3 Science, technology and Innovation Policy for Sustainability Transitions

The climate emergency requires nothing short of a total transformation of sociotechnical systems in areas such as energy, agrifood and mobility. STI has essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to support them. They need to design policy portfolios that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. Larger investments and greater directionality in research and innovation activities are required, but should coincide with a reappraisal of STI systems and their supporting STI policies to ensure they are "fit-for-purpose" to contribute to sustainability transitions. For example, STI policies need to support new modes of partnership (e.g. between researchers, businesses, governments and citizens) and develop enabling resources (e.g. finance, skills and knowledge) conducive to tranformative change. They also need to balance supply and demand side interventions that target both production and consumption. The chapter outlines ten sub-domains of STI policy where reforms are needed and highlights significant gaps between R&D funding and net-zero ambitions.

Key messages

- To address the climate emergency requires nothing short of a total transformation of energy, agrifood, and mobility systems. Science, technology and innovation (STI) have essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to meet these challenges.
- Governments may require altogether different STI policy frameworks and practices from those they commonly use today to help direct and accelerate the innovation cycle for low-carbon technologies. They should design policy mixes that enable transformative innovation and new markets to emerge, challenge existing fossil-based systems, and create windows of opportunity for low-carbon technologies to break through. Reforms concern all aspects of STI policy and governance, and the chapter sets out a checklist of STI policy sub-domains where these are needed.
- Significant levels of investment are needed across the entire innovation chain to meet the scale and pace of the net-zero transition. Governments should place greater emphasis on research, development and demonstration (RD&D), since achieving net-zero depends on technologies that are still far from market. Government incentives for low-carbon research and development (R&D), including public R&D grants, public procurement, and carbon pricing, should also pay greater attention to regime-changing radical innovations.
- Technological innovation is inherently uncertain, and technologies can often interact with one another in unexpected ways. Governments should diversify and pool their investments to search, develop and deploy a portfolio of technologies, while also continuously assessing potential trade-offs that may be created by these technologies.
- STI policies should encourage public-private partnerships and collaborative platforms operating at different stages of the low-carbon innovation chain to accelerate the pace of radical innovation. Wider society should also be actively engaged in STI processes and policies, since technological shifts need to coincide with transformations in behaviour, lifestyles and economic activity. Moreover, cross-government co-ordination will be essential, as policy efforts targeting RD&D and technology deployment are distributed across many different policy areas.
- International STI co-operation is also necessary, as global climate change requires collective action to meet net-zero targets. However, national research and innovation funding regimes can present barriers to international co-operation that governments need to address. It is also important for OECD member countries to co-operate on technological innovation with low- and middle-income countries, where the majority of growth in greenhouse gas emissions is expected to occur in the coming decades, but where scientific and technological capabilities for low-carbon innovation are underdeveloped.
- Gaps in the skills and capabilities of firms, governments and research actors need to be addressed to enact sustainability transitions rapidly. These gaps include both technological and "softer" capabilities related to new ways of working. Addressing these gaps requires a multi-agency approach that considers both supply- and demand-side perspectives, and also supports people of working age and communities in attaining new skills and opportunities as part of a just transition.
- Finally, the current knowledge and evidence base that supports policy decisions, such as evaluation and statistics, struggles to cope with the complexity and uncertainty of STI-enabled sustainability transitions. Governments need to invest in their "strategic intelligence" capabilities to monitor and evaluate sociotechnical transitions, and to formulate, design and implement effective STI policy agendas and measures.

Introduction

Sociotechnical systems in areas like energy, agrifood and mobility need to transform rapidly to become more sustainable and resilient, which will require simultaneous political, economic, behavioural, cultural and technological change, at multiple levels of governance (OECD, 2015[1]). STI has essential roles in these transformations, but governments must be more ambitious and act with greater urgency in their STI policies to meet these challenges.

Along these lines, the *OECD Science, Technology and Innovation Outlook 2021* argued for reforms of STI policy that favour greater directionality in support of sustainability transitions. It also suggested that the disruptive COVID-19 moment offers a “window of opportunity” to enact reforms, particularly in the context of ambitious recovery packages and renewed commitments to address climate change (OECD, 2021[2]). Governments may require altogether different policy frameworks and practices from those they commonly use today. Reforms will require revisiting STI policy models, visions, targets and instruments with a view to adapting them or displacing them in favour of others (Schwaag Serger and Palmberg, 2022[3]). All aspects of STI policy and governance are involved, including research and innovation funding, human resources for science and technology, research and technology infrastructures, STI system co-ordination mechanisms, and evaluation and measurement.

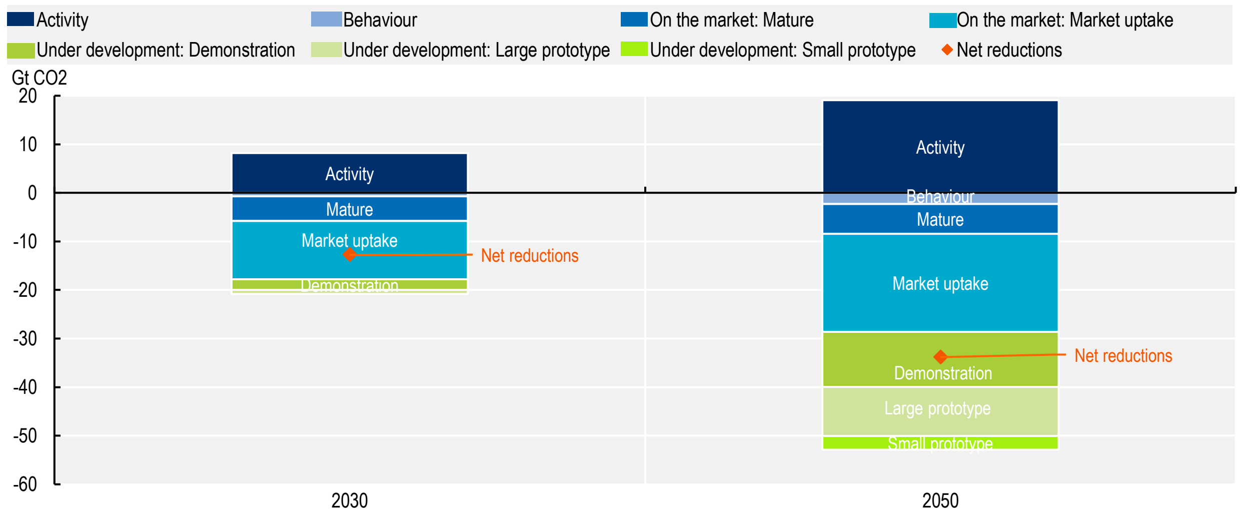
This chapter takes up the call for STI policy reforms and outlines those areas that need attention. It begins by outlining shifts in STI policy, including growing recognition of the need for greater directionality and a multilevel perspective on systems change. For STI to enable sustainability transitions, it needs to support new modes of partnership (e.g. between researchers, businesses, governments and citizens) and develop enabling resources (e.g. finance, skills and knowledge) conducive to tranformative change. It needs to balance supply and demand side interventions that target both production and consumption. The chapter outlines ten sub-domains of STI policy where reforms are needed. For example, it highlights important gaps between R&D funding and net-zero ambitions. A final section draws some lessons and presents a brief outlook on STI policy for sustainability transitions.

Towards a more directive and multilevel policy approach

The pace of low-carbon innovation needs to accelerate

Without a major acceleration in low-carbon innovation, reaching net-zero emissions by 2050 will be unachievable. For example, in the energy sector, achieving net-zero emissions by 2050 will require nothing short of the complete transformation of the global energy system. Instead of fossil fuels, two-thirds of total energy supply in 2050 will be from wind, solar, bioenergy, geothermal and hydro energy in the International Energy Agency’s (IEA) “Net-zero Emissions by 2050 Scenario” (NZE). Reaching this target requires rapid large-scale deployment of available technologies, such as wind and solar, as well as the development and widespread use of technologies that are far from mature today, such as green hydrogen. It also requires behavioural change.[1] Figure 3.1 shows that technologies that are available on the market today provide nearly all the emissions reductions required by 2030 in the NZE. However, by 2050, almost 50% of carbon dioxide (CO_2) emissions reductions in the NZE come from technologies currently at the demonstration or prototype stage, a share that is even higher in heavy industry (IEA, 2022[4]).

Figure 3.1. Global CO2 emissions changes by technology maturity category in the IEA's NZE



Source: IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050 (accessed on 15 December 2022)

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The urgency to achieve net-zero by 2050 points to the need to compress the innovation cycle for early-stage clean-energy technologies. In the IEA's NZE, most clean-energy technologies that have yet to be demonstrated at scale today would need to reach markets by 2030 at the latest. This is a much more rapid pace of development than has typically been achieved historically and places new demands on innovation systems, and by extension, on government policy. Innovation chains are fragile by nature, facing multiple "valleys of death" that can disrupt the flow of the "innovation pipeline". Many governments already try to deal with these, often playing wide-ranging roles in supporting innovation chains.

The sustainability challenge calls for greater directionality in policy making

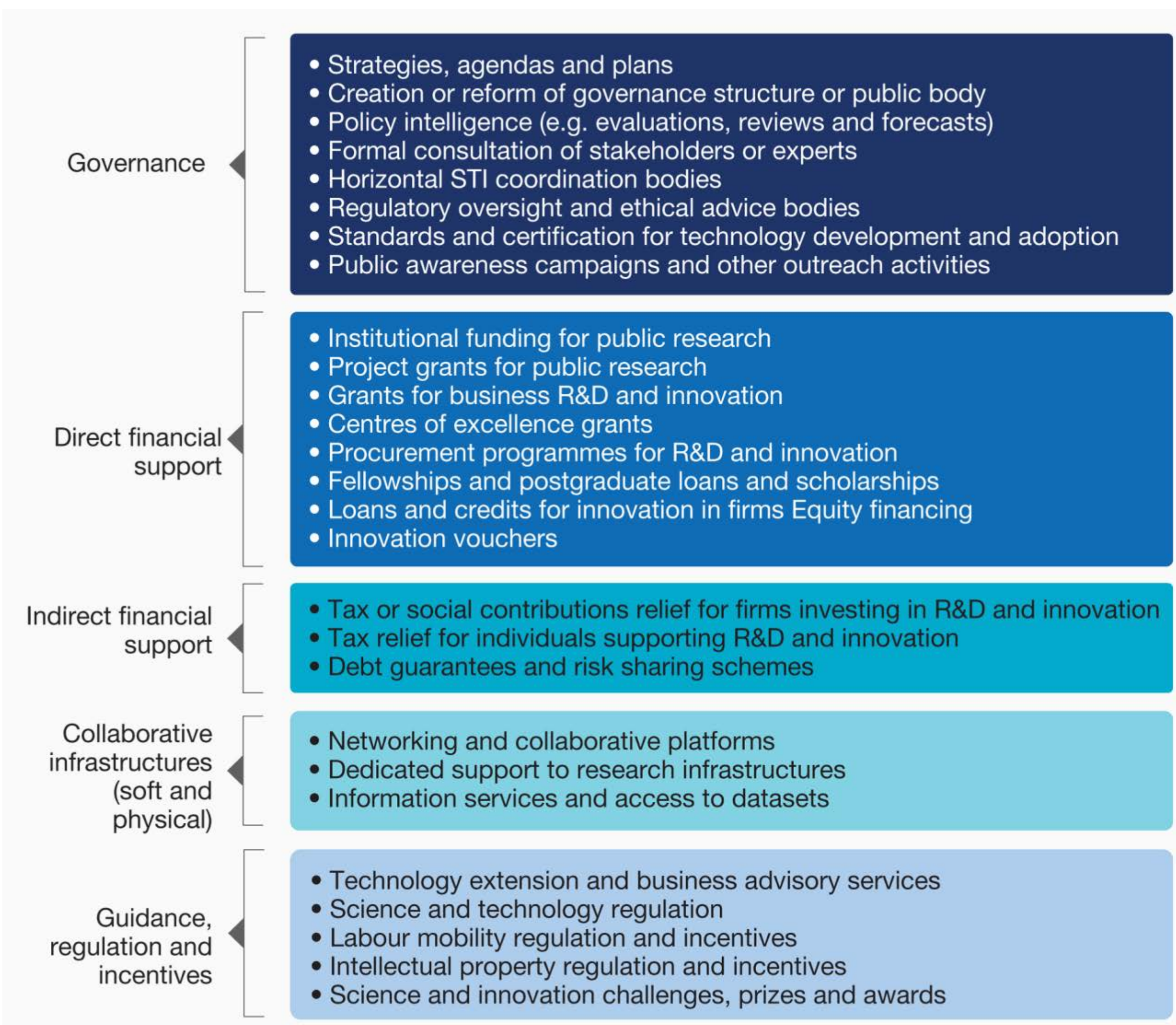
It is widely understood that sustainability transitions require a whole-system change, for example, in energy systems and agrifood systems. While research and innovation have critical roles to play in reconfiguring these systems, other factors are essential, including current social practices, institutions, infrastructures, and markets (Kern, 2012[5]). Sustainability transitions are therefore "sociotechical", insofar as technologies and societies co-evolve to meet the sustainability challenge. The breadth of change implies that firms, governments, public research actors and societies more broadly need to adapt. These actors have their own plans, strategies and agendas that shape the course of transitions. This creates complexity, uncertainty and ambiguity, so that the course of sociotechnical transitions remains impossible to predict and difficult to direct.

Shared goals and co-operation between different parts of the system can help reduce uncertainty and ambiguity, as multiple actors work towards common goals and solutions. An increasingly important focus of STI policy, therefore, is to help develop and articulate these common goals among diverse stakeholders. In this view, the traditional rationales for STI policy – fixing market failures and system failures – are joined by a further rationale – fixing directionality failures – which implies STI should support purposeful transitions (Weber and Rohracher, 2012[6]).

Directionality is implicit in all policy making by design, of course, but fixing directionality failures in STI systems presents a break from the recent orientation of STI policy, where, over the last couple of decades, the STI policy mix has become more horizontal and agnostic on the research and technologies it supports.[2] This is now challenged by the sustainability imperitive and the broader “securitisation” of STI policies discussed in Chapter 1, which are adding pressure on governments to make their STI policies more directive. Along these lines, governments are experimenting with new policy instruments, such as challenge-based funding and mission-oriented innovation policies (MOIPs) that bring together multiple actors, including firms and public-sector research organisations, to co-create and collaborate on pathways to net-zero (see Chapter 5).

Efforts like these can help “build up” and develop new structures, practices and technologies that contribute to sustainability transitions. Governments can use public policies to develop spaces for experimentation, notably through support for public R&D, but these spaces can extend to pilots, living labs, regulatory sandboxes (Attrey, Lesher and Lomax, 2020[7]) and other demonstrators that help develop alternative sustainable solutions, technologies, services, organisational processes and institutional practices. Public policies can also help scale up and anchor sustainable practices and solutions, including through subsidies or public procurement that promote low-carbon technology deployment. Figure 3.2 outlines an extended list of instruments commonly used to promote research and innovation activities; Box 3.1 highlights some of the most common STI policy instruments used to address net-zero.

Figure 3.2. List of policy instruments commonly used in STI policy



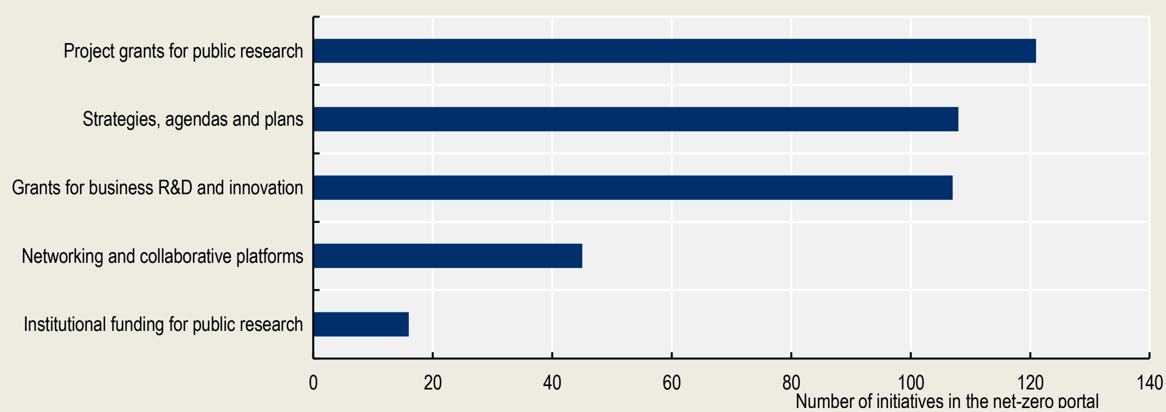
Source: EC-OECD STIP Compass, https://stip.oecd.org.

Box 3.1. "STI policies for net-zero" portal

To coincide with the 2021 United Nations Climate Change Conference (COP26), the OECD and the IEA joined forces in 2021 to launch the "STI policies for net-zero" portal as part of the EC-OECD STIP Compass infrastructure. The portal aims to support a better appreciation of the full landscape of STI policies targeting net-zero, which would benefit policy mix design, policy learning and, ultimately, policy coherence across governments. It provides information on hundreds of STI polices that explicitly support the transition to net-zero. The portal presents policy information in a series of interactive dashboards that provide both an overview of policy landscapes and options to obtain details on specific policy initiatives.

As of September 2022, the portal includes information on approximately 370 STI policy initiatives targeting net-zero in the energy sector. These policies come from 40 countries and the European Union, and involve around 180 government ministries and agencies. As Figure 3.3 shows, many of these initiatives use project grants for public research. Other commonly used instruments include national strategies, agendas and plans, grants for business R&D and innovation, and support for networking and collaborative platforms.

Figure 3.3. Top 5 STI policy instruments reported in "STI policies for net-zero" portal



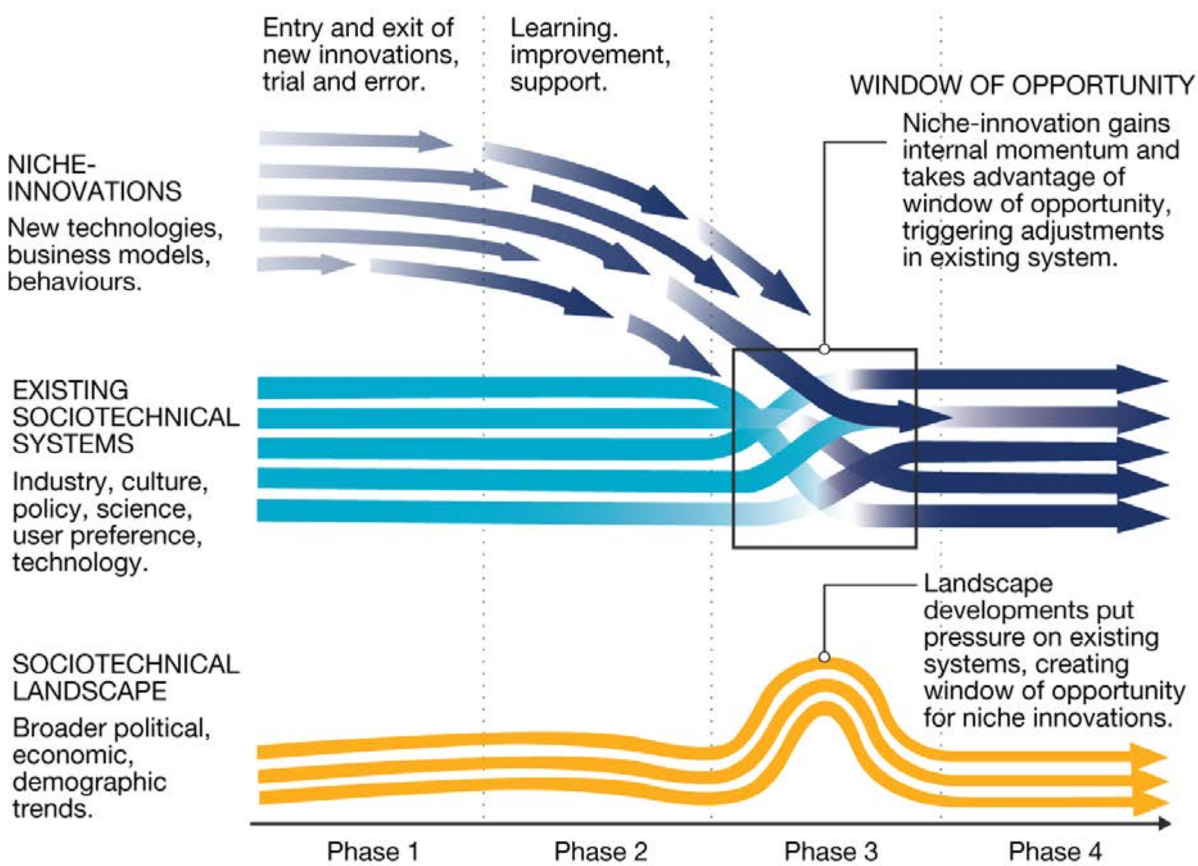
Source: EC-OECD (2021), STIP Compass: International Database on Science, Technology and Innovation Policy (STIP), September 2022 edition, https://stip.oecd.org/stip/net-zero-portal.

StatLink https://stat.link/tnj2zx

At the same time, sustainability transitions require the "breakdown" and discontinuation of unsustainable practices and structures, including the phase-out of polluting and high-carbon technologies (Kivimaa and Kern, 2016[8]). Without this breakdown, innovation experiments are often blocked from scaling up, since various lock-ins and path dependencies tend to preserve and protect incumbent fossil-based technologies and practices.[3] For example, other policies such as fossil-fuel subsidies support the stability of unsustainable sociotechnical systems and need to be phased out, but doing so is politically difficult. While governments need to reduce support to unsustainable and typically dominant technologies, they must also account for and mitigate the unintended social consequences that might result. For this reason, and to reduce the likelihood of resistance to transitions, transitional strategies need to incorporate adjustment measures, such as phased tightening of regulations, financial compensation, workforce retraining and regeneration programmes for disadvantaged regions (Geels et al., 2017[9]).

It is through the duality of these "buildup" and "breakdown" dynamics that sociotechnical transitions emerge.[4] In addition, the broader landscape of exogenous developments (e.g. slow-moving socio-economic trends) or shocks (e.g. elections, economic crises and wars) can trigger the destabilisation of the existing sociotechnical system and open up "windows of opportunity" for new low-carbon innovations to break through (Geels and Schot, 2007[10]). This "multilevel perspective", which is increasingly popular as a policy model for promoting sustainability transitions,[5] is summarised in Figure 3.4. Its key insight is that transitions occur through the alignment of mutually reinforcing processes within and between the three levels of build-up of "niche innovations", the breakdown of existing sociotechnical "regimes" and changes in the broader exogenous landscape. The resulting sociotechnical transitions go beyond the adoption of new technologies and include investment in new infrastructures, establishment of new markets, development of new social preferences, and support for people of working age and communities in attaining new skills and opportunities as part of a "just" transition (Geels et al., 2017[9]).

Figure 3.4. Promoting innovations to take advantage of windows of opportunity



Note: The multilevel perspective (MLP) sees system transitions as driven by interactions between three analytical levels: (i) the sociotechnical system itself, which is stabilised by lock-in mechanisms (such as sunk investments, core competencies, and institutional commitments) but experiences incremental improvements along path-dependent trajectories; (ii) niche innovations, which differ radically from the dominant existing system but are able to gain a foothold in particular geographical areas or market niches, or with the help of targeted policy support; and (iii) exogenous ("landscape") developments such as slow-changing trends (e.g. demographics and ideologies) or shocks (e.g. elections, economic crises and wars) that destabilise the system and facilitate the breakthrough of niche innovations. Instead of single drivers or a privileging of techno-economic factors, the MLP's key point is that transitions come about through the alignment of processes within and between these three levels.
Source: (Geels et al., 2017[9]).

Such alignments are difficult, if not impossible, to plan in a top-down manner, and transitions depend on multiple, often independent actions occurring at different levels that are galvanised by a shared common vision. These actions should be mutually supportive and create an "ambition loop" for technology development and deployment, initiating a positive feedback cycle in which policy reallocates finance towards low-carbon technologies, businesses innovate, technologies improve, and social support for the transition grows, enabling the next round of policies to move the transition forward (IEA, IRENA and UNFCCC, 2022[11]). This acceleration of sociotechnical transitions can be triggered by "positive tipping points" (Tàbara, 2021[12]; Sharpe and Lenton, 2021[13]) that reinforce feedbacks and virtuous cycles of subsequent transformative change (Box 3.2).[6] Public policies can enable positive tipping points, creating the spark for their initiation and the conditions for them to cascade through sociotechnical systems (SYSTEMIQ, 2023[14]).

Box 3.2. Enabling positive tipping points for sustainability transitions

Limiting global warming to well below 2 degrees Celsius (°C) requires rapid acceleration in sociotechnical transitions. There are plausible grounds for hope that tipping points can be activated to propagate rapid change through complex systems. This is because change in complex systems is often non-linear, and cause and effect do not have to be proportionate. A tipping point converts a small change in input to a large change in outcome, so that when a tipping point is crossed, highly disproportionate change can occur.

Positive feedback effects dominate the dynamics of a complex system at a tipping point, driving change upwards. In interconnected complex systems, the activation of one tipping point can sometimes raise the possibility of another at a greater scale. This is referred to as an "upward-scaling tipping cascade". Such cascades can induce rapid change on a broad scale, and several previous sociotechnical transitions began with disruptive technology innovations in niches that cascaded upwards through tipping points to society-wide transformation.[1] Any tipping point that gives a new technology a significant advantage, such as increased market share, easier access to finance or broader social acceptance, is likely to amplify its impact.[2]

Looking ahead, policy makers could activate tipping points and tipping cascades to meet climate-change targets. Policy may make a significant difference by investing in R&D for low-carbon technologies, diverting support from incumbents to disruptors, and reconfiguring markets and institutions. A more deliberate search for tipping points and tipping cascades could identify opportunities to accelerate decarbonisation, offering plausible grounds for hope that net-zero targets could still be met. Moreover, small groups of countries with sufficient political or economic clout in a given sector may be able to drive global change by co-operating on activating tipping cascades.

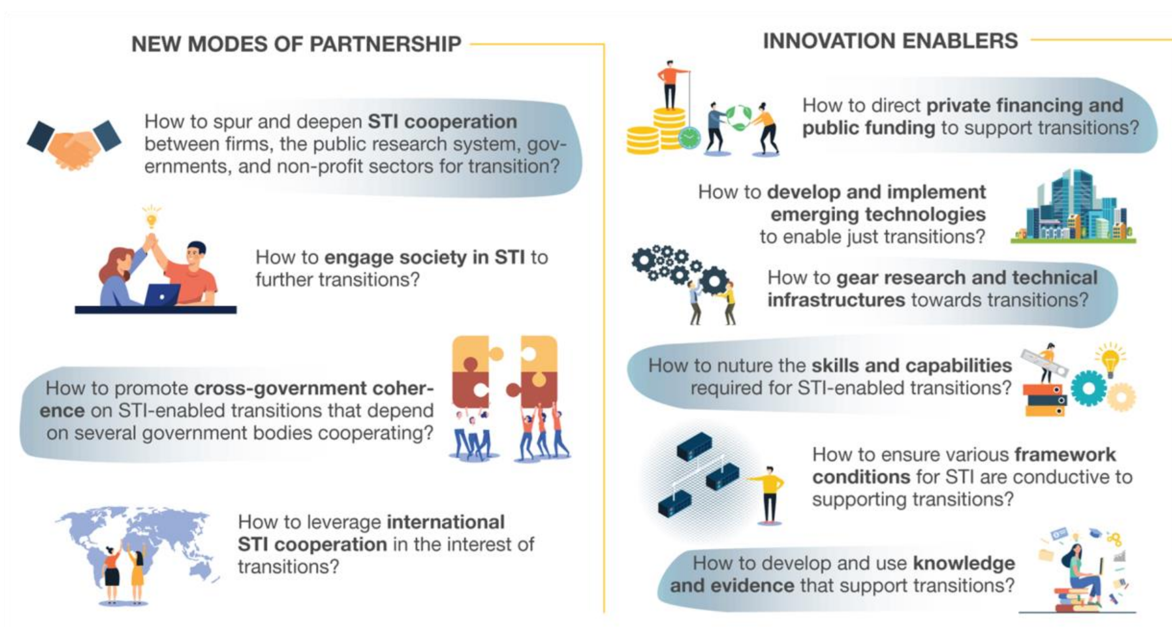
1. For example, citing (Sharpe and Lenton, 2021[13]), "the invention and refinement of the steam engine triggered a massive expansion of coal mining and the creation of a rail transport network, propelling the industrial revolution in England. At the start of the twentieth century, the transition from horse-drawn carriages to fossil-fuelled cars happened in just over a decade in US cities."
2. In a recent example, more than 50% of new vehicles now bought in Norway are electric, where progressive tax policies have made electric vehicles cheaper than petrol cars (Sharpe and Lenton, 2021[13]).
Source: (Sharpe and Lenton, 2021[13]).

Governments need to develop governance and institutional capacities to perform these buildup and breakdown tasks, exploit windows of opportunity in the broader sociotechnical landscape, search for opportunities to trigger tipping cascades and promote just transitions. These capacities are broad in scope and refer to the ways governments set directions and choose priorities; how they develop and maintain relationships with other actors in the innovation system, especially large R&D-performing firms; and how they learn, for example, through monitoring and evaluation. The crosscutting nature of sociotechnical transitions means these capacities should not be concentrated in a single ministry or agency, but widely distributed across government.

Promoting sustainability transitions in STI policy sub-domains

Sustainability transitions in sociotechnical systems like energy, food and transport depend on the development and deployment of enabling technologies. These, in turn, depend on well-functioning STI systems to generate relevant scientific knowledge and technologies at pace and at scale. Larger investments and greater directionality in research and innovation activities are needed, but these should coincide with a reappraisal of STI systems and their supporting STI policies to ensure they are "fit-for-purpose" to contribute to sustainability transitions. This reappraisal is perhaps best done at the level of policy "sub-domains" that constitute the broad STI policy mix. These are shown in Figure 3.5 and include various types of enabling resources (i.e. funding and finance, research and technical infrastructures, enabling technologies, skills and capabilities, various framework conditions and an evidence base to support decision-making) and a range of relationships in STI systems (i.e. between STI and society; between the public, private and non-profit sectors; across different parts of government; and at the international level). System thinking can help identify and understand critical linkages, synergies and trade-offs between these sub-domains that are frequently treated separately.

Figure 3.5. Key challenges for STI policy in promoting sustainability transitions



Source: OECD S&T Policy 2025 project website, https://www.oecd.org/sti/inno/stpolicy2025/, accessed on 15 November 2022.

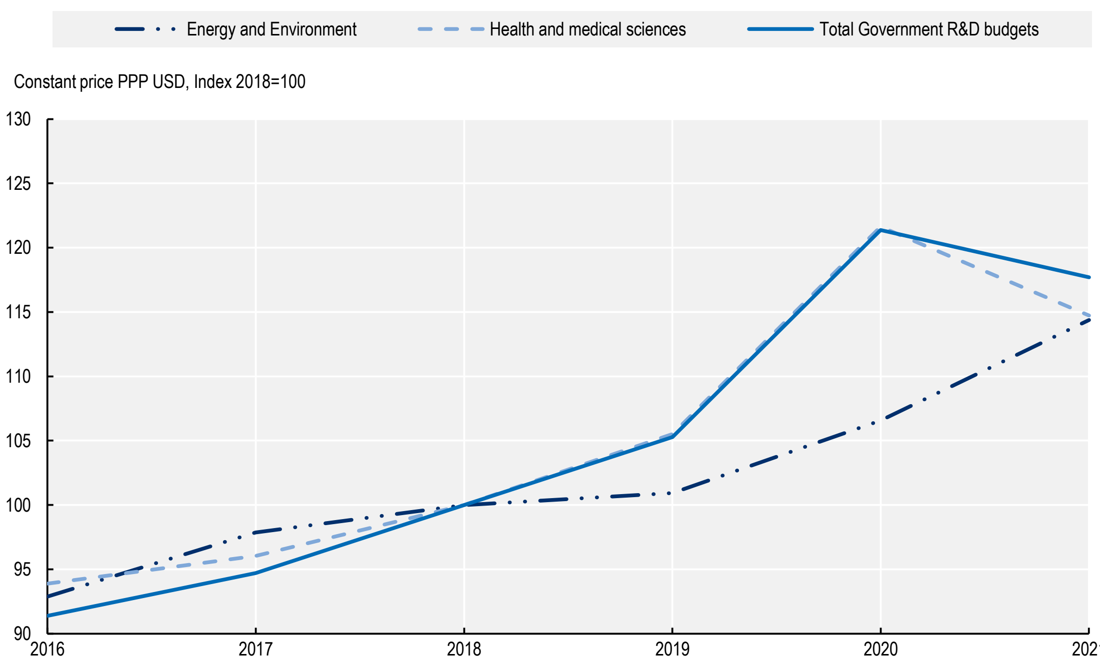
The sections that follow consider the prospects for transition-enabling reforms in these ten policy sub-domains. Given the systemic and multilevel aspects of sociotechnical systems, policy reforms will need to cut across these sub-domains, since many reform opportunities depend on progress in other sub-domains. Appreciating these interdependencies is essential and should empower policy makers to better recognise policy constraints and identify leverage points where they could act to unblock transition barriers.

STI funding and finance for sustainability transitions

Public research funding

While public investments in energy and environment R&D have increased in recent years (Figure 3.6), their growth will need to accelerate if technological developments are to keep pace with meeting net-zero targets. Sustainability transitions require transformational levels of investment over a long period, covering all parts of the innovation chain. The IEA estimates that the global public investment of its member countries on energy R&D and demonstration (RD&D) in 2021 was almost USD 23 billion (US dollars), most of which was targeted at low-carbon technologies. The annual increase of 5% was lower than the annual average of 7% from 2016 to 2020. Energy RD&D expenditure by the People's Republic of China (hereafter China) grew more than 2.5 times over 2015-21 (Figure 3.7), and China is estimated to be slightly ahead of the United States in public energy RD&D spending.[7] While these increases can be viewed positively, the levels of expenditures as a percentage of gross domestic product (GDP) are still less than half those of the late 1970s, when countries invested heavily in RD&D to deal with oil price shocks (Figure 3.8). The climate emergency is a larger challenge requiring arguably similar ambitious levels of investment.

Figure 3.6. Government R&D budget trends, 2016-21



Source: OECD R&D statistics, September 2022. See OECD MSTI Database, http://oe.cd/msti for most up-to-date OECD indicators.

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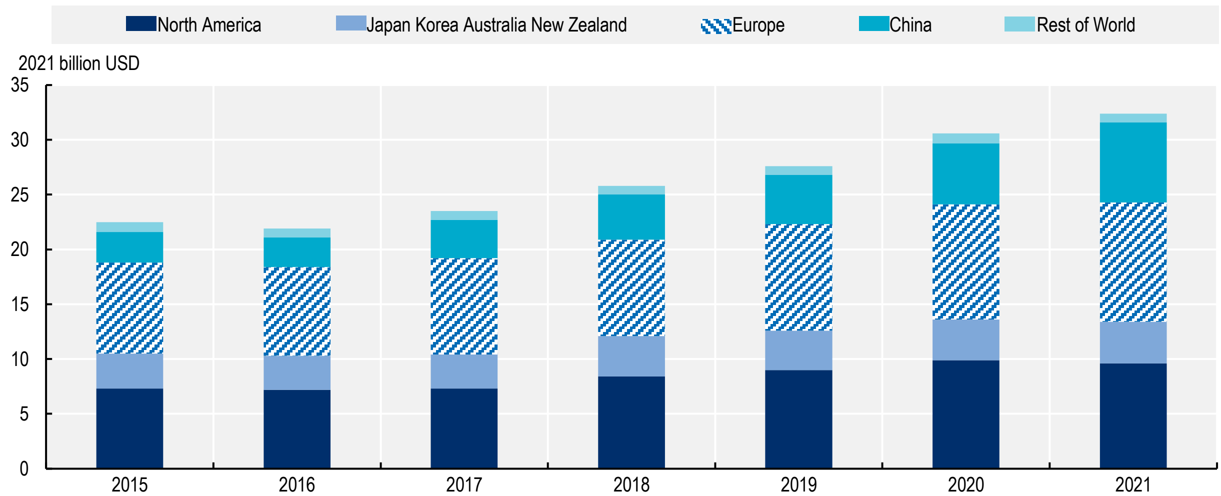
Figure 3.7. Key players in the global landscape

Global public low-carbon energy RD&D budget, 2015-21



Source: IEA, *Global public low-carbon energy RD&D budget, 2015-2021*, IEA, Paris, https://www.iea.org/data-and-statistics/charts/global-public-low-carbon-energy-rd-and-d-budget-2015-202, (accessed on 4 December 2022)

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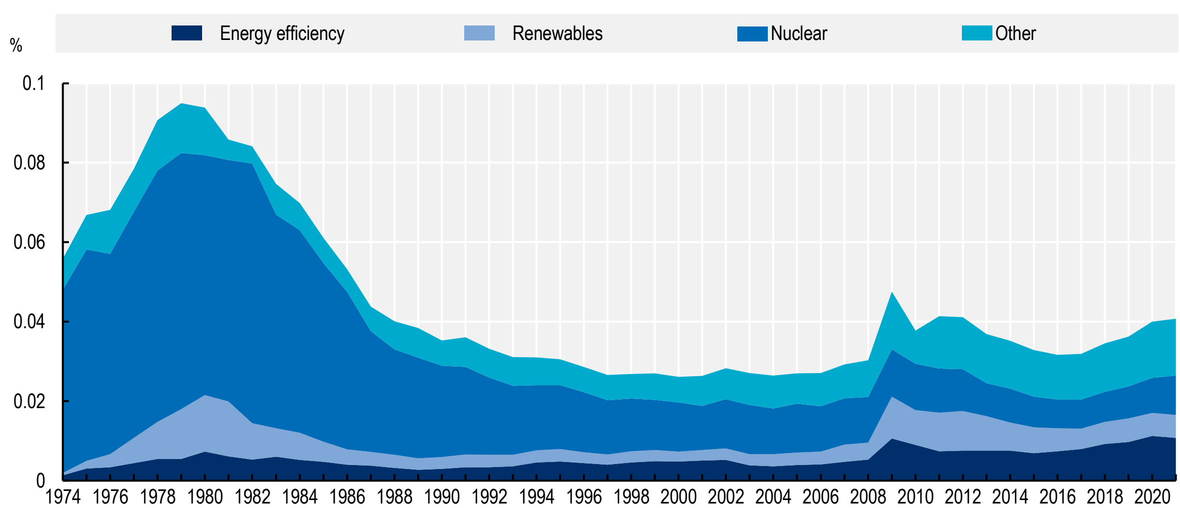
Figure 3.8. Low-carbon public RD&D expenditures in GDP across IEA member countries, 1974-2021

Percentage of GDP



Note: 2021 is estimated data. Data from 2016 for the United States are estimated. The "Others" category includes hydrogen and fuel cells, other power and storage technologies, and other crosscutting technologies and research. See https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2. IEA member countries are Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Lithuania, Luxembourg, Mexico, New Zealand, Norway, Poland, Slovak Republic, Spain, Sweden, Switzerland, the Netherlands, Türkiye, United Kingdom, United States.
Source: OECD calculations based on IEA, RD&D Budget, IEA Energy Technology RD&D Statistics (database), https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2, (IEA, 2023[15]) *and OECD National Accounts Statistics (database),* (OECD, 2023[16]) *(accessed on 17 February 2023).*

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As well as increasing levels of RD&D expenditures, governments need to consider the ways their investments are made and which parts of the innovation chain they target. Governments remain the main investors in fundamental discovery research, but this needs to be more solutions-focused and directed towards generating new knowledge and low-carbon technologies. This requires integrating expertise and insights from different disciplines and different sectors of society, as well as more inter- and transdisciplinary research (see Chapter 4). Such research is not currently mainstreamed and is poorly incentivised in academic research and assessment processes. While most countries are implementing policy initiatives to promote inter- and transdisciplinary research, and some pockets of excellence are emerging, these need to be urgently and substantially scaled up to support transitions to more sustainable socio-economic development pathways (OECD, 2020[17]).

A critical part of the climate innovation policy package is to close the funding gap for large-scale demonstration projects. The amount of funding needed is very significant, particularly in the industry sector.[8] The IEA estimates that at least USD 90 billion in public funding is needed globally by 2026 for demonstration projects in clean-energy technologies for these to be commercially ready by 2030 and help deliver net-zero emissions by the middle of the century (IEA, 2022[4]). Some progress is being made in this regard, with governments supporting major RD&D projects through their COVID-19 recovery packages (Box 3.3), as well as through a new generation of green industrial policies – including the US Inflation Reduction Act and Infrastructure Investment and Jobs Act, the EU Innovation Fund, Japan's Green Innovation Fund and China's 14th Five-Year Plan – with an increasing focus on heavy industry; hydrogen; carbon capture, utilisation and storage (CCUS); and other critical energy technologies (see Chapter 2). More specifically, the United States Government launched the Clean Energy Technologies Demonstration Challenge[9] in mid-2022 to meet the IEA's USD 90 billion target, an amount that was surpassed a few months later after several countries and the European Commission committed to making large contributions during the Global Clean Energy Action Forum in Pittsburgh in September 2022.[10]

Box 3.3. Will post-COVID-19 recovery packages accelerate low-carbon innovation?

The recovery packages adopted in the wake of the COVID-19 pandemic constitute a unique opportunity to accelerate the transition to a low-carbon economy. To assess the impact of recovery spending specifically on low-carbon technologies, the OECD is building the Low-carbon Technology Recovery Database (LTRD). The LTRD currently covers 14 countries within the project's scope of OECD, Group of Twenty (G20) and EU member countries. Combined, these countries represent 66% of global GDP and 53% of global annual CO_2 emissions. The final database, which will be released later in 2023, will include 52 countries.

According to the data gathered so far, a total of USD 1.2 trillion in funding for recovery packages has targeted low-carbon technologies. Half of the funding within the LTRD has been directed at the transportation sector and around one-third to energy generation, transmission or distribution. Around 85% of the measures target the deployment phase, and 15% the RD&D phase. Compared to the recovery packages following the 2007-08 Global Financial Crisis, the response to the COVID-19 crisis appears to have placed more emphasis on RD&D.

Among low-emission technologies that are still in the early stages of innovation and where significant investments in RD&D projects are necessary, hydrogen has been the main priority (especially in the United States, France and Germany), followed by CCUS and smart grids. Relatively small fractions of recovery packages are dedicated to nuclear innovation, zero-emission buildings and large-scale storage technologies.

The analysis shows that while recovery packages make a welcome contribution to closing the investment gap, they fall short of the substantial low-carbon technology investments requirements to be on track to meet the net-zero target. This overall shortfall, however, masks considerable heterogeneity across technologies. Low-carbon technology recovery funding contributes significantly to closing the investment gap for electric vehicles, CCUS and nuclear power; it is substantial for energy efficiency, clean-fuel supply (hydrogen), electricity network and renewables; but it is marginal in electric vehicle (EV) charging infrastructure and negligible in battery energy storage.

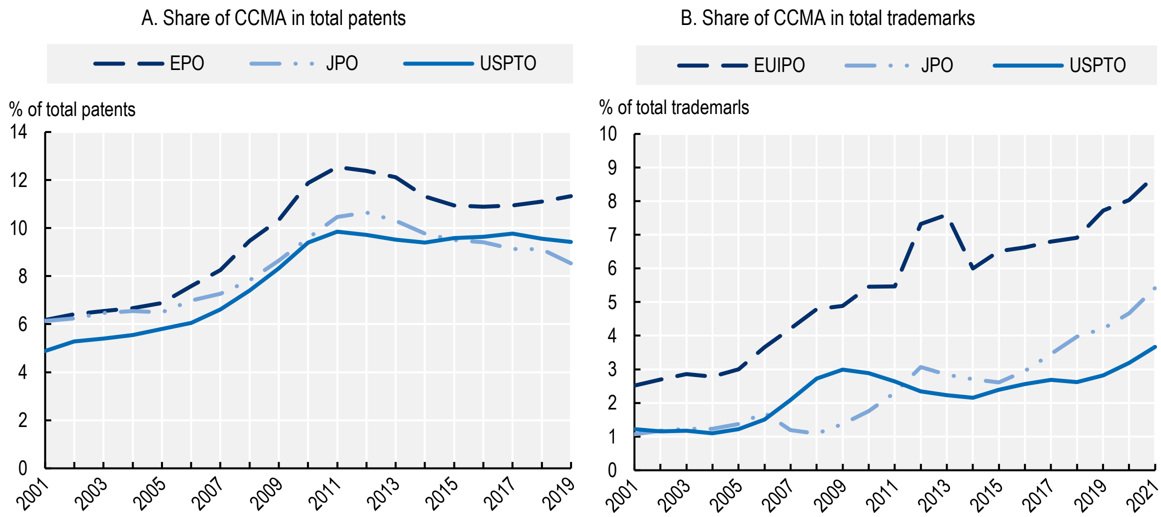
In short, while post-COVID stimulus packages have oriented investment towards sectors and technologies key for the low-carbon transition, they cannot by themselves close the investment gap as needed by 2030. They must now be accompanied by more ambitious complementary climate policies that would induce private investment and trigger the deeper structural changes made necessary by net-zero targets and the current fossil-fuel energy price crisis.

Note: These are preliminary findings of ongoing research on the impact of recovery packages announced in response to the COVID-19 pandemic on the development and diffusion of low-carbon technologies. The final results of this work are intended for publication later in 2023.
Source: (Aulie et al., 2022[18])

An important policy question is how much to spend on deployment of existing technologies compared to RD&D. The answer depends on the relative intensity of market failures associated with technology development, mainly knowledge spillovers at the RD&D stage and learning-by-doing at the diffusion stage. The relative importance of deployment support (market pull) vis-à-vis RD&D support (technology push) should increase with the movement from highly immature technologies towards technologies close to market competitiveness. Patent and trademark filing data can be used as one proxy among others to explore the relative effort assigned to RD&D and deployment (OECD, forthcoming[19]). Figure 3.9 shows that after a period of strong growth between 2006 and 2012, patenting in climate-related technologies has declined recently as a share of total patenting. This is mostly on account of higher growth in patenting in other technology areas, but also because of a sharp decline in climate-related technology patenting at the Japan Patent Office. Figure 3.9 also shows that, by contrast, the proportion of trademarks covering climate-related goods and services has grown markedly over the last two decades, a positive sign of success in technology diffusion and deployment. The patterns here need to be examined more closely and may differ markedly from one jurisdiction to another, but they suggest governments need to pay greater attention to RD&D if technologies currently at the research, development, demonstration or prototype stage are to make it to market by 2030.[11]

Figure 3.9. Patent filings and trademark registrations in climate-change mitigation and adaptation (CCMA) technologies

Percentage of total patents and trademarks



Note: Data refer to patents filed at the European Patent Office (EPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO). Patents in climate change mitigation or adaptation (CCMA) are identified using the Y02 tag of the Cooperative Patent Classification (CPC). For trademarks, data refer to trademarks filed at the EU Intellectual Property Office (EUIPO), the JPO, and the USPTO. CCMA trademarks are identified using keyword searches in the goods and services description of the trademarks. For a definition of CCMA technologies, see (Aristodemou et al., 2022[20]).
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, February 2023 (accessed on 9 February 2023).

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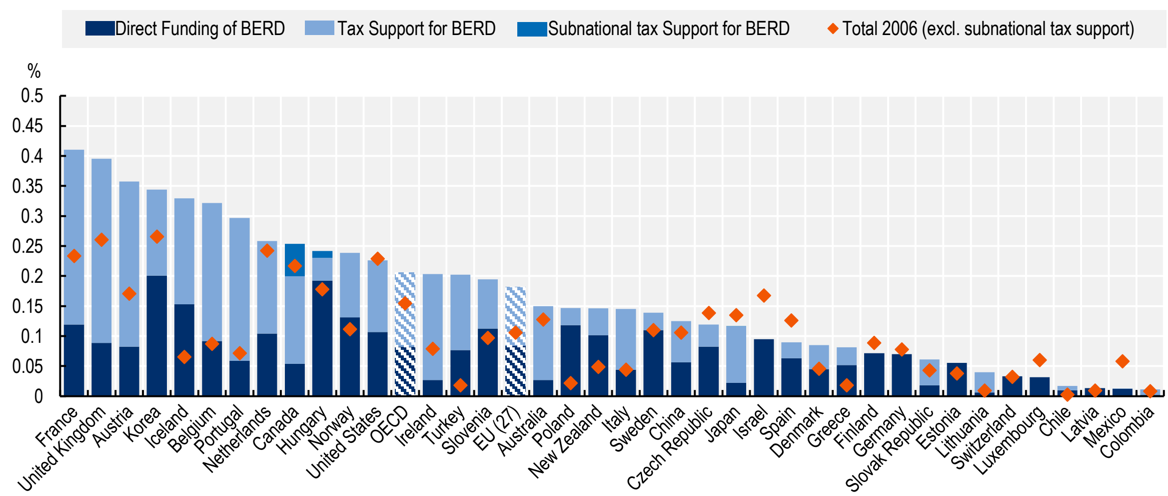
Public funding of business R&D and innovation

Businesses account for the largest share of expenditures on R&D in most OECD countries and are the main performers of innovation activities.[12] Governments vary in the level of support they offer businesses to encourage them to perform R&D and innovate. They also vary in the policy instrument portfolio they use (Figure 3.10). There has been considerable change in the business R&D support policy mix over the last two decades, with a near-universal shift from direct support instruments to a greater reliance on R&D tax incentives. Across OECD countries, R&D tax incentives represented around 60% of total government support for business R&D in 2019, compared to 36% in 2006 (Figure 3.11).

Figure 3.10. Direct government funding and government tax support for business R&D

As a percentage of GDP, 2006 and 2020



Note: Data on subnational tax support not available for China, Spain United States. For general and country-specific notes on the estimates of government tax relief for R&D expenditures, please see http://www.oecd.org/sti/rd-tax-stats-gtard-ts-notes.pdf.
Source: OECD R&D Tax Incentives Database, http://oe.cd/rdtax, January 2023

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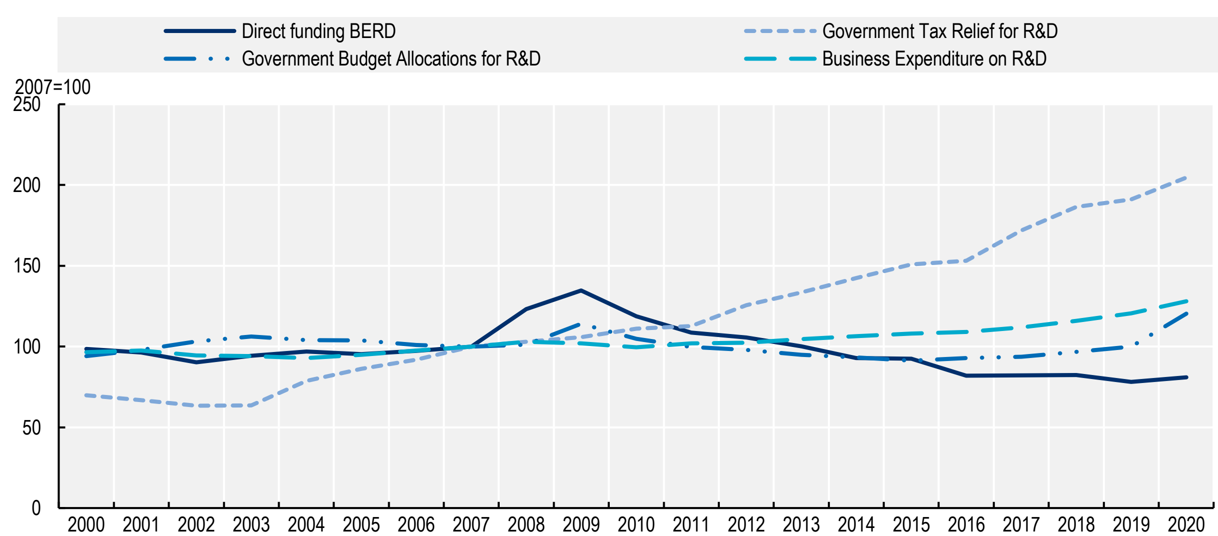
Figure 3.11. Continuing shift in government policy support mix for business R&D

Government funding of Business R&D in the OECD area, 2000-2020, normalised by GDP, 2007=100



Note: Estimates of total OECD direct funding of BERD cover OECD countries, except Costa Rica. Estimates of total OECD R&D tax support (central government level) cover all OECD countries. Direct support estimates include government R&D grants and public procurement of R&D services, but exclude loans and other financial instruments that are expected to be repaid in full. For general and country-specific notes on the estimates of government tax relief for R&D expenditures (GTARD), see http://www.oecd.org/sti/rd-tax-stats-gtard-ts-notes.pdf.
Source: OECD R&D Tax Incentives Database, http://oe.cd/rdtax, January 2023 and OECD R&D statistics, September 2022. See OECD MSTI Database, http://oe.cd/msti, for most up-to-date OECD indicators.

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After two decades of widespread deployment, there exists broad consensus that tax incentives are more suited, in principle, to encouraging R&D activities with near-market potential. By contrast, direct grants are more suitable for supporting longer-term, high-risk R&D, as well as targeting specific areas that either generate public goods or have particularly high potential for spillovers. Both types of measures provide useful support, but the growing urgency to deal with key societal challenges like climate change points to the need for a more directive approach using direct measures (OECD, 2021[2]). Large parts of such innovation funding will likely be channelled through sectors, such as energy and transport, and STI policy will need to co-ordinate with other parts of government to bridge various "valleys of death" across innovation chains. This shift in policy emphasis coincides with the growing use of cross-government industrial policies, including MOIPs, which require governments to make explicit innovation policy choices, in conjunction with other actors (notably firms), on where to focus their limited resources. At the same time, governments need to reacquire at scale the skills and capabilities to operate the sorts of direct financing schemes the net-zero challenge calls for.

Private financing of R&D and innovation

Even with this mix of support, government financing is insufficient to fill the funding gaps that prevent innovations for sustainability reaching the market, and private financing must crowd in.[13] For example, venture capital is a key complement to government support for technology, financing pilots and demonstrations of innovative ideas and prospective technologies, which are often the output of government-funded R&D. Venture capital is also important for small companies to move beyond an initial niche market (OECD, forthcoming[19]). Yet investing in the green transition remains a challenge for private investors for several reasons: insufficient profitability compared to investments with similar risk profiles; difficulty assessing risks owing to information asymmetries between innovators and investors; and challenges in meeting "internal rate of return" requirements or "return on equity" thresholds. These imperfections in the market for capital limit the amount of private capital available for low-carbon RD&D.

The concept of "blended finance", which initially emerged as an innovative tool in the development community to crowd in private financing for sustainability projects in developing countries, is gaining traction in the STI policy field as a way to combine public and private finance across the innovation chain (OECD, 2022[21]; Miedzinski et al., 2020[22]). It works by combining risk-mitigation tools, such as first-loss mechanisms, with debt and equity funding to help firms cross multiple valleys of death at various stages of the innovation cycle. Each instrument has distinctive features in terms of where the capital source comes from, how the return to investment is to be realised, and how to mitigate the risk against the potential return. Blended finance can help scale up private investments in R&D and innovation to better meet sustainability challenges in both developed and developing countries, and has the potential to introduce greater directionality into STI finance.[14] In particular, it can be used to help increase the amount of funding directed to R&D and innovation for "public goods" such as clean air and water systems. These are areas where there are high social returns but weak incentives to invest in STI projects with high economic and technological risk.

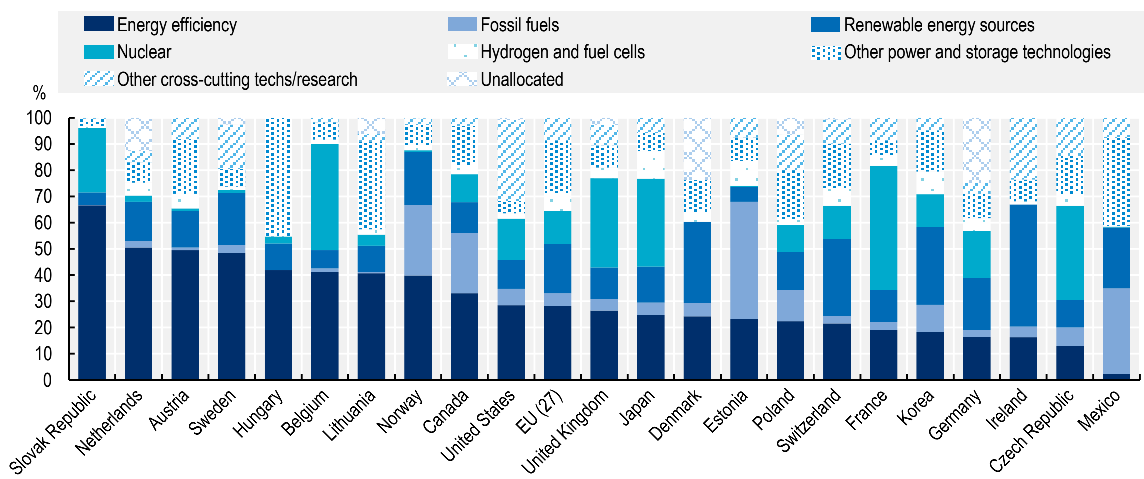
Enabling technologies for sustainability transitions

Recent years have seen widespread deployment of selected low-carbon energy technologies, notably photovoltaics, EV batteries and wind turbines.[15] This is thanks to sharp declines in their costs – for example, EV batteries and photovoltaics have both experienced cost reductions of 90% over the past decade. Costs reductions have been enabled by rapid technological progress, which has been driven by investments in R&D activities, generous subsidies (including feed-in tariffs), learning-by-doing and economies of scale. As a result, many sources of renewable energy are already cheaper than fossil fuels (OECD, forthcoming[19]).

Future technological development prospects are uncertain and often require major investments, particularly by the private sector. Governments are assuming more interventionist roles as they seek to compress the innovation cycle, which requires them to make technological choices. These choices are often informed by portfolio models that seek to "spread bets" on a diversity of technologies and to avoid technological lock-ins.[16] Nevertheless, countries vary in the priority they give to different technologies (Figure 3.12), reflecting in part historical technology commitments (e.g. as major fossil-fuel suppliers, Norway and Mexico devote sizeable proportions of their RD&D to this area, while nuclear technologies account for a large share of RD&D expenditures in France and other countries with large nuclear facilities). Hydrogen and fuel cells remain modest compared to other technology areas but are the fastest-growing area globally (Box 3.4).

Figure 3.12. Public RD&D budgets on renewable energy and other low-carbon technologies

As % of total public energy RD&D, by technology, 2020



Source: IEA, "RD&D Budget", *IEA Energy Technology RD&D Statistics* (database), https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2 (accessed on 21 December 2022).

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Box 3.4. The big push for hydrogen

Government support for the development of low-carbon hydrogen features in the recovery plans of several countries and is a key technology in net-zero emission scenarios by 2050. The potential of "green hydrogen" for decarbonisation has been the subject of particular policy focus recently and may serve as an example of the need for further innovation. Production of green hydrogen, i.e. hydrogen from water and renewable electricity through electrolysis, can contribute to reducing emissions through four channels. First, hydrogen is already a feedstock for a number of chemical products, and green hydrogen can make this production carbon-neutral. Second, hydrogen is a promising alternative to fossil fuels for high-temperature industrial processes in hard-to-abate sectors such as steel production. Third, hydrogen is necessary for the development of fuel-cell vehicles and can also, in specific circumstances, reduce emissions in the built environment by replacing natural gas. Finally, hydrogen can be used to store energy produced from intermittent sources, thereby supporting the supply of low-cost renewable electricity.

Most net-zero emission scenarios agree that hydrogen could play a pivotal role in decarbonisation at the 2050 horizon, particularly for agriculture and industrial applications, providing cheap and abundant renewable energy becomes available. However, in 2021, the production of green hydrogen was still about three times more expensive than grey hydrogen (made out of natural gas through steam reforming), even under the most favourable conditions. Major cost reductions – and the rapid deployment they would induce – are realistic in the next 10-20 years, but will crucially depend on massive improvements in the cost of electrolysers (through R&D and large-scale demonstration projects) and the availability of large volumes of cheap renewable electricity.

Against this backdrop, a number of countries have published national hydrogen strategies, which contain ambitious hydrogen production targets at the 2030 horizon. These targets are a significant improvement with respect to today's virtually non-existent green hydrogen production, but are still far from the necessary deployment at the 2050 horizon. Moreover, these targets mostly rely more on financial support for the deployment of new large electrolysers than on direct support for innovation. In this context, countries willing to support hydrogen should (i) ensure greater support for R&D in green hydrogen and demonstration projects; (ii) ensure a sufficient supply of renewable energy where possible, and encourage the creation of an international hydrogen market; (iii) establish clear carbon price trajectories to provide investors with the right incentives; (iv) reduce uncertainties for investors through regulatory action and standardisation; and (v) consider blue hydrogen (produced from natural gas with carbon capture) as an interim solution to facilitate the transition to green hydrogen.

Source: (Cammeraat, Dechezleprêtre and Lalanne, 2022[23]).

Alongside low-carbon and sector-specific technologies, net-zero will rest on innovation in other domains. The green and digital "twin transitions" offer the promise of leveraging digital technologies for sustainability transitions, with technologies like artificial intelligence (AI) and the Internet of Things (IoT) underpinning smart grids, for example (Box 3.5). Interactions between multiple innovations and sociotechnical systems is therefore an important consideration for STI policy makers, but there may also be trade-offs to manage. For example:

- AI-enabled products and services are creating significant efficiency gains, helping to manage energy systems and achieve the deep cuts in greenhouse gas emissions needed to meet net-zero targets. However, the computational needs of AI systems are growing, raising sustainability concerns. The physical infrastructure and hardware, together with software – collectively known as "AI compute" – require massive amounts of computational resources, which have their own environmental impacts (OECD, 2022[24]).
- The bioeconomy, generally defined as economic activities based primarily on biogenic instead of fossil resources, also offers potential solutions for finding sustainable materials and products. Several countries have introduced national bioeconomy strategies or programmes that aim to support the transition to a circular economy by developing materials that are easier to recycle and reuse (Box 3.6). However, the policy landscape remains complex because of potential sustainability trade-offs due to land and water use, and impacts on biodiversity (Philp and Winickoff, 2018[25]).

Box 3.5. Digitalisation and the green transition

The digital transformation could be a key enabler for reaching climate goals, thanks to technologies such as smart meters, sensors, AI, IoT and blockchain, and to digitally induced changes in business models and consumption.

In the energy sector, demand-side management can help balance the renewable-based electricity system. For example, AI can help forecast weather and electricity prices, mitigating intermittency problems in the system and increasing energy efficiency. Transmission and distribution system operators could use AI for real-time decision support (OECD, 2020[26]) (OECD, 2019[27]). Similarly, IoT devices could help buildings adapt in real time to weather conditions and prices, increasing energy efficiency (OECD, 2016[28]).

Smart mobility will change transport demand and efficiency: “smart” traffic lights can adapt to traffic flow, reducing air pollution and increasing energy efficiency of transport. Blockchain could help manage the distributed grid as it facilitates decentralised consumer-to-consumer selling of electricity and balancing supply with demand without needing a third party.

Industrial sectors will be reshaped through increased robotisation, smart manufacturing systems, additive manufacturing, IoT, smart appliances, sensors and AI, which can all improve energy and material efficiency. Digital solutions are equally important on the supply side, for example by accelerating low-carbon innovation with simulations and deep learning. Already, around 20% of patents protecting climate-change mitigation technologies have a digital component (Amoroso et al., 2021[29]).

The increased use of digital solutions can also change production patterns and trade, and bring production back to some countries (“reshoring”) with better environmental performance. However, digital technologies consume large amounts of energy, implying higher direct energy demand and related carbon emissions, which warrant further efficiency improvements.

Source: (OECD, forthcoming[19]).

Box 3.6. Carbon management for net-zero: Bioeconomy and beyond

Net-zero carbon emissions can be achieved, in part, by a transition in how carbon is “managed”, particularly the budget of carbon in the bioeconomy, carbon recycling and the creation of renewable energy required for various carbon pathways. But the frequently used term “decarbonisation” can be misleading as in some key economic sectors there is no alternative to carbon e.g., food and feed, chemicals, materials and cement. The more accurate term is “de-fossilisation” that implies leaving fossil reserves in the ground and exploiting other sources of carbon. This is the “renewable carbon” concept which entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere.

This resonates with the circular economy concept, an overarching objective of which is to close material loops to keep carbon circulating in the economy for as long as possible. This would break the pattern of “take-make-dispose” that has characterised the fossil era.

The renewable carbon concept largely supports the use of three sources of carbon as feedstocks, namely biomass, recycled solid carbon containing waste material or industry flue gases. Strengthening policies for reusing wastes as resources is a key action, since overly relying on biomass could have serious negative repercussions for biodiversity and food production. In the future, if the uncertainties around direct air capture (DAC) can be resolved, it may become more technically and economically feasible and be part of the solution.

In the meantime, bioproduction, if it can utilise industrial and domestic wastes as other feedstocks, offers promising opportunities, especially for CCU (Carbon Capture and Utilisation). CCU is effectively a value-adding proposition compared to CCS (Carbon Capture and Storage). Both will be necessary, but carbon capture will create a supply chain of pure and concentrated carbon also suited for CCU. Most CCU technologies are embryonic and there are many to choose from e.g., gas fermentation, biochar, advanced wood-based building materials, and chemical recycling of plastics. Recent OECD analysis demonstrates a need for hybrid technologies involving at least two different technologies.

This transition will need to be driven by public policy rather than the market as the feedstocks and energy sources are less efficient than the incumbent fossil sources. The policy types are many and can be arranged according to the innovation cycle. This calls for an holistic policy framework that highlights timing and sequencing for policy makers that aligns feedstock/technology push with market pulls for a more robust effect on the economic system.

Source: (OECD, forthcoming[30]).

These examples demonstrate that technologies can contribute to transitions, but can also generate negative externalities that STI policy should help anticipate and manage, for example, using some of the technology governance techniques outlined in Chapter 6. At the OECD, the Global Forum on Technology was launched in December 2022 to foster multi-stakeholder collaboration on digital and emerging technology policy (Box 3.7), and the 2021 Recommendation of the Council for Agile Regulatory Governance to Harness Innovation sets norms for rethinking governance and regulatory policy to better harness the societal impacts of innovation (OECD, 2021[31]).

Box 3.7. OECD Global Forum on Technology

International cooperation will be a cornerstone of effective emerging technology policy and governance, but the landscape of forums with a true multi-sectoral approach has been sparse. New forums for international cooperation on emerging technology policy are emerging. In December 2023, the OECD Digital Economy Ministerial meeting gave birth to a new OECD Global Forum on Technology that aims to provide a venue for regular in-depth dialogue to foresee and get ahead of long-term opportunities and risks presented by technology. It aims to facilitate multi-stakeholder and values-based discussions on specific technologies among OECD Members and partners, responding to gaps in existing fora.

Some of the other objectives include:

- Identifying and analysing specific technological developments where there are gaps in existing fora, where societal, economic, security, and sustainability impacts are likely to be significant, and where there are major potential implications for policy and regulatory frameworks.
- Exploring nascent approaches to policy challenges and opportunities posed by emerging technologies and business models.

Sharing of good practices for the governance of technologies to build trust among participants and foster common and coherent approaches based on mutual interests and democratic values.

Research and technical infrastructures

Various types of infrastructures are essential to research and technological innovation. Laboratories and research equipment are obvious examples, but other infrastructures include those supporting open science (e.g. digital repositories for research data) and open innovation (e.g. living labs, technology demonstrators and extension services). Many of these infrastructures – including large public research infrastructures (RIs) and technical infrastructures (TIs)[17] – require substantial initial outlays and must develop business models that distribute costs and benefits in fair and sustainable ways. Challenge-oriented transitions present them with new opportunities, for example, as sites of large demonstration and scale-up initiatives that are essential for sustainable transitions, but also difficulties in adapting to new constellations of actors and their research and innovation support needs.

Historically, structural siloes and bottlenecks have posed a significant challenge to effective collaboration between RIs and, more broadly, with potential users or partners operating in different disciplines and at different stages of the R&D pipeline, including TIs. This came to the fore during the COVID-19 response when established connectivity between system actors, such as those operating in basic, applied and industrial research was critical to accelerating the advancement of scientific solutions. The complexity of the crisis highlighted the value of cross-infrastructural workflows for projects that require the services of multiple RIs and TIs. It also emphasised their status as sites of collaboration between diverse and disparate partners, and as focal points for the development and dissemination of unique and cutting-edge research and data. Effective integration of crisis response capabilities into the mandates of RIs and TIs will require a shift from prioritising short-term financial efficiency to building strategic redundancies, resilience and long-term effectiveness. While this has a funding dimension, it also requires expertise, both for internal operations and for benefiting the broader STI system (Larrue, 2021[32]; OECD, forthcoming[19]).

Co-operation and partnerships within innovation ecosystems

Mobilising a diverse set of actors, including businesses, governments, the scientific community and citizens, to co-operate on transitions will be essential. Governments have a long tradition of promoting industry-academic links, using a mix of policy instruments, including funding, regulation, information services and governance arrangements, to spur and deepen relations. Governments increasingly use challenge-based funding and MOIPs to draw together diverse sets of actors into collaborative arrangements that target transitions (see Chapter 5). For mission-oriented collaborative platforms, the shift of national and international R&D programmes to more open and participatory models comes with a need for new governance processes for knowledge transfer, including alliance management, asset sharing, privacy, transparency, value creation and responsibility. Joint efforts between the public, private and non-profit sectors have encountered challenges to data sharing, ownership and value creation. Policies can help to share knowledge and resources, facilitate decision-making processes and align innovation with societal needs (OECD, 2021[2]).

As technology becomes more complex, innovation is increasingly shifting towards platform-based co-operation models. New institutional arrangements, such as collaborative platforms, are emerging to co-ordinate a diverse set of actors across the public and private sector, and create value by harnessing platform effects. They entail a technological architecture that allows their members to innovate rapidly, but also to collaborate with many external players who can use the platform for their own innovations. Many governments, along with partners in industry, start-ups and civil society, are developing experimental forms of these collaborative platforms to provide better linkages between research and innovation, and promote commercialisation. By bringing together experts from academia, industry and the philanthropic sector, collaborative platforms are often more flexible than national regulatory frameworks when it comes to setting technical standards for the application of technology and managing associated risks. Furthermore, government involvement in collaborative platforms can help de-risk investment in emerging technologies (OECD, 2021[2]).

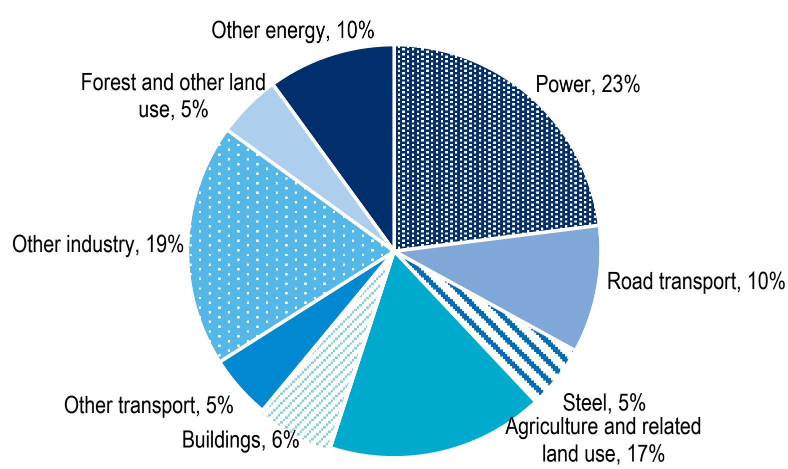
Finally, research funders in many countries are striving to promote transdisciplinary research (TDR), which can address complex problems beyond the reach of traditional science. TDR offers a practical way to address issues, such as sustainability transitions, that are highly contested and where stakes are high. It is a mode of research that integrates both academic researchers from unrelated disciplines – including natural sciences and social sciences and humanities – and non-academic participants to achieve a common goal involving the creation of new knowledge and theory. Given the scale and urgency of the human-environmental system challenges facing society, there is a strong argument that TDR needs to be scaled up singificantly and become a mainstream modus operandi for research. This would affect both the prioritisation of research areas and changes to funding processes, including funding criteria, peer review and evaluation (OECD, 2020[17]).

Cross-government co-ordination for transitions

Sociotechnical transitions are complex and uncertain, requiring multi-agency government responses. Cross-government linkages and policy coherence are therefore essential for transitions. However, like all large organisations, governments struggle with co-ordination challenges, which can lead to incoherence in the policy mix for transitions, and ultimately less policy effectiveness. This also applies to STI policies, and the mix of support measures governments offer might not adequately match the challenge at hand or the wider policy mix of regulation and incentives. Misalignments can be horizontal (between innovation policies and sectoral policies), vertical (between ministries and implementing agencies), or multilevel (between national and regional authorities).

Sustainability transitions cannot be achieved or even chiefly driven by STI policies, although they are certainly essential. A range of sectors contribute to greenhouse gas emissions (Figure 3.13), and sectoral policies in areas such as energy and agriculture are expected to do much of the heavy lifting. These sectors in many OECD countries have their own considerable STI activities and capabilities which, when taken together, can dwarf those under the direct responsibility of research ministries and their funding agencies. Government sectoral support covers the full range of innovation chain activities, from fundamental research to technology demonstration, diffusion and deployment. Governments also link achieving net-zero to growing industrial policy goals, where increasing the rate at which promising new technologies enter the energy system can potentially drive future economic growth. Energy security concerns also shape this policy agenda, for instance, through concepts like "strategic autonomy" (see Chapter 2). This wider framing therefore brings in other government policy domains, raising further co-ordination and coherence challenges.

Figure 3.13. Greenhouse gas emissions by sector, 2019



Source: (IPCC, 2022[33]).

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Domain specificities are therefore important considerations for STI policy when trying to promote and assemble configurations of actors to develop transition-enabling innovations. Sectoral STI activities operate with their own logics, institutions and policy practices that often differ from those of mainstream STI policy. This need not be problematic in itself, but it highlights the need for governance mechanisms that promote strategic alignment to deal with crosscutting issues like climate change. There are no “silver bullets”, and co-ordination failures are often caused by government budget structures, which tend to disincentivise co-operation and often promote competition between different parts of government. Various governance arrangements have emerged over the years to improve the overall coherence of STI policies, programmes and instruments across a range of government departments and agencies, as well as at different governance levels (e.g. regional, national, European Union). Among these are shared national visions, roadmaps and missions; new regulatory models that provide greater scope for experimentation; sectoral technology needs assessments; joint programming between research and innovation funding agencies; and strategic oversight by high-level cross-departmental committees. Beyond these “formal” mechanisms, informal arrangements and conditions (e.g. the circulation of civil servants) can also promote cross-governmental co-operation. Political leadership at the highest levels is also often a prerequisite for a directional approach that cuts across government.

In a similar vein, the recent turn to MOIPs attempts to bundle together a range of complementary public interventions to achieve ambitious goals for which more traditional fragmented STI policies have produced, at best, only mixed results. These specific ”co-ordinated packages” of research and innovation policy and regulatory measures can span different stages of the innovation cycle, from research to demonstration and market deployment; mix supply-push and demand-pull instruments; and cut across a range of policy fields with responsibilities for different thematic areas (Larrue, 2021[32]). Several countries are currently experimenting with different types of MOIPs to tackle all kinds of societal challenges, including net-zero, as outlined in Chapter 5.

Framework conditions for STI-enabled sustainability transitions

The roles science and technological innovation can play in sociotechnical transitions is shaped by a wide range of structural and institutional factors. For example:

- The disciplinary organisation of science and the autonomy of research-performing organisations, such as universities, all significantly shape the priorities and practices of public research and modulate the influence of public policy interventions.
- In technological innovation, the functioning of product and labour markets, the scope of regulation (including on carbon pricing, intellectual property, environmental protection, etc.), technical standards, firms’ business models and geography, among other factors, all influence the rate and direction of innovation. Low fossil-fuel energy prices also influence incentives for investment in low-carbon and energy efficiency innovation, with the trend in worldwide low-carbon patent intensity mapping closely to international oil price changes, i.e. the higher the oil price, the higher the patent intensity in low-carbon inventions.

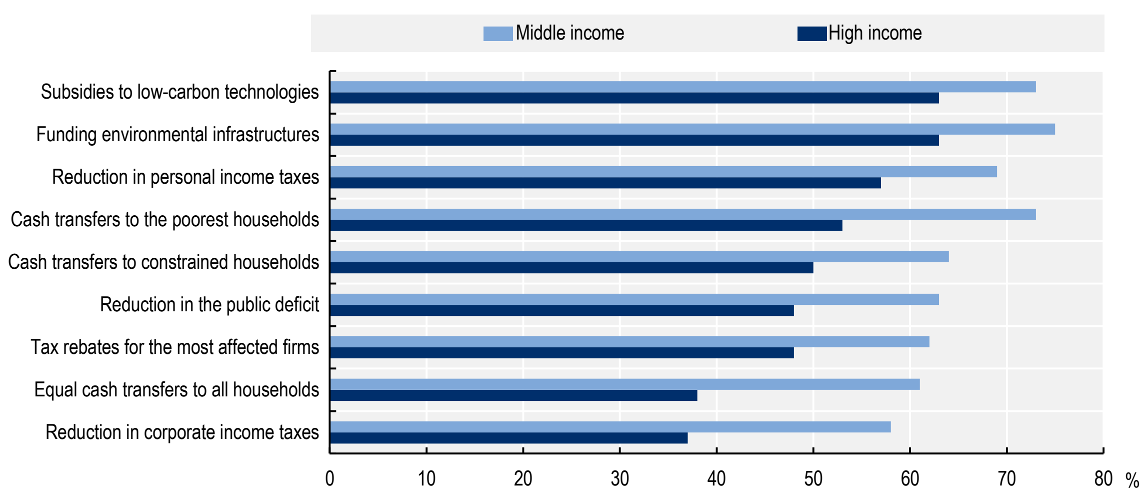
These framework conditions, which often have their origins outside of the immediate remit of STI policy, can either enable or hinder sociotechnical transitions. They are important leverage points for promoting transitions, but may also offer significant barriers and lock-in. This sub-section outlines three framework conditions that influence low-carbon innovation, namely business dynamism, standards and carbon pricing.

Lack of business dynamism may prevent low-carbon innovations from overtaking fossil fuel-based incumbents and secure market shares, even if they are more efficient. Start-ups are often the vehicle through which radical innovations enter the market, older incumbent firms often focusing on incremental changes to established technologies. Limits to competition can therefore slow down sustainability transitions. Concentration of market power can also be a challenge as long-term investors (e.g. asset-heavy banks, institutional investors) may favour incumbents because of perceived stable returns. Though alternative forms of financing (e.g. business angels and venture capital) can encourage greater risk-taking, they do not invest with a sufficiently long time horizon to drive transitions (OECD, forthcoming[19]).

Standards play key roles in shaping innovation trajectories, including in green technologies, where air quality and waste regulation (for example) have driven developments in clean technologies such as catalytic converters and incineration plants. Different types of standards can be used. For instance, a performance standard sets a uniform control target for firms, but does not dictate how this target is met. Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation, such as by requiring that a percentage of electricity be generated using renewable sources. In this way, standards help create demand for low-carbon innovations and induce technological change (OECD, forthcoming[19]); also see Chapter 2.

Because carbon pollution is unpriced by the market, there exist too few incentives for firms to develop or deploy technologies that can reduce carbon emissions. Carbon pricing is a way to make polluters pay for their greenhouse gas emissions, for example through a carbon tax or a cap-and-trade system. By making polluting emissions costly, carbon-pricing policies change the relative costs and benefits of competing technologies. This can lead to the development of new technologies and processes that are more energy-efficient and environmentally friendly. However, measures like carbon taxes are politically unpopular and are currently set at sub-optimal levels. STI policies can help reinforce the impacts of carbon prices by supporting innovations that lower the cost of green technologies, making them competitive with existing technologies. In this way, STI policies can partially substitute for low carbon prices, which supports the case for even stronger STI policies (OECD, forthcoming[19]). STI policies can also help create economic winners from the low-carbon transition, which can benefit the political acceptability of future climate policies. From a public acceptability point of view, STI climate policies also appear to be an attractive option. Recent research from a nationally representative population survey (Dechezleprêtre et al., 2022[34]) shows that subsidies for low-carbon technologies are systematically the most favoured climate policy compared to carbon pricing, bans or regulations (Figure 3.14).

Figure 3.14. Share of respondents who support climate-change policies (somewhat to strongly)



Note: Policy views are elicited on a five-point scale: "Strongly oppose," "Somewhat oppose," "Neither support nor oppose," "Somewhat support" and "Strongly support." The figure shows the share of respondents to answer: "Somewhat support" or "Strongly support." High-income countries participating to the survey are Australia, Canada, Denmark, France, Germany, Italy, Japan, Poland, Korea, Spain, the United Kingdom and the United States. Middle-income countries participating are Brazil, China, India, Indonesia, Mexico, South Africa, Türkiye and Ukraine.
Source: (Dechezleprêtre et al., 2022[34]).

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Societal engagement and just transitions

An inclusive and people-centred transition is key to the world moving rapidly, collectively and consistently towards net-zero emissions by mid-century (OECD, 2021[35]). Widespread social acceptance is needed to create legitimacy and support for strong transition policies and improve resilience against political setbacks (Geels et al., 2017[9]). Achieving momentum to address green sociotechnical transitions will require public support of policies that rely on technical evidence, as well as public reasoning about the future of technology in society. Moreover, in a context of high complexity, engaging citizens in STI policy can tap diverse sources of ideas and information, as well as help identify the real needs and concerns of different social groups, including those that are under-represented in science, innovation and respective policy spaces. This can promote more legitimate policy decisions that better respond to citizens' needs, and take into account their broader socio-economic impacts and ethical implications (see Chapter 6).

These are important considerations for a "just" transition, whose goal is to ensure that the costs and benefits of transitioning to a more sustainable future are shared fairly, and that no one is left behind (OECD, 2021[35]).[18] This can include measures such as providing support for people of working age who may be displaced by the low-carbon transition, investing in education and training to help people adapt to new industries, and ensuring that marginalised communities have a voice in the transition process.[19] For example, the European Commission has launched the Just Transition Mechanism, which mobilises around EUR 55 billion (euros) over 2021-27 to alleviate the socio-economic impact of the transition in the most affected regions. The IEA has established the Global Commission on People-Centred Clean Energy Transitions, which has unveiled 12 key recommendations designed to help citizens to benefit from the opportunities and navigate the disruptions created by clean-energy transitions.[20]

Finally, communicating scientific uncertainties to society and being transparent about conflicting or dissenting scientific views will continue to be a major challenge, and scientific mis- and dis-information risk undermining the critical role that scientific knowledge and new technologies have to play in any transformation to sustainable development. Governments, scientists and technologists need to draw lessons from the COVID-19 experience to formulate strategies and implement measures that combat mis- and dis-information, for example on the existence of climate change and the need for mitigation and adaptation measures (see Chapter 4).

Strategic intelligence for sustainability transitions

Transitions call for systemic and transformative STI policies that must act at pace under conditions of uncertainty. They also call for different sorts of knowledge and evidence bases to inform STI policy design, implementation, coherence and evaluation. Relevant methods include strategic foresight and technology assessment, modelling and simulations, systems and pathways mapping, monitoring and evaluation, and quantitative indicators development, all of which can be collectively referred to as "strategic intelligence". Whether existing strategic intelligence provision and use are well suited to the high ambition of transition policy agendas is doubtful. Transformative STI policies demand knowledge and evidence to support direction-setting, experimentation and learning in contexts that are systemic, transdisciplinary, complex and uncertain. These demands may require new or significantly adapted knowledge institutions and infrastructures, as well as new skills and organisational capabilities – essentially a transition in the production and use of strategic intelligence itself. A specific challenge for countries is to make sense of the range of data available, and in particular to combine and synthesise knowledge and evidence from different sources that have different formats and have been produced for different purposes.[21] With this in mind, several countries are in the process of developing crosscutting strategic intelligence infrastructures for STI policies to meet the transitions challenge.

Future-oriented technology analysis

Many national research ministries and funding agencies have used strategic foresight in recent decades to help them set research priorities, organise new configurations of actors, and become more agile as organisations in times of uncertainty. The “twin transitions” challenge has seen heightened interest in foresight practices, as signified for example by the European Commission recently appointing a commissioner for foresight, publishing an annual strategic foresight report since 2020 and organising a foresight network of ministers for the future from EU Member States.[22] Both long-term trends and drivers, as well as disruptive events like the COVID-19 pandemic, mean existing assumptions may no longer hold and the near-future may look considerably different from the recent past. Policy tools, such as strategic foresight, can help shed light on possible futures. They can also indirectly reduce uncertainty by promoting collective action around widely shared future visions, for example, on sustainability transitions (Cagnin, Amanatidou and Keenan, 2012[36]).

Technology assessment (TA) is an evidence-based, interactive process to bring to light the societal, economic, environmental and legal aspects and consequences of new and emerging science and technologies. It aims to inform public opinion, help direct R&D, and act as a source of strategic intelligence to shape policies that both promote and govern new and emerging technologies. TA is conducted for a variety of sometimes overlapping reasons. It is deployed to anticipate the potential impacts of new and emerging technologies, to avoid surprise and allow for risk and uncertainty management. It is also used to guide innovation and technology development towards societal goals, by informing and shaping agenda-setting and bringing to light key values and norms in the relationship between technology and society (OECD, forthcoming[19]). Chapter 6 discusses TA in the context of technology governance.

Monitoring, evaluation and statistical indicators[23]

The emergence of transformative STI policies brings new challenges for monitoring and evaluation, since current STI indicators and traditional evaluation approaches are unable to grasp the complexity of the underlying transitions of sociotechnical systems. Methods that can capture system-level effects and allow for reflexive learning and formative evaluation are needed (Janssen, 2019[37]), as are approaches that can account for policy interactions, the engagement of multiple stakeholders, and co-ordination among different domains and levels (Haddad et al., 2022[38]). Since policies set priorities for transformative change, evaluation should also capture whether the direction of innovation and change responds to societal needs.

Sociotechnical transitions are deep and wide-ranging, and many aspects are not well served by existing metrics. One key challenge for building evidence is the limited capacity to bring together data on innovation inputs with data about material flows that matter for sustainability transitions. While progressively advancing at a general level, the data-linking agenda is not moving as fast as required by the severity of the policy challenge and needs to go beyond the domain of economic statistics. This requires more effective policy co-ordination and regulation to ensure there are safe spaces in which data that may be deemed confidential can be safely processed and analysed to its full potential.[24] Several national statistical organisations are rising to the challenge, but the innovation perspective is still seen as residual.

The challenge straddles multiple disciplines and actors. This is therefore a shared agenda with other policy and statistical domains that requires breaching silo mentalities while preserving some degree of specialisation. The green transition challenge requires measurement and analysis to carefully account for the distinct nature of micro-level indicators, as well as indicators about the emergent properties of innovation at the local, regional, national and global systems, and their transformation. STI measurement and policy analysis should also equip itself with the necessary tools to depict and manage uncertainty.

As policy makers use indicators as incentives to steer the green transition, a major challenge for both policy and measurement is the tendency for generalised “greenwashing” of activity, which risks diluting the informational content of such indicators. Policy makers need to work with indicator experts to put in place robust, hard-to-cheat systems, approaching the challenge strategically. The larger the (economic, environmental, reputational) stakes, the larger the risk that biased information will displace high-quality data and analysis.

International co-operation

International co-ordinated action can accelerate innovation, enhance economies of scale, strengthen incentives for investment and foster a level playing field where needed. Sharing experiences between countries and industries can reduce individual risks and accelerate progress towards viable low-carbon solutions. Measures and commitments to deployment can accelerate economies of scale and the corresponding cost reductions (IEA, IRENA and UNFCCC, 2022[11]). Given the global scale and scope of challenges like climate change, there is a growing sense that more needs to be done at the multilateral level to promote technological development, deployment and diffusion. The United Nations negotiations on climate change have established a strong consensus for action, and a large number of countries have committed to significant individual actions through their nationally determined contributions (NDCs). A great many initiatives for practical global engagement are already operating and involve governments, businesses, international and multilateral organisations, civil society organisations, and investors. The number and diversity of collaborative international initiatives has grown remarkably over recent years, and many of these have already made important contributions to the progress in low-carbon transitions (IEA, IRENA and UNFCCC, 2022[11]).

Several recent international initiatives have been launched. They include "Mission Innovation", a global initiative launched alongside the Paris Agreement in 2015 that aims to catalyse action and investment in RD&D to make clean energy affordable, attractive and accessible to all countries in the next decade. Mission Innovation brings together governments,[25] public authorities, firms, investors and academia to work together on public-private action and investment through sector-specific "missions" that accelerate clean-energy innovation in critical areas.[26] Another initiative, launched during COP26 in 2021, is the "Breakthrough Agenda", which involves 45 countries[27] that are committed to working together to accelerate innovation and deployment of clean technologies, and making them accessible and affordable for all by 2030. The agenda is designed to help trigger tipping points (see Box 3.2) and stimulate international collaboration involving both the public and private sectors. It focuses on five key emitting sectors of the economy – power, road transport, steel, hydrogen and agriculture (IEA, IRENA and UNFCCC, 2022[11]). More recent initiatives include the proposed Group of Seven (G7) Climate Club (G7, 2022[39]), which aims to provide an intergovernmental forum to to promote ambitious climate policy around the world, and the OECD's Inclusive Forum on Carbon Mitigation Approaches, which aims to facilitate multilateral dialogue on climate-change mitigation policies (OECD, 2022[21]).

Wide access to clean technologies will require considerable technology diffusion, particularly to low- and middle-income countries that are expected to account for the vast majority of the increase in global carbon emissions until 2050. This is a complex issue requiring multiple interventions. A key determinant of international diffusion is the domestic level of technological development, or technological capabilities, in recipient countries. The latest IPCC report (IPCC, 2022[33]) discusses the main challenges and possible solutions at some length, and highlights emerging ideas for international co-operation on innovation. These include promoting developing-country participation in technology programmes, climate-related innovation system builders and the creation of universities in developing countries that play the role of central hubs for capacity-building, as well as encouraging sectoral agreements and international emission standards. The United Nations Framework Convention on Climate Change (UNFCCC) set up the Technology Mechanism in 2010 to facilitate support to developing countries on climate technology development and transfer. This includes financial mechanisms and capacity-building, and technical support to help countries implement their NDCs. The UNFCCC recently published guidance on stimulating the uptake of technologies in support of NDC implementation and its new work programme until 2027 for accelerating climate action through technology development and transfer (UNFCCC, 2021[40]). However, it remains grossly underfunded in view of its ambitious mandate (OECD, forthcoming[19]).

Skills and capabilities

Transitions call for wide-ranging changes – from lifestyles to the ways scientific research is carried out – involving many different types of actors, including research organisations, industry, government, entrepreneurs and civil society. Yet many individuals and organisations lack what might be considered transition-enabling skills[28] and capabilities (including dynamic capabilities that enable organisations to adapt to changing conditions). For example:

1. Research-funding and research-performing bodies need to adapt their disciplinary management processes and training to promote TDR, which has implications for their organisational capabilities and their employees' skill sets. For example, peer-review and programme development and management processes need to be adapted to take into account the specificities of TDR. Some research-performing organisations have already gone as far as articulating their missions and reorganising their faculty and departmental structures around societal challenges, while others have invested in inter-disciplinary and/or multi-stakeholder platforms. Yet others have adjusted their teaching and training activities to promote TDR. Still, much more needs to be done to foster TDR (OECD, 2020[17]).
2. In the public sector, the sorts of capabilities needed to promote sustainability transitions go beyond the skills of civil servants (important as these are) to also encompass organisational capacities and routines. These are not easy to develop quickly, nor can successful organisational capacities and routines be simply replicated, given their embeddedness in organisational histories and cultures. There has also been a certain degree of "hollowing out" of state capacities in many OECD countries over the last few decades, which means governments may need to rebuild the organisational capabilities necessary to carry out transition tasks (OECD, 2021[2]). This is at a time when many governments are looking to reduce their expenditures and reduce the size of their administrations.
3. In firms, a lack of skills and capabilities reduces their choices to invest in innovation. New technologies require new skills and business models to enable their development and diffusion, and the deployment of new infrastructure. A successful green transition is likely to entail, for example, upgrading skill sets in industries experiencing only minor adjustments; gearing up educational institutions and firms to provide the new skills for new occupations and sectors that will emerge from the green economy; and retraining and realigning skills in sectors that will decline as a result (OECD, forthcoming[19]).

Addressing new skills and capabilities requirements in the STI system brings together a number of policy areas, including the labour market, education and STI. On the one hand, it requires understanding the supply side of skills and capabilities, including labour-market dynamics and the performane of education systems. On the other hand, it requires an appreciation of changing demand as societal priorities increasingly aim to boost sustainability and other key technological developments. Policies for future skill and capability development in STI systems also need to target a broader range of societal, demographic and economic groups to avoid perpetuating inequalities and promote a just transition. For example, the engagement of younger generations in climate policy-making and action is increasingly seen as key to meeting net-zero targets. Education systems need to equip youngsters with the skills and competences that would help them adopt environmentally sustainable behaviours, including science skills (Borgonovi et al., 2022[41]). In the workplace, new types of jobs are being created while many existing jobs are changing with the adoption of cleaner technologies and greener work processes. At the same time, some sectors will face jobs losses, as societies move away from polluting activities. Work-based learning – and vocational education and training more generally – can provide opportunities for adults to up- and reskill for a greener labour market. These opportunities should be explored from a systemic perspective that incorporates innovation and industrial policy agendas (Cedefop, 2022[42]).

Outlook

Sustainability transitions will depend on science and technology for their success, but will also present challenges for research and innovation activities – and, by extension, for the STI policies that support them. This chapter has highlighted the need to compress the innovation cycle, which implies rapid changes in multiple systems simultaneously. This calls for greater directionality in STI systems, including in STI policies, which can help articulate shared visions that mobilise a wide range of actors. However, sociotechnical systems are complex and adaptive, and difficult to direct in a top-down manner. A systemic, multilevel perspective can help design policy mixes that simultaneously create windows of opportunity, build up innovative technologies and markets, and break down existing fossil-based sociotechnical systems.

To operationalise these insights in concrete terms, the chapter has outlined a simple framework that considers transition reforms from the perspective of ten different but interlinked STI policy sub-domains. Funding and finance are the first of these, where transformational levels of investment across the innovation chain, including low-carbon technology diffusion and deployment, are needed to meet the scale and pace of the net-zero transition. Moreover, the balance of funding support for public and private R&D should shift to become more directive and solutions-oriented than today's policy mix. A related policy mix consideration concerns which technology areas to target. Technological innovation is an uncertain activity, and technologies often interact with one another in unpredictable ways. Ideally, countries would spread their investments to develop domestic absorptive capacities for a range of technologies, but this is difficult for countries with smaller STI systems, who would benefit from co-operation with other countries to pool their efforts. Furthermore, technologies can create negative externalities, and potential trade-offs need to be assessed continually (see Chapter 6).

More directed and solution-oriented R&D and innovation imply strengthening co-operation and partnerships in STI systems, including between scientific disciplines and between technology areas, as well as between actors and activities at different stages of the innovation chain. This can help direct and accelerate the pace of technological change, strengthening innovation chain linkages through the co-design and co-production of science, technology and institutions, including markets. Wider society also needs to be actively engaged in these processes. Public RIs and TIs can be useful focal points for assembling constellations of innovation system actors, providing large-scale facilities for RD&D. However, to perform this role effectively, they need to acquire new skills and capabilities, and receive more long-term strategic funding.

While STI policy can enable sustainability transitions, other policy areas will likely take the lead – notably those responsible for the largest greenhouse gas emissions, such as energy, transport and agricultural policy. These have their own sizeable RD&D and deployment activities, together with supporting policy systems with which STI policy needs to interface. These policy areas also determine many of the framework conditions that shape technological development paths, including competition policies that encourage new innovative firms to challenge incumbents, standards that help create demand for low-carbon innovations and carbon pricing that incentivise firms to adopt clean technologies. Governments continue to experiment with new approaches to improve cross-governmental co-ordination, including MOIPs (as described in Chapter 5), but this is a long-standing challenge with no quick and easy solutions.

The global scale and scope of climate change mean that international co-operation is essential to meet net-zero targets. International STI co-operation can take many different forms, and its benefits can be wide-ranging. However, it faces several barriers, not least that the vast majority of public R&D funding is allotted within national boundaries, and international alignment between national calls and programmes in notoriously difficult to achieve. Many low- and middle-income countries also need to enhance their scientific and technological capabilities to absorb low-carbon innovations. The growing securitisation of STI policies and rising geopolitical tensions could also impede future international co-operation (see Chapter 1).

The systemic scale and scope of the sustainability transition, and uncertainties over its future course, call for a transformation of the knowledge and evidence base on which policy decisions will need to be made. Future-oriented technology analysis, including strategic foresight and TA, can enhance governments' anticipatory capacity and provide collective spaces where societal values and technological developments can be considered together. Monitoring and evaluating the contribution of policy interventions will be essential, not least to change course if necessary. There are, however, significant knowledge gaps on how to monitor and evaluate sociotechnical transitions, a challenge that extends to the lack of appropriate statistical indicators. There is potential here for governments to make greater use of data-linking and national statistical offices are carrying out experiments along these lines, but much more needs to be done and at a faster pace.

Finally, the need for new skills and capabilities cuts across all STI policy sub-domains. Many gaps exist within government itself, which is called upon to perform more active roles than in the recent past, working closely with business, researchers and citizens, and across government to advance sustainability transitions. Similar capabilities gaps exist in the business and research worlds. A further policy concern is supporting people of working age and communities in attaining new skills and opportunities as part of a just transition.

The policy goals and practices pursued in these STI policy sub-domains should reflect the kinds of sustainability transitions wanted. Transitions should be just and have democratic legitimacy. They should embody different forms of inclusivity in STI, for example, with respect to differences in geography, socio-economic status, gender and ethnicity. While it is beyond the scope of this chapter to articulate a definitive set of key values to which STI activities should adhere in support of sustainability transitions, the following aspirations may provide some guidance:

- *Sustainability*: ensure STI policies support sustainability in multiple dimensions (i.e. economic, social and environmental) by promoting equality, supporting ecosystem recovery and resilience, and promoting system change, without compromising the ability of future generations to meet their own needs
- *Diversity*: promote resilience by supporting a range of research and technology areas involving a range of actors working on different challenges, beyond the realm of traditional STI actors
- *Inclusivity*: support broad participation in science and innovation and sharing of resources that contribute to transparency, trust and collaboration, while targeting the development of solutions that provide equal access and opportunities for society and promote social justice
- *Agility*: encourage the ability to move quickly and timely in tackling societal challenges like net-zero, supporting the acceleration of change through experimentation and adaptation of research, innovation and governance systems
- *Ethics*: nurture norms and principles that foster progress towards sustainability, promote justice and fairness, and account for the trade-offs emerging among multiple system dimensions by proposing actions that are consistent with the "greater good" and "what's right".

Ultimately, science and technological innovation should offer hope and mobilise human creativity and ingenuity to tackle the most pressing contemporary challenges, including the race to net-zero. Aspirations like these should underlie policy practice and serve as a compass to guide policy reforms enabling just sustainability transitions.

Along these lines, the OECD has embarked on a new project, "S&T Policy 2025: Enabling Transitions through Science, Technology and Innovation",[29] to help governments further articulate the need for reform and transitions, and reformulate their STI policy agendas accordingly. One of the project's main goals is to develop an overarching guiding vision and policy framework that helps STI policy makers rethink, redesign and implement a new portfolio of STI policies that drive sustainability transitions. The project uses the simple policy sub-domain framework outlined in this chapter to formulate practical policy guidance on specific key challenges.

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Notes

[1] In the NZE, behavioural change refers to changes in ongoing or repeated behaviour on the part of consumers which impact energy service demand or the energy intensity of an energy-related activity. Three main types of behavioural change included in the NZE: (1) reducing excessive or wasteful energy use; (2) transport mode switching; and (3) materials efficiency gains. Three-quarters of the emissions reductions from behavioural changes in the NZE are achieved through targeted government policies supported by infrastructure development, e.g. a shift to rail travel supported by high-speed railways. The remainder come from adopting voluntary changes in energy saving habits, mainly in homes. Even in this case, public awareness campaigns can help shape day-to-day choices about how consumers use energy (IEA, 2021[43]).

[2] As stated in the previous sentence, directionality is implicit in all policy by design, and horizontal and agnostic policy support favours incremental rather than radical innovation, development rather than R&D, and mature rather than breakthrough technologies.

[3] (Aghion, 2019[49]) identify five determinants of path dependence: knowledge spillovers (as innovations build upon prior innovations in cumulative ways), network effects (when the attractiveness of a technology depends upon networks of other users or suppliers), switching costs (the cost of switching to a different technology, e.g. due to the need for different infrastructure and overcome incumbent interests), positive feedbacks (when technologies benefit from scale) and complementarities (when technologies have complementary roles, such as renewables and storage) (OECD, forthcoming[19]).

[4] These have been presented as "the X-curve" of sustainability transitions. See, for example, (Silvestrin, Diercks and Matti, 2022[44]), (Palavicino, Matti and Witte, 2022[50])

[5] For example, see (OECD, 2015[45]), (EEA, 2019[46]), (Geels, 2020[47]) and (IEA, IRENA and UNFCCC, 2022[11]).

[6] The concept of "positive tipping points" has emerged from scholars working on climate system tipping points. For a recent review of the latter, see (OECD, 2022[48]).

[7] https://www.iea.org/reports/clean-energy-technology-innovation.

[8] For example, a single 100 MW electrolyser for green hydrogen production costs EUR 50-75 million; in the case of CCS, demonstration projects currently cost around USD 1 billion, take five years or more to build and have a market value of around one-tenth of their cost (OECD, forthcoming[19]).

[9] https://www.energy.gov/ia/clean-energy-technologies-demonstration-challenge.

[10] For example, through its Horizon Europe, Innovation Fund and InvestEU measures, the European Commission will contribute over EUR 28 billion to the Clean Energy Technologies Demonstration Challenge by 2027 to advance clean energy innovation and deployment, mainly in hard-to-abate sectors.

[11] Re-balancing green technology policies towards more RD&D support also has to be considered from an industrial policy perspective. Some countries have specialised in the manufacturing of green goods, with the emergence of the Chinese solar PV industry in the recent decade as a prime example of this trend. However, while RD&D support policies by nature target domestic firms only, deployment subsidies benefit domestic and foreign firms alike. Indeed, the Chinese solar PV industry was built on the back of renewable energy subsidies in the United States, Europe and other regions (e.g. Australia). In line with recent industrial policy objectives (see Chapter 2), governments could design deployment support policies against a clear understanding of the domestic supply-side (firms, talents, infrastructure) so that they benefit both consumers and the domestic economy (OECD, forthcoming[19]).

[12] Business R&D is mostly “D”-oriented, i.e. it focuses on development, and less oriented to “R”, i.e. research. This is even more so when incentivised by R&D tax incentives.

[13] Philanthropy – for example, the Bezos Earth Fund and Bill Gates’ Breakthrough Energy initiative – is playing a growing role in promoting and funding technological innovation for net-zero. Breakthrough Energy, for example, has several initiatives – including Breakthrough Energy Ventures, Breakthrough Energy Catalysts, and Breakthrough Energy Fellows – that support research and innovation activities across the innovation chain.

[14] At the same time, recent changes in corporate governance and the emergence of environmental, social and governance (ESG) criteria, as well financial or fiscal signals such as carbon pricing and taxation, have helped stimulate interest among private investors in financing longer-term investments. Blended finance in this context represents only one part of a broader financing framework for sustainability.

[15] The IEA maintains the ETP Clean Energy Technology Guide, an interactive framework that contains information on over 500 individual technology designs and components across the whole energy system that contribute to achieving the goal of net-zero emissions. For each technology, the guide includes information on the level of maturity and a compilation of development and deployment plans, as well as cost and performance improvement targets and leading players in the field. See https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

[16] When framing their choices, governments use various labels (and underlying concepts) to describe technologies, such as “key”, “emerging”, “enabling”, “converging”, “general purpose” and “niche”. They also refer to technology-readiness levels to indicate a technology’s maturity, invoking the innovation cycle model. These descriptors have consequences for the types of policy interventions governments pursue.

[17] TIs in the public sector are often located in a type of public research institute known as “research and technology organisations”.

[18] The impacts of environmental degradation are concentrated among vulnerable groups and households. Yet the benefits and costs of mitigating environmental policies are likely to be unevenly distributed across households. For example, while carbon pricing is a central component of green policies, affordability concerns need to be taken into account as higher energy costs may put greater burden on low-income households and compromise their well-being. Moreover, higher taxes on road transport fuels may affect rural residents more than urban dwellers, since the former tend to rely more on private cars and have limited access to viable public transport alternatives. Green policies can also have important distributional implications for jobs at the sectoral or regional levels. For example, employment levels in carbon-intensive heavy industries and fossil fuels extractive activities are expected to fall, which can have gender and regional implications (OECD, 2021[35]).

[19] An integrated, systemic policy approach is needed to ensure reforms are both green and people-centred. These should include (i) mitigation of the possible regressive impact of pricing environmental externalities for vulnerable households, e.g. through well-designed revenue recycling schemes; (ii) investment in human capital, e.g. through active labour market policies, well-targeted income support measures, and upgrading skills to facilitate labour reallocation; and (iii) sectoral and place-based policies that address systemic inequalities, e.g. through policies that facilitate social dialogue, social capital investments, social protection, and skills and education investments to ease structural adjustment of local economies (OECD, 2021[35]).

[20] The Global Commission on People-Centred Clean Energy Transitions made 12 recommendations in four broad areas. *I. Decent jobs and worker protection*: 1. design transitions to maximise the creation of decent jobs; 2. develop tailored government support for communities and workers as well as a focus on

skills and training; and 3. use social dialogue, robust stakeholder engagement and policy co-ordination to deliver better outcomes. *II. Social and economic development*: 4. ensure that policies enhance social and economic development, and improve quality of life for all; 5. prioritise universal clean energy access and the elimination of energy poverty; and 6. maintain and enhance energy security, affordability and resilience. *III. Equity, social inclusion and fairness*: 7. incorporate gender, equality and social inclusion considerations in all policies; 8. ensure fair distribution of clean energy benefits and avoid the risk of disproportionate negative impacts on vulnerable populations; and 9. integrate the voices of younger generations in decision making. *IV. People as active participants*: 10. involve the public through participation and communication; 11. use insights from behavioural science to design effective behaviour change policies; and 12. enhance impact through international collaboration and exchange of best practice.

[21] Citing (Geels et al., 2017[9]) "Policy-oriented research on deep decarbonization requires complementing model-based analysis with sociotechnical research. Whereas the former analyzes technically feasible least-cost pathways, the latter addresses innovation processes, business strategies, social acceptance, cultural discourses, and political struggles, which are difficult to model but crucial in real-world transitions. Although full integration of both approaches is not possible, bridging strategies may enable iterative interactions in which models provide techno-economic checks of qualitative narratives, while sociotechnical approaches provide wider feasibility checks on model outcomes. Such analyses may underpin the development and implementation of policy strategies that are both cost-effective and socio-politically feasible."

[22] For further information, see https://ec.europa.eu/info/strategy/strategic-planning/strategic-foresight_en.

[23] The text on statistical indicators in this section is based on discussions during an S&T Policy 2025 policy dialogue, "Policies for data and evidence on STI in a world in transition", organised by the OECD Committee for Scientific and Technological Policy (CSTP) and the OECD Working Party of National Experts on Science and Technology Indicators (NESTI) on 15 September 2022. https://www.oecd.org/sti/inno/stpolicy2025.

[24] The OECD NESTI leads the OECD's statistical work on STI, contributing to the development of indicators and quantitative analyses needed to meet the requirements and priorities of the CSTP. In 2021, NESTI established the OECD Expert Group on the Management and Analysis of R&D and Innovation Administrative Data (MARIAD) to facilitate and support its work on international collaboration in the statistical processing and analysis of administrative data relevant to the study of STI systems and government policies. The central focus for MARIAD's objectives and scope of activity is the domain of administrative microdata for public support and funding of R&D and innovation. One of its key aims is to facilitate the exchange of best practices in the management of administrative data on R&D and innovation, a field of considerable complexity and under constant evolution.

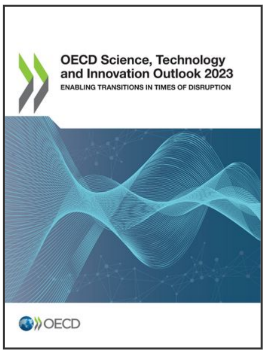
[25] Mission Innovation has 22 member countries, plus the European Commission: Australia, Austria, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, India, Italy, Japan, Morocco, the Netherlands, Norway, Korea, Saudi Arabia, Sweden, the United Arab Emirates, the United Kingdom, and the United States.

[26] See the "Mission Innovation" website for further information: http://mission-innovation.net/.

[27] As of 1 September 2022, the Breakthrough Agenda signatories are: Australia, Azerbaijan, Belgium, Cabo Verde, Canada, Chile, China, Denmark, Egypt, the European Union, France, Germany, Guinea Bissau, Holy See, India, Ireland, Israel, Italy, Japan, Kenya, Latvia, Lithuania, Luxembourg, Malta, Mauritania, Morocco, Namibia, the Netherlands, New Zealand, Nigeria, North Macedonia, Norway, Panama, Poland, Portugal, Senegal, Serbia, Slovakia, Korea, Spain, Sweden, Türkiye, the United Arab Emirates, the United States and the United Kingdom.

[28] There are many definitions of “skills for the green transition”, and most share that they refer to a broad set of technical and transversal skills that will be driven by, or contribute to, the green transition. A working group of the Inter-Agency Group on Technical and Vocational Education and Training, which includes the OECD, recently arrived at the following definition: ‘“Skills for the green transition” include skills and competences but also knowledge, abilities, values and attitudes needed to live, work and act in resource-efficient and sustainable economies and societies. They are: (1) technical: required to adapt or implement standards, processes, services, products and technologies to protect ecosystems and biodiversity, and to reduce energy, materials and water consumption. Technical skills can be occupation-specific or cross-sectoral; and (2) transversal: linked to sustainable thinking and acting, relevant to work (in all economic sectors and occupations) and life. Alternatively referred to as “sustainability competences”, “life skills”, “soft skills” or “core skills”.’ (Cedefop, 2022[42]).

[29] See the S&T Policy 2025 website: https://www.oecd.org/sti/inno/stpolicy2025/.



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