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continually as new information and models emerge. Useful here is the growing field of deep reinforcement learning, in which agents explore their evolving environment to find the best solutions. Applying such algorithms to materials discovery would make searches progressively more efficient and allow the learner to explore the space of molecules, just as chemists do.

WHAT NEXT

Developing machine-learning approaches is one of the main goals of the Clean Energy Materials Innovation Challenge run by the Mission Innovation global collaboration. The collaboration is funded by voluntary government pledges — and nations must deliver on their commitments with the necessary investments.

In summary, more investment is needed in artificial intelligence and robotics-driven materials research throughout the world. More data must be made available to people programming the robots. And experimentalists, robotics experts and algorithm designers should communicate and collaborate more to facilitate rapid troubleshooting.

Time is running out to find the new energy technologies the world needs. ■

Phil De Luna *is a graduate student in the Department of Materials Science and Engineering at the University of Toronto, Canada.* **Jennifer Wei** *is a graduate student in the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts, USA.* **Yoshua Bengio** *is a professor in MILA, Department of Computer Science and Operations Research, Université de Montréal, Canada.* **Alán Aspuru-Guzik** *is a professor in the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts, USA.* **Edward Sargent** *is a professor in the Department of Electrical and Computer Engineering, University of Toronto, Canada.*
e-mails: ted.sargent@utoronto.ca; alan@aspuru.com

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For the full list of co-signatories, see go.nature.com/2i8psoe.

A solar farm floats on a lake that formed after the collapse of a deep coal mine in Huainan, China.

Six principles for energy innovation

Decades of experience must inform future initiatives, urge **Gabriel Chan** and colleagues.

Last month, the European Union marked the tenth year of its Strategic Energy Technology Plan. It is one of many policy initiatives worldwide to accelerate innovation in energy technologies to reduce greenhouse-gas emissions. As the window of opportunity to avert dangerous climate change closes, we urgently need to take stock of these initiatives — what works and why?

Public investments in energy research, development and demonstration (RD&D) have risen since the low levels of the mid-1990s and early 2000s. In 2016, member countries of the Organisation for Economic Co-operation and Development spent US$16.6 billion on energy RD&D, compared with $10 billion in 2000 (adjusted for purchasing power parity). In October, the United Kingdom set out its Clean Growth Strategy to invest more than £2.5 billion ($3.3 billion) in low-carbon innovation between 2015 and 2021. In 2015, the EU and 22 nations pledged to double their investment in energy RD&D under the Mission Innovation adjunct to the Paris climate agreement. However, the overall goal might be out of reach given the proposed 35% cut in US President Donald Trump's 2018 budget for energy RD&D.

Different nations are pursuing various strategies and creating new types of institution. For example, the Advanced Research Projects Agency-Energy (ARPA-E) run by the US Department of Energy (DOE) targets grants at key technologies such as affordable energy storage. The DOE Energy Innovation Hubs form research teams to work on technologies such as nuclear-reactor modelling.

The United Kingdom has set up the Energy Technologies Institute (ETI), a public–private partnership to accelerate the development of low-carbon technologies. It also launched the Catapult programme, which aims to build bridges between universities and industry, and sustainability advisory services that are run by bodies such as the Carbon Trust. And China is reforming the Chinese Academy of Sciences and its national labs, as well as creating larger lab facilities.

At the international level, the United Nations Framework Convention on Climate Change (UNFCCC) Technology Mechanism enables technology development and transfer in developing countries to support the Paris agreement. Since 2013, the World Bank Group has opened seven climate-innovation centres in developing countries such as Kenya. The centres provide seed financing, policy guidance, networking and technical training. The Nairobi centre, for example, advises start-ups such as Futurepump, which is developing solar-powered water pumps.

Most of these bodies can claim successes. But a comprehensive global assessment of energy-innovation programmes is needed to learn from collective experience and to establish best practices. As a starting point, here we distil six principles to guide public initiatives for energy innovation. These are drawn from the scholarly literature and from third-party assessments of experience in UK, US and multilateral institutions.

GUIDING PRINCIPLES

Give researchers and technical experts autonomy and influence over funding decisions. Active scientists are better placed than managers to spot bold but risky opportunities. For instance, US national laboratories lead the development of a subset of projects that comprise 4% of their current budgets. Yet these projects produce more high-impact publications and commercially viable technologies than do those that are controlled by DOE headquarters (see 'Expert benefits')[1].

Such decentralized funding at the National Renewable Energy Laboratory in Golden, Colorado, has supported the development of more cost-effective methods of cultivating algae for biofuels, as well as groundbreaking research on perovskite-based solar cells[2].

Public labs that conduct energy RD&D should allocate a significant fraction of their budgets, say 10%, to internally selected projects. They need the flexibility to adjust goals as research proceeds. Funding institutions could follow the approach of ARPA-E and employ technical experts as programme managers to direct funds and to modify or cut projects as they progress[3].

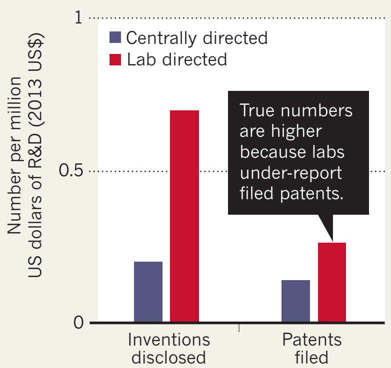
Incorporate technology transfer in research organizations. Public institutions that fund or perform energy RD&D must collaborate with private owners of energy infrastructure, as well as those that produce, deploy and operate new energy technologies. Otherwise, research can remain in silos and might never be put into practice. Formal technology-transfer programmes should be set up to build connections. This requires strong institutional backing. When political and financial support wanes, technology-transfer rates fall[1].

Formal programmes for technology transfer have built on the work of DOE national laboratories[4]. For example, since 1994, one-fifth of all new patents in advanced energy-storage systems for vehicles cite at least one DOE-granted patent[5]. Strategies are needed to innovate faster. Research universities have shown the value of sustained collaboration through a diversity of channels[6]. Sandia National Laboratories, which has facilities in New Mexico and California, has seen the value of giving researchers up to three years' leave to work in the private sector and commercialize technologies. Pilot programmes should be scaled up. For example, at

"Active scientists are better placed than managers to spot bold but risky opportunities."

EXPERT BENEFITS

Projects that are selected and managed internally by national labs* generated more inventions and patents than did projects controlled centrally by the US Department of Energy between 2007 and 2013.



*Under the Laboratory-Directed Research and Development programme.

SOURCE: REF. 1

California's Lawrence Berkeley National Lab, the Cyclotron Road and Visiting Entrepreneurial Research Fellows programmes lower barriers to collaboration and provide facilities, expertise and funding to entrepreneurs.

Focus demonstration projects on learning. Many viable technologies stumble at the demonstration stage when they reach the 'valley of death'. Companies are reluctant to finance pilot projects for new, risky technologies, such as carbon capture and storage (CCS). This makes it impossible to scale them up without public support. Demonstration projects are expensive and can be harshly judged. For example, the US Synthetic Fuels Corporation fostered technologies in the 1980s to create liquid fuels from substitutes such as coal. The failure of the programme to meet its goal of reducing oil imports has been used to argue against public investments in demonstration projects that aim to pick winners. Yet the programme created useful knowledge: technology trialled at the corporation's Cool Water plant is being considered for use in CCS[7].

Policymakers should set goals for demonstration projects on the basis of the knowledge they will generate about the cost and performance of future technologies[7]. Other important features include: an exit strategy to halt projects that miss milestones; design that acknowledges the possibility of failure while keeping other options open; involvement of a broad pool of private actors; and mechanisms to track and disseminate the knowledge produced[8].

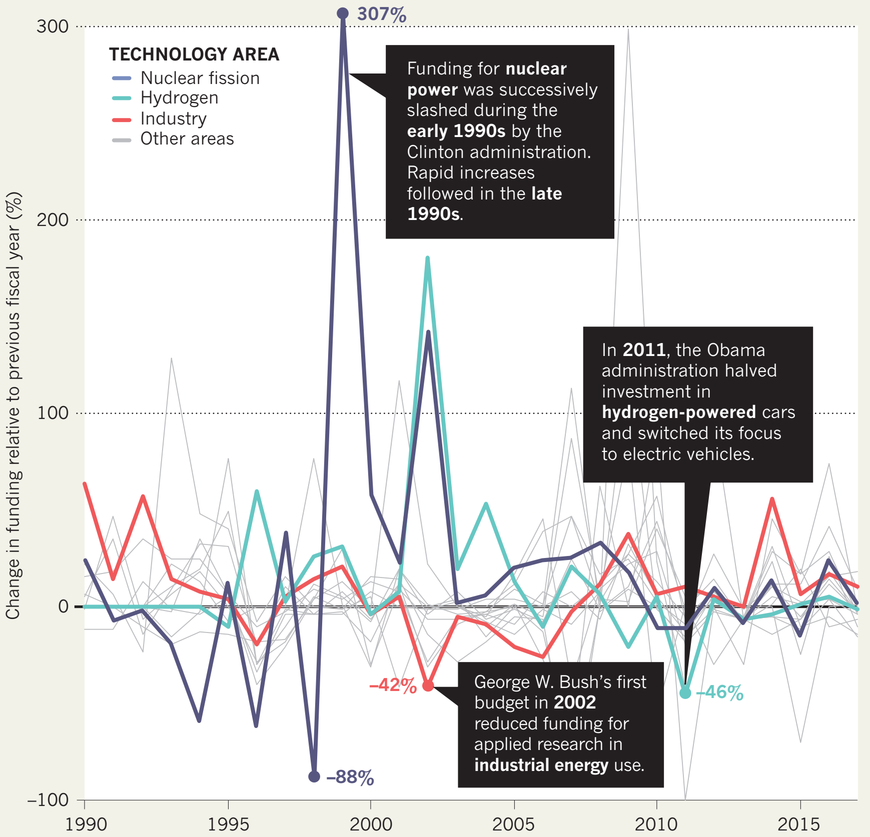
Incentivize international collaboration. International cooperation can accelerate innovation beyond the capabilities of a single nation. Pooling costs enables projects of greater scale, lessens duplication and integrates regional specializations. But more needs to be known about how to do this effectively. Few multilateral collaborations stretch beyond holding meetings and issuing joint statements. Deeper collaborations range from loosely coordinated pledges for domestic actions, such as Mission Innovation, to shared platforms for technology development, such as the International Energy Agency (IEA) Technology Collaboration Programmes. Some partnerships achieve integrated cooperative RD&D — 35 countries are involved in the ITER project to build the world's largest magnetic fusion device in southern France.

It can be fruitful for nations that have specific technical expertise to partner with those that are keen to exploit it. For example, the U.S.–China Clean Energy Research Center has helped US companies such as 3M to test technologies in China to improve the energy efficiency of buildings. The pace and scale of construction in China meant that US companies learnt more about real-world

SOURCE: REF. 10

VOLATILE FUNDING

US Department of Energy budgets for the research, development and demonstration of different technologies fluctuate between years as government policies and priorities change. Unstable funding lowers the efficacy of such programmes.



effectiveness than they would have done working only in the United States.

Barriers remain: collaborators must negotiate rights before outcomes are known, partners may lack trust, and domestic political support can fluctuate. Face-to-face interactions, long-term strategies and well-designed management plans are essential[9].

Adopt an adaptive learning strategy. Lessons must be drawn from a diverse range of experiences because energy innovation occurs in many different industrial and funding contexts. Efforts vary in their primary goals, such as competitiveness, security and environmental protection, as well as in their implementation strategies.

Mechanisms for evaluating and adapting programmes should be designed into institutions from the start. There are many ways to measure innovation-policy outcomes: from the money invested or the number of papers, citations, patents and start-ups that are generated, to economic measures such as productivity and qualitative measures that can be assessed through surveys. Public agencies should store and track data on operations and outcomes and release them to independent researchers.

New groups of experts might be needed. For example, the UK Behavioural Insights Team, created in 2010, incorporates findings from behavioural psychology into policies that encourage the use of energy-efficient heating and lighting systems. International institutions such as the IEA, the International Renewable Energy Agency, the UNFCCC Technology Mechanism and the World Bank should help governments to learn from others and develop strategies for adapting energy-innovation programmes.

Keep funding stable and predictable. Government funding for energy innovation is, in many cases, volatile. For example, between 1990 and 2017, US political shifts meant that each year, on average, one in five DOE technology areas saw a budget increase or decrease of greater than 30% (see 'Volatile funding' and go.nature.com/2zrodtc)[10]. Fluctuations in funding erode the cost-effectiveness of programmes by precluding strategic, sustained investments that are high risk but potentially high reward. A slashed budget for renewables in the 1990s led to the loss of decades of experience during layoffs at the US National Renewable Energy Laboratory.

Institutions for energy innovation have evolved just as erratically. In the United Kingdom, each prime minister since 2000 has focused on a different strategy. Tony Blair created the Carbon Trust, Gordon Brown the ETI, David Cameron the Catapult programme, and Theresa May has created a Faraday Challenge for batteries as part of the Industrial Strategy Challenge Fund. Although experimentation has benefits, there are also costs. Learning how to work with new programmes and people takes time and effort. For example, early engagers with the Carbon Trust applied for grants and incubator support, only to see the programme's scope limited in 2011 to providing advice and certification services.

Rather than overhauling institutions for energy innovation with different political cycles, existing programmes should be continuously evaluated and updated. New programmes should be set up only if they fill needs that are not currently met.

Let's learn from experience to accelerate the transition to a cleaner, safer and more affordable energy system. ■

Gabriel Chan *is assistant professor of science, technology and environmental policy at the University of Minnesota, Minneapolis, USA.* **Anna P. Goldstein** *is a research associate in the Harvard Kennedy School, Harvard University, Cambridge, Massachusetts, USA.* **Amitai Bin-Nun** *is vice-president of Securing America's Future Energy in Washington DC, USA.* **Laura Diaz Anadon** *is professor of climate change policy at the University of Cambridge, UK.* **Venkatesh Narayanamurti** *is research professor of technology and public policy at Harvard University, Cambridge, Massachusetts, USA.*
e-mail: lda24@cam.ac.uk

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Supplementary information accompanies this article online; see go.nature.com/2akywjn.