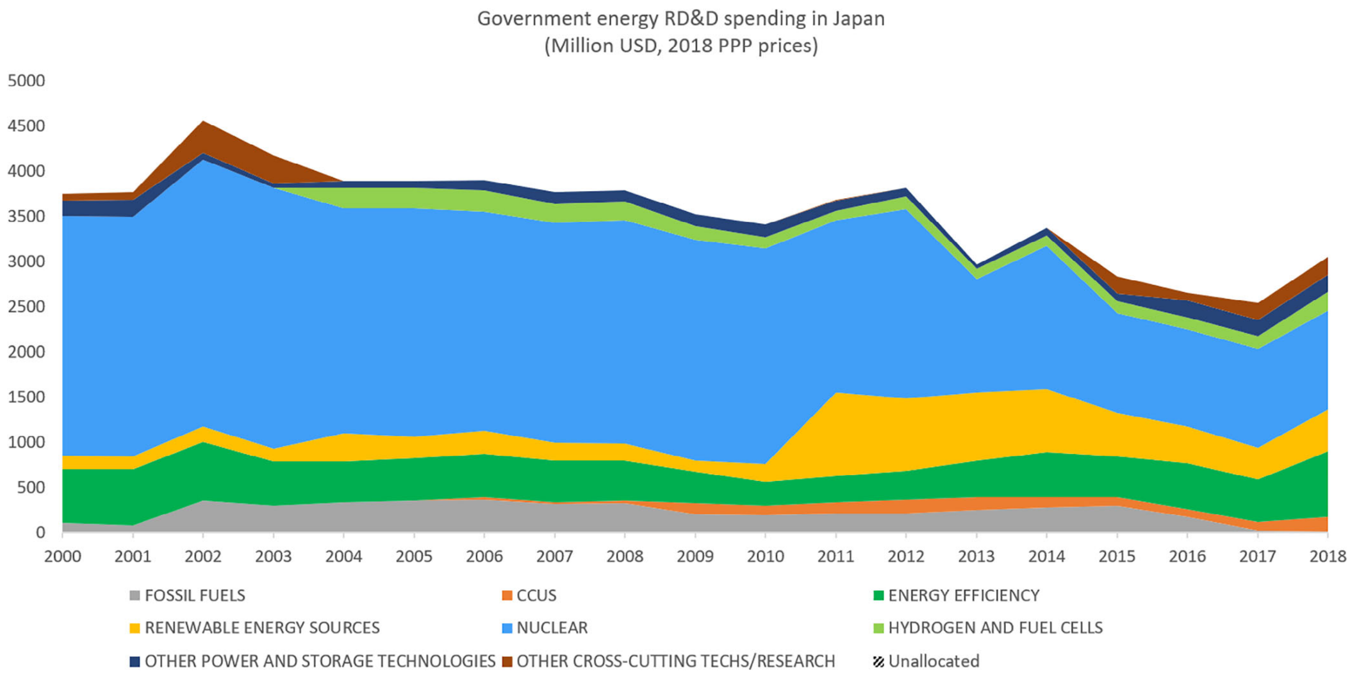

FIGURE 10 Government energy research, development, and demonstration (RD&D) spending in Japan. *Source*: The data are from International Energy Agency (IEA) Energy Technology RD&D Budget Database. They are budget spending and include demonstration

Japan's RD&D priorities for renewables are increasingly focused on energy efficiency, hydrogen, and offshore wind. Japan's RD&D budget spending in energy efficiency roughly tripled between 2010 and 2018. The offshore wind RD&D focus has been on lowering the cost of fixed bottom offshore wind projects and demonstration for floating installations for offshore wind along the coast of Japan (Government of Japan, 2018). Japan's RD&D budget spending in fossil fuels has focused on developing non-conventional resources (METI, 2017).

5.4 | China

The Chinese government consistently increased its investments in energy R&D since the turn of the century. China's government (non-SOE) energy R&D spending reached US$5 billion in 2018, more than three times the 2009 level (Figure 11a). In 2018, more than one-third of all government energy R&D was allocated to renewable energy. Fossil fuel and nuclear power R&D only account for 7%. In its reporting to MI, China specified that up to US$2.5 billion fossil fuel energy R&D are for "cleaner fossil fuels" (MI, 2019). Fossil fuel energy R&D remains one of the main pillars of China's energy innovation portfolio, however, when SOEs are included in total public R&D figures (Figure 11b).

Although granular data for China's public R&D spending in the energy sector are not available, a closer look into the National Key R&D Program, the most crucial national R&D program in China, is revealing (Table 2). Funding for clean coal and energy-saving technology is 20% more than renewables and hydrogen. Notably, new energy vehicle technologies receive twice as much as any other technology.

China's priorities for expenditure can be explained both by the forces of both path dependency for existing fossil fuel infrastructure and its new national strategy to promote low-carbon energy transition. Historically, China's energy

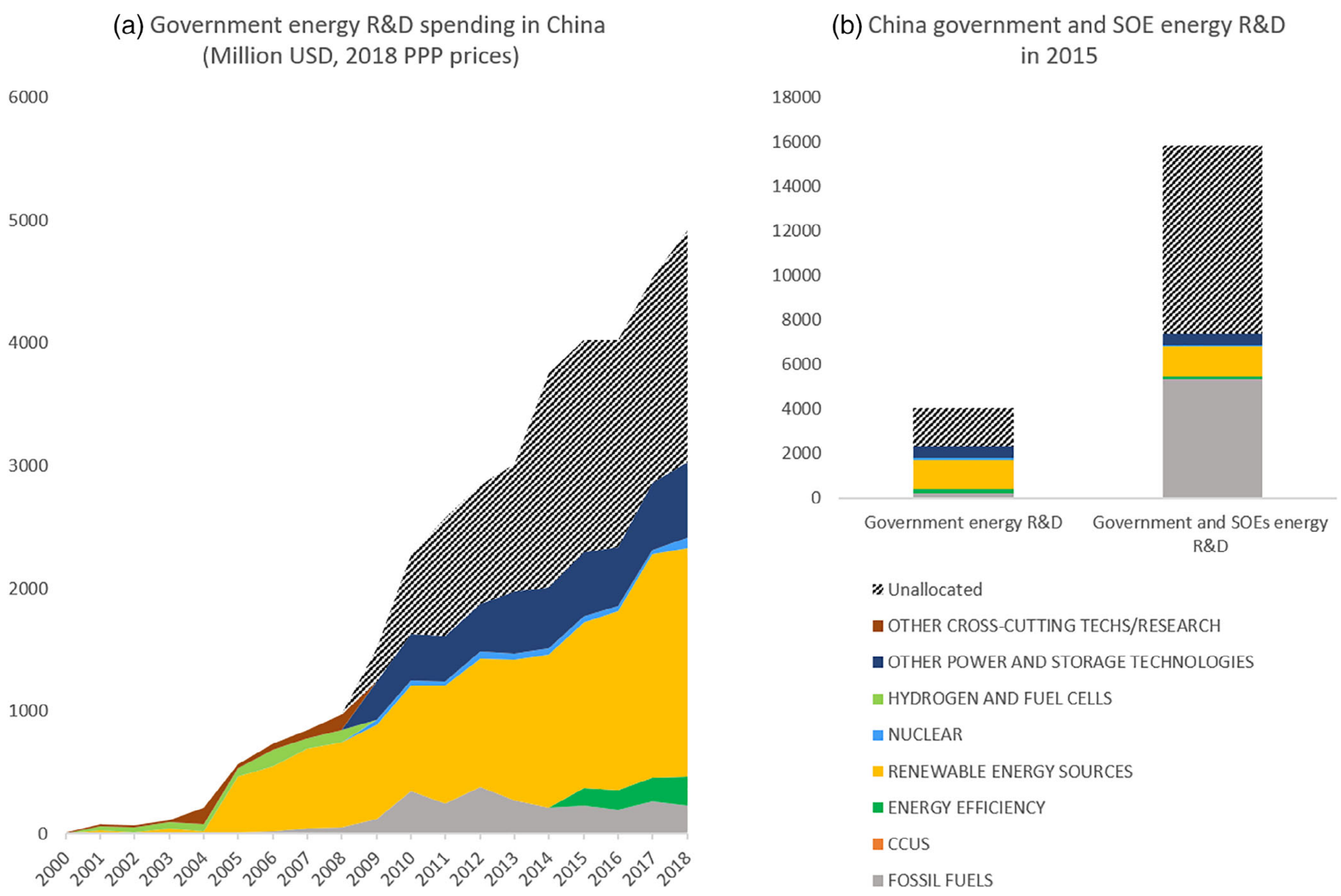

FIGURE 11 Government and state-owned enterprise (SOE) energy research and development (R&D) spending in China. *Source*: Government and SOE R&D data are from China Statistical Yearbook on Science, Technology and China Statistical Yearbook on Science and Technology Activities of Industrial Enterprises and Bloomberg New Energy Finance database. carbon capture, utilization and storage (CCUS) is included in fossil fuels in China. No R&D information on hydrogen and fuel cells and other cross-cutting technologies is provided due to a lack of precise data and the associated difficulty of disentangling them from the unallocated category. The R&D spending in China does not include demonstration spending

TABLE 2 Research and development (R&D) investments in clean energy plus nuclear technologies from the National Key R&D Program of China since 2016

Program	Starting year	Total 5-year funding (million US$)
Clean and high-efficiency utilization of coal and new types of energy-saving technology	2016	360.13
Renewable energy and hydrogen technology	2018	290.87
Nuclear safety and advanced nuclear technology	2018	218.15
Smart grid technology and equipment	2016	288.10
New energy vehicles	2016	720.25
Advanced transportation	2016	360.13
Green building and construction industrialization	2016	360.13

Source: Adapted from data submitted by China representative to the third Mission Innovation ministerial 2018.

system has been highly dependent on coal. Thus, China places a strong emphasis on the R&D investment of "clean coal," which China defines as including coal gasification and highly energy-efficient coal-fired power plants. Coal-related SOEs, particularly central SOEs (e.g., Shenhua and China's five major power generation groups), represent the vested interests of the coal industry and have invested vigorously in clean coal. More recently, however, China has embarked on a fundamental transition of its incumbent energy system to address the multiple challenges of energy security, air pollution, industrial modernization, and climate change. Under its stated new national strategy to build an ecological civilization and to promote a low-carbon energy transition, the Chinese government (not including its SOEs) has invested heavily in a variety of clean energy technologies. Considering China's recent pledge of carbon neutrality by 2060, more resources are likely to be allocated to national strategic emerging industries (e.g., renewable energy, smart grid, new energy vehicle, and green building).

5.5 | India

India's energy R&D budget spending is dominated by nuclear and fossil fuels. Average annual fossil fuel R&D budget spending decreased steadily from 2009 to 2018 but still accounted for 28% of total energy R&D in 2018 (Figure 12). Nuclear energy budget spending increased steadily from 2009 to 2018 (US$2.1 billion to US$2.5 billion). India's continued R&D budget spending in oil and gas exploration and nuclear is driven by the motivation to reduce import dependence and become energy secure (Sharma, 2020). India invests a substantial amount in nuclear energy R&D in terms of the amount of budget spending, thanks to its goal to indigenize its nuclear program. India seeks to indigenize nuclear power plant materials and reactor technology by developing an Advanced Heavy Water Reactor that uses thorium as its main fuel (Banerjee & Gupta, 2017; Mohan, 2016; Vijayan et al., 2017). The government aims to more than triple its current nuclear power capacity to achieve 22.5 GW by 2031(Vishwanathan & Garg, 2020).

India's stricter SO_2, NO_x, and $PM_{2.5}$ emission standards for power plants and policy shifts to favor renewable energy have led to stranded coal assets alongside a significant increase in renewable energy capacity. Renewable energy R&D investments more than doubled in 2010 compared to 2009 (US$124 million vs. US$51 million) but remain relatively tiny in the overall portfolio. Grid-related R&D investments in technologies increased substantially from 2009 to 2015 and then plateaued. India's innovation data analysis could be strengthened further with improved data reporting. For instance, India's recent reporting to MI states that its total R&D spending across all clean energy technologies doubled from 2014 to 2018 to reach US$356 million (US$110 million in nominal terms) (MI, 2018), significantly higher than what this paper reports.

5.6 | Mexico

Mexico initiated a major energy reform in 2013, which sought to partially privatize the country's national oil company (Pemex) and electricity company (CFE) and allow for further participation by the private sector in the country's energy

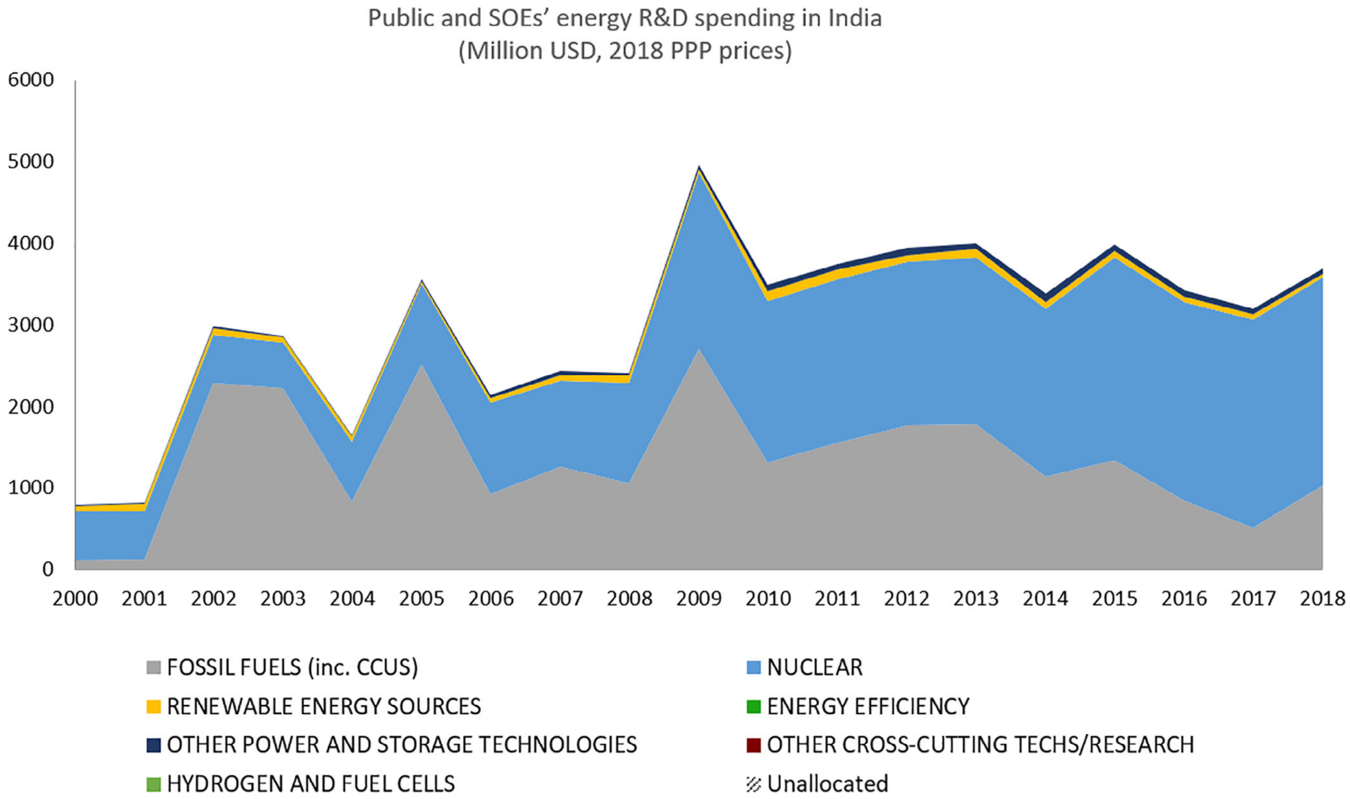

FIGURE 12 Public and state-owned enterprises (SOEs)' energy research and development (R&D) spending in India. *Source*: Government R&D data are from annual reports of ministries (such as Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES), Ministry of Coal (MoC) and Department of Atomic Energy) available through the Union Budget documents. SOE's data are from annual reports of 100% SOEs (including National Hydroelectric Power Corporation (NHPC), National Thermal Power Corporation (NTPC), the Oil Industry Development Board (OIDB), as well as R&D budgets of 100% government owned petroleum companies in India) and partially SOEs, the loans for R&D activities to partially SOEs through the Oil Industry Development Bank. The data do not cover energy related research expenditures of the Center for Scientific and Industrial Research (CSIR), PowerGrid Corporation of India (PGCIL), Department of Biotechnology (DBT)'s biofuels research, development, and demonstration (RD&D) spending, and other smaller RD&D contributors due to lack of availability of consistent data. All the data are budget spending. Demonstration is not included

industry (Lajous, 2014). The Electricity Industry Law in 2014 set a target of 35% of renewable energy generation by 2024. President Andres Manuel Lopez Obrador, elected in 2018, slowed the energy reforms and called for spending to focus on modernizing Mexico's aging refineries in an effort to reduce imports of petroleum products. The government also reversed some of the structural changes of the oil industry established in the energy reform. Notably, President Lopez Obrador signed a moratorium on auctions for oil exploration in 2019 and cancelled the fourth clean energy auction (Gross, 2019). Investment in renewables (RD&D and deployment) has noticeably slowed since 2014.

Mexico's public clean energy R&D spending together with local SOEs' R&D spending has decreased from US$309 million in 2014 to US$152 million in 2017 (Figure 13). This decrease reflects a change in Mexico's internal methodology to calculate the amount of funds dedicated to energy innovation channeled primarily through its energy sustainability fund.[4] This decreasing trajectory differs from what Mexico claimed in its submission to the MI Secretariat, where the reported values are lower (MI, 2019). Mexico's government and SOEs have allocated energy R&D funding predominantly to fossil fuels. Investment in nuclear R&D has been stable over the years—Mexico has one nuclear power plant in Veracruz (Laguna Verde) that generates 4% of total electricity. While fossil fuel technologies remain a priority, the percentage of total public and SOEs' R&D spending on fossil fuel innovation has declined over time to 52% in 2017.

5.7 | South Africa

South Africa has one of the highest emissions' intensity for electricity generation than any other country in the world. Coal-fired electricity constitutes 90% of the generation fleet of South Africa's national electricity monopoly Eskom (Ting &

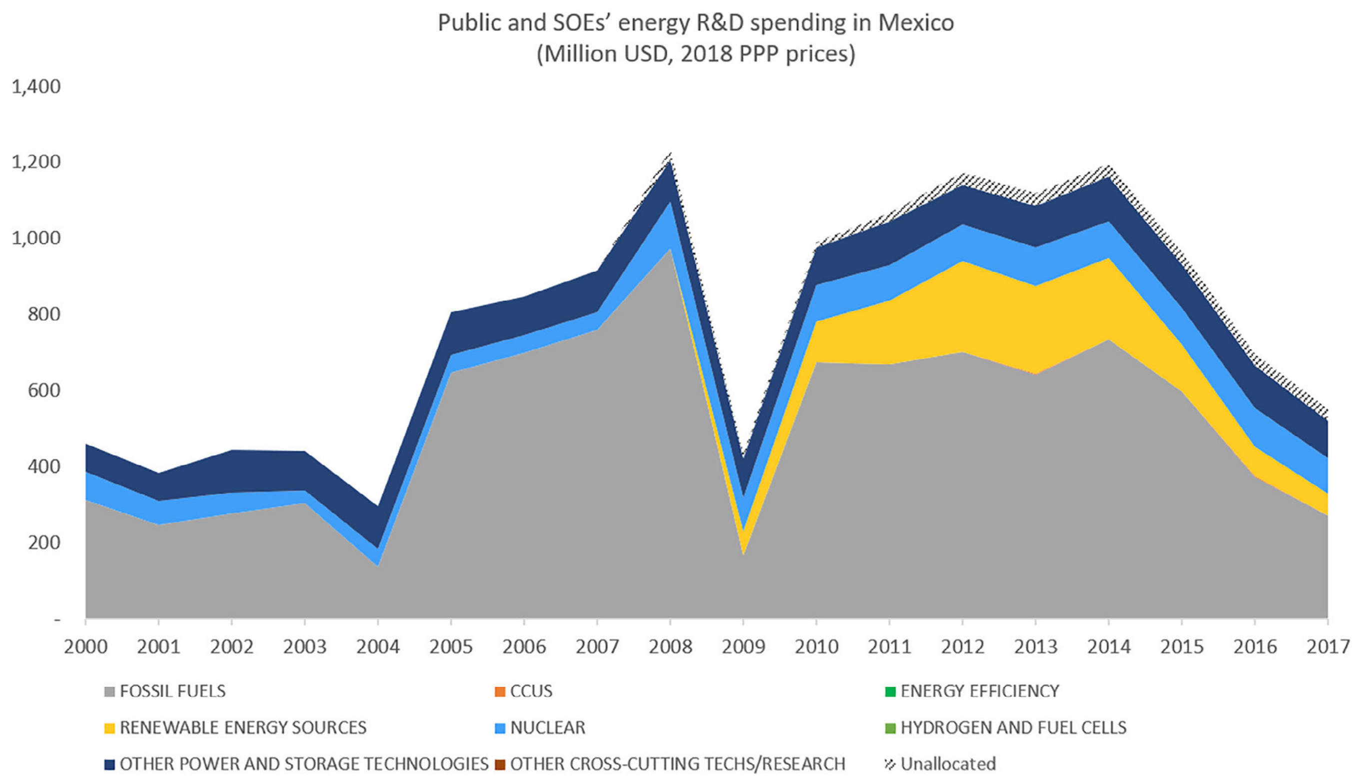

FIGURE 13 Public and state-owned enterprises' (SOEs) energy research and development (R&D) spending in Mexico. *Source*: Government R&D is from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and International Energy Agency (IEA) Energy Technology Research, Development, And Demonstration (RD&D) Budget Database. SOE data are from CONACYT Annual Reports. The data are all spending data and do not include demonstration spending. The year 2017 is the latest available year for public R&D energy investment, based on available reports from CONACYT. The CONACYT report also includes R&D spending in the transportation sector but because it is not clear how much belongs to energy R&D; it is not included in this graph

Byrne, 2020). The Department of Science and Technology (DST)'s identified energy security as one of the five grand challenges for science and innovation in South Africa. The DST's plan required that by 2018, South Africa achieve an energy infrastructure with 80% of capacity addition coming from clean coal and nuclear technologies, 10% of energy from renewables, and a 30% reduction in energy demand through efficiency improvements (Academy of Sciences of South Africa. [ASSAF], 2014). In 2011, South Africa introduced a renewable energy auctions program. Eskom, however, later viewed renewables as a threat and stopped signing power purchase agreements (PPAs) (Ting & Byrne, 2020). The inconsistency of policy signals to the electricity sector has created an uncertain market for renewable energy investments.

Figure 14 provides an overview of South Africa's public and SOEs' energy R&D investments between 2009 and 2018. The South African government and SOEs directed their energy R&D funding mostly toward fossil fuels and nuclear energy, with marginal renewable energy R&D investments between 2009 and 2018. Nuclear energy R&D spending was cut in half in 2010 following the termination of funding to develop pebble bed modular reactors. Sasol, a private oil company with government pension funds as the majority shareholders, reduced its fossil fuel R&D by more than 30% after 2015. The South African National Energy Development Institute (SANEDI), a subsidiary of the Department of Energy, however, invested US$13.25 million on CCUS in 2018. Besides SANEDI, about one-fifth of Eskom's R&D funding was used for coal DNA characterization, underground coal gasification demonstration, and CCUS. Finally, about half of Eskom's R&D budget between 2009 and 2018 went toward grid-related technologies and another one-fifth went toward renewables and energy storage technologies.

6 | MAJOR FINDINGS AND DISCUSSION

6.1 | What has changed and what hasn't since 2010?

Global public RD&D spending began to pivot away from fossil fuels and toward clean energy around the 2008–2009 financial crisis, which ushered in a period of economic stimulus spending and also coincided with the global climate

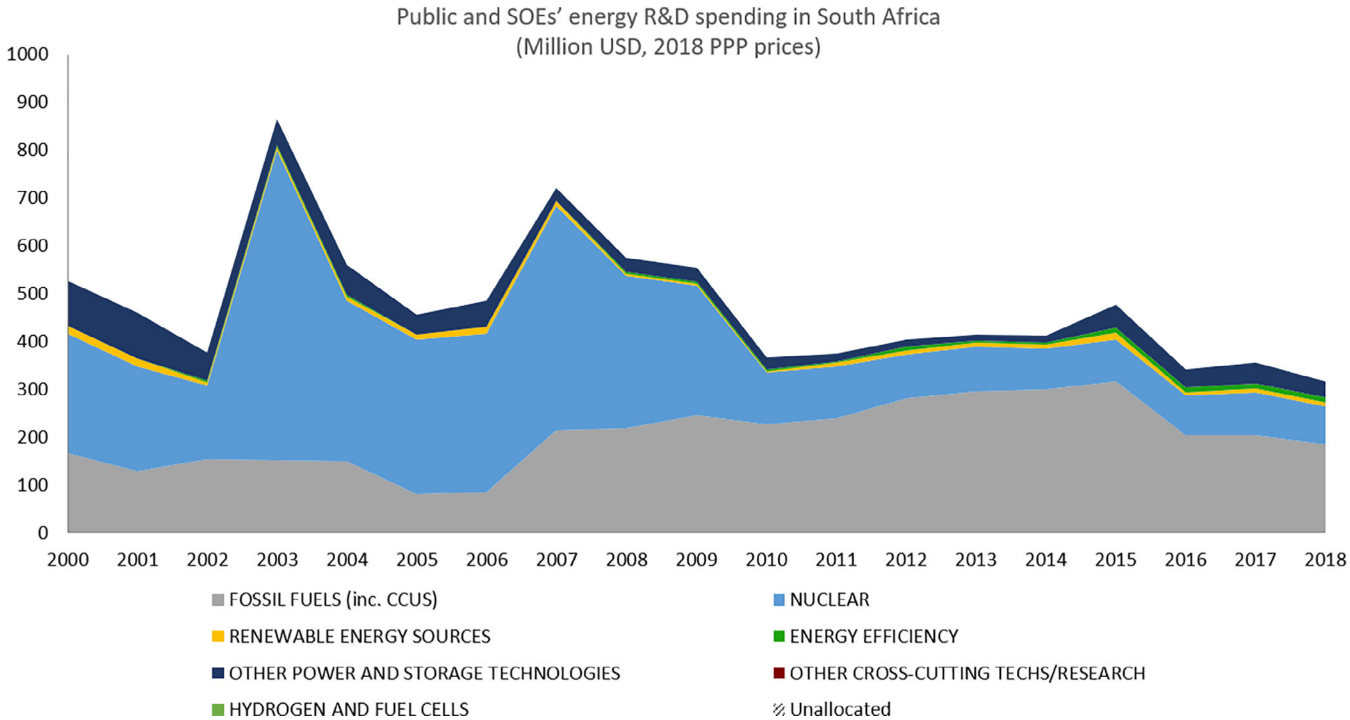

FIGURE 14 Public and state-owned enterprises' (SOEs) energy research and development (R&D) spending in South Africa. *Source*: The data include expenditures by government subsidiaries South African National Energy Development Institute (SANEDI) and South African Nuclear Energy Corporation (NECSA). SOE data are spending data from annual reports of Eskom and Sasol. Sasol is included as its major shareholder is the government employee pension fund. The data do not include demonstration spending. Eskom reported total R&D spending for all years. But the percentage share of R&D for different fuel sources were interpolated for certain years, as it was not available. 2012, 2013, and 2014 percentage shares were interpolated based on 2011 percentage allocations; 2015 and 2016 based on 2017/2018 percentage allocations

negotiations in Copenhagen in 2009 where world leaders committed for the first time to hold global average temperatures to 2°C. Subsequently, government clean energy RD&D investment spending leveled off, but then was reinvigorated in 2017 in the aftermath of the 2015 Paris Agreement. The 24 governments that joined MI pledged to double their investments in clean energy innovation. As of 2018, public clean energy RD&D investments amounted to US $12 billion (or US$19 billion when nuclear energy is included), seven times higher than direct government fossil fuel RD&D spending over the same period at US$1.7 billion. Despite this pronounced change in the composition of the public energy RD&D portfolio, total public investments in energy RD&D have plateaued in recent years.

The rise of China and India as major players in global public energy R&D is a significant change in the last decade and holds out the promise for future growth in R&D spending through renewed global competition in energy innovation among major economies. As China has already committed to carbon neutrality by 2060, China is likely to allocate more resources toward clean energy technologies. Both China and India's SOE investments are mostly invested in fossil fuel and nuclear technologies, however, highly skewing the portfolio and confounding the trend toward cleaner public energy innovation in China.

Many SOEs continue to allocate their RD&D to fossil energy and nuclear due to strong path dependence. Data available from Brazil, Russia, India, Mexico, China, and South Africa suggest that up to US$16.7 billion was spent in energy RD&D by the SOEs from these countries in 2015, of which US$9.8 billion was spent on fossil fuels (and the rest mainly on unallocated). When SOE RD&D figures are added to global tallies in 2015, 29% of all public RD&D spending went to fossil fuels. SOEs do not generally disclose their demonstration spending except in Russia case, which means that the total SOE RD&D spending could be underestimated.

Going forward, SOE investments in RD&D should be reported with greater transparency so they can be better factored into the overall portfolio of government investments. While most SOEs seem to be currently investing in fossil fuels, there is also evidence that a few are beginning to invest in clean energy (Prag et al., 2018) as well as CCUS and biofuels. The recent announcement by PetroChina that it is now aiming for near net zero emissions by 2050 demonstrates that SOEs could become a powerful force for energy innovation. PetroChina has indicated that it plans to invest in geothermal, wind, solar and hydrogen. Reform of SOE spending on energy RD&D could be an important factor in promoting the energy transition.

An important caveat is that data collection and reporting on energy RD&D remains maddeningly partial, opaque, and haphazard. The government investments in RD&D reported in this study reflect only some of the kinds of technologies that will contribute to reducing GHG emissions. RD&D for CCUS and cross-cutting technologies for non-IEA member countries, and digital RD&D for all countries are usually not captured in government or private sector RD&D reported data. If the clean aspects of cross-cutting technologies and unallocated data could be disaggregated and included, the global public clean energy RD&D amount would likely be even higher that what has been reported here. This is particularly relevant for the United States where spending on smart grid and other cross cutting technologies is an important part of the American RD&D energy budget. Moreover, SOEs in IEA countries are not included in the country's energy R&D data. The magnitude of SOEs' energy RD&D in fossil fuels might be even bigger than what has been disclosed as well. India's large nuclear energy RD&D spending likely reflects some administrative spending for the country's nuclear program, and thus, might not fully reflect true innovation investments. China's unallocated R&D category needs to be broken down in much greater detail. In addition, most of R&D data for emerging economies do not include demonstration spending, potentially underestimate their total energy RD&D investments.

6.2 | Implications of the new changes in global energy RD&D

China and India have emerged as major new players in global public energy R&D. Specifically, a new race between the US and Chinese governments to dominate in clean energy RD&D has commenced. China, surpassing both the United States and Germany, has become the largest government RD&D investor in renewable energy. India has replaced Japan to become the largest investor in nuclear technologies. In energy efficiency the United States, United Kingdom, Germany, France, and Korea now dominate. The United States has lost its early leadership in power and storage technology RD&D investments because China is now the largest investor, followed by Japan, Germany, South Korea, and the United Kingdom. Leadership in these technology fields will likely fluctuate in the coming decades depending on changing government policies and priorities.

6.3 | Major factors shaping global public energy RD&D trends

Historically, investments in public energy RD&D followed oil prices but that traditional pattern appears to be ending. Oil prices are at unusual lows, the climate crisis is ever more apparent, and the COVID-19 pandemic may prove to create a political opportunity for governments to sharply adjust their energy RD&D as part of new “greener” economic stimulus packages. During the 2008–2009 financial crisis, several governments, including the United States, China, and the European Union linked part of their economic stimulus to investment in energy. As a result, global government energy RD&D increased by almost one third in a single year. Only a handful of countries, including China, Germany, the United Kingdom, Turkey, Korea, and Sweden sustained the higher level of energy RD&D spending once the 2009 financial crisis passed, however. Given the importance of clean energy RD&D, a steadier commitment to increasing and maintaining spending levels would produce superior innovation outcomes as compared with those resulting from volatile bursts of funding.

Global government clean energy RD&D (regained momentum in part due to the establishment of MI in 2015 (Myslikova & Gallagher, 2020) but commitments to clean energy RD&D have varied greatly by country from 2016 to 2018. Clean energy RD&D steadily increased in China after it joined MI (not including investments by SOEs), but not in Japan or South Africa.

Changes in energy RD&D allocations are fundamentally influenced by factors that differ from country to country. For China, Japan, and India, improving energy security by reducing import dependence is a major motivation for energy RD&D investments. The influence of SOEs in major emerging economies has resulted in continued RD&D in fossil fuels and nuclear, however, due to strong path dependence and a resistance to change in these companies. As renewable energy has become less costly than coal-powered electricity, market forces are now driving the shift toward cleaner technologies in many countries, including the United States, Germany, United Kingdom and parts of India.

Low oil prices have also spurred major oil exporting countries like the United Arab Emirates, Saudi Arabia, Mexico, and Brazil to boost clean energy RD&D.

Going forward, the private sector could become increasingly important. Financial markets have lately exhibited a preference for companies pursuing clean energy. Giant tech firms in the United States and China are increasingly targeting energy technology innovation, but data on private sector investments in energy remain largely unavailable.

Finally, while the tide is finally turning toward clean energy in government energy RD&D investments (not including SOEs), the overall trend does not reflect a strong urgency in response to the climate crisis. Clean energy public energy RD&D quadrupled between 2000 and 2018, but after the sharp rise in 2009 plateaued at around US$ 12 billion overall. The laggardness of state-owned enterprises to transition to clean energy innovation points to a major challenge for governments to reform these firms so that they are aligned with the low-carbon energy transition.

ACKNOWLEDGMENTS

The authors would like to thank the anonymous reviewers and Amy Jaffe for her valuable suggestions and editing. All errors remain the sole responsibility of the authors. This work is supported by BP (BPAE/PAT/50621(5)/63365), NSFC (71721002), William and Flora Hewlett Foundation (2019-9914), Rockefeller Brothers Fund (19-635) and Alfred P. Sloan Foundation (G-2021-14173). This work does not benefit from research resources support.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Fang Zhang: Conceptualization; data curation; formal analysis; methodology; project administration; validation; visualization; writing - original draft; writing-review & editing. **Kelly Gallagher:** Conceptualization; data curation; formal analysis; funding acquisition; methodology; project administration; supervision; writing-review & editing. **Zdenka Myslikova:** Data curation; formal analysis; methodology; validation; visualization; writing - original draft; writing-review & editing. **Easwaran Narassimhan:** Conceptualization; formal analysis; writing - original draft; writing-review & editing. **Rishikesh Bhandary:** Conceptualization; formal analysis; methodology; writing - original draft; writing-review & editing. **Ping Huang:** Conceptualization; formal analysis; methodology; writing - original draft.

ENDNOTES

[1] "Other Crosscutting Technologies" is subdivided into (1) energy system analysis, (2) basic energy research not allocated, and (3) other. While almost half of the total energy RD&D spending in the United States in 2018 was allocated into the cross-cutting category, the ratio of fossil to nonfossil energy in this category is not clear and cannot be broken down further. The category could include, for example, spending in smart grid technologies, but also anything else that is uncategorized as well. According to IEA reports, this is the category that the Office of Science at the US Department of Energy, reports under its "Basic Energy Sciences" category, which contains basic energy sciences research that includes materials sciences and engineering research, chemical sciences, geosciences, and energy biosciences, construction. For more information about the cross-cutting category, see https://www.iea.org/reports/energy-technology-rdd-budgets-2020 and https://www.energy.gov/sites/prod/files/2017/05/f34/FY2018BudgetStatisticalTablebyAppropriation.pdf.

[2] The data are from World Bank through https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?end=2014&start=1960.

[3] Based on the current nominal exchange rate: 1 EURO = 1.18 US$.

[4] Since 2008 until 2015, the R&D funds were estimated as a percentage (0.65%) of the value of the crude oil and natural gas extracted during a year, meaning an estimation base on the real value of oil and gas production (Federal Law of Rights–Ley Federal de Derechos 2005). After 2015, the R&D fund's base change to a fraction (0.65%) of oil revenues approved in the Mexico's Revenue Law, an estimate based on the financial expectations for the upcoming year (updated in Federal Law on Budget and Fiscal Responsibility (Ley Federal de Presupuesto y Responsabilidad Hacendaria 2020).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

RELATED WIREs ARTICLES

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FURTHER READING

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How to cite this article: Zhang, F., Gallagher, K. S., Myslikova, Z., Narassimhan, E., Bhandary, R. R., & Huang, P. (2021). From fossil to low carbon: The evolution of global public energy innovation. *Wiley Interdisciplinary Reviews: Climate Change*, e734. https://doi.org/10.1002/wcc.734

APPENDIX A

The IEA database distinguishes eight technological categories (energy efficiency, fossil fuels, renewable energy, nuclear, hydrogen and fuel cells, other power and storage technologies, cross-cutting technologies and research, and unallocated). IEA includes CCUS in fossil fuel energy category. In our database, we differentiate fossil fuel and CCUS for countries that report CCUS numbers separately. To allow comparison to IEA data, for non-IEA RD&D data, we use the same eight categories to reveal details of all energy RD&D in a specific country,

Non-IEA countries generally lack available information on CCUS government spending and are often wrapped into fossil-fuel RD&D numbers. In addition, there are many instances where countries interpret various categories differently, including what is categorized as “unallocated,” which in some cases includes mostly basic science spending and in others reflects a less defined grouping of expenses. These eight categories allow for the widest range of cross-country comparison and the broadest historical sample.

We converted nominal dollar amounts into PPP values based on conversation rates published by the OECD to minimize distortions and temporal foreign exchange currency volatility, especially in key emerging countries. However, it is possible, in some cases, that this methodology, designed to capture the closest indication of the impact of spending within the emerging market country economy context, potentially overcorrects to the upside.

It should be noted that the demonstration aspect of the data lacks high certainty. The data reported by the IEA include demonstration but not for all the countries. It may not be consistent over the whole period of time (e.g., Luxemburg and Poland). It also is possible and not entirely clear whether countries that only report R&D do not mistakenly include demonstration in the development category (Gallagher et al., 2011), but information about the process of gathering and compiling data by each member country is limited so this cannot be determined with certainty (refer the IEA Database documentation at https://iea.blob.core.windows.net/assets/90dab698-eec6-4068-9d40-9ac4a226fcfc/RDD_Documentation1.pdf). However, it is important to keep in mind that the database provided by the IEA is the most complete and harmonized to date. For the non-IEA member countries, when demonstration activities are explicitly excluded in the government documents, we included a note in the text of the paper referring to energy R&D (Mexico and China). Otherwise, we assume that their data include or RD&D.

The Snapshot of government energy RD&D for all the countries in 2018 and energy RD&D by SOEs in large emerging economics in 2015 are in Table A1 and Table A2.

TABLE A1 Snapshot of government energy RD&D for all the countries in 2018 (Million US$, 2018 prices and PPP)

	Energy efficiency	Fossil fuels	CCUS	Renewable energy sources	Nuclear	Hydrogen and fuel cells	Other power and storage technologies	Other cross-cutting techs/ research	Unallocated	Total budget
Australia	22.63	48.99	15.70	45.76	6.05	22.20	14.00	1.64	1.83	163.09
Austria	87.22	0.78	0.35	29.21	2.39	10.54	29.26	28.52	0.00	187.92
Belgium	73.89	1.09	0.00	15.01	100.57	2.62	19.66	12.06	0.00	224.89
Canada	226.22	305.24	156.74	94.23	124.13	19.20	95.82	18.66	0.00	883.49
Czech Republic*	0.96	4.88	1.26	9.22	14.38	1.07	9.42	4.27	0.00	44.19
Denmark	13.10	0.91	0.00	45.66	0.00	10.42	19.45	1.57	0.00	91.10
Estonia	6.82	0.34	0.00	1.57	0.42	1.02	1.57	2.31	0.00	14.05
Finland	124.81	1.37	0.00	41.74	23.45	0.00	12.07	17.51	0.00	220.96
France	243.53	44.12	20.09	177.21	839.75	37.21	67.93	135.61	0.00	1545.36
Germany	190.40	62.86	57.33	280.59	287.93	37.28	151.19	75.10	341.66	1427.02
Greece	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hungary	15.87	0.56	0.00	7.79	0.00	1.54	3.85	0.00	0.00	29.62
Ireland	4.82	0.87	0.13	11.40	0.00	0.13	1.56	6.36	0.00	25.14
Italy	102.53	133.33	12.00	129.81	136.78	15.05	79.33	67.81	0.00	664.64
Japan	724.74	177.87	160.42	462.67	1094.38	207.11	192.67	190.18	0.00	3049.62
Korea	184.94	58.50	19.80	183.73	78.80	48.40	142.79	42.41	0.00	739.56
Luxembourg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Mexico#	N/A	235.9	N/A	67	0.4	1.1	1.67	102.1	N/A	417.77
Netherlands	84.62	27.23	13.25	124.12	8.33	14.72	16.86	10.88	2.48	289.25
New Zealand	6.01	3.01	0.00	7.47	0.00	0.17	0.00	0.00	3.98	20.66
Norway	80.18	107.30	48.35	61.91	10.46	7.85	27.80	10.50	1.10	307.10
Poland	23.37	21.55	0.22	33.51	9.22	1.33	11.14	12.56	1.06	113.74
Portugal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	115.28	115.28
Slovak Republic	5.18	0.05	0.00	1.80	0.65	0.16	0.56	0.02	0.00	8.41
Spain	19.79	1.52	0.17	100.80	1.43	6.98	27.85	1.82	0.00	160.19
Sweden	113.17	0.63	0.05	45.03	1.89	2.04	18.39	21.51	0.00	202.66
Switzerland	76.18	8.21	4.56	104.23	46.05	21.13	47.72	29.00	2.01	334.53

(Continues)

TABLE A1 (Continued)

	Energy efficiency	Fossil fuels	CCUS	Renewable energy sources	Nuclear	Hydrogen and fuel cells	Other power and storage technologies	Other cross-cutting techs/research	Unallocated	Total budget
Turkey	54.74	12.31	0.18	72.81	0.32	8.67	28.68	0.03	0.06	177.62
UK	365.68	30.72	12.25	110.59	291.49	15.96	98.00	63.55	65.99	1041.98
USA	1248.84	571.12	198.77	755.05	1079.17	115.00	41.00	3253.00	84.34	7147.52
Brazil	15.9	0.00	N/A	157.7	N/A	N/A	66.7	N/A	51.8	292.2
Russia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
India	N/A	277.1	N/A	33.6	2534	N/A	44.95	N/A	N/A	2909.2
China	230.7	233.7	N/A	1866.4	85.6	0.4	613.5	N/A	1888.3	4918.5
South Africa	1.20	13.25	N/A	5.22	82.86	0.42	0.88	0.00	0.00	103.84
Chile	N/A	8.1	N/A	N/A	N/A	N/A	N/A	N/A	8.00	16.10
Indonesia*	N/A	101.6353198	N/A	N/A	N/A	N/A	N/A	N/A	N/A	114.8376968
UAE*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	12.20	12.20
Saudi Arabia*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	90.10	90.10

Note: Countries marked with # represents the data are from the latest available year 2017; countries marked with * represents the data are from the latest available year 2016. The demonstration aspect of the data lacks high certainty.

Abbreviations: BNEF, Bloomberg New Energy Finance; CCUS, carbon capture, utilization and storage; IEA, International Energy Agency; MI, Mission Innovation; PPP, purchasing power parity; RD&D, research, development, and demonstration; SANEDI, South African National Energy Development Institute.

Source: (1) IEA countries' data are from IEA Energy Technology RD&D Budget Database. They are budget spending and include demonstration; (2) non-IEA countries' data are from their national governments' annual reports, supplemented by data from Mission Innovation Country Highlights (fifth MI ministerial 2020). Specifically, China's data are spending data from China Statistical Yearbook on Science and Technology and BNEF. India's data are budget spending from annual reports of ministries (including Ministry of Petroleum and Natural Gas (MPNG), Ministry of Power (MoP), Ministry of Earth Science (MoES), Ministry of Coal (MoC) and Department of Atomic Energy) available through the Union Budget documents. Mexico's data are spending data without demonstration spending from the National Council of Science and Technology (CONACYT) annual reports, Pemex Annual reports, and IEA Energy Technology RD&D Budget Database. Brazil's data are spending data from annual reports of Ministry of Science, Technology and Innovation (MCTI). South Africa data are expenditures by government subsidiaries SANEDI and South African Nuclear Energy Corporation (NECSA). All the data of China, India, Mexico, Brazil, and South Africa do not include demonstration.

TABLE A2 Snapshot of energy RD&D by SOEs in large emerging economics in 2015 (Million US$, 2018 prices and PPP)

In 2015	Fossil (incl. CCUS)	Nuclear	Renewable energy	Energy efficiency	Hydrogen and fuel cells	Other power and storage	Other-cross-cutting techs/ research	Unallocated	Total
Brazil	1066.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1066.4
Russia	1909.3	1252	N/A	N/A	N/A	440	N/A	N/A	3601.3
India	755.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	755.2
Mexico	N/A	N/A	N/A	N/A	N/A	N/A	N/A	31.1	31.1
China	5091	N/A	N/A	N/A	N/A	N/A	N/A	6736.8	11,827.8
South Africa	157.5	N/A	4.1	8.8	N/A	32.6	N/A	N/A	203
Total	8979.4	> > 1252	> > 4.1	> > 8.8	N/A	474.6	N/A	6767.9	17,484.8

Abbreviations: CCUS, carbon capture, utilization and storage; IEA, International Energy Agency; MI, Mission Innovation; PPP, purchasing power parity; R&D, research and development; RD&D, research, development, and demonstration; SANEDI, South African National Energy Development Institute; SOEs, state-owned enterprises.

Source: (1) China's data are from China Statistical Yearbook on Science and Technology Activities of Industrial Enterprises. (2) India's data are from annual reports of 100% state-owned enterprises (including National Hydroelectric Power Corporation (NHPC), National Thermal Power Corporation (NTPC), the Oil Industry Development Board (OIDB), as well as R&D budgets of 100% government owned petroleum companies in India) and partially SOEs, the loans for R&D activities to partially SOEs through OIDB. (3) Mexico's data are from the National Council of Science and Technology (CONACYT) annual reports; (4) Brazil's data are from annual reports of Eletrobras and Petrobras; (4) South Africa's data are from annual reports of Eskom and Sasol. Sasol is included as its major shareholder is the government employee pension fund. (5) Russia's data are from annual reports of state-owned oil, power and transmission companies, including Gasprom, Bashneft, Lukoil, Russneft, Slavneft, THK-BP, Surgutneftegas, Irkustk, Rosneft, Tatneft, Rosseti, Rosatom. The SOE's R&D data in India are budget spending and all the others are actual spending. All the national data do not include or explicitly include demonstration, except in Russia case.