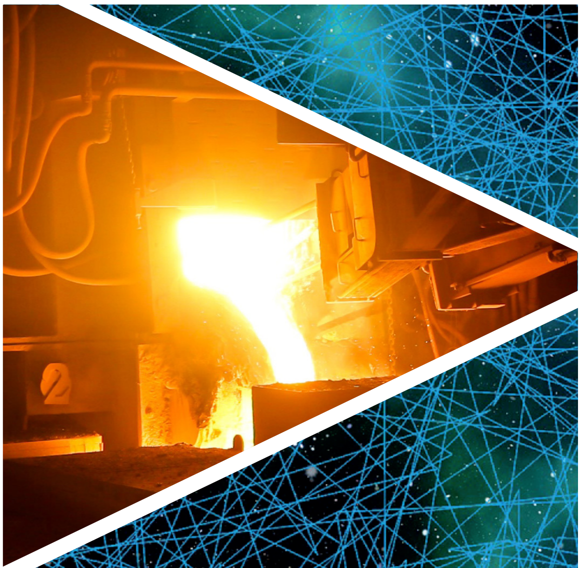

ACCELERATING THE LOW CARBON TRANSITION

The case for stronger, more targeted and coordinated international action

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BROOKINGS

With the support of
ENERGY TRANSITIONS COMMISSION

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MEETING CLIMATE GOALS REQUIRES...

"

Rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems. These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed...

Intergovernmental Panel on Climate Change (2018)

"Over 40 countries are still investing in new coal power plants, despite renewable power being cleaner and, in most markets, cheaper. A more coordinated offer from the international community of finance and assistance for clean power is needed, to ensure that all countries are able to take advantage of the low-cost renewable technologies now available."
Francesco La Camera, Director-General, International Renewable Energy Agency

"*A decade of individual action to address deforestation in global supply chains has resulted in incremental gains. The only way we will get to more transformational steps to reduce deforestation is through collective action – which requires a reconfiguration of how all the actors in the system are working together."*
Justin Adams, Director, Tropical Forest Alliance

"*If several major vehicle markets around the world were to coordinate on the adoption of tougher, long-term regulations for emissions reduction, they could give an immense boost to industry investments in new technologies and accelerate the global transition to zero-emission mobility."*
Drew Kodjak, Executive Director, International Council on Clean Transportation

"*The buildings and construction sector can and must fully decarbonise by 2050. Radical international collaboration is needed to scale up existing solutions, including zero carbon standards and financial incentives."*
Cristina Gamboa, CEO, World Green Building Council

"*In all of the industrial sectors we have worked with, we see large potential for coordinated action to accelerate transitions – by accelerating technology development, enabling deployment in competitive markets, and overcoming the problem of supply and demand for new technologies each waiting for the other."*
Adair Turner, Chair, Energy Transitions Commission

"*Energy is a critical part of any sector's emissions profile, so decarbonising energy use will be critical to all sectors as they head towards net zero emissions. The energy sector must work with all other sectors in a coordinated, international push to accelerate the energy transition and meet the goal of the Paris Agreement. Governments will be key to enabling coordination within sectors and ensuring it has its full impact."*
Ben van Beurden, CEO, Shell

"*Only a just transition can be a successful transition. Getting a Just Transition requires social dialogue with workers and their unions, employers, and governments. People will support real climate action when they're at the table making plans for it, when they see hope on the other side, and when workers and communities are at the centre."*
Samantha Smith, Director, Just Transition Centre, International Trade Union Confederation

"*Thinking of the challenge of decarbonisation in terms of transition, and not in terms of marginal change, leads to very different policy recommendations. The challenge is not to start by doing a little, and then gradually do more over time until you have zero emissions. It is to start by doing a lot, to change the patterns of growth, so that further change becomes increasingly easy over time."*
Stephane Hallegatte, Lead Economist, Climate Change Group, the World Bank

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FOREWORD

When the world's first coal-fired power station opened for operation on Holborn viaduct in London in 1882, it signalled the onset of a new era. The world's use of fossil fuels, already rising rapidly, grew exponentially over the following century. As first coal, then oil, and then gas came to world markets in abundance, economies and societies reconfigured themselves around these new energy sources and the new technologies they required and enabled. Networks of road, rail, pipelines and power lines were created to bring fuels to where they were needed, and to distribute their energy. Homes, farms, factories and cities took on new forms, designed to make the most of the new possibilities for production, mobility, comfort and communication. Rules were written, and institutions built, to govern the new systems of activity that emerged.

Now climate change demands a new reconfiguration. We must change all these structures, moving rapidly to clean energy sources to eliminate greenhouse gas emissions. Over recent years, the United Kingdom has reduced emissions from the power sector faster than any other country in the world. We have achieved this by acting on every point in the system. We have invested in research and development, rewritten the rules of the market, created new financing instruments, and opened new spaces – from rooftops to the continental shelf – for the installation of new technologies and infrastructure. We have been rewarded with clean power that is cheaper than fossil power, and with the creation of new jobs and economic opportunities.

We are proud of our progress, but humbled by the knowledge of how much we have been helped by others. The first wind powered machines were developed in the Middle East and Central Asia in the ninth century. The thousand-fold falls in the cost of solar energy modules over the last half-century have been driven by early support for research and development in the US and Japan, policy incentives for deployment in Europe, and massive investment in production in China. Each country's actions to accelerate progress assist the efforts of all others.

Despite this progress, power sector emissions globally are still rising. That is why two years ago we launched, together with Canada, the Powering Past Coal Alliance, to share learning and coordinate efforts to accelerate the transition away from unabated coal power. The alliance now has 91 national, subnational and business members, together sending a far stronger signal to global markets than any country could on its own.

As the challenge of reducing global emissions becomes ever more urgent, there is a critical need for stronger and more coordinated action to accelerate transitions in each of the sectors that generate emissions – across power, industry, transport, buildings, agriculture and land use. In each, we need robust institutions, alliances, and alignment behind strong policies to reshape markets, shift investment patterns and accelerate the development and diffusion of clean technologies.

Next year when the UK hosts the United Nations climate change talks (COP26), we will take this responsibility seriously. Complementing the formal negotiations, we will seek to bring strength, focus and coordination to practical action. We will invite all countries to join us in building on what has been achieved so far, and in laying stronger foundations for the future. In this way, I believe we can bring global emissions onto the downward path that is so urgently needed, and open up a new era of sustainable prosperity and opportunity.

Nick Bridge,
UK Foreign Secretary's Special Representative for Climate Change

1. INTRODUCTION AND SUMMARY

Context and purpose of this report

The world is committed to acting on climate change. At least since the signing of the United Nations Framework Convention on Climate Change in 1992, the international community has been united in its commitment to preventing 'dangerous anthropogenic interference with the climate system'. In the Paris agreement of 2015, almost all countries set out individual targets or actions they would take towards meeting this collective goal. Earlier this year, the UN Climate Action Summit highlighted many examples of governments, businesses and civil society groups leading the way to a low carbon economy. There is general consensus on the need for deep cuts in emissions as rapidly as is practical. However, it is equally clear that emissions are still rising, not falling, and economic change is not happening anywhere near quickly enough.

Since diplomatic talks on climate change began around 1990, annual global CO_2 emissions have risen by over 60%,[1] and they could plausibly keep rising a few per cent per year for at least the next decade, if not longer. Future emissions are 'baked in' – already made likely to arise from the high carbon energy infrastructure we already have, and more of this infrastructure is still being built and planned. At this rate, agreed goals for limiting the rise of global temperatures are becoming ever harder to meet, and a future climate that tests the limits of the adaptive capability of our economies, ecologies and societies is becoming ever harder to avoid. The need to accelerate progress is therefore unquestionable. The question is how to do it.

This report is for the governments and businesses that are interested in accelerating deep decarbonisation of the world economy. We aim to highlight where their actions can have the greatest impact, by bringing together knowledge from three areas:

- First, an understanding of how **technology transitions** happen – drawing on lessons from historical shifts such as from horses to cars, coal to gas, and wells to piped water systems;
- Secondly, an understanding of how **international cooperation** has succeeded in the past – looking at what has worked for problems in trade, security, and the environment – and what this means for how coordinated action can steer and accelerate technological transitions;
- Thirdly, the application of these insights to the main greenhouse gas emitting sectors, focussed particularly on identifying **points of leverage** for coordinated international action to accelerate low-carbon transitions.

In comparison with previous reports, what is new is our focus on the **processes of change**, rather than on the end goal. We consider not just which technologies are viable, but which actors could develop and deploy them, and how policy might motivate them to do so. We also consider how international cooperation can itself evolve to become stronger over time, with actions at each stage laying the foundations for deeper agreements later. In this way, we aim to develop a new understanding of how the international community's climate change goals can be met. We suggest that the broad-based multilateralism of the Paris Agreement must be complemented with forms of international action that are stronger, more coordinated, and more focussed on the critical actions that can accelerate change across the global economy.

Key messages

Two key messages emerge from this report:

- **Nationally: focus policy on system transitions.** Stopping emissions requires fundamental innovation, rapid diffusion of new technologies, and the reshaping of markets and socioeconomic systems. This requires actions far beyond simply putting a price on carbon or adopting bold emissions goals. A more targeted, hands-on and strategic approach to policymaking is required to reconfigure the technologies, business models, infrastructure and markets in each of the greenhouse gas-emitting economic sectors.

  Central to this message is the recognition that the low carbon transition is not a purely technological or economic exercise, but also a social transition. It must take place within the context of societies' other goals, many of which are often given higher priority. Aligning interests so that governments, industry and society support each other in a reinforcing feedback or 'ambition loop' towards ever stronger action is likely to be essential for success – so that transitions, once begun, become self-sustaining politically, technologically and economically. Also essential is finding ways to support the communities that stand to lose out from the change. A just transition is a desirable goal in itself. It may also be the only kind of low carbon transition that can be sustained.

- **Internationally: coordinate action within sectors.** It is within economic sectors or systems that new technologies can be created and diffused eventually to reshape the social and economic activities of which they are a part. This process depends on the actions of policymakers, firms, consumers and civil society actors who, in today's economy, are connected globally. Coordinated international action, appropriate to the phase of the transition, can accelerate this process: by identifying viable technologies more quickly; by increasing incentives for investment and economies of scale; and by levelling playing fields so that first-movers are not held back by the constraints of competitiveness. This means that while formal climate diplomacy tends to be organised around countries, the real focus both for governments and for industry should be coordinating actions in sectors or systems. Much more effort is needed to convene the key actors in each sector in order for the goals of the Paris Agreement to be met.

Organising institutions for success: the most urgent priority

The picture that emerges from this study reveals an enormous opportunity to accelerate the low carbon transition through stronger and more coordinated international action focussed on the key actors and technologies within each sector. It is striking, and disturbing, that so little political and industrial effort has been mobilised for deep decarbonisation despite three decades of international talks on climate change. Few institutions with the ability to redirect industries have been oriented around this goal. In many sectors, the institutions that are needed to support coordination are still nascent or do not exist at all. Those that do exist desperately need to be strengthened: through a focus on coordinated action that goes far beyond the mere sharing of information; serious funding and much stronger engagement from governments; and broader participation, to move from coalitions of first movers to the critical mass that can reconfigure the global market in each sector.

This is an urgent priority. It is not merely a matter of filling some gaps in the institutional landscape. It is a strategic shift toward more effective methods of international cooperation – to complement the economy-wide commitments of many nations and the multilateral climate negotiations. This strategic shift must focus on mobilising and applying the resources needed to solve practical problems and scale up the processes of deep decarbonisation. **Alongside the policy actions for decarbonisation, a strategic commitment to institution-building is therefore the single most important activity that can be undertaken by any government wishing to lead the global response to climate change.**

In creating much more capable institutions for deep decarbonisation one of the most vital strategic challenges will be understanding when new institutions must be built, and when existing ones must be strengthened. Vigilance is needed to ensure that existing institutions, directed to the goal of deep decarbonisation, actually become stewards of change within their industry and not merely mechanisms to reinforce the status quo. An important role for leading governments, firms and non-governmental organisations (NGOs) to play is to ensure that institutions tasked with deep decarbonisation remain adequately focussed on that mission.

Approached this way, the goals of the Paris Agreement will still be a challenge to achieve, but we can take on that challenge with well-grounded optimism and realistic hope.

Priorities for action

Putting this into practice means taking a targeted approach to international action in each of the main emitting sectors – as a vital complement to economy-wide approaches to managing down global emissions. Two clarifications may be important at this point. Firstly, the focus on sectors does not mean we are proposing a business alternative to diplomacy. Emphatically, success will require strong action from governments as well as from industry. Secondly, while the purpose of this report is to highlight the opportunities for effective *international* action, this does not in any way diminish the critical importance of actions at national or even local levels.

Despite the diversity of the various greenhouse gas emitting sectors, some common themes emerge as priorities for action:

- **In sectors where the low carbon transition has barely begun, such as steel, cement, plastics, heavy road transport, aviation and shipping, the priority should be to create niches for the first demonstration, testing and deployment of new technologies.** Government procurement can be a particularly powerful policy lever. **If countries coordinate this testing and deployment, the incentives for industry to invest will be greater, and the process of learning will be accelerated**. Governments will then be able to support deployment on a larger scale. A delicate, strategic process must be followed, so that coordination helps to ensure exploration of a wide landscape even as competition between firms and countries creates incentives for improving performance. In the transport sectors, coordination on standards and infrastructure investment is needed between the ports, cities or countries at all the nodes of major routes. In shipping and aviation, governments should demand more from the international rule-setting bodies that already exist, to match sector-wide targets with firm policies that can mobilise investment at scale in clean solutions.

- **In sectors where diffusion is beginning, such as power, cars and buildings, the priority is to support the growth of the market share of low carbon technologies, through market-shaping policies such as subsidies, standards, and phase-out of high carbon technologies. If countries coordinate on the choice of technologies, on the standards applied, or on credible commitments around the rate of phase-out, low carbon technologies will benefit from greater economies of scale at an earlier stage.** New entrants will be attracted by the benefits of a larger market, and incumbents will be more strongly incentivised to reallocate their investment towards new technologies.

- **In highly trade-exposed sectors where there are competitiveness concerns around decarbonisation, countries should lay the foundations for future reconfiguration by developing options for how these may be overcome through coordinated standards or carbon pricing. Trade measures – linking these standards or carbon prices to market access – are likely to be needed to create a level playing field in which low carbon innovators are not undercut by high-emitting competitors.** In most of these sectors, this will be a long-term effort. In aviation, however, there is an immediate opportunity for coordination on standards to begin the deployment of low carbon fuels. In agricultural commodities there is an immediate need for coordination on supply chain standards to prevent the accelerating destruction of the world's forests.

A guide to this report

Chapter 2, *Technology Transitions*, describes how research has identified three main overlapping processes that explain where and how transition actually occurs: emergence of a new technology, diffusion through markets, and reconfiguration of socioeconomic systems. The perspective presented here is important because it reveals how profound changes in industrial systems can become self-sustaining, even when change at the outset seems impossible or daunting. Historical case studies are used to show how critical actions can enable or accelerate transitions in each of these three phases.

Chapter 3, *International Cooperation*, considers how well-targeted international cooperation can help coordinate actors and accelerate progress through each transition phase. The practical experience of international cooperation in environment, security and trade suggests principles for effective coordination that can be applied to the low carbon transition. These are summarised in Table 1 below. These principles imply a focus first on coordinated testing of the elements of the transition, then on coordinated deployment so that new decarbonised practices diffuse more widely into service, and finally on changing the rules that define the structure of the relevant economic sectors and systems. As most sectors and most countries are at the early stages of deep decarbonisation, it is not yet clear whether the technologies, industrial and agricultural practices needed for deep decarbonisation will eventually become superior on their own – and thus relatively easy to apply globally – or if ongoing policies, such as strong border trade measures, will be needed for the long term. What is clear is that complete reconfiguration of global practices will ultimately be needed in all sectors, so that warming emissions are reduced essentially to zero, and climate change can be stopped.

Chapter 4, *Application*, takes the principles and lessons from the two previous chapters and offers a sketch of their application to the sectors and systems that are the main sources of global emissions. These include the socioeconomic systems of power, transport (land, sea and air), buildings and food; and the upstream sectors of industrial production of steel, cement and plastics; which together account for around 80% of global emissions. We consider each sector in a broad sense: not just the technology and its production, but also the systems of its use, financing, ownership, infrastructure and governance. We find points of leverage for accelerating change in these systems that could be activated by stronger and more coordinated international action. A summary of these opportunities is shown in Figure 1 below.

> Alongside the policy actions for decarbonisation, a strategic commitment to institution-building is the single most important activity that can be undertaken by any government wishing to lead the global response to climate change.

TABLE 1: OVERVIEW OF CORE PROCESSES, ACTIONS AND PRINCIPLES

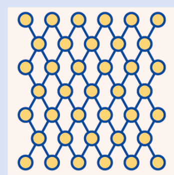
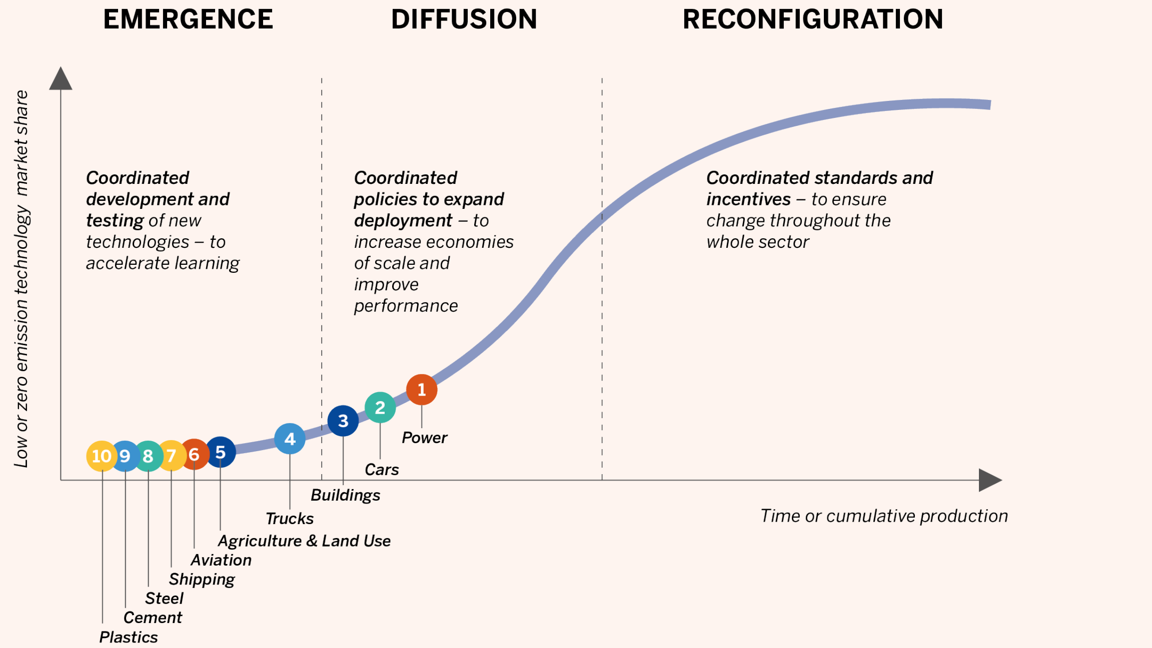
Stage of transition and core processes	*Key policy actions to accelerate transition*	*Dominant mode of international cooperation*	*Principles for effective cooperation*
EMERGENCE  *Processes:* *Experimentation* *Stabilisation of dominant designs*	*Stimulate R&D and real-world demonstration projects* *Stimulate knowledge sharing between projects, firms and regulators* *Articulate visions or missions* *Nurture the building of transformative coalitions* *Public procurement and other strategies to create early application niches*	**EXPERIMENTALIST LEARNING** 	*Break problems down into manageable pieces that are aligned with how industries and policies are organised* *Create institutions to review the lessons from experiments and figure out what's working (and not)* *Coordinate action among a critical mass of willing actors to establish niches and give credible assurance to innovators* *Focus on bringing interests of key actors into alignment*
DIFFUSION  *Processes:* *Multiple reinforcing feedbacks supporting growth of new technology market share* *Resistance from incumbents leading to economic, business and political struggles*	*Taxes and regulations to alter the economic playing field* *Purchase subsidies, favorable price-setting, public procurement to stimulate demand* *Capital grants, loans, performance standards to shape firm investment* *Public infrastructure investment* *Accelerate and manage the consequences of declining industries*	**COORDINATED DIFFUSION** 	*Coordinate action to scale up niches into larger market shares - work in small groups: coalitions of first movers* *Focus on markets where agreement is easier* *Focus on joint actions that, with experience and diffusion, can plausibly lead to reconfiguration of interests*
RECONFIGURATION  *Processes:* *Complementary changes in institutions, infrastructure, business models, user practices, views of normality, technical capabilities, professional standards*	*Stimulate whole system realignment* *Anchor the new system in regulations,standards and market signals.* *Develop agencies with new roles and responsibilities* *Mitigate negative socio-economic effects with 'just transition' policies (e.g. compensation, retraining).* *Realign trade and investment policies*	**CONTRACTING** 	*Create detailed, reciprocal agreements around known solutions that address known barriers to further application* *Negotiate among parties that constitute a critical mass of the market in the relevant sector* *Establish credible incentives for participation and compliance, and penalties for the reverse* *Set standards; monitor and verify compliance*

FIGURE 1: PROGRESS OF SECTORS' LOW CARBON TRANSITIONS, AND PRIORITIES FOR COORDINATED INTERNATIONAL ACTION



Sector	Emissions & stage of transition	Nature of the problem now	Priorities for international action	Priority for institutions
POWER 1	***25%*** *of global GHG emissions* DIFFUSION ***Renewable technologies diffusing rapidly; others at earlier stages***	*Infrastructures and markets designed around old technologies.* *High up-front costs and unproven performance of many non-renewable low-emission systems.*	***Coordinated financing and assistance*** *to provide developing countries with a better clean power offer.* ***Coordinated phase-out of unabated coal power****, to send clear signals to global markets.*	*Move from sharing information to coordinating action; – on policy, finance and technology.*
CARS 2	***7%*** *of global GHG emissions* EARLY DIFFUSION ***Innovation has stabilised around electric vehicles Alternative technologies (fuel cells) much earlier stage***	*High up-front costs of electric vehicles.* *Incumbent industry pushing for weak policy.* *Charging infrastructure supply-and-demand problem.*	***Coordinated tightening of regulatory trajectories*** *towards zero emissions, to send a strong signal of demand and accelerate the shift in industry investment*	*Move from sharing information to coordinating action.* *Expand participation to include emerging economies.*
BUILDINGS* 3	***6%*** *of global GHG emissions* ***Construction:*** EMERGENCE ***Heating & cooling:*** DIFFUSION	*Weak demand for efficient buildings; low innovation in industry.* *High cost of low emission heating & cooling options.*	***Coordination on standards***** *for efficiency of buildings and heating and cooling technologies.* ***Coordinated refocussing of policy support*** *for low emission heating away from biomass.*	*Strengthen government engagement.* *Expand participation to include emerging economies.*

** Buildings also account for roughly half of the emissions from the power, steel and cement sectors*
*** Standards will vary by country, but coordination can ensure comparability and enable greater flows of finance to genuinely high efficiency and low emission buildings*

Sector	Emissions & stage of transition	Nature of the problem now	Priorities for international action	Priority for institutions
TRUCKS 4	***3%*** *of global GHG emissions* EMERGENCE ***New technology yet to enter market at scale***	*High cost of zero emission trucks.* *Weak demand due to lack of policy in most markets.* *Infrastructure supply-and-demand problem.*	***Coordinated market-creating policy*** *– such as emissions standards and purchase subsidies – to send a strong demand signal to truck manufacturers.*	*Move to more substantial government to government engagement in tandem with industry.*
AGRICULTURE & LAND USE 5	***24%*** *of global GHG emissions* ***Agriculture:*** EARLY EMERGENCE ***Land use:*** DIFFUSION	*Low resource efficiency of agricultural production.* *Weak incentives to avoid deforestation in places that already have weak governance.* *Few incentives to absorb carbon in soils.*	***Coordination on standards linked to trade*** *to avoid deforestation in commodity supply chains.* ***Coordinated development and testing*** *of low emission production techniques along with new methods for soil carbon absorption.*	*Move from business to government leadership in coordination on supply chain sustainability standards.*
AVIATION 6	***1.5%*** *of global GHG emissions* EARLY EMERGENCE ***New technologies yet to stabilise or enter markets***	*Low emission options prohibitively high cost in competitive industry.* *Supply-and-demand problem for clean fuels.*	***Coordination by airports****, supported by governments, on* ***mandates for use of sustainable aviation fuel*** *on routes between them – to create initial niches for deployment.*	*Establish more practical cooperation between leading countries and airports, focused on testing and deployment of technology, fuels and infrastructure.*
SHIPPING 7	***1.6%*** *of global GHG emissions* EARLY EMERGENCE ***New technologies yet to stabilise or enter markets***	*Low emission options not yet demonstrated at scale, and prohibitively high cost in competitive industry.*	***Coordinated large-scale demonstration and testing*** *of sustainable fuel technology to establish viability and ensure safety.* ***Coordination between ports on emissions standards*** *to be applied on routes between them.*	*Focus cooperation on technology development, demonstration and deployment.*
STEEL 8	***4%*** *of global GHG emissions* EARLY EMERGENCE ***New technologies yet to stabilise or enter markets***	*High cost of low emission production processes is prohibitive in competitive global commodity market.*	***Coordinated testing and demonstration*** *of low carbon production plants at full industrial scale – to identify and prove viable technologies.*	*Create a forum for international government-industry coordination of actions on steel decarbonisation.*
CEMENT 9	***3%*** *of global GHG emissions* EARLY EMERGENCE ***New technologies yet to stabilise or enter markets***	*High costs of low emission production are prohibitive in competitive global industry.* *No demand, in absence of policy.*	***Coordinated testing and demonstration*** *of low carbon cement production technologies.* ***Coordinated government procurement*** *to create initial demand.*	*Expand participation from industry to governments.* *Focus coordination on practical experiments and creation of markets.*
PLASTICS 10	***3%*** *of global GHG emissions* ***Recycling (in some countries):*** DIFFUSION ***Production:*** VERY EARLY EMERGENCE	*Recycling industry fragmented and not well organised for scale-up.* *High cost of low emission production prohibitive in competitive market.*	***Coordinated development, testing and demonstration*** *of options for low carbon plastics production.* ***Coordinated market-creating policy*** *such as extended producer responsibility to incentivise production of more recyclable products.*	*Create a forum for international government-industry coordination of actions to decarbonise plastics production.*

2. UNDERSTANDING SYSTEM TRANSITIONS

What are system transitions and how do they come about?

System transitions are transformative sector-level changes in the methods of producing, selling, transporting and using goods and services. They are multi-actor processes involving interactions between a wide array of actors, including firms, consumers, policymakers, innovators, and civil society groups. The actions of these groups are motivated not only by cost-benefit calculations, but also by interests, beliefs, and identities, and are conditioned by the availability of financial, technical, and organisational resources. Typically, strategies, motivations and resources change as transitions unfold, through learning, redefinition of interests, and many other processes that can be hard to predict.

This chapter discusses the main processes, first providing an overarching 'big picture' framework, and then addressing core actions, including policies, that are relevant for the three specific transition phases: emergence, diffusion, and reconfiguration. Throughout this chapter, we use historical examples to illustrate and anchor conceptual discussions. The examples also show that in the past major transitions have occurred – usually with varying degrees of active policy management and steering – implying that it will indeed be possible to steer future low-carbon transitions.

Though we can learn from the past, low-carbon transitions have some special attributes separating them from historic examples of transitions, and these require attention. For example, while many (though not all) historical transitions were opportun ity-driven, low-carbon transitions are problem-oriented. While public policy was (to varying degrees) involved in most historical transitions, it will be policymakers who make up the crucial *drivers* of low-carbon transitions (by creating policies that nurture innovation, shape firm behaviour and investment strategies, and coordinate actors). And while many historical transitions took several decades, limiting climate change to internationally-agreed goals – such as the halting of warming below 2˚C above pre-industrial levels – requires low-carbon transitions to be far-reaching and fast. Another difference is that incumbents in many historical transitions were politically more dispersed and thus weaker and less able to block change, whereas many carbon-intensive sectors and industries are well organised and deeply entrenched, and therefore better able to resist change.

Nonetheless, lessons from history can guide the future – including how best to address these particular attributes in order to achieve the deep decarbonisation transitions needed.

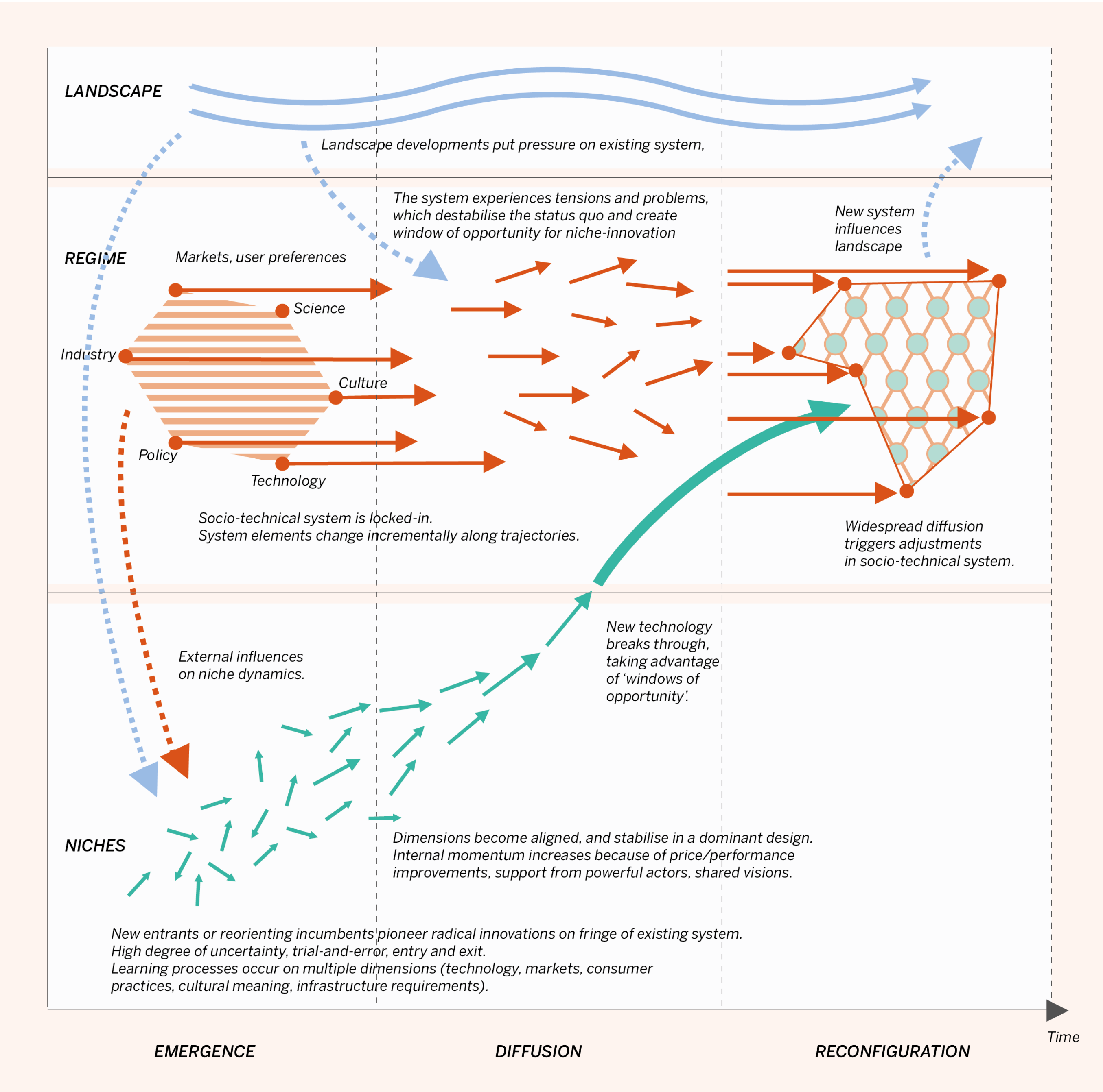
Starting with the 'big picture' framework, transition processes play out along multiple levels, as shown in Figure 2. At the start of transition there are niches – protected spaces that nurture the emergence of radical innovations. Then there are the existing cluster of technologies, infrastructures, government institutions, consumer practices and incumbent actors with vested interests – often referred to as a regime. These are the conditions in which these niches are found, and are how new ideas emerge from niches into more widespread application. The wider landscape, including exogenous shocks such as wars and industrial accidents, along with trends in what society wants, sets the broader context that also contributes to shaping the transition process.

The central challenge in transitions concerns how radical innovations get a footing in niches and then compete with and transform existing regimes. This is often an uphill struggle because niche-innovations are initially more expensive and face social acceptance problems, while existing regimes and incumbents are locked into place: they have set rules and expectations, and they control the infrastructure, which is designed for incumbency rather than novelty. This is why a broad system transition often takes decades to run its course completely. It's also why many radical innovations that could yield massive transformations actually fail to take hold.

Overcoming incumbency typically proceeds through three phases, which we use to organise this report: emergence, diffusion and reconfiguration*. There are* distinct processes involved within and between each of these phases (Figure 2).

In the *emergence* phase, niche-innovations are developed by pioneers (or diversifying incumbent actors) who engage in experiments and learning. They build coalitions of supporting firms, governments and customers that set the stage for technologies to spread more widely. In the *diffusion* phase, radical innovations begin to spread when learning processes improve technical performance, lower costs, and generate clarity about how the new technology can align with consumer preferences and functional requirements. The watchwords for diffusion are competition, increased social acceptance (resulting from widespread positive visions and mitigation of negative side-effects), and regime destabilisation, which may relate to exogenous landscape pressures. The *reconfiguration* phase is characterised by overthrow and wider system adjustments. During reconfiguration the new entrant becomes incumbent;

FIGURE 2: THE MULTI-LEVEL PERSPECTIVE ON SUSTAINABILITY TRANSITIONS



Source: Adapted from Geels, F.W., Sovacool, B.K., Schwanen, T., Sorrell, S., 2017, Sociotechnical transitions for deep decarbonization, Science, 357(6357), 1242-1244)

infrastructures shift and create new lock-ins around the new technology; adoption becomes pervasive, and the transition is complete. (Often in this new equilibrium, the seeds of the next transition are being planted and growing in niches. Transitions in industrial technologies run continuously.)

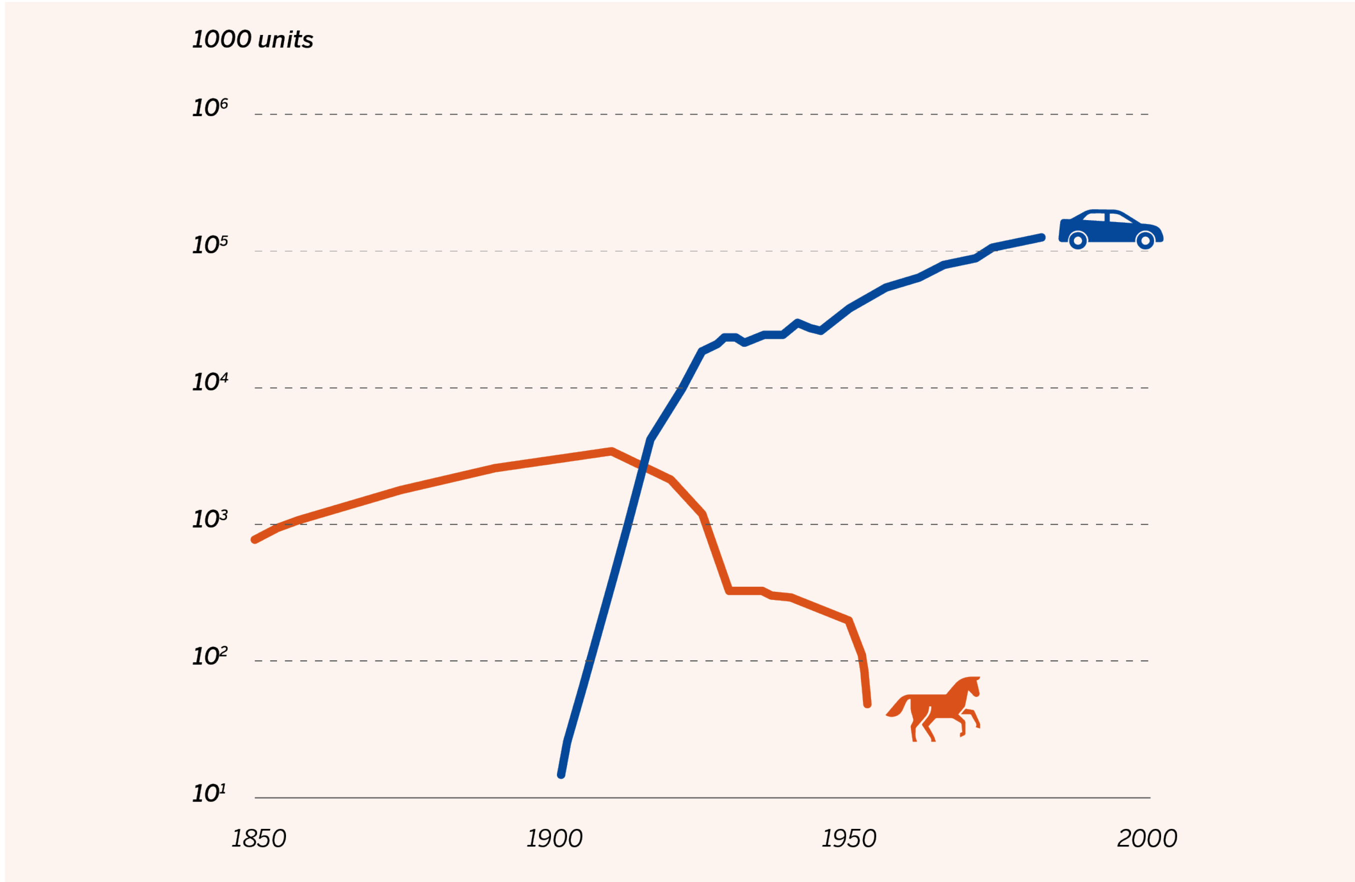
The transition from horse-drawn carriages to automobiles in the United States, which took several decades, starting in the 1880s, offers an instructive illustration of these three phases.[2]

Automobiles emerged in the 1880s and 1890s, when pioneers added steam engines, electric motors and internal combustion engines (ICE) to carriages and tricycles. These early cars were heavy, fragile, slow, and they frequently broke down. They were expensive 'toys for the rich' that were used in small application niches: promenading in parks and on boulevards (electric vehicles), speed races (electric, steam and ICE vehicles), long-distance races (ICE vehicles) and touring in the country-side (ICE vehicles). These application niches stimulated learning processes, leading to improved performance in battery storage content, horse-power, speed, sturdiness, and power transmission (cogwheels, belts, and chain-drives).

The broader landscape development of an expanding middle class, with more money and free time and the accompanying new values of sport, adventure, and 'fun', established the popularity of racing and touring niches. Sales of ICE vehicles powered by gasoline consequently raced ahead, while sales of electrics and steamers stagnated. In the early 1900s, elite niches expanded to include other new groups that were beginning to use gasoline cars for more utilitarian purposes, such as travelling salesmen and insurance agents, doctors, wealthy farmers, and taxi drivers. These growing niches stimulated the search for cheap, sturdy cars which, after years of trial-and-error, culminated in Henry Ford's Model T (1908). This dominant design allowed the emerging car industry to focus on incremental product innovations (like the 1911 electric starter, which made it much easier to use ICE vehicles) and improvements in the production processes, notably in mass production, to further decrease prices.

Early cars faced social acceptance problems, because speeding on unpaved roads killed people and livestock, and created dust waves that hindered pedestrians and wagon drivers. In response, policymakers started regulatory processes, introducing speed limits, traffic rules, car registration, driving schools and licensing.

FIGURE 3: TRANSITION FROM NON-FARM HORSES TO PASSENGER CARS



Adapted from Nakićenović, N., 1986, The automobile road to technological change: Diffusion of the automobile as a process of technological substitution, Technological Forecasting and Social Change, 29(4), 309-340.

Policy-makers also funded more road pavements to make urban environments more suitable for cars. Automobiles benefited not just from policies that made them address the harm they caused, but also from growing attention and policy action against the incumbents: horses. Urban expansion lengthened travel times and increased road congestion in narrow streets; the sanitary movement heightened medical and cultural concerns about horse excrement in streets; and horse-tram and -bus companies faced high operating costs related to stabling and feeding thousands of horses. As the internal combustion engine improved within its niche, these differences in performance between old and new became more apparent.

Figure 3 shows the diffusion of passenger cars between 1910 and 1940. As the process unfolded the total number of "vehicles" rose exponentially: horses exited while cars took over nearly all the market share. Mass production lowered the cost of passenger cars from US$850 in 1908 to US$360 in 1916. More market niches opened: for example, when rural farmers started buying cars to help alleviate rural problems, such as isolation and declining schools, churches and shops. Road infrastructures were further expanded and highways (a new kind of road used only by cars) were built in and around cities. Rural road construction was coordinated by the newly created federal Bureau of Public Roads and supported by an increasingly powerful road lobby of highway engineers, suppliers (e.g., cement and asphalt, and construction firms), urban planners, and automobile clubs. Educational campaigns taught children and pedestrians new routines for crossing roads, and public perception of a road's function changed from a social meeting place to a transport artery.

Horses continued to be used in the 1920s and 1930s, but their markets shrank to specialised niches (e.g., freight transportation of non-perishable goods and some elements of rural farming). Horse-transport related social groups (e.g., smiths, wagon makers, fitters, painters, coachmen, carriers, horse-keepers, stable-keepers) were thus not immediately threatened with mass unemployment, which reduced social protests.

Complete reconfiguration followed after the Second World War. Lower costs and higher incomes made cars affordable to the broader masses, which entrenched the new car regime socially, economically and infrastructurally. A car culture emerged as automobiles were embedded in daily life routines: commuters travelled daily between suburban homes and down-town jobs; shopping malls appeared on the edge of cities, reachable only by car; people went on holidays with cars, leading to campgrounds and motels; and people could relax in drive-in cinemas and eat in drive-in restaurants. The car industry, including its supply chains, became a crucial economic sector, with downstream linkages such as the petroleum industry and public works. Economic centrality meant political gravitas. As a reflection of that centrality, a cross-continental infrastructure (the Interstate Highway System) was created between 1956 and 1992, costing US$114 billion (US$521 billion in today's prices), 90% of which was funded by the federal government. This ensured the complete triumph of cars over mass transit alternatives and firmly established automobiles as the dominant system.

90% Proportion of the cost of creating the US Interstate Highway System between 1956 and 1992 that was funded by the federal government

Emergence phase

Radical innovations typically emerge through the pioneering activities of researchers, entrepreneurs, activists or other relative outsiders. As these innovations initially have low performance and high costs, they cannot immediately compete head-on with existing systems and regimes. Therefore, to begin with, niches form 'protected spaces' that shelter radical innovations from mainstream market selection and nurture learning and development processes.[3] This protection can take various forms, such as sheltered R&D laboratories, real-world demonstration projects, or small application domains related to customers that tolerate or seek cutting edge technology even when costly – for example, the military or rich enthusiasts. These early applications can offer real world information about how to improve performance, social acceptance, design supporting infrastructure, and a host of complementary innovations needed to support the fledgling technology. Through sequences of projects, knowledge sharing between projects, and efforts to develop more generic lessons, learning about technical performance can reduce uncertainties and stabilise the innovation trajectory into a 'dominant design', underpinned by shared heuristics, models, and theories.[4] In the case of cars, for example, internal combustion engines emerged as the dominant design (extinguishing steam and electric rivals), and from there subsequent diffusion and reconfiguration followed.

In the emergence phase, there are two central challenges for policy. One is identifying which fledglings have real promise for successful flight – something that is hard to do, because in the history of radical system transition the successful pioneers are often only spotted long after the fact. Thus, policy must be designed for uncertainty – backing a host of potential winners and actively adjusting in light of information about promise. The other challenge often involves doing the opposite – providing reliable support for niches even when performance is unknown. This support is needed because niche innovations are often up against a steady drumbeat of evidence and political pressure from incumbents insisting that new technologies are not competitive. As a practical matter, the kinds of policy instruments that can have an impact in these settings include:

- Supporting niche creation through R&D investments and subsidies for demonstration programmes and experiments, including efforts to focus R&D on particular industrial and market challenges.
- Creating early application domains through public procurement or government agencies acting as early adopters.
- Articulating visions or missions – for example, credible technology roadmaps – that provide guidance for learning processes and convince diverse actors about the general direction in which change should occur.
- Facilitating knowledge sharing between projects – for example, by allowing industrial innovators to discuss and exchange information (often prohibited by competition policy), and tasking intermediary actors (e.g., implementation agencies or regulators) with collecting, comparing, stabilising and disseminating knowledge and best practice lessons.
- Nurturing the building of transformative coalitions and innovation networks (for example, in coalitions of first movers that will not only demonstrate technology, but also mobilise political support for additional action) through financial incentives or convening power.
- Reducing barriers that prevent new entrants from gaining access to infrastructures – for example, introducing "open access" rules that help overcome performance regulations designed by incumbents.

Aviation case study

KEY POLICY ACTIONS:

- Subsidies
- Public procurement
- Infrastructure investment

The rise of civil aviation offers a good example of how emergence of a fledgling technological system occurs[5] – because it is a system that has aligned technology (eventually jet aircraft), users, cultural meanings and support, as well as supporting infrastructures such as airports.

Since the 1890s, inventors began developing aircraft, adding light-weight piston engines and propellers to gliders. After the Wright brothers succeeded in 1903, pioneers further improved the technical performance of components and experimented with design variations (e.g., wing shapes, materials, and front or back propellers). Aircraft remained 'toys for the rich' without much practical use, until a landscape shock (World War I) boosted the production of bomber, fighter and reconnaissance aircraft. About 200,000 airplanes were built between 1914 and 1918. Increased government resources and technical requirements stimulated technical developments. Over the course of that war procurement period, for example, engine power increased from 100 to 400 hp.[6]

The war ended, government contracts were cancelled, and many leading aircraft manufacturers in the US went bankrupt. Due to imperial policy, military strategy and political prestige, however, European governments continued to support the aviation industry, accepting and advocating the optimistic vision of a coming 'air age'.[7] Newly created airline companies provided line services between major cities (e.g., London-Paris in 1919), but comfort in converted bombers was minimal (passengers wore leather jackets and goggles) and a commercially viable market niche did not materialise. Where the industry survived it was mainly due to niches that were created by direct government subsidies which, in the 1920s to 1930s, formed up to 80% of airline incomes.[8] In the US, airmail transport became the pivotal market niche. This niche was created by the 1925 Contract Air Mail Act, which provided major indirect subsidies that made up around 50% of airline revenue between 1931 and 1939. Airmail, coordinated by the Post Office, also helped create a network of air routes and airports, as well as fuelling and repair infrastructures. The 1926 Air Commerce Act mandated the federal government to regulate aviation (e.g., pilot licensing, aircraft registration and inspection, and airspace control).

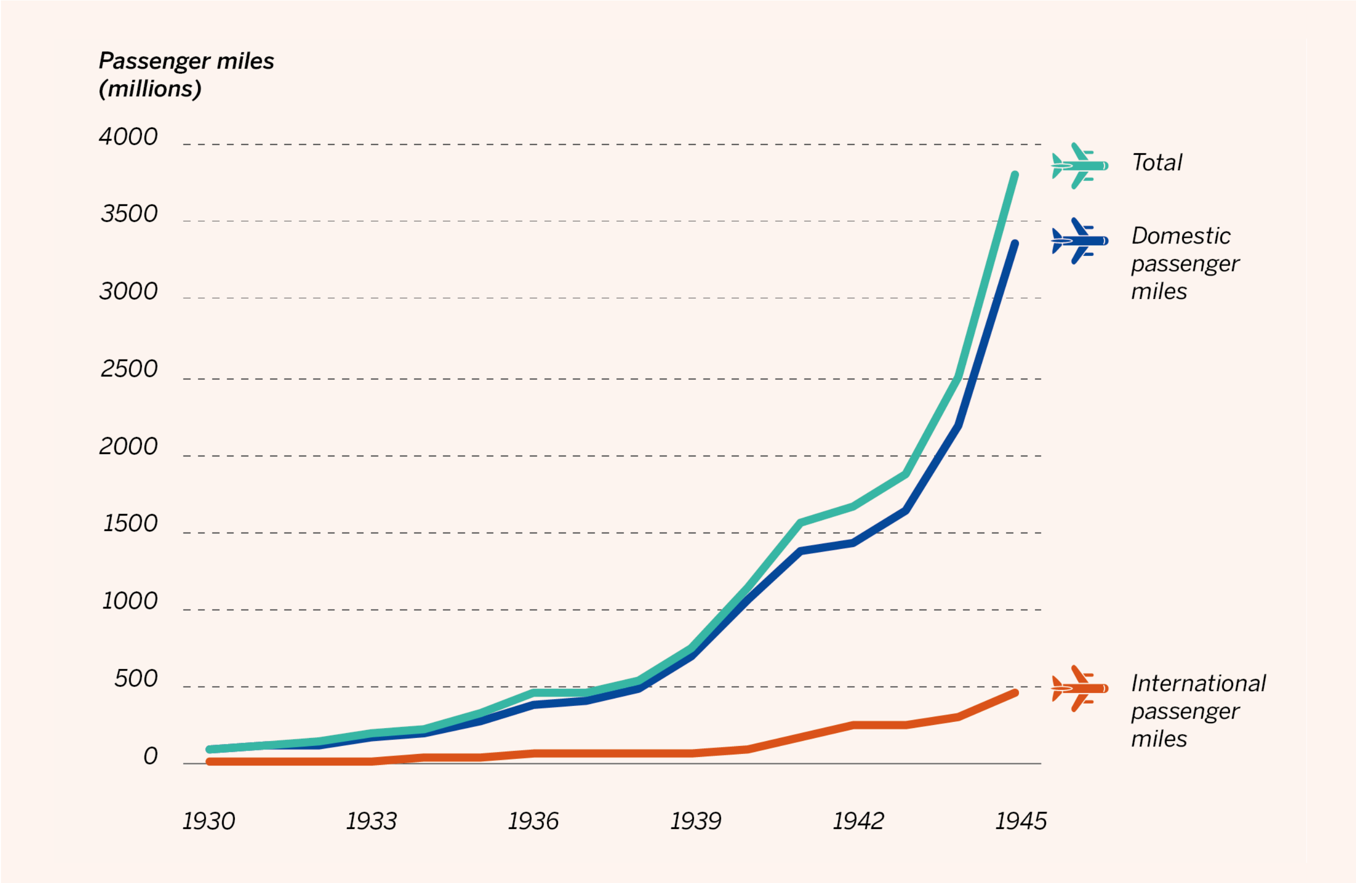
In the late 1920s, air races and entertainment formed another niche, which pushed technological developments (e.g., the shift from bi-planes to sleeker and faster monoplanes) and stimulated cultural enthusiasm. Long-distance flights (e.g., Lindbergh's 1927 crossing of the Atlantic) and 'barnstormers' (who took people for paid airplane rides and performed flight stunts such as wing walking) fostered air-mindedness and generated a 'winged gospel' with prophets predicting how aircraft would change society for the better.[9] As is usually the case, the prophets were often wrong: for example, visions of an 'airplane in every garage' and widespread personal use did not manifest. But their key roles were as crucibles for cultural transformation and acceptance. Although the military niche remained small, it stimulated innovations aimed at radical improvements in performance, such as the shift from wooden to metal aircraft structures (which was advantageous in protecting pilots from gunfire and critical to the strength needed for dogfighting and high-speed flying).

These niches – airmail, military and racing – yielded learning and generated innovations that combined in the DC-3 (1936), which became the dominant design for commercial aviation. It combined high fuel efficiency (important for costs and range) along with strength and safety that gave passengers confidence to fly. Early commercial passengers were mainly businessmen and politicians, who appreciated the dramatic and modern imagery of aviation. To set the stage for wider diffusion, airline companies launched public relations campaigns featuring celebrity passengers and female pilots, whom they hoped would domesticate flying and purge associations with danger. The spread from early niches to more widespread applications in the 1930s – the hallmarks of the shift from emergence to diffusion (Figure 4) – saw the effects of technological learning reinforced with complementary investments in infrastructures. In the US, 75% of the cost of airport expansions was paid by New Deal arrangements (that emerged in the aftermath of the Great Depression) between 1932 and 1938.

A major crash in 1935 provided the incentive to tighten formal rules and regulations. The concept of 'controlled airspace' was developed in 1936, which specified the airways to be monitored by new air traffic control systems. Air traffic controllers were given more authority to issue binding directions for flight plans, take-off and landing routes. The Civil Aeronautics Act (1938) created the Civil Aeronautics Authority with power to regulate airline tariffs, airmail rates, mergers, and safety standards.

The early history of civil aviation is one where the key policy actions arose within countries and focussed on joint action by government and business. In the decades since, of course, there has been more experience with international cooperation around the emergence phase of technological transition. For example, the Concorde involved joint R&D and creation of initial market niches by two governments (France and UK). That effort failed to engender a wider transition in aviation because Concorde proved noisier, more polluting, less energy efficient and costlier than was needed in the aviation markets of the 1970s (when the aircraft appeared). More recently, joint procurement of advanced military aircraft (e.g., the Joint Strike Fighter) is creating niches for advanced fly-by-wire and aircraft materials. The role for international coordination has risen, as well, because a larger fraction of today's air travel involves cross-border movement. The ICAO (International Civil Aviation Organization) was established in 1944 to ensure safe and orderly growth of international air transport. No major technological innovation in commercial aviation today can succeed without coordinated agreement by regulators: for example, the rise of Global Positioning Systems (GPS) navigation and, today, the rising use of biojet fuels.

FIGURE 4: THE DEVELOPMENT OF AMERICAN CIVIL AVIATION



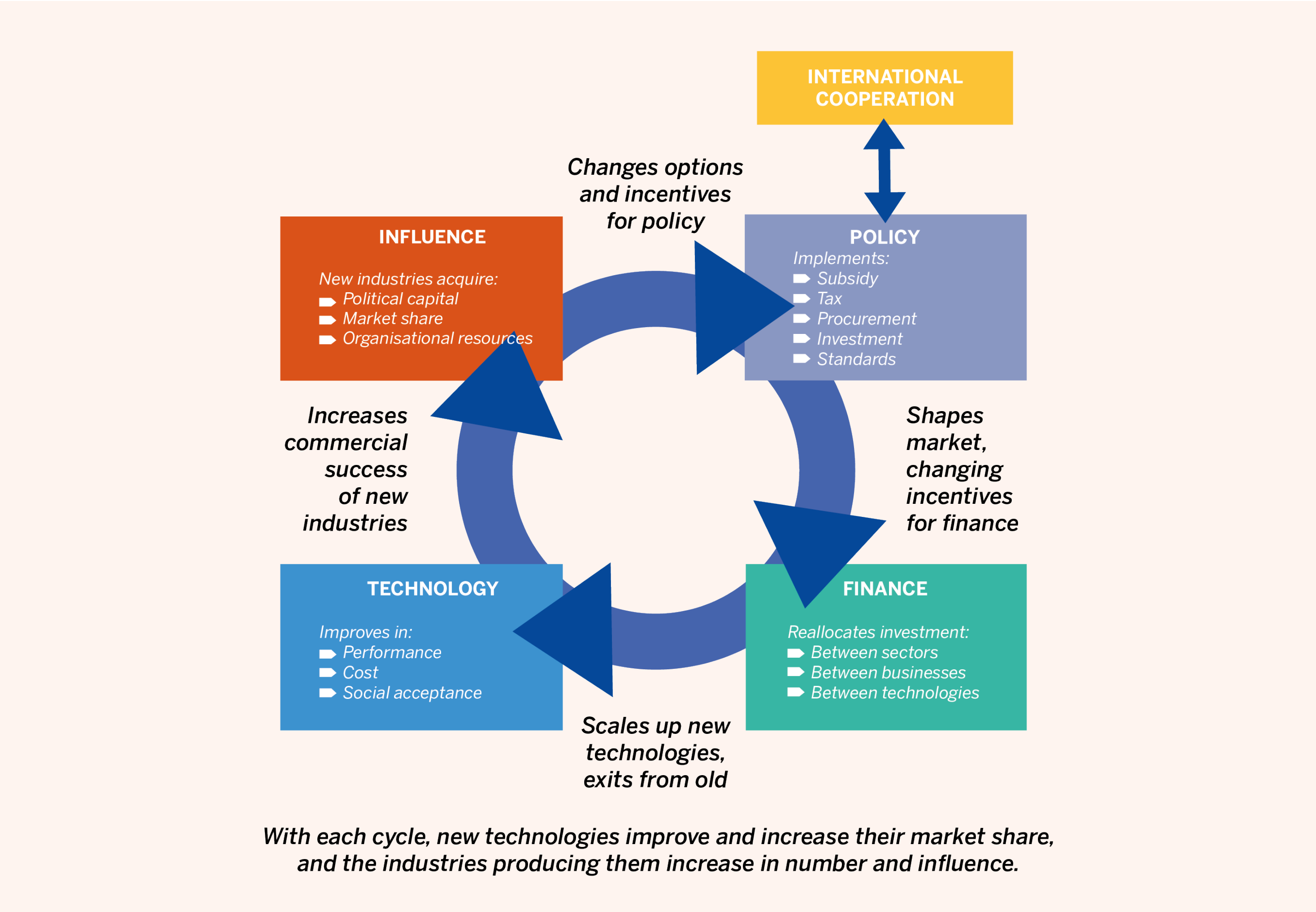
Based on data from the Air Transport Association of America, http://airlines.org.

Diffusion phase

In the diffusion phase, radical innovations move beyond protective niches and spread more widely into mainstream markets and society. This shift is reflected in the rising role for economic performance in guiding purchase decisions: adoption is shifting from early niches (where narrow economics does not rule) to uptake, which is guided by economic calculations, attitudes, beliefs, and norms that often vary across adopters (e.g., age, gender, income, lifestyle, and market position of firms). Diffusion usually follows an S-shaped curve, starting slowly (as it spreads from early market niches), and then accelerating (as it enters mass markets), and then slows down (as 'laggards' adopt belatedly).[10]

As technologies diffuse, there are often self-reinforcing positive feedbacks that lower costs and improve performance, such as economies of scale (which allows the costs of improvements to be amortised over a larger market), learning-by-doing effects (incremental improvements in manufacturing processes), and the increasing availability of complementary technologies that improve performance.[11] These price/performance improvements help increase the market share of new technologies and associated firms, which enhances their political influence. Improved new technologies also change the options for policymakers which, combined with more effective lobbying, leads to new policies that shape market conditions and attract more financial investments. Figure 5 schematically portrays the feedback loop that may accelerate diffusion processes.

FIGURE 5: REINFORCING FEEDBACK IN THE DIFFUSION OF NEW TECHNOLOGIES AND GROWTH OF NEW INDUSTRIES



Diffusion is not necessarily a smooth process and may involve business struggles between new entrants and incumbents, potentially leading to the latter's downfall.[12] Political struggles are also common in the diffusion phase because incumbents can visibly see the consequences of competition – whereas during the emergence phase the future threats from a fledgling new entrant might be harder to understand – and are likely to resist adjustments in subsidies, taxes and regulations.[13]

Policymakers can accelerate diffusion in various ways by:

- Changing the economic playing field with generic financial instruments (e.g., taxes);
- Stimulating demand for new technologies with purchase subsidies, loans, grants, price-setting and information campaigns;
- Stimulating firm investments through interest-free loans, capital grants, investment subsidies, *specific* performance standards (that specify how much firms should produce or sell of a particular technology), or *generic* performance standards (which articulate desired outcomes, but leave it to firms to decide how to meet them);
- Creating suitable contexts through public infrastructure investment; and
- Enhancing social acceptance through public relations campaigns and positive visions.

Two examples illustrate the roles of policymakers in accelerating widespread diffusion.

Self-reinforcing positive feedbacks that lower costs and improve performance include:

- economies of scale;
- learning-by-doing;
- increasing availability of complementary technologies.

Farming case study

KEY POLICY ACTIONS:

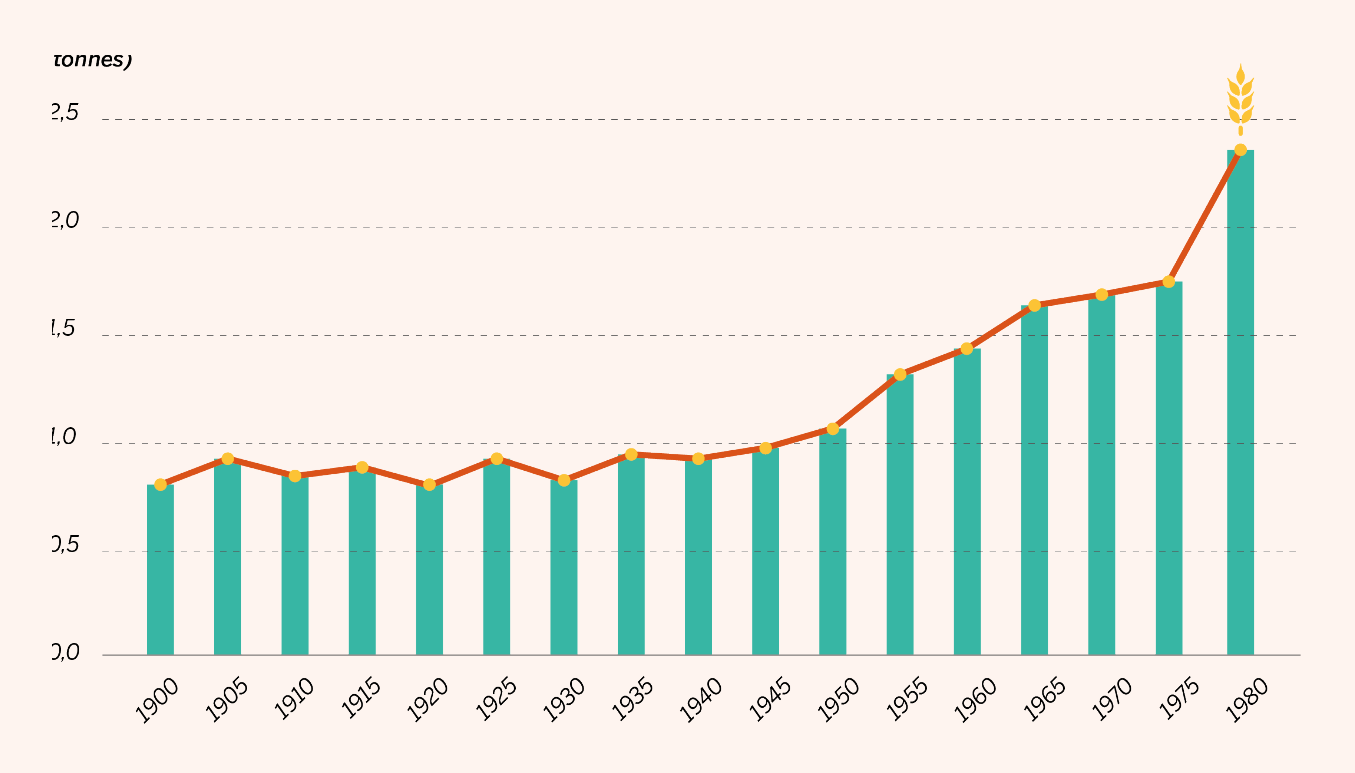
- **Price-setting**
- **Grants and cheap loans**
- **Communication of best practices**

One example is the UK transition from mixed agriculture to specialised wheat farming.[14] In the 1930s, modern wheat agriculture was a small niche-innovation in the UK, because the technologies needed for larger scale operations faced many barriers rooted in contemporary farming practices, land tenure, and related policies. Tractors were more expensive and less flexible than horses since their wide turning radius was problematic on predominantly small UK farms. Tractors also required land drainage schemes to reduce risks of getting stuck in muddy fields. Complementary technologies like combine harvesters were largely absent. Farmers were also sceptical about modern technologies and had little money to make investments, because their finances were eroded by cheaper foreign imports from Canada and the United States. Farmers therefore preferred to stick with the existing mixed farming regime, in which cleaning crops, such as turnips or parsnips, were grown as livestock feed and to eliminate weeds and pests. Animal manure was then used as the primary fertiliser.

The Second World War was a major landscape shock because German U-boats disrupted wheat imports and created existential concerns about wartime food security. To increase domestic wheat production, the government introduced drastic policy interventions that accelerated the diffusion of modern farming innovations that had already been proven in other markets. Those active policies included market controls that enabled the setting of wheat prices, which created stable attractive markets; capital grants and cheap loans to enable investments in machinery, land improvement and drainage schemes; technological extension schemes (e.g., home visits and organised trips to demonstration farmers) that helped disseminate new knowledge and techniques to farmers; and War Agricultural Executive Committees, whose creation made it possible to manage food production at the local level.

Farmers responded. In 1930 there were more horses than tractors in the country; by the 1940s tractors (which rose radically) were ten times the number of horses. Horses were not so much out-competed as simply left to decline without replacement – a slow process. Drainage infrastructures and the area of land under cultivation rose. Increased machinery use also led to the simplification of farm layouts, scale increases and specialisation, which made mixed agriculture less viable and increased the use of pesticides and fertilisers. Support policies continued after the war and the resulting transition greatly boosted wheat yields (Figure 6). Along the way, thousands of smaller and less competitive farms went out of business. Negative environmental consequences, such as water pollution, eutrophication, and acidification, became pertinent in the 1970s.

FIGURE 6: WHEAT YIELDS PER ACRE IN THE UNITED KINGDOM, 1885-1970



Constructed from data in Mitchell, B.R., 2011. British Historical Statistics. Cambridge University Press, Cambridge.

Coal to gas case study

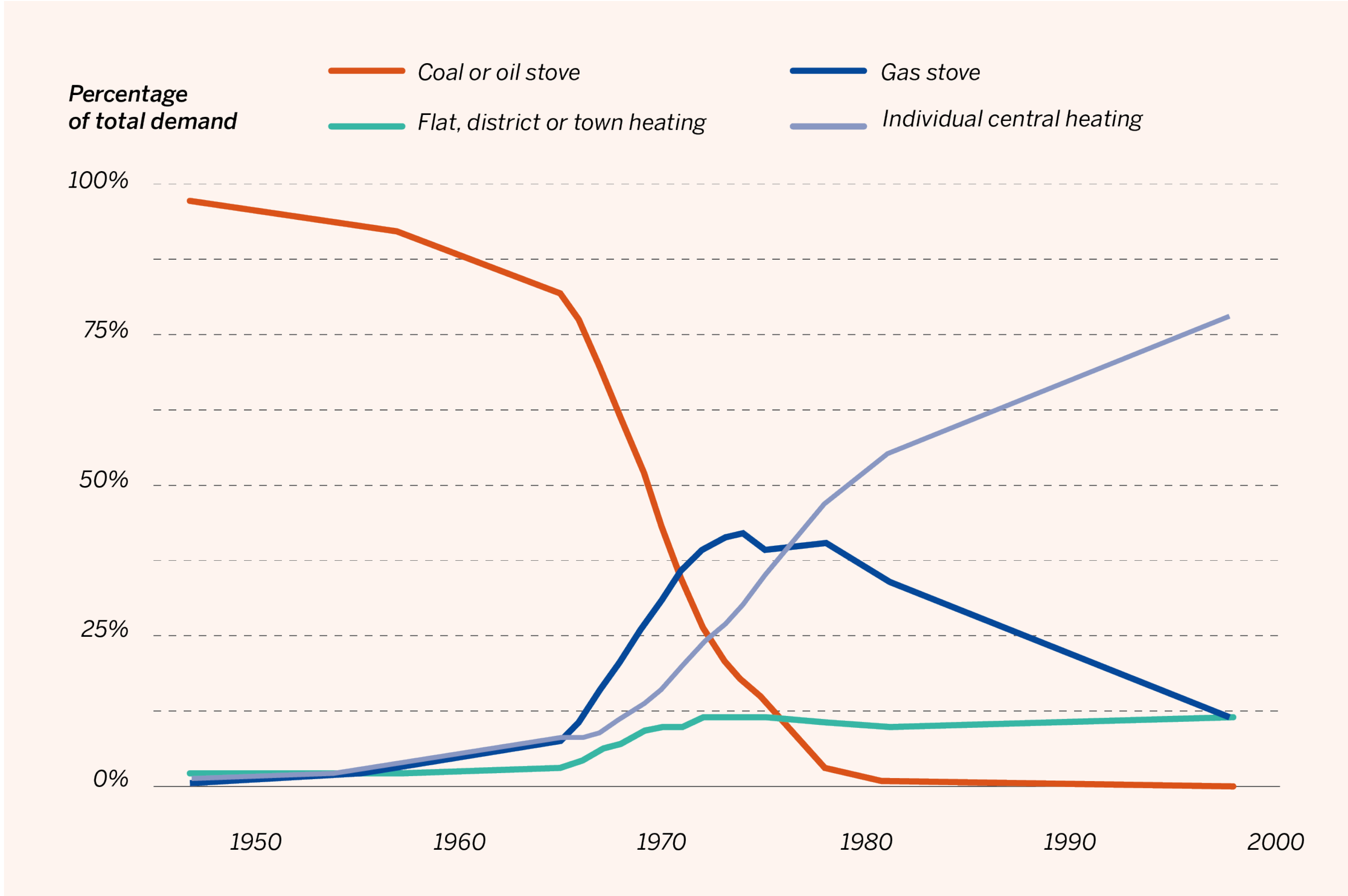
KEY POLICY ACTIONS:

- Infrastructure investment
- Public communications
- Compensation of 'losers'

Another example of policy-mediated diffusion was the Dutch transition from coal to natural gas.[15] In 1959, NAM (an alliance of Exxon and Shell) discovered a huge and easy-to-exploit natural gas field, which led to negotiations with the government about exploitation strategies. The government asked the giant coal mining company DSM (Dutch State Mines) to negotiate on its behalf because of its energy-related commercial experience and as a compensation strategy (because coal was a likely 'loser' in the transition). Shell preferred to use natural gas in high-value market niches (cooking, lighting), while Exxon envisaged a wider transition that also included heating. The state was interested in revenue maximisation and supported Exxon's vision, once simulations demonstrated its feasibility and profitability. Negotiations also focussed on responsibilities and revenue sharing, leading to agreement that the gas field would be exploited by a new organisation of which 30% was owned by Shell, Exxon and DSM and 10% by the state. The state would additionally levy various taxes and fees, which enabled it to recoup approximately 70% of total net revenues. Due to infrastructure investment, consumer subsidies, public communications, and compensation for losers, once agreement was in place – marked by a white paper published in 1962 – the transition unfolded quickly (Figure 7).

Construction of a national gas transmission infrastructure, paid for by a newly created consortium GasUnie (owned half by Shell and Exxon and half by the state) began in 1963 and completed in 1968, connecting all Dutch cities to the gas field. Municipalities paid for the conversion (and extension) of existing distribution networks, which had been designed to carry "city gas" (made by gasifying coal) and were now repurposed for natural gas. With supplies assured, the state stimulated consumption and helped maximise profits for gas firms by setting retail prices at levels similar to, or slightly cheaper than, alternative fuels. This was a process that required prices that had been adjusted by volumes and customers, since the rival options varied. The state also provided subsidies to encourage switching. These took the form of rebates on the cost of replacing oil boilers for gas boilers. In addition to price, a key advantage for natural gas was increased convenience and comfort, especially in the form of central heating, which entailed a qualitative shift from heating single rooms towards heating the whole house. A public relations campaign portrayed natural gas heating and cooking as clean, convenient, comfortable, and modern. Meanwhile, groups that were harmed by the construction of underground pipelines were compensated. These included agricultural interests, urban planners, and road and railway organisations that were disadvantaged by the construction of underground gas pipes. Coal mining interests also enjoyed compensation through financial stakes in natural gas exploitation, new development and employment projects for coal and city gas workers, and industrial assistance, as the industry (represented by DSM) reoriented towards bulk chemicals.

FIGURE 7: TECHNOLOGICAL TRANSITION IN THE DUTCH HEAT MARKET, 1947-1998



Constructed from data in Van Overbeeke, P., 2001, Kachels, Geisers en Fornuizen: Keuzeprocesses en energieverbruik in Nederlandse huishoudens 1920-1975 ('Heaters, boilers and furnaces: Choice processes and energy use in Dutch households, 1920-1975'), PhD thesis, Eindhoven University of Technology, Netherlands.

Reconfiguration phase

In the third phase, the new technology replaces the old one, which can have wider effects that reconfigure entire regimes.[16] Firstly, the new technology may require changes in complementary technologies, infrastructure, business models, and professional standards.[17] Incorporation of the new technology into daily life may also lead to new user practices and views of normality, as the example below illustrates. Secondly, actors may redefine their interests and adopt new roles and responsibilities, which help lock the new system into place. Thirdly, the transition may alter the boundaries between sectors or have reinforcing effects on other systems: such as when the ubiquitous use of automobiles realigned human settlements, shopping, holidays and entertainment.

The decline of existing industries may have negative effects on jobs or (local) tax revenue, and this may motivate employees, firms or regions to resist transitions through public protests, media campaigns or political lobbying. Well targeted government policy can lessen such resistance by engaging with workers, their unions and communities, and supporting them through the transition. In Japan and Korea during the second half of the twentieth century, government policies facilitated the movement from traditional domestic-oriented industries to modern export-led industries by protecting, to a degree, the people who would be the losers following successful transition. That included direct protections for traditional industries like agriculture and textiles, with safety nets aimed at reasonable but not unlimited or open-ended protection. Thanks to this policy, the population remained supportive enough to avoid a policy backlash, which would have slowed, if not stopped, the transition.[18]

Reconfiguration is important because it helps to ensure the most widespread adoption of the technologies, and also reduces the need for active policy support. With reconfiguration, the new technological system redefines the status quo. Policymakers can support system reconfiguration in various ways. They can:

- Stimulate the development of complementary technologies or infrastructures that support or improve the functionality of the focal technology;
- Introduce regulations or performance standards that anchor the new system, boost consumer confidence, underpin markets, and guide further company investments;
- Create new agencies or institutions with new roles and responsibilities;
- Stimulate the articulation of new professional standards; and
- Mitigate negative consequences for affected social groups and work towards 'just transitions' with policies that offer compensation (e.g., redundancy payments and early retirement benefits) or assist reorientation (e.g., skills upgrading, retraining, and regional innovation policies).

The Dutch coal to gas transition is a good example of both compensation and reorientation policies.[19]

Water supply case study

KEY POLICY ACTIONS:

- **Infrastructure investment**
- **Creation of legal obligations**
- **Monitoring and standards**
- **Public communications**

The Dutch transition in fresh water supply – which moved from collecting buckets of water at pumps, wells, canals or rivers to piped systems that delivered clean water indoors – offers a good example of the wider effects of system reconfiguration and the roles of policymakers and other actors.[20]

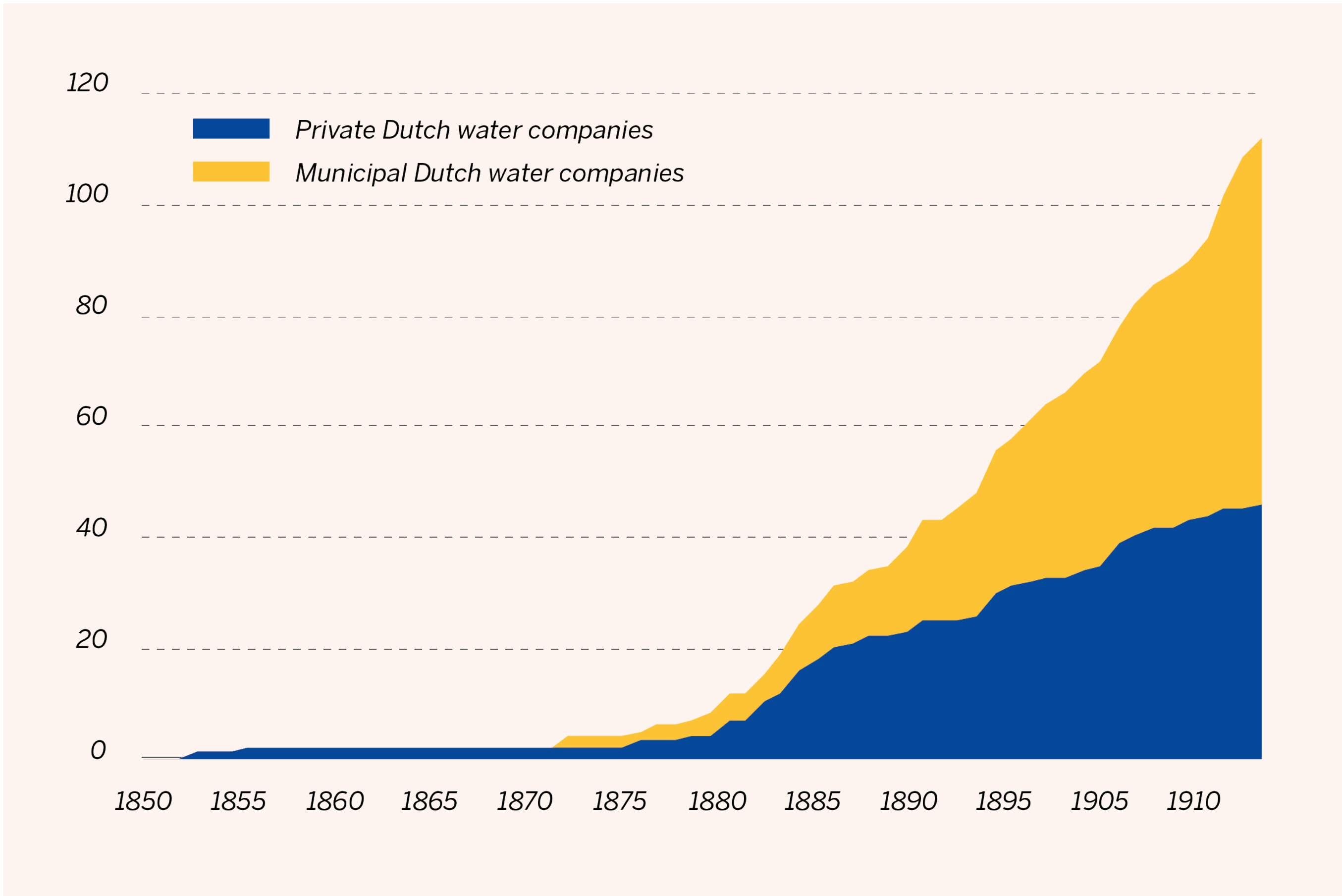
The traditional water supply regime faced increasing problems in the late 19th century. Expanding urban populations produced larger amounts of urine, excrement and other waste that polluted traditional water supplies. Concerns about polluted water increased as medical doctors in the 1850s and 1860s statistically linked it to infectious diseases like cholera, and Louis Pasteur provided a scientific explanation, based on micro-organisms, in the 1880s. Large cities close to the sea (Amsterdam, Rotterdam, The Hague) also faced quantitative problems, because of brackish ground water supplies.

Piped water systems, which transported relatively clean water from lakes or underground reservoirs to cities, first emerged in Amsterdam (1853) and Den Helder (1856) and diffused more widely in the 1880s and 1890s (Figure 8). City governments were initially hesitant to get involved, because laissez-faire liberal political ideology preferred limited state involvement in the economy. Most early systems were therefore built by private water companies that would sell water to rich private households with subscriptions, or at taps connected to the main infrastructure. But since private initiative could be slow and hesitant (because of uncertainties about sufficient demand to warrant investments in infrastructure), city authorities increasingly started constructing waterworks themselves. From the late 1890s, growth in public (municipal) water systems outstripped private suppliers. Both public and private water companies first connected rich citizens and certain firms (e.g., beer breweries, paper factories, and the textile industry), who were willing to pay for more comfort or clean water. Local distribution networks were subsequently extended to other neighbourhoods and social groups. By 1900, around 40% of the Dutch population was connected to piped water, mostly in cities, giving rise to several wider reconfigurational impacts.

Firstly, reconfiguration proceeded because local and national governments became more centrally involved in water supplies. A wider redefinition of their roles made local and national governments responsible for improving urban life for all residents, and this led to a more interventionist policy style. This redefinition was stimulated by expanded voting laws and increased cultural sensitivity about working class living conditions. The 1901 Housing Law stipulated that newly built houses should have sufficient access to clean drinking water. The newly created (1913) State Office for Water Supply performed technical and scientific research, advised local policymakers, created a water laboratory to analyse water quality samples, and became a champion for extending piped water to rural areas. These government-subsidised rural extensions happened in the 1920s and 1930s and were accompanied by propaganda campaigns to convince farmers that piped water was better than traditional water sources.

Secondly, a new 'water culture' emerged, as consumers started to use water not just for drinking and cook-

FIGURE 8: THE NUMBER OF MUNICIPAL (YELLOW) AND PRIVATE (BLUE) WATER COMPANIES IN THE NETHERLANDS



Adapted from Groote, P.D., 1995, Kapitaalvorming in infrastructuur in Nederland, 1800–1913 (Capital investment in infrastructure in the Netherlands, 1800–1913). PhD thesis, Groningen University. Capelle aan den IJssel: Labyrint; 1995.

ing, but also for bathing, showering, flushing toilets, and washing. These new user practices aligned with the cultural desire for cleanliness, morphing from its traditional role in social distinction (between the middle classes and the 'unwashed') into a hygienic ideology that linked cleanliness, personal care and health. These developments – which in effect created new social norms around modernity – inspired sales of new artefacts (WCs, showers, baths, wash basins) and new products (soap, shampoo, and synthetic detergents). The new hygienic routines spread through schools, as well as via a stream of brochures, leaflets and educational campaigns.

Thirdly, the water industry professionalised. It created the Dutch Water Association (1899), which engaged in political lobbying and knowledge propagation for its members, disseminating information, for example, about new water purification techniques such as ozone and chlorine. In 1909, the association also developed water quality norms, articulating the minimum chemical and biological properties of drinking water.

Summary

System transitions progress through the three phases (emergence, diffusion, and reconfiguration) in complex ways. Historical experience, however, also suggests a few general patterns, which are summarised in Table 2 below. This table also summarises concrete policy actions that can accelerate the transition. The complexities of transitions are a reminder that one-size-fits-all policies are implausible, but that patterns in mechanisms can guide a tailored, strategic approach to policy.

TABLE 2: SUMMARY OF ACTIONS IN DIFFERENT PHASES OF TRANSITIONS

	FIRMS	USERS	CIVIL SOCIETY	POLICYMAKERS: ACTIONS TO ACCELERATE THE TRANSITION
EMERGENCE	• Entrepreneurs and new organisations engage in experiments and learning processes • Incumbent firms are locked-into existing regimes and focus on incremental improvement of existing technologies	• Uncertainty about consumer preferences, potential markets, and new functionalities • Lead users with special interests (military, rich enthusiasts) may form early application niches	• Public concerns about existing problems may create pressures for change • Negative side-effects of new technologies may create social acceptance problems	• Stimulate R&D and real-world demonstration projects • Stimulate knowledge sharing between projects • Articulate visions or missions • Nurture the building of transformative coalitions • Public procurement to create early application niches
DIFFUSION	• Improve technological performance and lower costs • Investments in factories, supply chains and infrastructures • Redefinition of interests and strategies • Stronger coalitions lobby for policy change • Incumbent firms may begin to reorient towards the niche-innovation	• Mainstream users adopt the new technology because of economic calculations and attitudes, beliefs and norms • New functionalities (e.g., comfort, speed, freedom) and addressing pre-existing concerns are particularly important	• Public enthusiasm and positive visions about new technologies may shape consumer preferences and appropriate policy support	• Taxes and regulations to alter the economic playing field • Purchase subsidies, favourable price-setting, public procurement to stimulate demand • Capital grants, loans, performance standards to shape firm investment • Public infrastructure investment • Public relations campaigns
SYSTEM RECONFIGURATION	• New entrants overthrow incumbents, or incumbents reorient • New companies enter to develop complementary innovations and products	• Users may develop new routines and practices as they gain experience • Alignment with wider trends may generate new user cultures	• New cultural conventions and views of normality • Concerns about jobs and disadvantaged communities may threaten social acceptance	• Stimulate whole system adjustment • Anchor the new system in regulations and standards • Develop agencies with new roles and responsibilities • Mitigate negative socio-economic effects with 'just transition' policies (e.g., compensation, retraining)

3. ROLES FOR INTERNATIONAL COOPERATION

In the previous chapter we outlined how technological transitions occur – a process that begins in niches, diffuses more widely, and then reconfigures systems and actor-interests so that the transition deepens and becomes entrenched. Inter-governmental cooperation did not figure much in the story because, historically, most major exemplars of technology transition occurred within singular or closely connected markets. Moreover, a wide array of processes aimed at advancing cooperation on climate change already exist – notably the Paris Agreement – so why should the international community do more to cooperate?

The answer to this question is rooted in the direction, speed and durability of the agricultural and industrial transformations needed for deep net reductions in emissions. CO_2 and other warming pollutants mix globally in the atmosphere, which means that transition must eventually eliminate nearly all global emissions. In most sectors today – and even more sectors in the future – the firms whose processes must be decarbonised compete in a global market, so the transition must at key moments address the practical realities of industrial competition. In this context, more and different cooperation can yield several practical benefits that can accelerate the transition to deep decarbonisation:

- If more firms and governments conduct a wider array of policy and technological experiments, there will be more potential niches from which decarbonisation transitions can take off. Generating and disseminating the insights from these experiments can help identify viable solutions more quickly.
- In many niches, early adopters are faced with both real and perceived fears that their actions to make costly reductions in emissions will erode competitiveness. Cooperation can help level the playing field – rewarding success rather than penalising effort.
- If different countries support the same new technologies and implement comparable support policies then the scaling up, improvements in performance, and reduction in cost that are typical of technological diffusion will happen faster and with broader scope. This will also speed up efforts to overcome resistance from incumbents and reconfigure infrastructure and political support needed for deeper global decarbonisation.

Therefore, efforts to steer the decarbonisation transition could benefit from cooperation across borders. This chapter examines what has been learned from the history of international cooperation in its various forms. What emerges from the analysis is the need for careful strategic choices, because trade-offs are numerous. For example, governments have proven highly adept at negotiating and joining large numbers of international agreements – especially agreements aimed at addressing a wide array of topics on the sustainable development agenda. But these global agreements are often aspirational and thin on content, reflecting the least common denominator of what is agreeable. By contrast, agreements with more restricted membership and sharper focus often require much greater effort by their members – a greater impact, often, on changing the behaviour of the status quo – but at the cost of narrower geographical coverage.[21]

Understanding how to make these strategic trade-offs requires theory and experience to guide which approaches work best under different circumstances – so that the real-world practice of cooperation is aligned with the goals.

The logic of cooperation

What works in international cooperation depends on the nature of the problem and the interests of the parties that design and join international agreements. It is useful to distinguish problems along two dimensions. One dimension is whether the nature of the actions needed to address a problem are understood: are the necessary policies, technologies and business models needed known, as well as their cost? The other dimension is whether the key players agree on the level of effort needed and how to allocate the burdens and benefits of cooperation.[22]

This "understanding vs. consensus" matrix, shown in Figure 9, helps to map the ways that cooperation can affect technological transitions and, ultimately, solve environmental problems.

Cooperation can help solve problems marked by low understanding and lack of agreement (upper left corner) through experimentation, trial projects, puzzling and learning. In this mode, cooperation does not require widespread agreement or understanding – simply the motivation in enough political jurisdictions and firms to jump-start the process of experimentation and testing of ideas in niches. The watchwords for governance are **experimentation and learning**.[23] It is in these early stages that the raw information needed for learning and wider understanding emerges. Learning from these niche experiments is not an automatic process. It requires institutions that can review the lessons from experiments and decipher what's working (and what's not). Often those institutions are technical bodies – such as industry associations, regulators, and expert bodies set up by treaties – and they help frame the policy options for further effort.

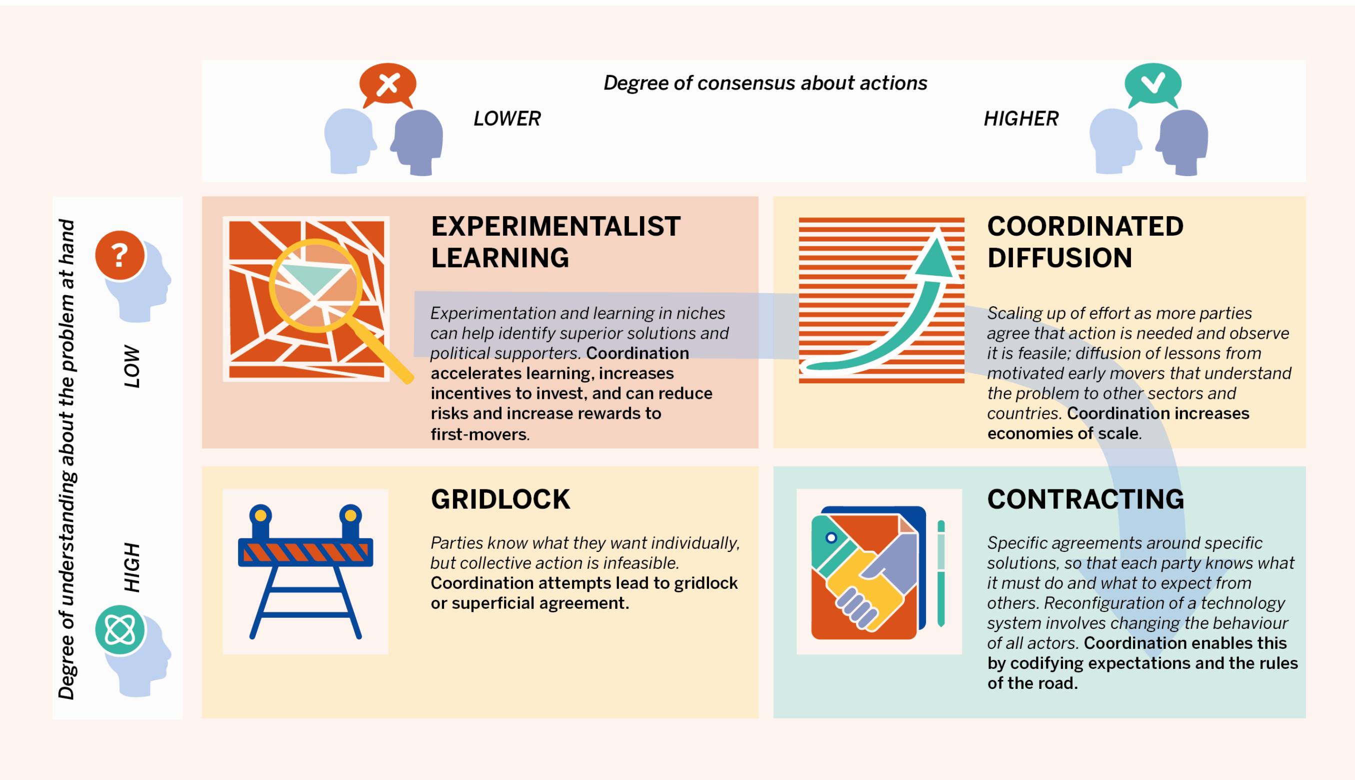
With experience and deeper understanding of the nature of technological and policy transitions, a wider array of niches with successful new industries can emerge. These applications help build experience with the relevant technologies, allow the creation of infrastructures and rules that facilitate even larger market shares. Experience and understanding also changes the nature of political support for transition. Due to their revenues and other resources that flow from deployment, and thanks to concrete information about what works, firms, governments and their political supporters, become increasingly powerful politically as they discover tangible information about the costs and benefits of transitions. If all equal, this diffusion process will happen faster and with greater impact if the markets where the technology takes off are larger and more numerous. The watchwords for international cooperation here are **coordinated creation of markets, joint procurement, and coordination of deployment**.

Finally, as diffusion proceeds and the industrial base anchored in the transition economy grows, the underlying interests shift. Interests are reconfigured to support further action, and detailed knowledge about the industries and policies needed grows quickly. Here, the watchwords for governance are **contracting** – that is, detailed agreements around known solutions that address known barriers to further application. Much of the formal literature on international cooperation has emphasised, in various ways, contracting approaches. This is because many scholars start with the assumption that collective action is difficult to achieve, because even when there are potential joint gains from cooperation, the self-interest of countries leads them to focus more narrowly on protecting their own individual interests. Joint action does not happen unless there is confidence that collective solutions will be followed. [24]Our approach here emphasises the roles of uncertainty and learning in the early stages, followed by the discovery of places where, indeed, contracting will be needed.

Throughout this report we will focus on these three styles of governance: a) experimentalist learning, b) coordinated diffusion, and c) contracting. These roles for governance correspond, respectively, to the phases of technological change mapped out in the previous chapter. As with the processes of technological change, governance is dynamic and recursive. For example, the knowledge that market shares will grow through diffusion and contracting against inferior (more pollution-intensive) technologies creates incentives for firms to invest in experiments and learning around superior technologies.[25]

Thus, cooperation leads to successful problem solving by performing different functions that lead clockwise around Figure 9 – from the upper left to the lower right. Cooperation is not magic and it does not always work. Badly designed early efforts can lead to gridlock if parties, as they learn, don't also create a transition in political consensus on the need for action (lower left corner). This danger of gridlock is why efforts at cooperation must be closely informed by insights into how pervasive transitions in technologies, infrastructures

FIGURE 9: COOPERATION MATRIX



and industries actually happen. There are many forces that can lead to diplomatic gridlock. For example, it is widely accepted that agreements with large membership are highly legitimate because they reflect broad consent. At the same time, content is often necessarily watered down in order to reach legitimate consensus. Or, in the most extreme forms of gridlock, efforts to obtain consensus can't find any meaningful agreement at all.[26]

The world is complex and, of course, there are many other defining characteristics of problems. For example, there can be cooperation that involves a small number of players versus cooperation that implicates much larger groups. Analysts have shown that the former problems are much easier to address than the latter, because it is easier to craft compromises, especially over contested topics, with fewer competing interests and voices.[27] Often, when the number of parties is very small, cooperation can even emerge tacitly – by parties knowing what is needed and observing other parties – without any formal agreement at all.[28]

The difficulty of working in large groups aimed at reaching full consensus informs one of the most important policy challenges today. A sound, workable framework for certain kinds of cooperation has been created through the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. That framework must be supported. By itself, however, it cannot provide all the functions needed for successful cooperation, especially in the early stages of transition (where the world currently stands), during which understanding and consensus about needed actions is low. In addition to the Paris Agreement, other efforts and institutions are needed.

We now unpack in more detail how cooperation can accelerate the processes of transition by looking at three cases: the Montreal Protocol (which protects the ozone layer), the Limited Test Ban Treaty (which stopped atmospheric and oceanic testing of nuclear weapons and set the stage for broader cooperation on nuclear weapons control), and the World Trade Organization (which helps stabilise expectations around the need for open borders to trade). These three cases are drawn from three of the most important domains of international cooperation: environment, security and trade. Each has involved managing uncertainties and learning about the nature of underlying problems and their solutions. Each also provides lessons about effective cooperation in each of the three modes, as well as how progression between modes is important for societal objectives to be reached. We start with Montreal, because of its importance in the history of environmental cooperation, and then look at the other two cases, because they help to round out the lessons from history.[29]

Cooperation at work: the ozone layer experience[30]

Beginning in the 1970s, scientists detected chemical reactions that would cause a thinning in the atmospheric ozone layer that protects most life on earth from ultraviolet radiation. The cause was traced to emissions of chlorofluorocarbons (and later other chemicals, including halons) that were then widely used in applications from refrigeration and aerosol sprays to fire extinguishers and Styrofoam. After more than a decade of contentious debate, two global treaties emerged: The Vienna Convention (1985) and the Montreal Protocol (1987).

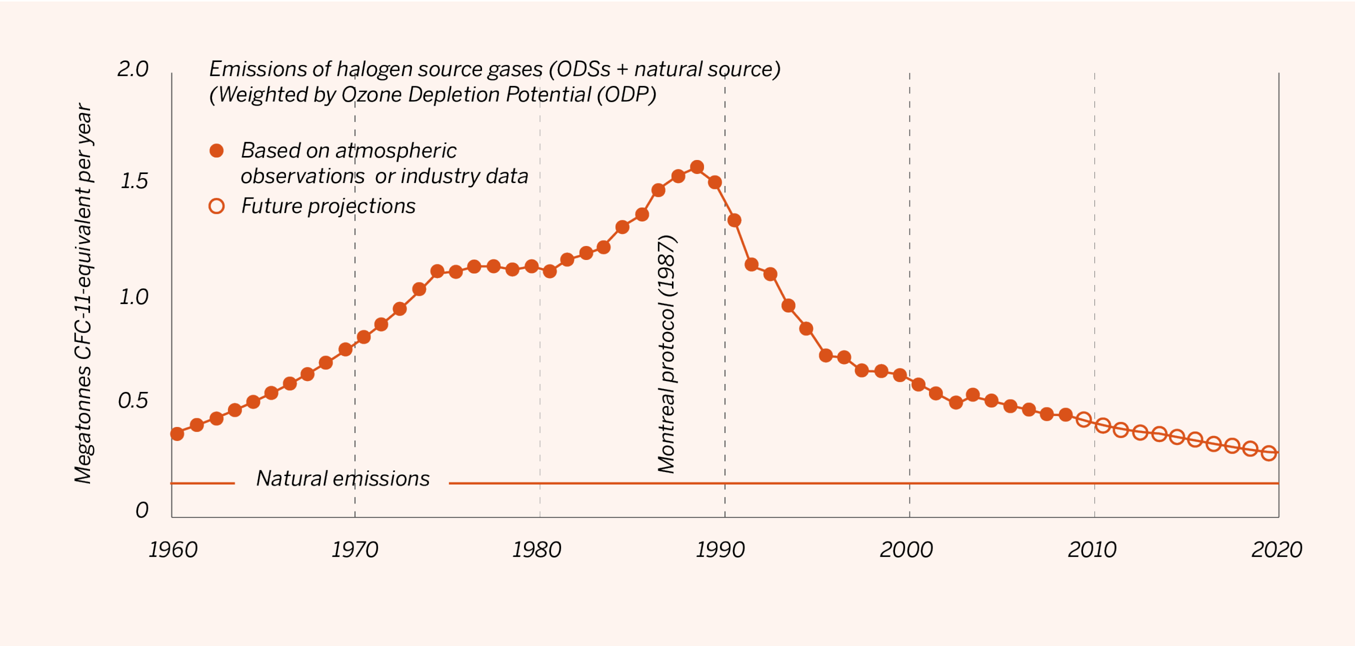
Looking back at history, it is often claimed today that what made these agreements work was strong science, ambitious binding targets, and timetables that were applied eventually globally, accompanied by a regular tightening of these obligations. The parties knew what to do and the Montreal Protocol helped to focus scientific and political effort on the needed actions. In reality, success stemmed from something quite different: the Montreal Protocol was designed for uncertainty. Most of what was needed to cut ozone-depleting substances (ODS) was, at the time Montreal was first drafted, unknown in efficacy and cost. Montreal worked by creating incentives to innovate and test ideas. Once workable solutions appeared with a known cost they could be diffused more widely. When regulation proved easier than expected, Montreal worked faster. This is why, today, it is seen as the world's most effective international environmental treaty, and for our purposes, it usefully illustrates the three modes through which international cooperation helps advance transition: coordinated learning in niches, diffusion through coordinated deployment and funding, and reconfiguration through contracting.

Experimentalist learning

The core of the Montreal Protocol commitments consisted of an initial, adjustable schedule to control and eventually eliminate nearly all ODS. Legally, those obligations took the form of country-by-country limits on consumption of ODS – akin to the country-based emission targets for greenhouse gases that are often discussed in the context of cooperation on global warming. However, as key governments and firms came down heavily on ODS, they didn't think or plan in terms of economy-wide targets. Instead, they decomposed these targets into specific implications – in terms of ODS consumption and technological practices – for individual sectors and often individual countries. Formally, countries agreed to economy-wide targets that were codified for groups of similar ODS that were organised into baskets. Success, however, came from a finer-grained focus. It helped that the economy-wide targets quickly became, essentially, zero, and thus the sectoral and technological approaches could focus on zero.

In September 1987, when the first targets were set, it was not wholly evident what was causing ozone depletion. (The key experiments – flying aircraft into the Antarctic ozone hole – only took place the following month.) Nor was it clear which ODS substitutes would work. So, the architects of Montreal adopted limits that were as strict as all the countries that were willing to sign at the time were willing to implement: a cut in half of all the major known ODS. The exact target mattered less than the clear signal sent that the screws were tightening. At least a few firms responded, convinced that they should work on solutions lest they suffer damage to their reputations and lost market share. That pattern has been replicated many times ever since: initial targets sent signals to firms, at least a few responded and found solutions, and as the solutions were better understood then governments jointly (and thus reciprocally) agreed to tighten the limits. The year 1987 marked the peak of ODS, and as the Protocol evolved, consumption was rapidly reduced (Figure 10).

FIGURE 10: EFFECT OF THE MONTREAL PROTOCOL



Adapted from Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project–Report No. 52, 516 pp., World Meteorological Organization, Geneva, Switzerland, 2011, NASA, NOAA, WMO, EPA. http://www.theozonehole.com/ozonedestruction.htm.

Coordinated diffusion

Designing for uncertainty meant that the measures controlling ODS are reassessed every few years in accordance with current scientific, environmental, technical and economic information. That process of review and reassessment is done by expert committees that then frame major policy options – for example, changes in ODS targets – to be taken by policy makers. (In addition to these technology-focussed committees, a variety of expert bodies, led by the World Meteorological Organization and the United Nations Environment Programme, also periodically assessed the overall state of ozone science, much as the IPCC does for climate science. What's different between such broad assessments and the technical committees, however, is that the latter works with faster turnaround and is focussed squarely on problem-solving and the practical experience from policy and technology experiments in the field, and has a much greater technical input from industry. This expert process is highly detailed and informed by the latest technology, and it works by framing a range of possible technology outcomes and then learning quickly what is feasible.

What makes this technology-driven process interesting is that it does not focus mainly on the ozone problem overall, nor on ODS overall. Instead, the key technical analysis is focussed sector-by-sector – such as on solvents, plastic foams, refrigerants, and on halon fire-extinguishing agents.

The technical committees are comprised of ODS users and producers who have run pilot projects and tested the performance of new substances and processes. This approach prevented the regime from over-reaching – from imposing aggressive, astringent controls faster than the underlying sectoral experience and technology allowed – or under-reaching by setting goals that were too conservative in light of uncertainties that technological innovation and learning were resolving.

As these are global technologies traded in global markets, de facto the industry and leading governments quickly coordinated around standards and expectations. This, in turn, helped provide clear standards to the global industry about what to expect: for example, when to expect the need to shift away from certain ODS applications and the expected rate of change.

When the search for ODS substitutes and work-arounds came up short, the Montreal process – a combination of technical committees and political diplomatic oversight – authorised exemptions for 'essential' and 'critical' uses, or extended the timetables for meeting the phase-out obligations. When the Montreal regime phased out the use of ODS in metered dose inhalers (MDIs) – a device that asthmatics, for example, use to inhale needed drugs safely into the lungs – at first countries that had a high usage of MDIs were given exemptions. Then, the technical committees scoured information about pilot projects on the safety and efficacy of ODS-free MDIs. Once a reliable selection had succeeded, they endorsed the tightening of the ODS rules, exemptions were narrowed and finally eliminated.

Initially the Montreal Protocol focussed on industrialised countries, for they had the highest consumption of ODS and were most concerned about ozone thinning. But soon it became clear that solutions were essential worldwide, and the same basic process of commitments and engagement was extended to other nations, with one big difference: developing countries (consuming less than threshold amounts of controlled substances per capita) could defer control measures (initially for a decade) and draw on the support of a multilateral fund financed by the rich countries to pay the full costs of compliance. Membership to the fund required that prospective members establish a national ozone unit to oversee preparation and execution of a comprehensive regulatory framework with sector-by-sector plans for phasing out production and use of ODS. This made it possible for lessons learned anywhere in the world about best practices to diffuse quickly to the rest of the world. The Fund also made it easier for the global regime to evolve in a manner highly informed about local possibilities and experiences with regulating ODS in places where political and administrative constraints were higher. This was vital to the processes of diffusion and reconfiguration.

Contracting

As it became clear exactly what to expect for compliance, it was also possible to create specific incentives to ensure the desired outcome – as well as to reconfigure markets, ultimately globally, around low ODS applications. The multilateral fund offered positive incentives, and every country that was a member was also expected to have dedicated authorities and procedures in the nation that offered a well-informed, single point of contact between the country and the Montreal regime.

In addition, Montreal installed penalties in the form of trade sanctions against members that failed to comply. Formally, the parties agreed to ban trade in controlled ODSs between parties and countries that weren't members of the treaty. Such a measure was rare, because the incentives within the treaty encouraged broad membership as the costs of compliance for least developed countries were paid by the Montreal Multilateral Fund. These trade measures were threatened periodically, though never eventually used – a sign, not of impotence, but of their strength in keeping behaviour aligned. For example, all parties to Montreal were required to report data on ODS consumption, and developing country parties were paid the full cost of creating those systems. Nonetheless, a small number did not report. Threats of trade sanctions, along with the removal of funding, quickly changed that behaviour.[31]

The incentives meant that most parties, for most of the time, participated in the Montreal Protocol in good faith. Formalised trade sanctions helped maintain the alignment. But in a few cases the incentives to violate the agreement were much stronger, and more severe penalties were needed. For example, Russia appears to have harboured illegal ODS factories in the mid-1990s. Since then, a few other countries have engaged in similar behaviour.[32] The formal legal regime did not have penalties strong enough, so a strategy for enforcement required sympathetic countries to step in. For example, the European Union threatened additional trade sanctions, and several western countries put together an assistance package. Facing new penalties and rewards, to a degree Russia changed its behaviour, resulting in the example of a growing violation diminishing from a threat to the integrity of the regime, to a more minor problem requiring ongoing management.[33]

Beyond Montreal: many other experiences

In the language of our study, Montreal began as an agreement focussed on experimentation. With experience and success, it became a vehicle for diffusion of successful regulatory, technological and business strategies. As the best strategies were learned, some contracting problems arose: such as the need to ensure that countries and firms could not gain commercial advantage by avoiding ODS regulation and selling unregulated products on the world market.

Montreal is now more than 30 years old, and because practical problem-solving unfolded relatively quickly, the full cycle of these different modes of cooperation-accelerating-technological transition are on display. Every case depends on the particulars of the costs of response, the organisation of the industry, evolution in national interests, and many other factors. In the case of ozone depletion, for example, production of the original ODS was highly concentrated in a few firms, and some of them – notably, DuPont – broke ranks with other ODS producers (and with nearly all the firms, like refrigerator manufacturers and foam blowers, that used ODS) to find solutions. They soon discovered costs (at least for the initial ODS) were not as high as feared, and some of the new product lines were more profitable. The search for solutions also helped DuPont (and soon others) avoid potentially catastrophic reputational and regulatory risks in their largest and most regulated market at the time – the United States.[34]

Climate change is likely to be different because the organisation of industrial processes and interests are less aligned to find and apply solutions. In some sectors, however, a similar dynamic may play out where solutions prove easier than expected, and some firms and governments quickly coalesce around solutions. The rapid deployment of renewable power and of electric vehicles, discussed in more detail below, offer partial examples. If the search for viable business and technological deployments of carbon capture and storage, hydrogen, green steel, green plastics, and sundry other options bespoke to particular sectors, prove effective, then Montreal-like dynamics may play out there as well (though perhaps at a slower speed). The fact that the opportunities, the unknowns, and the industrial interests are organised differently in every sector is one of the chief reasons why a sectoral approach to problem solving – breaking big problems down into smaller units that can be addressed coherently and effectively – is so important.

The Montreal example maps well on to all three of the modes of international cooperation discussed in Figure 9, but many other examples help to flesh out the picture. When looking for examples that are relevant to climate change, there has been a tendency to consider other global multilateral experiences – not just Montreal, but also experiences relating to biological diversity, endangered species, the oceans, sustainable development, human rights, and so on. Yet, in reality, much of the practical experience with international cooperation that is focussed on problem-solving – as opposed to broad, legitimacy-building diplomacy organised within grand agreements and institutions – occurs in highly specified, often technical agreements and organisations.

This is how the International Maritime Organization (IMO), for example, catalysed a big reduction on oil pollution from tanker ship operations in the 1970s. They did it by identifying technological solutions from experimentation, creating standards that encouraged diffusion, and then reconfiguring the global market around specific contractual rules that tanker owners (and their insurers) and port operators could implement.[35] (The IMO is now doing something similar with regard to Sulphur air pollution from shipping.) The most effective work of the International Civil Aviation Organization (ICAO) operates in similar ways. Specialised organisations that work on food safety standards, such as an arm of the World Health Organization (WHO) and the Food and Agricultural Organization (FAO), play this same role by helping national governments learn about, diffuse and adopt common standards.

As these national standards have had larger effects on international trade, these kinds of learning and diffusion mechanisms focussed on national regulatory coordination have become an important laboratory for focussed coordination within much larger agreements, such as in the World Trade Organization (WTO). The WTO, which we discuss in more detail below, explicitly empowers focussed technical coordination bodies to address many of these tasks that would otherwise be too unwieldy in a global consensus organisation that addresses much broader issues of trade.[36] In finance and accounting, focussed technical coordination that is oriented around experimentation and learning, followed by diffusion and contracting through standard-setting, is commonplace. And many additional examples of focussed sectoral cooperation exist – some oriented around business, some focussed on governments, and many now operating in both spheres.

It is also instructive to look at examples beyond the usual arsenal offered up from international environmental diplomacy. For example, the 1963 Limited Test Ban Treaty (LTBT) halted the atmospheric and oceanic testing of nuclear weapons. These tests had become a growing environmental problem, with radioactive clouds occasionally drifting downwind from test sites, and large amounts of background radioactivity accumulating in the global environment. The milk of mothers became measurably more radioactive, with unknown effects on babies, and sundry other effects mounted. Moving testing underground – a known option with unknown practicality in the late 1950s – solved the problem. As often happens with environmental agreements, broadening and deepening public concern helped push governments to act. The halting of atmospheric tests emerged as social movements arose in the West combined concerns about health effects with even broader concerns about nuclear weapons production getting out of control.

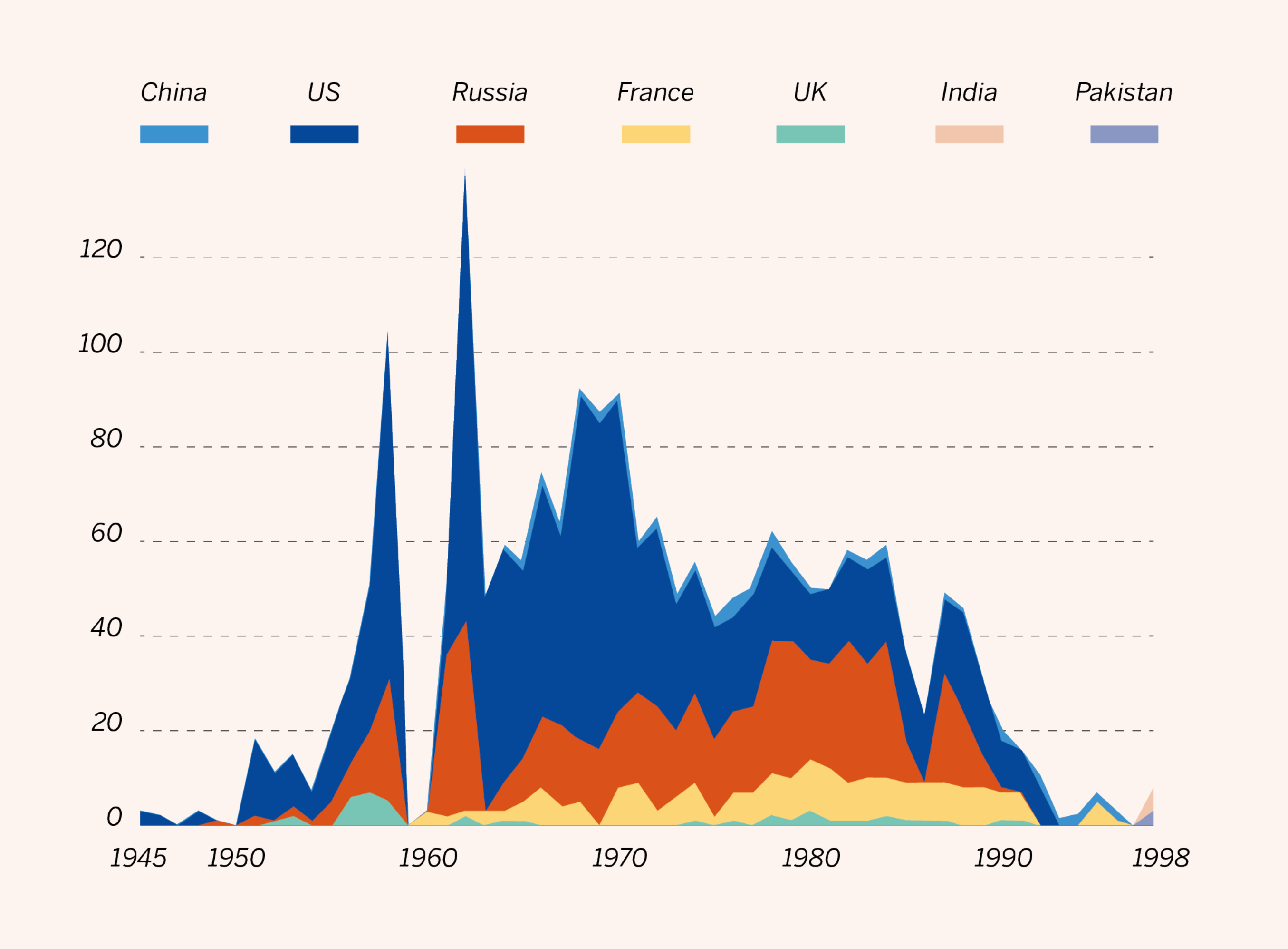
Three aspects of the LTBT history are particularly relevant for our study because each illustrates how broad concerns about testing of nuclear weapons were translated into concrete areas for cooperation that then changed behaviour. As is often the case on matters perceived as vital to national security, suspicions were high and thus the process quickly moved to contracting, so that every party that cooperated knew that others would do the same.

Firstly, even as pressure mounted for action – such as a dozen resolutions against testing in the UN General Assembly from the 1950s and early 1960s – the question of exactly how to conduct tests underground, and how to monitor testing by others, remained unknown. An advantage, beyond the lower cost, of atmospheric testing was that the signal of a test was readily detected from spy planes and atmospheric sniffers. Thus, the US, and the Soviet Union and their allies, ran a series of experiments to gain confidence in underground testing and in the ability to measure, seismically, the tests of others. It is no accident that these governments were big backers of research in geophysics during this period, because that science made it possible to observe the developments of adversarial weapons (along with a host of other security related activities, such as the movement of submarines and the capabilities of missiles). In this case, R&D activities were oriented toward geophysics and military capabilities, and this made further cooperation and joint problem-solving possible.

Secondly, significant cooperation can emerge tacitly – at least when the parties that must move first are small in number and their behaviour easily observed. From 1959 to 1961 neither the US nor the USSR tested any weapons – a result that remained stable for a while (Figure 11). This reveals how coordination of joint projects and policies can often arise simply by stabilising expectations – making clear what is expected so that efforts can focus on particular solutions. When the moratorium broke in 1961 the US, that same year, only tested underground – an important experiment that confirmed the viability of that approach. A year later, the moratorium broke even further, and both superpowers tested prodigiously in the atmosphere. (The global backlash against 1962 testing, along with the October 1962 Cuban Missile Crisis, focussed minds on the need for solutions.) Tacit cooperation helped start broader cooperation.

Thirdly, as is often the case with tacit coordination, the results are not stable on their own. Contracting was needed to keep behaviour focussed on favoured solutions. In the case of the Limited Test Ban Treaty, the contract was relatively easy to frame. All that was needed was a piece of paper and agreement on what was expected. The parties, on their own, could monitor compliance and, through the tacit cessation of testing, had demonstrated that bad behaviour would resume if the other side blinked first. The same principle of reciprocity ensured the effectiveness of the Threshold Test Ban Treaty, agreed in 1974, which limited the magnitude of underground testing. In contrast with the Limited Test Ban Treaty, in this instance a more complex agreement to coordinate action was needed. Once again, both sides required joint experimentation by scientists

FIGURE 11: NUMBERS OF NUCLEAR WEAPONS TESTS



Based on data from the Oklahoma Geological Survey Observatory via: https://ourworldindata.org/nuclear-weapons.

to provide the superpowers with the confidence to enter into an agreement, with contracting to ensure that the desired outcome was sustained.

Finally, the LTBT reveals how cooperation can have a large impact on directing behaviour in the right direction even in the absence of enforcement mechanisms. In 1996, many governments also signed a Comprehensive Test Ban Treaty that aimed to go one big step further and ban testing altogether – a task that has proved tough politically (because a number of countries want continued development of weapons) as well as technically (because very small tests, which are still useful for weapons development, can be hard to measure). Experimentation and the identification of technical solutions does not automatically change national interests and behaviour without the broader diffusion and reconfiguration processes running their full course. In the case of nuclear weapons testing, reconfiguration is far from complete: some critical countries still think testing is a vital option. Yet tacit cooperation remains at an all-time high. No country but for North Korea has tested a weapon since 1998, and nearly all global testing of nuclear weapons has ceased since 1991.[37]

All of these lessons are likely to be relevant to climate change mitigation. In areas where the exact solutions are not yet known, joint research, development and experimentation will make further cooperation and joint problem-solving possible. Tacit cooperation between key firms or governments will also help get the process started, as long as that cooperation is focussed on doing conspicuous things, and actively watching others do the same, rather than writing down the details of what is to be done. When uncertainty is high, detailed action plans announced ex ante may be considerably less valuable than tangible demonstrations. Finally, contracting may be needed to ensure that the whole industry follows in each sector. Reciprocity can support the effectiveness of this approach, even if enforcement mechanisms are not strong.

One striking difference between the history of arms control agreements and most efforts at international cooperation on environmental issues is that the former has been obsessed with monitoring and verification.[38] Environmental cooperation, by contrast, has not: it often emphasizes roles for reporting and reviewing, but those mechanisms are just as frequently less robust and independent. They are oriented not for assessing compliance but towards helping parties learn about implementation problems and to adjust accordingly.[39] This disparity reflects the different stakes and structures of the two kinds of challenges. Often, the role of formal cooperation in arms control focusses on areas seen as central to national security, so wariness about other countries not honouring agreements is particularly high. Environmental issues, by contrast, tend to involve problems that accumulate. The need to spot and respond to violations is less acute. Moreover, management of environmental issues tends to follow the logic outlined in Chapter 2 of this report: solutions are tested in early niches, strategies and technologies diffuse, and then reconfiguration locks this new reality into place. For arms control, reconfiguration is often less evident, and suspicions of other countries' motives higher.

Despite these differences, it is apparent that managing some environmental problems requires more attention to monitoring and enforcement – the watchwords of a contracting approach to international cooperation where knowledge about risks and benefits is high and parties' interests are not perfectly aligned. On this front, the most relevant experiences are those related to international trade, where contracting has played a vital role in ensuring that each country plays its part.

> Managing some environmental problems requires more attention to monitoring and enforcement – the watchwords of a contracting approach to international cooperation where knowledge about risks and benefits is high and parties' interests are not perfectly aligned.

Opening borders: the experience with trade and roles for contracting

Briefly, we will also look at important lessons from the history of international trade. Trade matters because, as we will show in the detailed sectoral studies in the next chapter, most of the products that are implicated in deep decarbonisation are traded in global markets and many are commodities. Globalisation has made these markets highly efficient in rewarding least-cost suppliers. This is an attribute that has yielded many benefits for the global economy. However, it also penalises firms and countries that move first if such moves affect the cost, reliability and other attributes of products that make them less competitive in the global market. This is a widely recognised challenge, and the experience in trade – in the World Trade Organization (WTO) and in many trade agreements that cover subsets of the globe – reveals some solutions. These trade agreements reveal all the modes of cooperation from Figure 9. As discussed above, experimentalism and diffusion around key trade topics such as regulatory coordination is devolved to expert agencies. These agreements themselves have evolved through learning: from agreements that focussed on tasks that were relatively easy for governments to perform (e.g., coordinating border tariffs and government procurement – mechanisms that governments control directly), to more challenging "behind the border" factors that affect trade and financial flows, such as environmental, social and investment policies. Through broader awareness of the benefits of trade discipline and greater access to markets, the scope of trade agreements has expanded massively, notably within the WTO, which now counts nearly every significant economy as a member.

Here we focus on one particularly important aspect: contracting within trade agreements. It is vital to one of the most central functions for international cooperation in the area of decarbonisation: to tilt the playing field for trade so that first movers are not penalised for moving first.

One of the central challenges in opening economies to trade is building and ensuring confidence that other governments will adopt similar policies, so that openness creates advantages for all competitors, not disadvantages to the firms and governments that are first movers. The World Trade Organization (WTO) was designed to address this problem head-on with a scheme for binding dispute resolution. As trade is an intrinsically bilateral and often reciprocal activity, monitoring and enforcement occurs through disputes. Parties that are harmed by violations of trade rules are intensely aware of the damage and thus ideally positioned to launch a dispute. The collectivity of disputes, in turn, provides the WTO's overall enforcement system.

A central challenge for WTO enforcement of trade measures is presented by the difficulty in knowing which trade measures are legitimate (because they are designed to fit local or national priorities, such as environmental or other social goals) and which measures are merely protectionism in disguise. Contracting efforts cannot proceed until there is agreement on what is legitimate and what is a violation.

The place where this logic has evolved most is in disputes about environmental and health protection – an area where legitimate and illegal measures are easily co-mingled and hard to distinguish between. Through a series of disputes – over hormones in meat, genetically modified foods, imported fish, protection of turtles caught during shrimp fishing, the use of dangerous asbestos in ceiling tiles, and sundry other topics – the WTO dispute settlement system has clarified standards around when trade restrictions are legitimate.[40] In effect, countries have experimented with different trade measures and learned how to design measures that provide desired local benefits while not violating WTO strictures.

Experimentation and learning in legal enforcement have, in turn, laid a foundation for better contracting. Greater clarity about which border measures are valid has made it possible to develop policy strategies – such as the setting of border tariffs on carbon, or the linking of market access to emissions-related standards – that align with existing practice and expectations in trade law. Those policy strategies that have been worked out in trade are familiar within the framework offered in this study. Where knowledge about the best measures is high and interests can be aligned, precise contracting and standards are possible. This is a situation that exists already in many areas of food safety and other "behind the border" measures that affect trade today. Where governments can choose between different measures to achieve the same environmental goals, they should opt for those that have less of an impact on trade and are less discriminatory. By contrast, where the technological possibilities are uncertain and real-world experimentation immature, trade measures should be provisional, with periodic re-assessment and adjustment to align with any new information.

Using trade measures that have been developed through experimentation and practice within the WTO and other trade institutions raises the odds that, in the case of climate change, policy strategies aimed at rewarding first movers will actually work. They have high (though not perfect) odds that they will not be overturned by the WTO's dispute resolution system, for example. It is important, nonetheless, to remember that international institutions are often fragile, and their durability depends upon national interests and acceptance. The WTO, today, is in the middle of a crisis that may render it in gridlock and may also hobble its dispute resolution machinery. (Many smaller trade agreements are thriving, however, in part because of troubles at the WTO. Standards for contracting and creating incentives for first movers that are developed with the WTO's jurisprudence in mind may still gain widespread traction, but with different legal authorities.)

Moreover, many of the industries implicated in deep decarbonisation are strategically central to key countries. The power sector affects the costs of energy supply and thus a nation's competitiveness. Commodities such as cement, steel and plastics are strategically central to many nations' industrial policies, and so the real-world practice of forging international cooperation around climate change will always be fraught with difficulties that require strategic choices. When governments see industries as strategically central, they tend to focus on "relative gains" – that is, whether their industries are doing better than competitors in other countries. In general, efforts that focus on relative gains tend to be less agreeable than those where cooperation aims to create larger joint gains – that is, dividing a fixed pie is harder than making pies bigger.[41] By contrast, solving the problem of oil discharges from tankers, or eliminating ozone destroying substances was, even at the time, considered less daunting, as well as strategically central to national development.

Using trade measures that have been developed through experimentation and practice within the WTO and other trade institutions raises the odds that, in the case of climate change, policy strategies aimed at rewarding first movers will actually work.

Will continued international policy coordination be needed?

Perhaps the single most strategic question that will arise as diffusion and reconfiguration proceed is whether the new technologies, business practices and systems will become superior in their own right. In retrospect, and as discussed in the previous chapter, most technological revolutions are cemented in place because, in time, the new systems dominate the incumbents across a number of dimensions. They push out the incumbents and lock themselves in place – eventually across every market – until the next new rival comes along. As new systems triumph, the need for ongoing policy is diminished.

The answer to this question may prove to be one of the most important strategic challenges in global deep decarbonisation. In the early stages of emergence there is a clear role for policy: to facilitate experimentation and to create niche markets and early diffusion. Cooperation by small groups of countries focussed on particular sectors is one way in which international cooperation can play a role. Creating the incentives for this cooperation is not a trivial matter: early movers must coordinate, and markets must be created and then expanded. The challenges for international cooperation, however, may grow more daunting as diffusion and reconfiguration proceed. If the new technologies do not become superior on their own then ubiquitous diffusion and reconfiguration must confront a particularly difficult challenge for collective action: ensuring that all firms and governments in the global economy follow the path of deep decarbonisation. If those incentives and new technologies arise quickly, as in the Montreal Protocol, then global technological change may follow quickly as well. If not, deep decarbonisation globally will not happen without ongoing policy coordination that engages essentially all governments and markets.

PATTERNS AND PRINCIPLES

The logic of how cooperation can help accelerate and direct the processes of system transition, along with the case studies, reveal patterns that often repeat across the many different experiences with international cooperation. These patterns, in turn, help to identify a set of principles that can guide more effective cooperation on climate:

- *Problems are often hard to solve, initially, because they are framed in grand terms and viable solutions are unknown.* Daunting problems that create harm to many different and diverse interest groups yield gridlock. Solutions can emerge with a focus on key processes and actors, and learning through experimentation. Successful cooperation in this mode begins by breaking big, unwieldy problems down into manageable pieces that are aligned with how industries and policies are organised. This approach makes it easier for solutions, and their industrial and political supporters, to be identified. It lays the groundwork for eventual diffusion and contracting – rather than trying to go directly into the more difficult tasks where levels of knowledge and political consensus are low.
- *Cooperation depends on interests, which are dynamic.* A central purpose of experimentation is to identify supporting interest groups and practical industrial strategies that can, eventually, solve problems. It is through experimentation that firms willing to break ranks with the rest of the industry – or new entrants that offer a radically different way of solving a problem – can be identified. Diffusion reflects a broader spread of information and technology, so that more actors see that it is in their interest to change. Contracting helps to cement those interests in place, with credible incentives for participation and compliance, and penalties for the reverse.
- *It is hard to overcome problems that are rooted in lack of knowledge or lack of agreement in large groups with consensus decision-making.* Thus, small groups play a critical role. Moreover, it is important to focus on places where agreement is easier. For example, it is hard to reach a meaningful agreement on targets when the feasibility of the targets is uncertain. It can be better to agree on actions, which governments and firms control more directly, along with mechanisms for accountability and revision of such actions, than to focus solely on targets.
- *The progress from small group solutions to larger groups is mediated by shared knowledge and then shared agreement.* Therefore, it is important to focus early efforts in cooperation on places where countries and firms can reliably agree, so that they focus on joint actions that, with experience and diffusion, lead to the reconfiguration of interests. That reconfiguration makes it easier to align interests needed to achieve contracts and pervasive scaling.

Bringing together the principles in this chapter and its precursor, Table 3 below summarises for each stage in transition the styles of international cooperation and ways that cooperation could accelerate the transition process. It also identifies principles that can guide co-operation and make it more effective.

TABLE 3: OVERVIEW OF CORE PROCESSES, ACTIONS AND PRINCIPLES

Stage of transition and core processes	*Key policy actions to accelerate transition*	*Dominant mode of international cooperation*	*Principles for effective cooperation*
EMERGENCE *Processes:* *Experimentation* *Stabilisation of dominant designs*	*Stimulate R&D and real-world demonstration projects* *Stimulate knowledge sharing between projects, firms and regulators* *Articulate visions or missions* *Nurture the building of transformative coalitions* *Public procurement and other strategies to create early application niches*	**EXPERIMENTALIST LEARNING**	*Break problems down into manageable pieces that are aligned with how industries and policies are organised* *Create institutions to review the lessons from experiments and figure out what's working (and not)* *Coordinate action among a critical mass of willing actors to establish niches and give credible assurance to innovators* *Focus on bringing interests of key actors into alignment*
DIFFUSION *Processes:* *Multiple reinforcing feedbacks supporting growth of new technology market share* *Resistance from incumbents leading to economic, business and political struggles*	*Taxes and regulations to alter the economic playing field* *Purchase subsidies, favorable price-setting, public procurement to stimulate demand* *Capital grants, loans, performance standards to shape firm investment* *Public infrastructure investment* *Accelerate and manage the consequences of declining industries*	**COORDINATED DIFFUSION**	*Coordinate action to scale up niches into larger market shares - work in small groups: coalitions of first movers* *Focus on markets where agreement is easier* *Focus on joint actions that, with experience and diffusion, can plausibly lead to reconfiguration of interests*
RECONFIGURATION *Processes:* *Complementary changes in institutions, infrastructure, business models, user practices, views of normality, technical capabilities, professional standards*	*Stimulate whole system realignment* *Anchor the new system in regulations,standards and market signals.* *Develop agencies with new roles and responsibilities* *Mitigate negative socio-economic effects with 'just transition' policies (e.g. compensation, retraining).* *Realign trade and investment policies*	**CONTRACTING**	*Create detailed, reciprocal agreements around known solutions that address known barriers to further application* *Negotiate among parties that constitute a critical mass of the market in the relevant sector* *Establish credible incentives for participation and compliance, and penalties for the reverse* *Set standards; monitor and verify compliance*

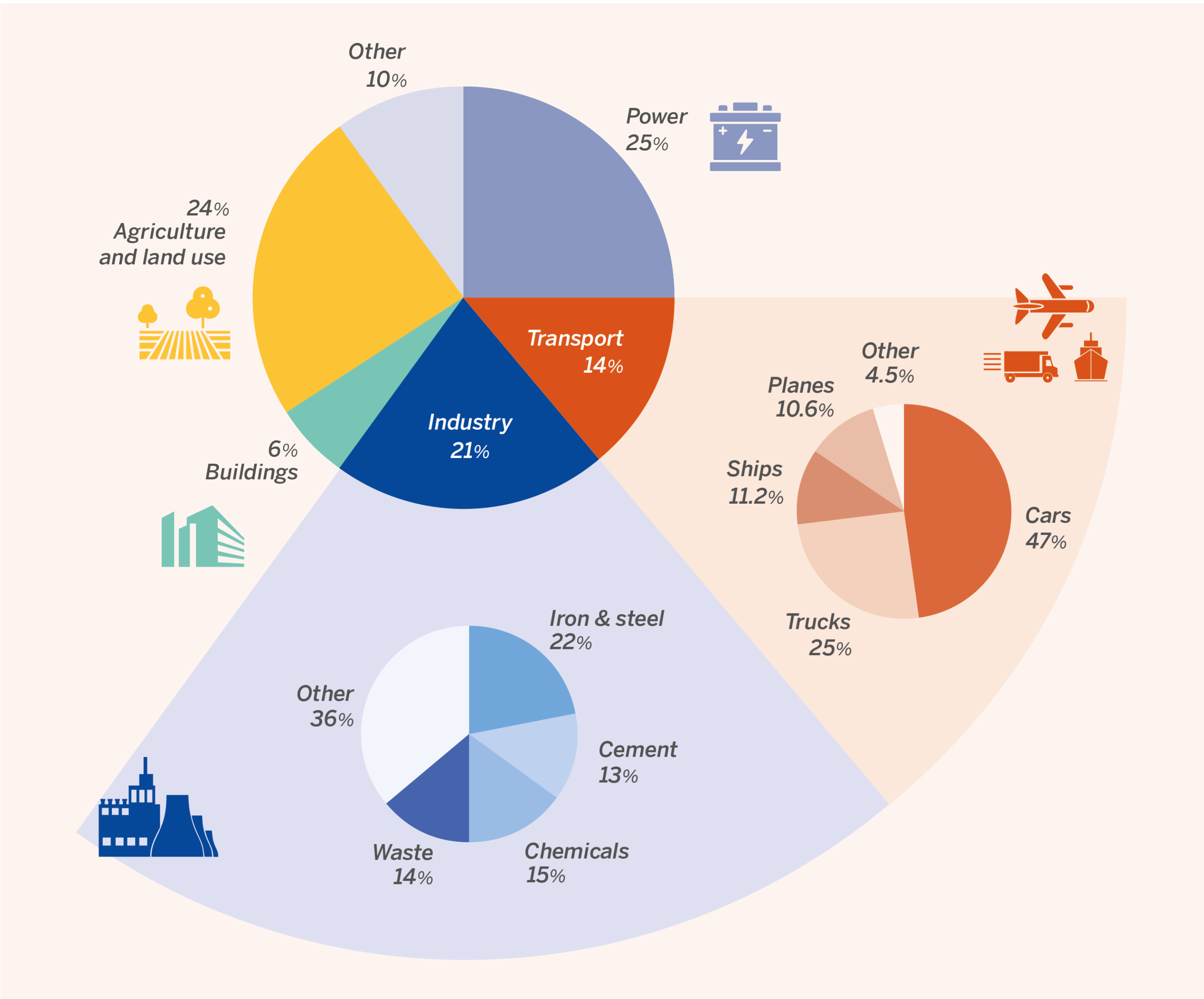
4. APPLICATION TO THE LOW CARBON TRANSITION

This chapter looks at how we can put theoretical principles into practice: taking what we know about technology transitions and international cooperation, and applying these insights to the challenge of accelerating the low carbon transition. The contribution of this report is to combine these two sets of theoretical insights with the practical knowledge of the opportunities to decarbonise the economic sectors that contribute the most to global emissions.

Why sectors?

Reducing global emissions in fact requires not just one low carbon transition, but many. As the Intergovernmental Panel on Climate Change wrote, meeting climate change goals will require *'rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems. These system transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors...'*[42]

FIGURE 12: GLOBAL EMISSIONS BY SECTOR



Source: Emissions data is from the IPCC's Fifth Assessment Report, Working Group III, 2014, and refers to shares of total global greenhouse gas emissions. The split between cars and trucks in road transport emissions is based on the IEA's Energy Technology Perspectives, 2017, since this is not given in the IPCC source.

The sector, or system, level is important because it defines a pattern of activities by which goods or services are produced and used for a social purpose. It is within these roughly defined boundaries that new technologies can be created and diffused, eventually to reshape the social and economic activities of which they are a part. As Chapter 2 made clear, system transitions involve changes in business models, infrastructures, markets and even social customs. Focussing only on individual technologies would miss the wide range of actions that must be taken if low carbon transitions are to be realised at pace.

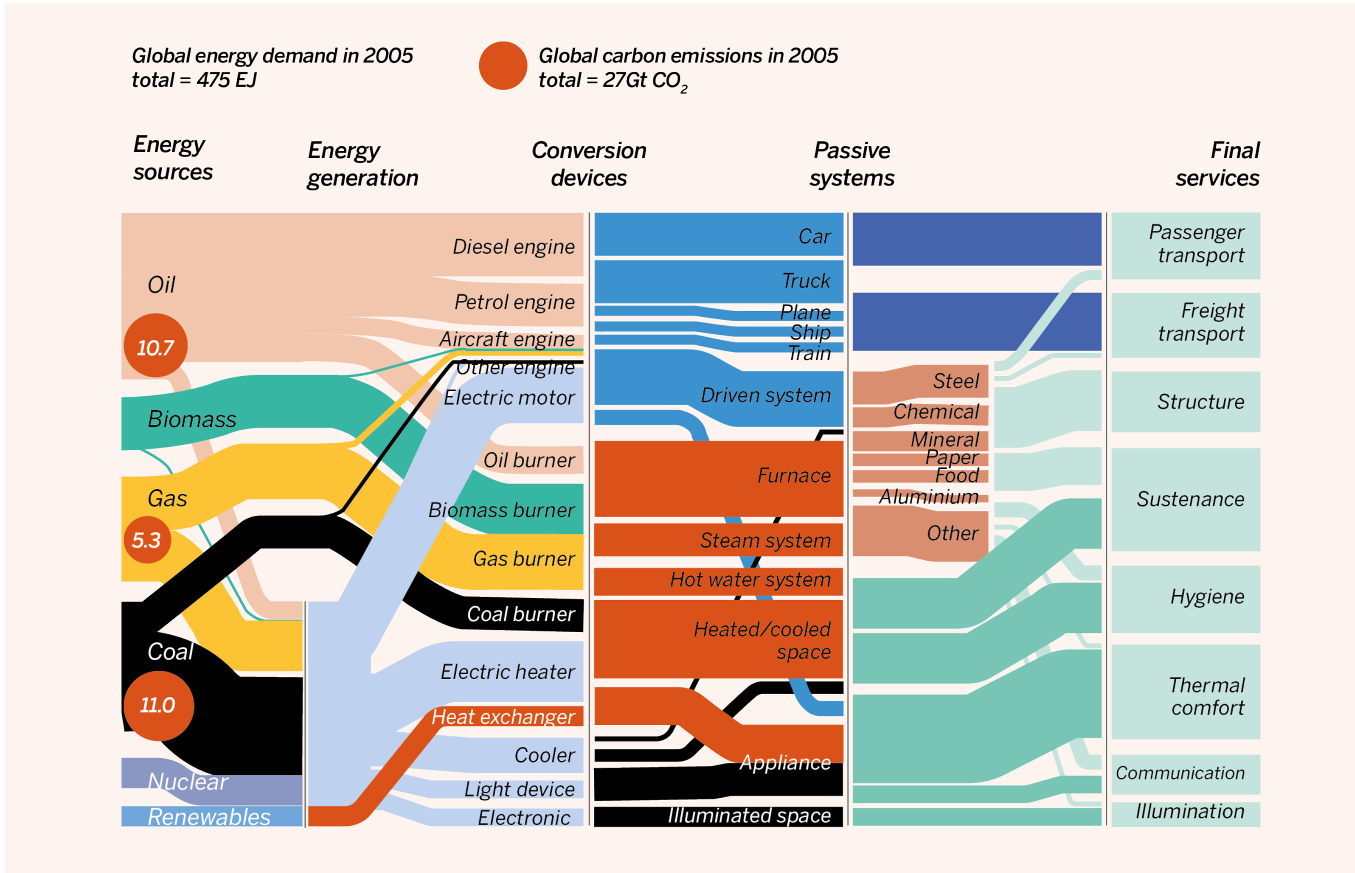
Equally, the history of international cooperation described in Chapter 3 makes clear the importance of breaking down a problem into manageable parts. For climate change, a focus solely on the 'macro' level of national economy-wide emissions targets would fail to do this. Each of the main emitting sectors of the global economy is distinct in its political economy, its high and low carbon technologies, its financing structures and industrial composition, and the nature and extent of its international connectedness. Recognising these differences allows international cooperation to work in each sector in the way it can be most effective, instead of forcing all cooperation to proceed at the pace of whichever sector's actions are most difficult to achieve.

Which sectors?

In this report, we consider ten of the highest-emitting sectors of the global economy: power, agriculture and land use, cars, trucks, shipping, aviation, buildings, steel, cement and plastics. As shown in Figure 12, these together account for around four fifths of global emissions.

It must be recognised that these are not the only way that sectors can be defined. As Figure 13 shows, the global system of energy and emissions has several stages: from primary energy sources, through conversion into various forms of useful energy, then conversion into materials or products, and finally into services.

FIGURE 13: GLOBAL EMISSIONS SANKEY DIAGRAM



Adapted from https://www.uselessgroup.org/global-energy-sankey.

The ten sectors we have chosen include one energy carrier (electric power), three materials (steel, cement and plastics), and six systems of energy use that are closer to final demand (cars, trucks, shipping, aviation, buildings, and agriculture and land use). Why choose these and not others? While there is no single 'correct' place to draw the boundaries, if our purpose is to identify the strongest points of leverage with which to propagate decarbonisation through the global economy, then there are some criteria we can apply to our selection:

- **First, how large a proportion of global emissions are contributed by a coherent economic sector?** A coherent economic sector may be thought of as one that has broadly one kind of product. So, the power sector (25% of global emissions), which produces electricity, and the automotive sector (7% of global emissions), which produces cars, are more coherent than 'industry' (21%) which is a collection of many subsectors each producing different materials. The coherence of sectors is likely to change over time – some will become more clearly defined, while others will disperse or disappear – so there will be times when this assessment will need to be updated.
- **Second, how high are the chances that the interests of dominant actors in the sector could be realigned with the efforts needed for deep decarbonisation?** The chances are likely to be higher if the sector is coherent as an industry or system, as described above. In addition, as a general rule, potential for alignment of interests is likely to be stronger on the demand side than on the supply side. At the stage of primary energy supply, the potential value of fossil fuel resources is highly concentrated in the hands of their owners, who have every incentive to ensure their continued use. Hence it is easier to change the form of energy demanded by the power sector (by changing its technologies) than it is to stop coal mining. Similarly, it is likely to be easier to place lifecycle emission standards on buildings and cars that reduce their use of energy-intensive materials than it will be to decarbonise the production processes of steel, cement and plastics. An important exception to this rule may be the growth of new sectors around technologies for the supply of zero emission energy, since the developers of these technologies have every incentive to promote their wider use. The availability of cheap zero emission power has the potential to decarbonise large parts of light transport and heating. The development of cheap zero emission hydrogen could do the same for heavy transport and much of industry.

The strategies for achieving alignment of interests of dominant actors will depend strongly on a third consideration: **how internationally connected is the sector?** A sector can be internationally connected through cross-border flows of technology, trade, finance and knowledge. Its industries can operate locally or globally. While some of the most far-reaching options for emissions reduction may involve actions in the 'final services' category – e.g., mode shifts from driving to cycling, from aviation to teleconferences, or towards less meat-based diets – the international connectivity at this stage is low. Decisions on urban planning are inherently local, and social norms around flying and eating are not easily exportable. National or subnational actions are likely to be most important in these areas. In contrast, emissions-related standards for vehicles, aviation fuel or imported agricultural commodities can have strong and immediate impacts on global markets and value chains. In these sectors, coordinated international action could play a critical role.

Our choice of sectors roughly reflects the combination of these criteria and considerations – which together suggest a focus for international cooperation that is mainly in the middle-right of Figure 13 – the sectors where energy is consumed in the production or use of some kind of product. But this choice is not intended to close down the debate. The shape of these sectors will change over time. New energy vectors such as hydrogen, and technologies such as energy storage, will strengthen the interlinkages between them. As low carbon transitions progress in parallel with other areas of social and technological change, some materials and some products are likely to become obsolete. And as reliance on fossil fuels begins to decrease, it may over time become viable for the international community to consider supply-side restrictions.

A focus on the processes of change

In each of the sectors discussed in the following sections of this chapter, we aim to understand who are the important actors, their interests, and how the structure of industries affects the feasibility and speed of change toward decarbonised futures. We also consider what stage of the low carbon transition the sector has reached, and what critical obstacles stand in the way of further progress.

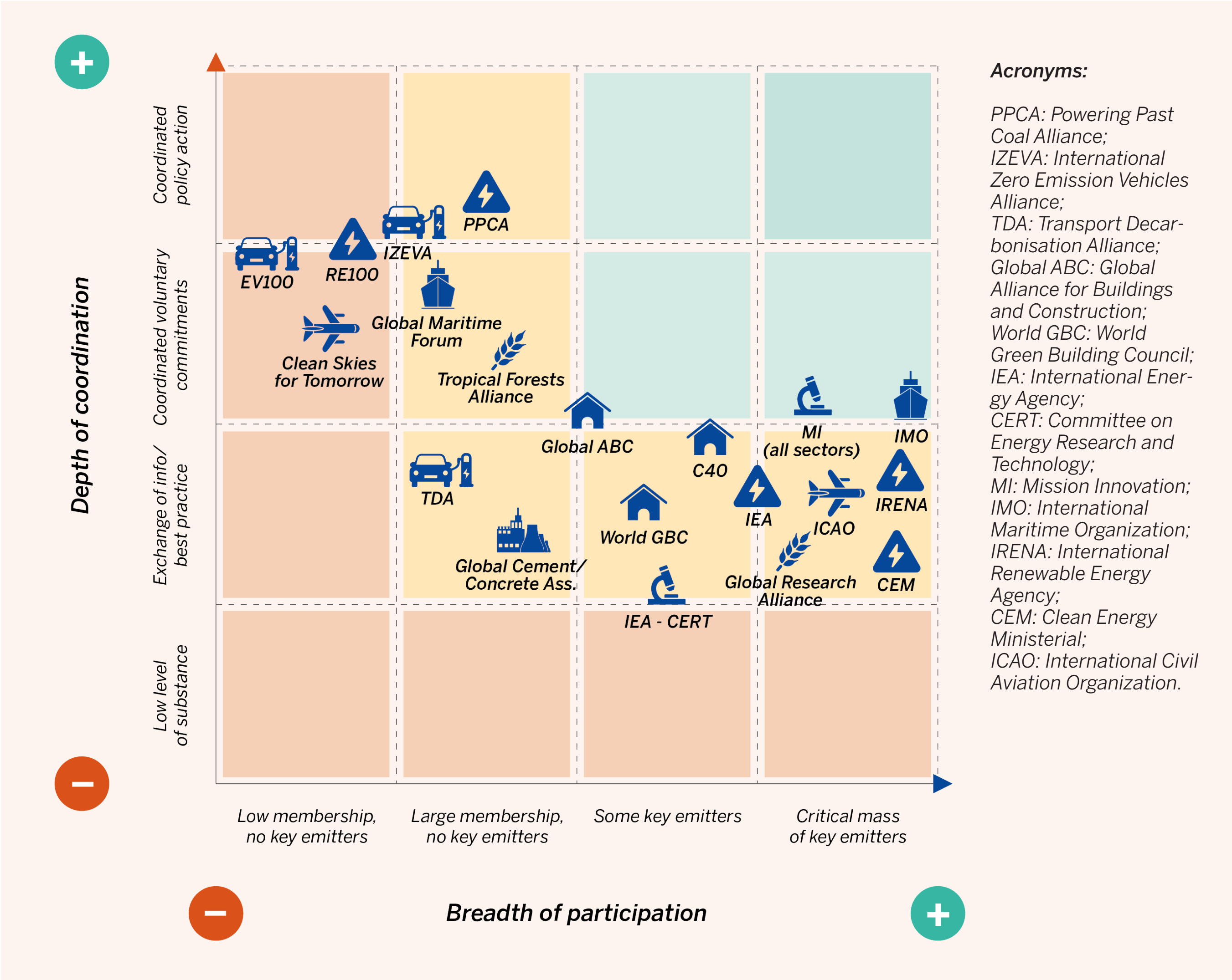
We focus on technologies and business practices that could allow for deep cuts in emissions. The approach of looking at industries in the context of their production methods, profitability and investment strategies, allows us to focus on how efforts – within nations and through international coordination – can align the interests of the most relevant actors. That alignment is needed for each of the three phases of action: the emergence of radical innovations and niche markets, the diffusion of best practices and technologies more widely, and eventual broader reconfiguration of markets around deep decarbonisation. In any sector, a multitude of actions are needed, so we illustrate what is needed (and by whom) rather than offer an exhaustive description of every stone that must be turned. Deep transitions in whole systems is a complex process, and often it is more helpful to focus on the big picture than on the details.

With this analysis, we aim to describe not the desirable 'end state' of a low carbon economy, but the processes of change that can take us towards that goal. We focus not on what countries, cities, governments or businesses can do individually, but on how their actions together can be more than the sum of their parts.

Institutions

Focussing on the actions needed to accelerate transitions and the alignment of key actors requires a close look at the institutions and platforms in which these processes are discussed and steered. Institutions play an essential role in engaging the actors who matter in each sector – actors who would not otherwise organise the sharing of information or pursue new directions automatically. Institutions stabilise expectations about what actions are required and how risk-taking will be rewarded; help channel resources towards new technologies; and provide platforms for discussion and agreement of coordinated action.

FIGURE 14: THE INSTITUTIONAL LANDSCAPE FOR COORDINATION WITHIN SECTORS



In many sectors, the needed institutions and platforms do not yet exist. There are many intergovernmental groups engaged in valuable information-sharing on technologies and best practices in policy, but which have not yet taken the next step of proactively coordinating action. There are business leadership coalitions that aim to coordinate action to accelerate transitions, but which lack the serious engagement of governments that could achieve change with the necessary scale and pace. Government is often indispensable because it can channel resources and organise policies, such as trade and investment measures, that firms on their own could not deploy. Stronger government engagement is also needed in the global rule-setting organisations that already exist in shipping and aviation, for these to make the most of their potential. Across all sectors, many of these groups and organisations have a predominance of members from Western Europe and North America, and not enough from the emerging economies whose growing industrial capability and market power will be crucial to shaping the trajectory of global economic development. Figure 14 offers a rough sketch of this institutional landscape.

As the previous chapter discussed, in institutions for cooperation there is an inevitable trade-off between breadth of participation and depth of cooperation. It will be difficult for any institution to score highly on both these criteria, especially when transitions are in their early stages and confidence is low in the feasibility of solutions. This view of the landscape, however, suggests several strategies for strengthening institutions for effective cooperation:

1. **In sectors where no institutions for international cooperation on decarbonisation exist, find or create an institution that can play this role.** Giving an existing institution a new mandate or focus on decarbonisation will often be preferable, but if this is not politically or practically possible, it may be necessary to create a new one. In sectors where there are multiple competing institutions, it may be helpful to consolidate the landscape by strengthening one or two, and abandoning others.
2. **In institutions with high levels of participation, push for deeper cooperation**: move from sharing information to coordinating action.
3. **In institutions that are already focussed on deep cooperation – coordinating action – expand membership** to include more of the large and influential countries and industry players. The architects of these institutions will play crucial roles in making sure that membership expansion does not come at the debilitating cost of diminished content and impact.
4. **In all sectors, strengthen government engagement in the leading institutions.** Industry can bring to the table an understanding of what is technically possible, and what barriers need to be overcome. Only governments can change the shape of markets, the incentives for investment, and the rules of the road at the pace required for rapid emissions reduction.

Vigilance is needed, as well, to ensure that existing institutions become stewards of change within their industries, and not protectors of the status quo.

The opportunity for a new approach

What emerges from this chapter is a view of international cooperation that is less anchored in broad mandates, and more focussed on key sectors and key actors. Our view of cooperation bridges the gap between domestic policymaking in the relevant sectors, and international cooperation on climate change. These are two areas of government action that must be intimately linked, not 'stove-piped', to have a practical impact on the direction of technological change and emissions in each of these key industries. And our view of cooperation in every sector is not one of government or business, but both.

It may reasonably be asked whether this approach has not been taken for a good reason, or indeed whether it has already been tried and subsequently failed. Our view is that broadly speaking, this approach has not yet been seriously tested. Institutions for practical cooperation, such as the Major Economies Forum and the Clean Energy Ministerial, have been established, but governments' engagement with them has been weak and non-committal. By bringing cooperation on all sectors within a single organisation, these attempts lacked focus and were highly vulnerable to obstruction by any member country that saw their work as conflicting with its interests. An approach that brings together the willing and influential actors separately in each sector will be less vulnerable to such disruption, and more able to focus on the forms of cooperation that are appropriate to the stage of the transition in each sector.

A further difference between what has been envisaged previously and what is proposed now concerns the choice between targets and actions as a focus for cooperation. In the aftermath of the Kyoto Protocol, ideas were floated for sectoral cooperation that involved imposing quantified emissions targets on global sectors, and allowing the trading of permits within sectors to determine where the emissions savings would be found. These ideas failed to gain support, in part because they

were abstract. There was no reliable constituency that favoured government-business sector cooperation, and the efforts that did emerge did not cause much of a transition toward deep decarbonisation. In this context, it was understandable that many governments had low confidence in setting quantified targets. Yet, within countries and across some markets, the elements of a partial decarbonisation were taking shape. The experience of the last two decades shows that when governments implement policies for decarbonisation, they often achieve far more than they expect. The International Energy Agency's central scenario for global deployment of solar power in the year 2020 – based largely on governments' own targets – increased by a factor of ten between 2006 and 2016.[43] Rates of cost reduction and market growth in wind power and electric vehicles have also outpaced expectations. Focussing cooperation on actions takes advantage of the confidence in what can be done now, instead of being held back by the fundamental uncertainty around what might be achieved in the future.

A focus on actions has the additional benefit of bringing to the fore a wider range of options for policy and coordination. Whereas previously it might have been assumed that putting a price on carbon emissions and making them tradeable offered the most efficient way to reduce emissions, it is now increasingly recognised that most progress so far has been achieved through targeted investments in low carbon technologies.[44] There are reasons to believe the same may be true in future.[45] Coordination around such investments, the creation and scaling up of niches for the deployment of low carbon technologies, and the standards to ensure their widespread diffusion, may offer a more attractive and feasible proposition for developing countries than earlier approaches that focussed on limitations and constraints. At the same time, for those countries that have adopted strong constraints, in the form of net zero targets or carbon budgets, the approaching need to decarbonise competitive industries is sharpening the incentives for coordination.

With the Paris Agreement in place, there is talk in the climate change community of a shift 'from negotiation to implementation'.[46] The sections in this chapter aim to set out how that can be done: with a new role for international cooperation, focussed on the points of leverage for accelerating the low carbon system transitions.

> Coordination around investments, the creation and scaling up of niches for the deployment of low carbon technologies, and the standards to ensure their widespread diffusion, may offer a more attractive and feasible proposition for developing countries than earlier approaches that focussed on limitations and constraints.

POWER

SECTOR: POWER

IMPORTANCE

*Accounts for about **25%** of total global greenhouse gas emissions.*

GHG 25%

This sector is a route to decarbonising parts of transport, industry, heating & cooling.

STAGE OF TRANSITION: DIFFUSION

*Renewable power makes up **2/3** of global capacity additions. Other technologies such as carbon capture and storage at much earlier stages of development.*

NATURE OF THE PROBLEM NOW

- *Infrastructures and markets designed around old technologies*
- *Regional economies and government revenues dependent on coal*

OPTIONS FOR DECARBONISATION

- *Solar and wind: 7% of global generation; zero emissions and falling rapidly in cost; cheaper than new gas and coal plants in two thirds of countries*
- *Hydro, nuclear, bioenergy, geothermal, coal or gas with carbon capture and storage*

CO_2 CO_2 CO_2 CO_2 CO

INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

1 ACTIONS TO ACCELERATE EMERGENCE

- *The transition in the power sector globally has passed the emergence stage, with stabilisation around dominant technologies (renewables).*
- *New technologies will still be valuable in creating a wider array of options, but their main applications will be to accelerate diffusion and bring forward reconfiguration.*

INSTITUTIONS

International Energy Agency; International Renewable Energy Agency Clean Energy Ministerial; Powering Past Coal Alliance

***PRIORITY**: move from sharing information to coordinating action*

2 ACTIONS TO ACCELERATE DIFFUSION

- *Coordination between multilateral funds and bilateral donors on **investment and assistance in clean power** – to provide developing countries with a better offer for clean power than for higher emission sources*
- ***Mutual learning on market creating policy**: to identify top priority problems, and to demonstrate and communicate solutions*
- ***Coordinated procurement of renewable power** by governments and businesses: to increase economies of scale*

3 ACTIONS TO ACCELERATE RECONFIGURATION

- ***Coordinated phase-out of unabated coal power**, to send clear signals to global markets*
- ***Mutual learning for a just transition** away from coal: exchange of best practice in the socioeconomics of the transition*
- ***Development of complementary technologies** such as those needed to integrate renewables at large scale: energy storage, demand side response, smart systems & zero carbon sources of flexible dispatch generation*

Importance to emissions

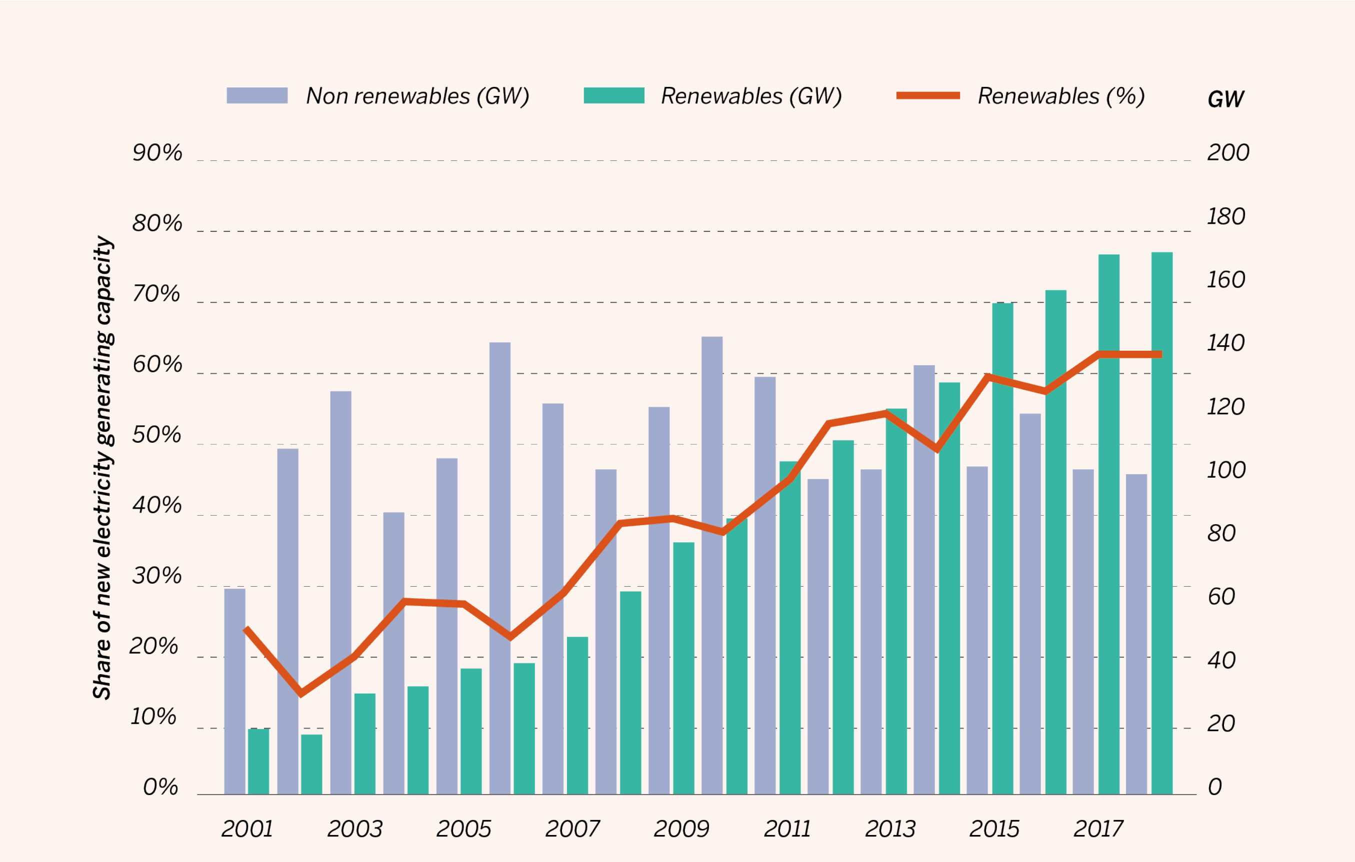
The power sector accounts for 25% of global emissions. In addition, clean power offers a route to decarbonising large parts of other sectors, including transport, heating and cooling, and many industrial processes.[47] Consequently, the power sector is the most important of all sectors for the low carbon transition. In all the major countries that have begun to reduce their emissions, the power sector has been at the centre of those efforts. Nevertheless, globally, power sector emissions have doubled over the past 27 years.[48]

Global demand for electricity is projected to increase by over 60% by mid-century.[49] Expansion of supply is critical to serve the needs of the billion people who lack access to electricity, and the billions more for whom its supply is unreliable or unaffordable. Demand growth could be even higher if transport and heating become increasingly electrified. At present, the growth of the sector is more than offsetting its decarbonisation, meaning that its emissions are continuing to rise – by 2.5% in 2018.[50] The International Energy Agency has projected that under current and announced policies and targets, power sector emissions could be roughly the same in 2040 as they are now, and estimates that decarbonisation of the power sector needs to proceed at roughly four times its current pace for the goals of the Paris Agreement to be met.[51]

Stage of the transition and technology options

The core technologies of a low carbon transition in the power sector have entered the diffusion stage globally. Renewable power's share of global new capacity additions has increased from around one fifth to nearly two thirds, within the last two decades (see Figure 15).[52] While in some countries the transition has progressed far enough for there to be signs of approaching reconfiguration, in many others it is still in the early stages of diffusion.

FIGURE 15: RENEWABLE POWER'S GROWING SHARE OF GLOBAL ELECTRICITY GENERATION CAPACITY ADDITIONS

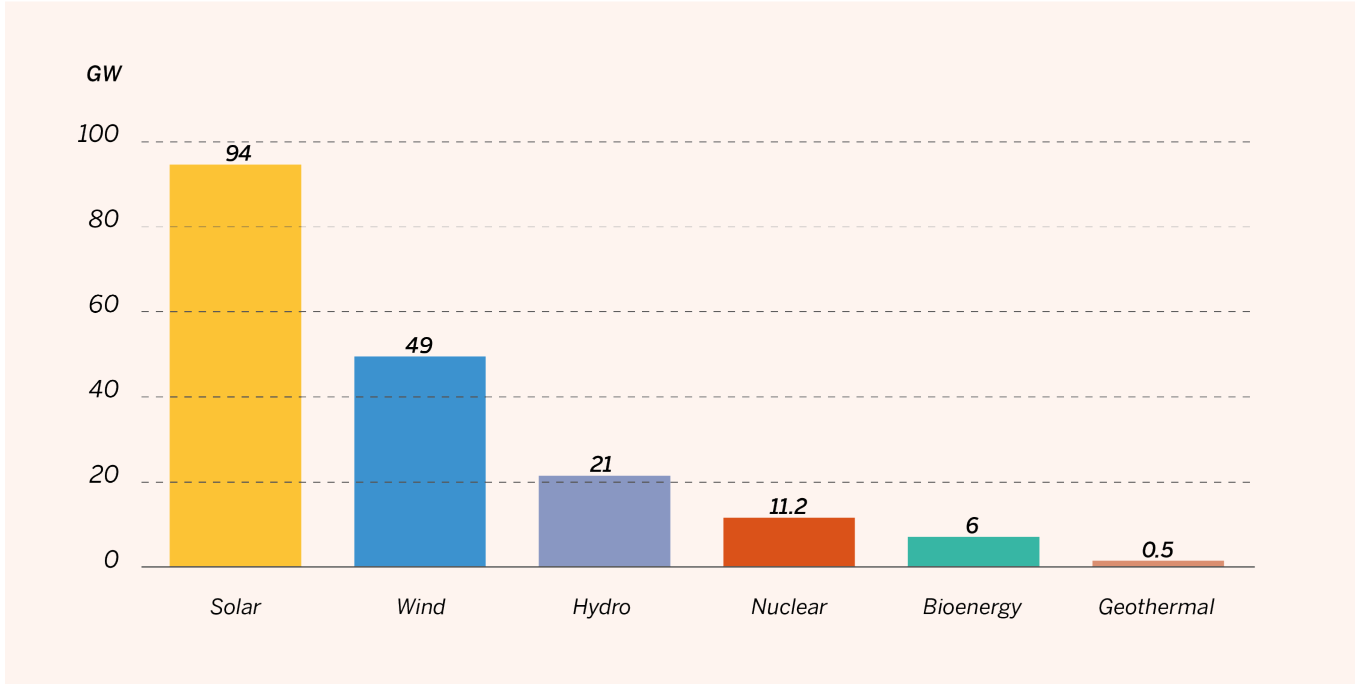


Adapted from IRENA, Renewable Capacity Statistics 2019. https://www.irena.org/newsroom/pressreleases/2019/Apr/Renewable-Energy-Now-Accounts-for-a-Third-of-Global-Power-Capacity.

This transition is being led by the **expansion of solar and wind power**, which together accounted for 84% of growth in renewable power capacity in the last year,[53] and now provide 7% of global electricity generation.[54] Both technologies are continuing to see rapid cost reductions: since 2010, the cost of solar power has fallen by 85%, and that of wind by 49%.[55] Solar and wind power are already cheaper than new coal and gas power plants in two thirds of the countries in the world, and are projected to undercut even existing coal and gas plants in China and the US by around 2030.[56] Their competitiveness is aided by the falling costs of battery storage. Alternative technologies using the same energy sources are also making progress: offshore wind is now competitive with gas in the UK, its largest market, and the cost of concentrated solar power has fallen by nearly a half since 2010.[57] A range of other zero emission power technologies exist, but none are currently experiencing the rate of expansion seen in solar and wind (see Figure 16), and all face challenges that may limit the extent of their global deployment in future. These alternative zero emission power technologies include:

- **Hydropower**: this is still the largest source of renewable power generation[58], but its potential for future scale-up is limited by the constraints of geography and political feasibility.
- **Nuclear**: this is capable of providing consistent dispatchable zero emission power – including base-load power – but with cost a challenge in many countries. Its cost has, if anything, increased over time, as safety measures have become more stringent.[59] This at least is the case in western countries, whereas in emerging economies the experience has been more promising. In western countries that have been the traditional base of nuclear power it has also faced social opposition. For example, opposition has led to policies to eliminate all existing nuclear plants in Germany, and slowed its recovery in Japan following the Fukushima incident.
- **Bioenergy**: this is an option for dispatchable power that can be low emission and low cost, provided secure supplies of sustainably-sourced feedstocks are available. Bioenergy can be particularly competitive where there are streams of industrial waste to use as feedstock that would otherwise need to be disposed of.[60] However, the overall supply of sustainable biomass is limited at the global level, and as noted in other sections of this chapter, it may be advisable to prioritise its use in sectors where there are few alternative zero emission technologies (of which the power sector is not one).
- **Bioenergy with carbon capture and storage**: this is used in many economic models as a way of generating the large amounts of negative emissions needed in most of the scenarios designed to

FIGURE 16: GLOBAL LOW CARBON POWER CAPACITY ADDITIONS IN 2018



Adapted from IRENA; IEA: https://www.irena.org/newsroom/pressreleases/2019/Apr/Renewable-Energy-Now-Accounts-for-a-Third-of-Global-Power-Capacity; https://www.iea.org/tcep/power/.

be consistent with meeting climate change goals. Given the additional cost of carbon capture and storage infrastructure, however, as well as the constraints on sustainable feedstock supply, it may be difficult for this to compete for a large share of the market.

- **Geothermal**: this is a source of reliable zero emission power in places where good high temperature resources exist, but is likely to be inherently limited by geography.
- **Coal or gas with carbon capture and storage**: as renewables increasingly become cheaper than coal or gas power, adding carbon capture and storage (CCS) to coal or gas will only make it more difficult for those technologies to compete. Only two large-scale carbon capture and storage power projects were in operation at the end of 2018.[61] However, this could be a viable option in places where CCS infrastructure has been constructed for use by other sectors (e.g., heavy industry), where coal or gas power plants are relatively new and efficient, and where the supply of fossil fuels is relatively cheap. New policy incentives, such as the 45Q system of tax incentives in the USA, could encourage a new wave of investments in CCS projects of various types.

While none of the above options appear likely to challenge solar and wind for dominance in the diffusion stage of the power sector's transition, any of them could be important as complementary technologies in the sector's eventual reconfiguration. As intermittent renewables' share of power generation increases, so will the value of dispatchable power that can be turned on to meet peaks of demand or to compensate for troughs in intermittent supply. In those countries that are already moving towards reconfiguration, this is supported by the deployment of 'flexibility technologies' – including energy storage, demand side response, interconnectors and smart grids. Dispatchable zero emissions power and flexibility technologies will both complement and compete with each other, and their relative importance for reconfiguration remains to be discovered.

Nature of the problem now

The immediate challenge is to accelerate the diffusion of zero emission power technologies while reducing the market share of unabated (i.e., without CCS) fossil power technologies, especially coal. This must be achieved in the context of most governments' top priorities for energy policy being energy access, security and affordability.

The faster diffusion of zero emission power requires innovation not only in technology but also in market design, business models, grid infrastructures, and system operation.[62] In many countries these changes can be held back by limited administrative capacity. While most countries are not yet approaching reconfiguration, for those that are, the challenge is to incorporate increasingly high levels of renewables into power systems, while reliably meeting demand throughout daily and annual cycles. This can be assisted by further development of complementary technologies, such as energy storage (including inter-seasonal storage), smart grid and demand-side response technologies, and more flexible and dispatchable zero carbon generation.[63]

Reducing the share of coal in power generation is, for many of the largest-emitting countries, as much a socioeconomic challenge as a technical one. Although the new jobs created by the low carbon transition are expected to significantly outnumber the jobs lost,[64] the closure of coal mines can cause unemployment and economic downturns in regions that are heavily reliant on this industry. This is a major concern for many countries. In China, the coal sector employed 5.3 million people in 2013, and is expected to employ fewer than 3 million by 2020: a loss of 2.3 million jobs.[65] Coal supports over 500,000 jobs in India,[66] 200,000 in the EU, 80,000 in South Africa,[67] and 50,000 in the US.[68] Often these jobs are concentrated in certain regions, where the industry is an important source of local government revenues: for example, coal makes up almost half the revenues of some Indian states.[69] In countries including the US[70] and Indonesia,[71] the coal industry is also a significant source of funding for local and national political campaigns. This means it can wield significant influence even in places where it supports relatively few jobs. Aligning the interests of communities and local governments in coal-producing regions with low carbon transition – and achieving a 'just transition' for those communities – is therefore a critical task.

At the same time, preventing the construction of new coal power plants is a necessity, if the sector's emissions are to be brought in line with climate change goals. Over 500GW of new coal plants are planned globally,[72] which risks locking in high emissions for decades to come. (Coal plants can operate for over 40 years, as have existing fleets in the US and Europe).[73]

How coordinated action can accelerate the transition

The progress already made in the transition to clean power is the cumulative outcome of actions taken by many countries around the world. Early support for research and development in renewable technologies by the US and Japan, incentives for their early deployment in Europe, and massive investment in their production by China, have all contributed to the dramatic falls in cost (by a factor of 3,000 over the last 60 years, in the case of solar energy modules)[74] that are transforming the options available to policymakers worldwide. While the power sector transition is now in many ways characterised by competition between countries and businesses aiming to lead in supplying global markets with zero emission technologies, there remain opportunities for coordinated action to accelerate its progress.

ACTIONS TO ACCELERATE DIFFUSION

Countries can act individually to accelerate diffusion of zero emission power through policies such as:

- **Long-term contracts for zero emission generation** that reduce financing costs by providing confidence in returns;
- **Regulations** that require utilities to produce a given (rising) proportion of their power from zero emission sources;
- **Feed-in tariffs** to incentivise deployments: for example, the development of community energy and micro-grids;
- **Carbon pricing** at a level high enough to ensure that low-carbon power sources gain an advantage (as in the UK, where this has combined with support for renewables to accelerate the decline of coal power and drive the fastest power sector decarbonisation in the world);[75] or at least removing subsidies for fossil fuel power, wherever these are in place; and
- **Market reforms** to ensure available zero emission generation is able to take advantage of its increasing cost competitiveness and be used first, ahead of unabated fossil fuel generation. Market reforms can also ensure a stable transition for grids while fossil baseload is being replaced: for example, through supporting the deployment of flexibility technologies. Many high-carbon sources of power enjoy subsidies – including the failure to pay for the pollution they cause – that market reforms could realign.

These policies are important for attracting private finance into zero emission power investments, which may otherwise be seen by investors as high risk or not commercially viable, despite their falling costs. Integrating such policies within a strategic energy plan, with clear goals and a widely-agreed direction of change, can help align the expectations, incentives and actions of stakeholders throughout the system.

Countries that take these actions – whether motivated by reducing emissions, reducing energy costs, or competing for industrial leadership in new technologies – will be reinforcing each other's efforts. The costs of renewables have fallen exponentially in proportion to their cumulative global deployment,[76] so each additional deployment in a market that is served by global equipment vendors contributes to reducing costs for all countries.

On top of this, there are opportunities for more deliberate coordinated international action to accelerate diffusion. These include:

- **Coordinated learning**: The sharing of policy best practice is already taking place on a large scale, through international organisations such as the **International Energy Agency (IEA)**, **International Renewable Energy Agency (IRENA)**, and **Clean Energy Ministerial**; through multilateral development banks and funds, bilateral engagements between many countries, and contacts between regulators. Despite this, the fact that over 40 countries are still planning to build more coal power plants[77] suggests that not all policymakers yet have the confidence to plan for zero carbon power systems. **There is scope for the organisations, governments and regulators involved in the power sector transition to come together even more closely, to identify the top priority policy problems to solve, demonstrate solutions, and communicate these in the most highly-visible way possible.** Consultations supported by the International Renewable Energy Agency (IRENA) suggest that although power systems vary greatly between countries, many countries' main concerns are how to support renewables in a cost-effective way, how to make the regulatory reforms to integrate them efficiently into grids, and how to mobilise private finance.[78]
- **Coordinated investment and assistance**: Clean power receives a large portion of the international climate finance provided by multilateral funds and bilateral donors, and with good reason: international investment on concessional terms can demonstrate the viability of renewables, reduce perceived risk, unlock private investment and lower the cost of capital. At the same time, however, G20 nations, and the multilateral development banks in which they hold influence, financed US$38 billion in coal projects internationally (compared to only US$25 billion in renewables projects) between 2013 and 2016.[79] While many institutions, including the World

Bank, the European Bank for Reconstruction and Development, and the European Investment Bank are now moving away from financing new coal power, international investments still account for the majority of the estimated US$28 billion a year for coal power. This sum is provided by public finance institutions, such as bilateral development banks and export credit agencies.[80] **Stronger coordination between the multilateral funds and bilateral donors that support clean power could help to provide developing countries with a more coherent offer of support, and a more attractive alternative to new unabated coal power.** This could include larger packages of finance at lower cost, supporting large-scale clean power investment programmes rather than a multitude of small projects. Alignment of strategic intent between these actors and China – which provides around three quarters of all international coal finance,[81] but which has clearly stated its intention of greening its Belt and Road Initiative investments[82] – could be game-changing.[1]

- **Coordinated buying power**: Businesses can help accelerate the transition to clean power by committing to buy only from zero emission sources. To the extent that this creates additional demand for zero emission power, it helps to scale up deployment and bring down costs.[83] The **RE100** initiative is a notable example, with its 191 corporate members committed to sourcing 100% of their power from renewables in the shortest time possible.[84] Consumers in some countries can exercise a similar power by choosing electricity suppliers that commit to using only zero emission generation sources.

The power sector is not short of institutions to discuss decarbonisation. Several have been mentioned above. Some of these have impressive membership: for example, IRENA's annual assembly attracts over 100 ministers from some 170 countries, and involves detailed ministerial and CEO-level roundtable discussions on specific policy challenges. The need in this sector is not for new institutions – if anything, it might do better with fewer – but for greater coordination between the largest providers of finance and the regulators of the largest markets. Serious political engagement, at head of government level, may be needed to achieve greater alignment on strategic objectives between the major providers of international finance in this sector – to ensure their investments support the transition, rather than make it more difficult.

1 In one initiative that aims to support this kind of coordination, leading multilateral and bilateral donors and technical institutions have developed a set of 'key principles for improving the support to strategic energy planning in developing and emerging economies.' Crucially, these aim to catalyse a shift towards supporting countries to develop a coherent vision for the energy sector as a whole, rather than focussing on supporting multiple individual projects. This statement of principles now needs to be taken forward to implementation, including through the development of information-sharing protocols, and the expansion of the range of organisations involved.

ACTIONS TO ACCELERATE RECONFIGURATION

The reconfiguration of the power sector requires not just the diffusion of zero emission technologies, but also the phase out of high emission forms of generation. The highest priority must be the **phase out of unabated coal**, the most carbon intensive power source. For advanced economies this means stopping the building of new plants and retiring existing plants, which can be achieved by regulation (including tight air quality standards and planning restrictions) or with carbon pricing. **International coordination of air quality standards**, enforced by environmental regulators and collectively monitored, could be one way for countries to work together to achieve this. For emerging economies, phasing out coal means first scaling back coal investment plans and switching investment to clean sources, and later decommissioning existing plants or converting them to clean energy sources. Where coal is used to provide combined heat and power, cleaner thermal energy sources – such as geothermal, nuclear, or CCS – may be valuable options. For developing countries, phasing out coal means avoiding becoming locked-in to a highly polluting and increasingly uneconomic power source, and choosing alternatives.

In the context discussed above – of concerns over loss of jobs and provincial revenues resulting from the transition away from coal – questions of a 'just transition'are likely to play a central role in determining how fast this reconfiguration can be achieved on a global scale. Equally, the handling of the low carbon transition could have a profound effect on the economic prospects of many communities.

> Stronger coordination between the multilateral funds and bilateral donors that support clean power could help to provide developing countries with a more coherent offer of support, and a more attractive alternative to new unabated coal power.

Research suggests that opportunities will exist for highly skilled coal workers to move into new energy industries. Skills and experience from the coal industry – in electrical and mechanical engineering, working under difficult conditions, and operational safety – are highly valued in clean energy industries, including wind, solar, geothermal and hydropower. However, early planning, and implementation through re-training and investment, will be vital in taking advantage of these opportunities.[85] Government industrial strategy and investment in regional economies can make a substantial difference. In the city of Fuxin, China, strategic investment in wind power manufacturing has seen this sector lead the city's gradual recovery from the economic slump brought about by the depletion of its coal reserves and the decline of its mining industry.[86]

At the same time, many basic coal mining skills are not so easily transferable to clean energy sectors. Achieving a 'just transition' – in which coal regions support and benefit from the low carbon transition – is likely to require multiple interventions, including not only re-training, regional redevelopment, and infrastructural investment, but also social security and the application of strong employment standards in new industries. The most important factor of all may be social dialogue with affected workers and their unions, employers, communities and local governments, to agree plans for the transitions that all sides agree are fair. Canada's Just Transition Taskforce for coal power workers and communities and Germany's Coal Commission are examples of this approach.

Given these challenges, **coordinated learning on phase out of conventional coal and the 'just transition'** could be important for accelerating the reconfiguration of the power sector. The **Powering Past Coal Alliance**[87] links practical assistance with the coordinated commitments of its members to phase out unabated coal power and move to clean power generation. These commitments help to align expectations around the future of the sector, influencing investors as well as governments. The **Just Transition Centre**[88] of the International Trade Union Confederation is a growing centre for the exchange of best practice and practical support on the social aspects of the transition. Within the EU, the **Platform for Coal Regions in Transition**[89] provides advice and support on economic diversification, technological transition, and access to relevant EU funds. Bringing more countries into these exchanges could be a valuable way to support the global transition.

On a technical level, **coordinated development of complementary technologies** can help bring forward reconfiguration of the power sector. Full reconfiguration is likely to involve significant development in technologies, such as large-scale and inter-seasonal energy storage, smart grids, demand-side response, and zero carbon sources of flexible dispatch generation. Cooperation between technical experts takes place notably through the IEA's **Technology Collaboration Programmes**,[90] and cooperation between public funders of research and development takes place through the **Mission Innovation** initiative.[91] There is scope for these processes to move further: to go beyond information exchange and towards proactive coordination of research, development and demonstration activities, with clear priorities and gaps identified, and actions to meet them agreed. Greater cooperation on large-scale demonstration could be particularly important for moving new technologies closer to commercialisation.

Geography and access to resources usually play a significant role in determining the scale and pace of energy transitions, implying that countries can be expected to choose pathways that suit their own circumstances, even if at a global level certain technologies take a large share of the market. This suggests a wide range of technologies are likely to be important to reconfiguration, and that efforts to accelerate their development will need to continue for some time.

> The reconfiguration of the power sector requires not just the diffusion of zero emission technologies, but also the phase out of high emission forms of generation. The highest priority must be the phase out of unabated coal, the most carbon intensive power source.

AGRICULTURE AND LAND USE

SECTOR AGRICULTURE & LAND USE

IMPORTANCE

Accounts for about ***24%*** of total global greenhouse gas emissions.

GHG 24%

Potential for negative emissions in future.

STAGE OF TRANSITION EMERGENCE

Practices and technologies for near-zero agricultural production are in early emergence; practices for avoiding deforestation are more established, but vary widely by region.

NATURE OF THE PROBLEM NOW

- *In agricultural production: low resource efficiency of production; challenge of knowledge, skills & capabilities; existing policy regime focused on production with known methods, rather than decarbonization*
- *In land use: strong profit incentives linked to global trade driving deforestation; difficulty of enforcement where activity is illegal*

INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

OPTIONS FOR EMISSIONS REDUCTION

- *Afforestation instead of deforestation*
- *Resource efficient farming, including carbon-absorbing practices*
- *Low emission fertilisers and feeds*
- *Alternative proteins, coupled to less meat-intensive diets*

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1 ACTIONS TO ACCELERATE EMERGENCE

- ***Coordinated research and development*** *of sustainable and resilient crops and livestock, low emission fertiliser and feed, alternative proteins, precision agriculture, & other options for deep emissions reduction of agricultural production*
- ***Coordinated procurement and testing*** *of these options to establish viability and acceptance*

INSTITUTIONS

Global Research Alliance for Agricultural Greenhouse Gas Emissions; Tropical Forests Alliance; UN Food & Agriculture Organisation

PRIORITY*: move from business leadership to government-to-government talks on demand-side policy to reduce deforestation*

2 ACTIONS TO ACCELERATE DIFFUSION

- ***Sharing of policy best practice, supported by financial and technical assistance*** *– in resource efficient farming, land management, reducing deforestation, and reorienting agricultural subsidies to encourage a shift to low emission practices*
- ***Use of coordinated buying power to promote sustainability in commodity supply chains*** *– especially soy, palm oil, beef, paper & pulp – to reduce deforestation*

3 ACTIONS TO ACCELERATE RECONFIGURATION

- ***Coordination on standards linked to trade*** *to avoid deforestation in global commodity supply chains – especially soy, palm oil, beer, paper & pulp – supported by targeted assistance to producer countries*
- ***Coordinated monitoring of deforestation****, to support compliance with standards*

Importance to emissions

Agriculture and land use account for around a quarter of global emissions. Roughly half of these emissions are due to changes in land use such as deforestation, or the conversion of peatlands, mostly as a result of agricultural expansion. The other half come from the many processes of agricultural production. Land use is even more important than its share of emissions implies, because of its potential to act as a net sink of emissions instead of a net source. Emissions from agriculture are rising steadily, while emissions from forestry and other land use show fluctuations, but no clear upward or downward trend over time.[92]

Stage of the transition and technology options

Given the many causes of deforestation and the many forms of agricultural production, agriculture and land use is in reality a collection of sectors, and for the purpose of accelerating transitions, most of these would benefit from being considered separately. Generally speaking, the transition to low emissions systems of agricultural production is at an early stage. There is wide variation between countries in levels of efficiency and sustainability. In temperate and boreal regions, agricultural productivity is growing while the area of land under cultivation is shrinking. Meanwhile, in tropical regions, this is not the case. Even in the most advanced countries, however, the technologies and practices for near-zero emissions agriculture are still in emergence. The transition to sustainable land use more broadly may be considered more advanced, in the sense that knowledge around forest protection has progressed significantly, although its application is highly uneven. Between 1990 and 2015, forest cover increased in much of Asia, Europe, North America and North Africa, but during the same period there were large losses in Latin America and Sub-Saharan Africa.[93] Global deforestation in 2017 was 29.4m hectares, which is roughly equivalent to a football pitch every second, the second highest rate since monitoring began in 2001, with essentially all the net loss occurring in tropical countries.[94]

Despite the land use sector's potential to act as an emissions sink, there are risks that its role as an emissions source will increase, as global food demand is expected to grow by around 55% by 2050 in a business as usual scenario.[95] This risk is compounded by the likely negative effect of climate change on crop yields in tropical regions, which could increase the pressure for further expansion of agricultural land.

Nature of the problem now

Land use and agriculture feed both local and international markets. Activities are predominantly carried out by the private sector, but supported by extensive public policies and subsidies. The range and number of companies involved is vast. Nevertheless, there are a number of dominant international companies that control large market shares in the international food, forestry and agro-chemical sectors. At present, few national standards exist to address carbon emissions from any of these sectors.

The immediate problem for agricultural production emissions is low levels of productivity leading to inefficiency in the use of land and resources (such as fertilisers). This is a challenge of knowledge, skills and capabilities. Much of the roughly US$700 billion per year of agricultural subsidies globally worsens the situation, by incentivising inefficient and unsustainable practices.[96] Governments are wary of reforms because of uncertainty around consequences for food security, and because of the political risks of imposing change on the industry and farming communities.

Over the longer-term, deep emissions reduction in agricultural production will require shifts in consumption patterns and more fundamental changes in technologies and techniques. These will be needed to eliminate as far as possible the emissions from sources such as livestock digestion (mostly from the burping and farting of cows and other ruminants) and fertiliser use – currently the sources of 39% and 29% of agricultural production emissions, respectively.[97]

Deforestation is primarily a problem of land management, control and incentives. High profits are available from the production and export of the commodities that drive deforestation, making forest protection policies difficult to enforce. Short-term profit opportunities incentivise deforestation even though numerous studies have shown that lands cleared in forests, because they are remote and not tilled with best practices, are often highly unproductive. Governments often want to slow or stop deforestation, but are unable to because the activities occur in places where their ability to exercise authority is limited. Businesses face some consumer pressure for sustainable sourcing of food, but competitiveness concerns limit their willingness to act individually. More importantly, individual corporate actions cannot address the underlying drivers of deforestation as long as they represent only a small portion of market demand.

How coordinated action can accelerate the transition

Agriculture and land use emissions can be addressed on the supply side, in the places of agricultural production and deforestation, and on the demand side, in the places where commodities produced on the land are consumed. Actions on the supply side are inherently local, but can benefit from international assistance. These can be complemented by actions on the demand side, which are much more strongly international and work through the leverage of global markets.

The complex nature of the transition increases the importance of accelerating all its stages simultaneously: catalysing the emergence of technologies and techniques for deep emissions reduction; promoting the diffusion of current best practices; and bringing about the reconfiguration of some markets to prevent ongoing deforestation.

ACTIONS TO ACCELERATE EMERGENCE

- **Coordinated research and development** of the techniques and technologies for deep emissions reduction in agricultural production is important now, to enable their use in the future. Priorities include the development of methane inhibitors and vaccines, the breeding of low emissions cattle, improved livestock feed and nutrition, improved manure management, fertilisers, alternative proteins (to reduce meat consumption in the future), the breeding of more sustainable and resilient crops (including with the potential for biological nitrification inhibition) and livestock, and techniques such as precision agriculture, water management in rice paddies, vertical farming, and synthetic biology. Technology for enhanced supply chain transparency could also be important for linking emissions reduction actions on the supply and demand sides.

A wide array of new technologies may also emerge to assist in the enhancement of carbon stocks. For example, plants might be adapted to maximise their carbon absorption below ground. Mass planting of these crops, along with no-till farming techniques, might ultimately enable the net absorption of large amounts of carbon in agricultural soils.[98] Such techniques, if successful, could eventually be applied more widely beyond mass commodity crops.

The institutions to support research in these areas have strong participation – the **Global Research Alliance on Agricultural Greenhouse Gases**[99] has 58 member countries, including most of the largest producers and consumers; and the former Consultative Group for International Agricultural Research (now **CGIAR**),[100] another leading forum, operates in around 100 countries globally – though it could benefit from a higher level of political support.

- **Coordinated procurement and testing**: Almost all potential emissions reduction technologies and practices in agriculture require evaluation in situ to validate their efficacy. This makes developing and commercialising new technologies even harder than in some of the industrial sectors discussed later in this report. Even after their viability is demonstrated, new technologies for emissions reduction in agri-food production face considerable barriers to uptake. Barriers include regulatory compliance, consumer perceptions and farmer acceptance. International cooperation in the testing and demonstration of new technologies in relevant production settings could help to lower these barriers and reduce costs, as well as helping to develop a shared evidence base for regulatory compliance.

As these new technologies and techniques are developed, support to farmers and agri-food businesses may be needed to encourage their rapid adoption. This can include information campaigns, targeted subsidies, and strengthening of networks for the sharing of best practice, and can take place at local, national and international levels.

ACTIONS TO ACCELERATE DIFFUSION

Diffusion of best practice in the use of existing technologies and techniques is an urgent priority, given the wide variations that exist between and within countries in relation to both the efficiency of agricultural production and the effectiveness of forest protection and land restoration.

Countries acting individually can accelerate the diffusion of low emissions land use through actions:

- **To reduce agricultural production emissions**: In the short term, this can include promoting best practice in efficient and sustainable farming (including the adoption of existing technologies for this purpose) through information campaigns, practical support to farmers, and the reorientation of agricultural subsidies. This can increase productivity as well as reduce emissions, but should be coupled with integrated land-use planning to ensure that improvements in efficiency are not gained at a disproportionate expense to other ecosystem services. In the longer term, as some of the new technologies mentioned above become available – such as low emission fertilisers, feeds, and alternative proteins – policies such a subsidies, taxes and information campaigns are likely to be important to promoting their diffusion.

- **To reduce deforestation, and protect critical ecosystems**: The priorities are to strengthen regulations and policy frameworks around legal and illegal deforestation, and improve policing and law enforcement in deforestation hotspots. Establishing stable land tenure regimes can be important in supporting better livelihoods for farmers, and to protect the rights of indigenous and smallholder communities. Increasing and reorienting the flows of finance – such as those from agricultural subsidy schemes – to reward conservation and sustainable use of forest resources can increase the incentives for good land management practices.

- **To enhance carbon sinks**: Afforestation, restoration of forests, peatlands, and coastal wetlands, agroforestry, and soil carbon sequestration can all increase the capacity of land to act as a carbon sink.[101] As with reducing deforestation, there are opportunities to encourage these actions through the reorientation of agricultural subsidies.

These actions can be difficult to implement, given the context, discussed above, of political risks associated with change, the available profits from unsustainable activity, and the limits to governmental authority. In this context, coordinated international action can play a valuable role in accelerating diffusion.

- **Sharing of policy best practice**: This is a no-regrets way to accelerate the transition to low emissions agriculture. This can help countries understand how best to promote efficient farming practices, reorient agricultural subsidies, prevent deforestation and promote reforestation. Although many initiatives exist for the purpose of developing knowledge in this space (such as those mentioned above under emergence), few have the direct participation of countries' ministries of agriculture. There is currently no widely recognised forum for inter-governmental cooperation and coordination on policy in this area. Establishing such a forum with appropriate political engagement should be a high priority. Options could potentially include broadening the focus of the Global Research Alliance from research to policy (though this would require changes to its current mandate), or establishing a process under the UN's Food and Agriculture Organization. Involving the right parts of government – environment ministries (who are often responsible for forests) as well as agriculture ministries – and getting them to work together, will be important.

- **Technical and financial assistance**: This is a valuable complement to the sharing of best practice. At present only a few percent of climate finance globally is devoted to agriculture and land use, which is a disproportionately low level compared with its high share of global emissions. Germany, Norway and the UK have so far led the way, by committing US$5 billion to the protection of tropical forests by 2020. There is considerable scope for this to be increased, including through the coordinated actions of donor countries and multilateral development banks. International 'Reducing Emissions through Deforestation and Degradation' (REDD+) programmes can also help, by providing results-based payments to reduce deforestation, improve sustainable forest management, and enhance forest carbon stocks.[102] The impact of financial assistance could be increased by a much stronger effort to promote managerial expertise and rural enterprise as a vehicle for the diffusion of best practice. This would recognise the reality of farmers' roles as entrepreneurs, rather than treating them simply as aid recipients. **Setting common standards** for carbon accounting and verification can support any such arrangements linking finance to sustainable land use.

- **Coordinated buying power**: Agri-food businesses and governments can use their buying power, exercised through choice of suppliers and contractual requirements, to significantly reduce emissions from agricultural production and deforestation. Coordinated action can be especially effective at points of concentration in the supply chain: for example, there are tens of thousands of palm oil producers – 40% of them smallholders – but only four to five traders that dominate the market. Similarly, beef packing plants in North America are largely owned by just four companies. Four major traders control as much as 90% of the global grain trade. However, as discussed above, the incentives for businesses to exercise this leverage may be limited by competitiveness concerns. To drive change across global markets, a policy or regulatory approach may be needed – as discussed below, under reconfiguration.

International trade negotiations could potentially play a role in accelerating diffusion of low emission agricultural practices, if steps to reorient financial support towards sustainability were included in any agreement on agricultural subsidies. So far however, reaching any agreement in this area has been particularly difficult.

Countries can also contribute to reducing agricultural emissions by taking steps to reduce food loss and waste, and to encourage shifts toward healthier, more sustainable and less meat-based diets – for example, through public health campaigns.

ACTIONS TO ACCELERATE PROGRESS TOWARDS RECONFIGURATION

Reconfiguration will necessarily involve a global shift from deforestation to afforestation and the enhancement of carbon sinks, as well as low emissions agriculture technologies and practices becoming completely pervasive.

To avoid deforestation, a contracting approach is likely to be important in the near term, first to open and protect niches for sustainable supply chains, and later to extend them to cover the whole of relevant market segments. A precedent has been set by regulations implemented by the EU, US, Australia, Japan and South Korea to prohibit illegally logged timber from entering their markets. Together these cover enough of the global timber market to have been broadly successful in excluding illegally logged timber from international trade. The EU's Forest Law Enforcement, Governance and Trade (FLEGT) initiative has complemented these measures by supporting the establishment of legality and licensing systems in producer countries, helping them to meet the eligibility criteria for international trade. This has led to a measurable decline in illegal logging in a number of countries.[103,104]

To have a greater impact on deforestation, policy needs to go beyond timber and address a wider range of commodities that are a greater threat to forests. Agriculture is estimated to cause somewhere between 50% and 80% of global deforestation. Just four commodities – palm oil, soy, beef, and wood products – account for more than 40% of tropical deforestation.[105] Unless market demand requires these to be sourced sustainably, actions on the supply side – to protect forests – are likely to remain difficult to enforce.

Brazil's Soy Moratorium, implemented from 2006, provides an example of what can be achieved through collaborative efforts. It involved major soybean traders agreeing not to purchase soy grown on deforested land in the Brazilian Amazon, with compliance checked by a satellite and an airborne monitoring system developed by industry, NGOs and government partners. Over this period, the proportion of soy expansion achieved through deforestation in the Amazon fell from nearly 30% to around 1%. The concentration of buying power, the simplicity of compliance requirements, the transparency of monitoring, and collaboration between government, industry and NGOs have all been cited as factors contributing to its success.[106] These factors are not present or easy to create in all sectors or all countries, but the example nevertheless illustrates how powerful coordinated action on the demand side can be.

Replicating this success across a wider range of commodities and geographies is likely to require an international approach. Around 29 – 39% of deforestation-related emissions is estimated to be driven by international trade (higher than the 23 – 26% of fossil carbon emissions estimated to be embodied in international trade).[107] Voluntary, business and civil society-led initiatives to improve supply chain sustainability have made important progress. The **Roundtable on Sustainable Palm Oil**[108] and the **Roundtable on Responsible Soy**[109] have developed standards for sustainable production and certification schemes that have so far been adopted by producers covering 19% and 3% of their respective global markets. The **Tropical Forest Alliance**[110] works with governments, businesses and civil society on the supply and demand sides to reduce deforestation from the production of palm oil, soy, beef, and pulp and paper. Fora including the **Consumer Goods Forum**[111] and the **Soft Commodities Forum**[112] of the **World Business Council for Sustainable Development**, have supported valuable business-to-business exchange of best practice. However, business leaders and experts say that ultimately, widespread change in the sector is unlikely to occur without strong government action on the demand side (in the form of regulatory standards linking market access to sustainability), as well as on the supply side. **International coordination on standards for avoiding deforestation in global commodity supply chains could therefore be a very strong point of leverage.**

Countries that import large quantities of food are well placed to exert this leverage. The EU, India and China together import almost 60% of all palm oil (80% of which is produced in Indonesia and Malaysia). China alone accounts for almost two thirds of global soy imports, with the EU as the second-largest importer. The US and EU are major beef consumers, although they import little from countries where forests are at risk. Consumption of beef in emerging economies is rising. China, India, Brazil and Indonesia together account for around 40% of global demand for the main deforestation-causing commodities,[113] while the EU accounts for a third of demand for the portion of deforestation-causing commodities that are traded internationally.[114] Figure 17 shows the proportion of internationally-traded soy and palm oil accounted for by the main importing countries and regions.

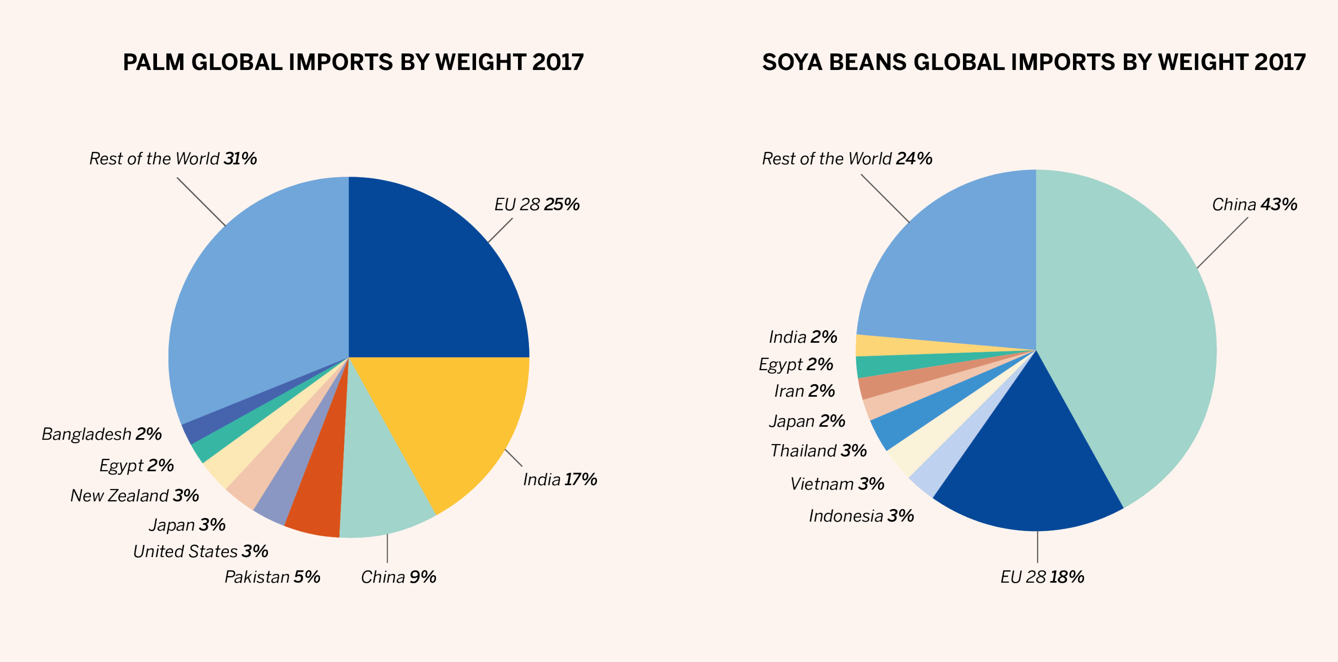
Just four commodities – palm oil, soy, beef, and wood products – account for more than 40% of tropical deforestation. Unless market demand requires these to be sourced sustainably, actions on the supply side – to protect forests – are likely to remain difficult to enforce.

For the multinational companies involved in food distribution and retail, it is not worth the effort to apply more than one standard to their supply chains. Their incentive is to level up to the highest standards required by any sufficiently large market. Therefore, **a few large consumer countries acting together could have a large effect on the global market.** The EU appears likely to be a first-mover here, given the support for this approach of the seven of its Member States that make up the **Amsterdam Declarations Partnership** – which promotes learning and coordination across national supply chain sustainability initiatives.[115] California has also shown willingness to move early, using public procurement to require all companies contracting with the state government in deforestation-risk commodities to demonstrate deforestation-free supply chains. China's largest state-owned commodity processor and trader, the China Oil and Food Corporation (COFCO), is working to improve the sustainability of its supply chains, and joined the Round Table on Responsible Soy in 2019. Given perceived first-mover risks, a coordinated approach could encourage more countries to participate in these efforts. **There is currently no recognised government-to-government forum in which this kind of coordination is discussed by producer and consumer countries, and so establishing one should be considered a high priority.**

The examples of success mentioned above suggest that coordinated standard-setting should be complemented by **monitoring of compliance** – with monitoring of deforestation increasingly feasible using satellite imagery – and **targeted support to producer countries**, for example through international climate finance. Without a collaborative approach, supply chain standards can be perceived as a market barrier to exports. In contrast, experience shows that productivity improvements can increase agricultural output without requiring land expansion. Much of the deforestation in producer countries is illegal anyway. Implementing strong forest protection practices can therefore support domestic policies, as well as providing a competitive advantage in exports.

The measures needed for full reconfiguration of agricultural production towards near zero emissions are not yet clear. This stage of the transition is still some way off. A contracting approach could potentially be relevant to some of the important causes of emissions. For example, nitrogen inhibitors in fertilisers are available but not widely used, because of their higher cost – a barrier that could potentially be addressed through coordinated standards or border adjustments. However, difficulties of measurement may limit the extent to which this approach can be applied to the many contributing sources of methane and nitrous oxide emissions.

FIGURE 17: COUNTRY SHARES OF TOTAL GLOBAL IMPORTS OF SOY AND PALM OIL



Based on data from https://resourcetrade.earth/data?year=2017&category=78&units=weight.

Just transition risks and opportunities

Developing countries face particular difficulties in moving to low emission agriculture. Many have a predominance of smallholder farms, which may limit the applicability and take-up of decarbonisation options. For example, more than one-third of palm oil and two-thirds of the world's cocoa are produced by smallholder farmers.[116] They may struggle to meet standards, and to conduct inspection or certification processes to verify that standards have been met. Any standards-based approach will need to take these issues into account, so as not to disadvantage developing country producers.

At the same time, many of the policies to reduce emissions through increased resource efficiency can improve productivity, yields, and export opportunities, and so contribute to addressing the need of the 800 million people who still go hungry in the world, and the additional two billion who suffer from micronutrient deficiencies.[117] In addition, combining assistance for improved efficiency and climate resilience of farming can support the 500 million smallholder farmers who are already facing climate change stresses. Investment in research, development and deployment of climate resilience crops; provision of advisory services to farmers; investment in ecosystem restoration; and strengthening of social safety nets can all enhance the resilience of food systems, rural livelihoods, and societies. The international exchange of best practice, development assistance and collaboration – including through initiatives such as the **Just Rural Transition** initiative[118] – can help countries take advantage of these opportunities.

Across all sectors, the use of bioenergy will need to be considered in the context of the need for land and water for food production. By competing for these resources, large-scale production of biomass could negatively affect food security – a problem likely to be amplified by the reduction in land productivity caused by climate change.[119] Managing this risk will be essential for achieving a 'just transition' on a global scale, and is likely to involve prioritising the production of biofuels from feedstocks that compete least for resources (such as those produced from waste flows or from marginal land), and prioritising their use in sectors where there are the fewest viable alternatives, such as aviation.

Many of the policies to reduce emissions through increased resource efficiency can improve productivity, yields, and export opportunities, and so contribute to addressing the need of the 800 million people who still go hungry in the world.

CARS (LIGHT ROAD TRANSPORT)

SECTOR **CARS**

IMPORTANCE

*Accounts for about **7%** of total global greenhouse gas emissions.*

GHG 7%

STAGE OF TRANSITION **DIFFUSION**

Beginning of diffusion – innovation has stabilised around a dominant technology: electric vehicles.

NATURE OF THE PROBLEM NOW

- *Electric vehicles' up-front costs still high*
- *Industry pushing for weak policy*
- *Charging & refuelling infrastructure supply-and-demand problem*

OPTIONS FOR DECARBONISATION

- *Electric vehicles (2-3% of new car sales globally)*
- *Hydrogen vehicles*

INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

1 ACTIONS TO ACCELERATE EMERGENCE

- *At a global level, the transition to electric vehicles is beginning the diffusion stage – though progress varies significantly by region*

2 ACTIONS TO ACCELERATE DIFFUSION

- ***Coordinated tightening of regulatory trajectories** for reducing emissions intensity, to send strong signal of demand and accelerate the shift in industry investment*
- ***Coordinated procurement of electric vehicles** by governments and businesses – to increase economies of scale*
- ***Mutual learning on market-creating policies** (such as purchase incentives, regulatory standards, city-level policies, & infrastructure investment)*

3 ACTIONS TO ACCELERATE RECONFIGURATION

- ***Coordinated phase-out of fossil fuelled vehicles** – to provide clear long-term signals to guide industry investment and innovation*
- ***Coordinated development and deployment of complementary technologies** such as smart charging, vehicle-to-grid charging, & advanced materials*

INSTITUTIONS

International Zero Emission Vehicle Alliance; Clean Energy Ministerial; EV100; C40 Cities

***PRIORITY**: move from sharing information to coordinating action; expand participation to include emerging economies*

Importance to emissions

Cars currently contribute around 7% of global emissions – over half of the emissions from transport as a whole. Transport emissions have more than doubled since 1970, with road transport accounting for almost 80% of the increase.[120] Car ownership globally is projected to nearly double by 2040,[121] with most of this growth taking place in emerging economies. This suggests that emissions from the sector could grow substantially unless a transition to low or zero emission vehicles takes place.

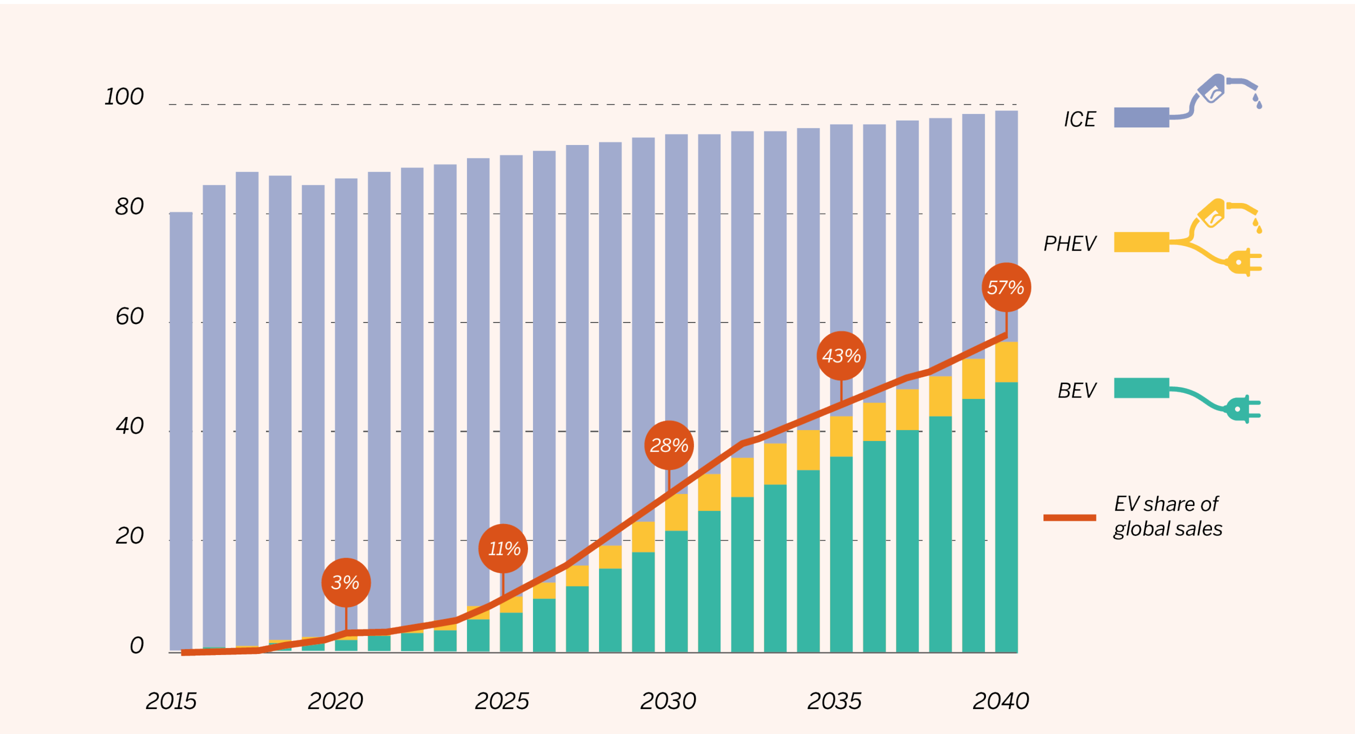
The car industry is worth an estimated US$2 trillion per year in global sales,[122] its supply chains are increasingly global, and it directly employs over eight million people worldwide.[123]

Stage of the transition and technology options

Efforts to catalyse a transition to lower emission cars have been made in various countries over at least the past two decades. During this emergence phase, competing visions for the future of the industry have been based around four main technology options: ultra-high efficiency internal combustion engines, biofuels, hydrogen, and electric. Expectations of which technology would become dominant have fluctuated over time, with each technology experiencing cycles of 'hype and disappointment'[124]

In the last five or so years, a stabilisation of expectations has taken place, with electric vehicles now clearly emerging as the dominant low emission technology. Global sales of electric vehicles grew from 1.3 million[125] in 2015 to 5.1 million in 2018,[126] achieving a 2 – 3% share of all new car sales. Hydrogen fuel cell vehicles are still seen by some in the industry (and certain governments, e.g., Japan) as a significant long-term option, but at present they are not being deployed at a rate that even comes close to comparable, with total global sales of only around six thousand vehicles between 2013 – 2017.[127] Manufacturers are shifting an estimated US$300[128] billion of investment into electric vehicle (EV) development, with the number of EV models on the market increasing from around 40 in 2019 to 333 by 2025 in Europe alone.[129] While there remains competition between plug-in hybrids and battery electric vehicles, only the latter can be zero emissions, and so are expected to establish a clear dominance (see Figure 18).

FIGURE 18: ELECTRIC VEHICLE SHARE OF GLOBAL LIGHT DUTY VEHICLE SALES



Adapted from Electric Vehicle Outlook 2019, Bloomberg New Energy Finance.

This stabilisation indicates the end of emergence and the beginning of the diffusion stage of the transition. Progress, however, is geographically uneven: around half of all EV sales are in China, and most of the rest are in developed countries. At the global level, analysts have in recent years repeatedly revised upward their expectations of the future EV market share, and some now expect this to exceed 50% of all new sales by 2040.[130] While this is encouraging, the pace of this transition needs to be roughly doubled to be in line with climate goals.

Nature of the problem now

The upfront costs of electric vehicles are still relatively high, and there remain technical challenges to solve to improve the performance, lifetime, and energy density of batteries, as well as to extend their range. However, the strong reinforcing feedbacks of the diffusion phase are at work on these problems. The industry's investment and innovation are improving performance and reducing cost (with battery costs falling at around five to 20% per year),[131] encouraging customers to buy electric vehicles in greater numbers, and so incentivising further investment. This process is being catalysed and supported by government policy.[132] Electric vehicles are now expected to be cheaper over their lifecycle than petrol or diesel cars by the mid-2020s[133] – though this varies depending on vehicle-type, habits of use, and levels of fuel tax. It remains to be seen how far this cost reduction can progress, and it must be remembered that the costs of transition are not limited to the relative cost of vehicles.[134] Two main problems are now holding back the pace of the transition: industry pressure, and the need for infrastructure.

Industry pressure is a significant factor in many developed countries, where car manufacturers have deep expertise, long experience, and well-developed supply chains for the production of conventional fossil-fuelled vehicles. These manufacturers face a dilemma: they want to compete in the production of the cars of the future, while wanting at the same time to continue using their existing manufacturing assets and selling the currently-much-more-profitable cars of the present for as long as possible. Firms are resolving this dilemma by investing heavily in new zero emissions models and technologies, while at the same time pressuring governments to slow the pace of the transition. Threats to relocate production make this pressure hard to ignore, and some evidence suggests it is effective: the number of electric vehicles required to enter global markets by governments' policies is now lower than the number planned to be produced by manufacturers themselves.[135]

Infrastructure is the second challenge. Drivers want to know that extensive charging networks are in place before they commit to buying an electric vehicle – and that those charging facilities are compatible with their vehicles. But private investors in charging networks are reluctant to invest at scale until there are more electric vehicle drivers. In rural areas with fewer drivers, the economic incentives for private investment in charging infrastructure are particularly weak. This may remain the case unless governments require companies to provide universal coverage in the same way they have done for mobile telephones. The policy challenge for the early stage of the transition is to simultaneously create this infrastructural network and increase the number of vehicles using it, while also stabilising standards for the recharging technologies. As the transition progresses, governments also need to ensure electricity grids are prepared to handle the additional load and the changing demand profile. This includes finding ways to fund the grid connections or reinforcements required by new fast-charging infrastructure, which can be prohibitively expensive for site owners. The infrastructural requirements of the transition are particularly challenging for developing countries that have lower levels of available public finance, administrative capacity, and electricity infrastructure.

How coordinated action can accelerate the transition

The range of options for reducing road transport emissions is of course broader than the transition to zero emission vehicles. Demand for car travel can be reduced through investment in rail networks for long- and short-distance travel, public transport within cities, and – for growing cities – through urban planning. However, the continuing growth in car ownership globally makes a transition to zero emission vehicles essential, and the global character of the industry presents opportunities for coordinated action to accelerate that transition. The focus of this section is on identifying those opportunities.

ACTIONS TO ACCELERATE DIFFUSION

Government policy can have a strong effect on accelerating the diffusion of zero emission vehicles, and there are many actions that governments can take individually. The most effective policy measures include:

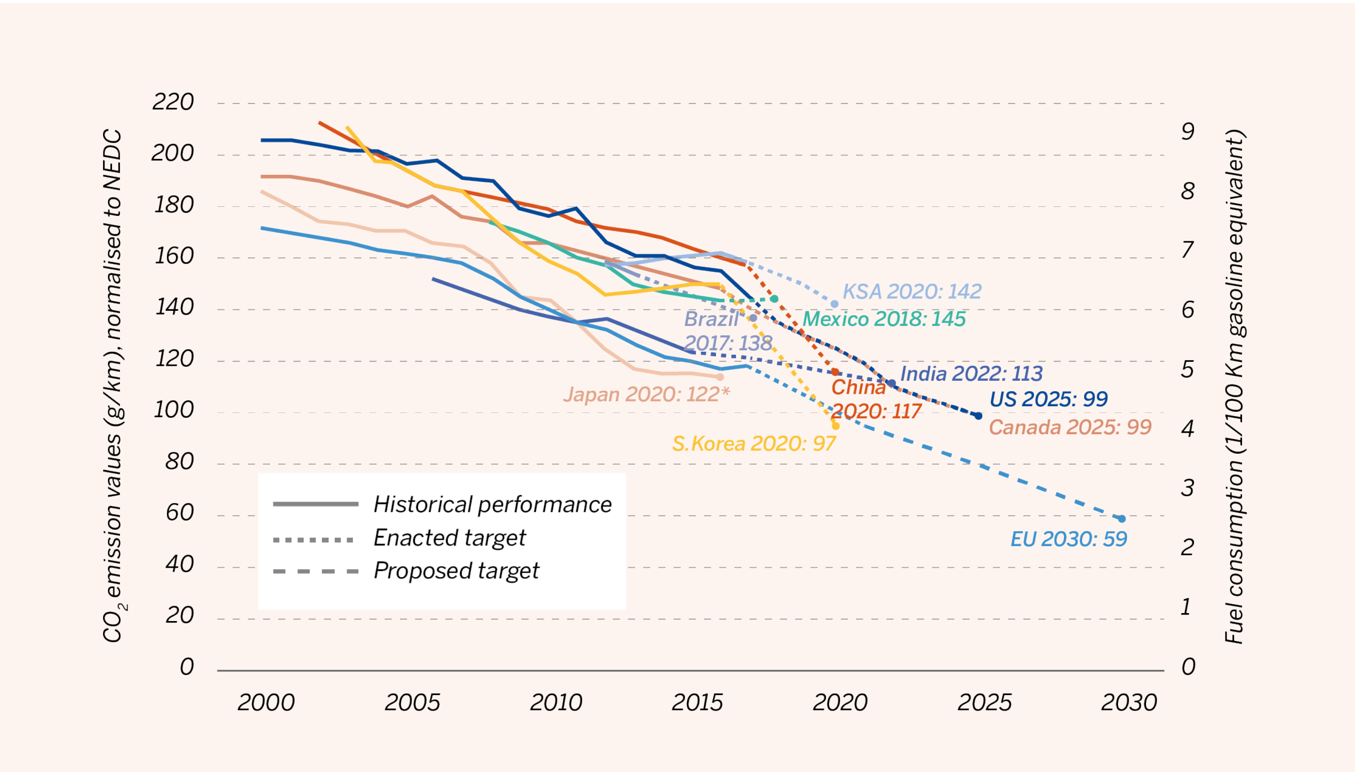
- **Purchase incentives** to lessen the upfront cost differential between ultra-low or zero emission vehicles and conventional vehicles. In Norway, a combination of tax and subsidy has made zero emission vehicles cheaper to buy than equivalent petrol- or diesel-powered models. Although this is complemented by many other policies, it is cited by the Norwegian government as the main reason why electric vehicles have achieved a nearly 50%[136] share of all new car sales in their country, compared to less than 5%[137] almost everywhere else.[138]

- **Regulatory standards** to limit vehicles' allowable emissions intensity of use – usually calculated as an average across a manufacturer's portfolio of models. While in the past such standards generally served the purpose of improving the efficiency of conventional vehicles, they are now increasingly being used to push the transition to ultra-low and zero emission vehicles – including in the major markets of the EU and China.
- **Public investment in charging infrastructure** and supporting electricity grid infrastructure, to leverage private investment and ensure that adequate charging networks are in place to support the growth of the market. Similarly, public investment in hydrogen refuelling infrastructure is likely to be important in countries where hydrogen vehicles are desired as an additional option. **International coordination on standards for charging infrastructure** could help to remove a barrier to investment and improve the appeal of electric vehicles to drivers.
- **City-level policies** that discriminate in favour of ultra-low or zero emission vehicles: for example, by allowing them the use of special lanes or access to designated clean air zones, or by imposing pollution charges on petrol and diesel cars. In China, several major cities have made a strong impact on the market by giving buyers of electric vehicles fast access to new number plates, while buyers of conventional vehicles face a long wait.

while purchase incentives and city-level policies can have a strong impact on consumers' decisions, it is probably regulatory standards that have the most powerful impact on manufacturers' investment decisions, since these set clear parameters for the nature of future market demand. Standards in the EU, China, and California are driving the reorientation of incumbent manufacturers' investments, at the same time as new entrants, such as Tesla, seek actively to take a lead in opening up the zero emission vehicle market.

A coordinated tightening of regulatory trajectories among some of the major economies could be a very high point of leverage for accelerating diffusion. Many

FIGURE 19: REGULATORY TRAJECTORIES IN MAJOR CAR MARKETS



Adapted from the International Council on Clean Transportation, 2019, CO2 emission standards for passenger cars and light-commercial vehicles in the European Union: https://theicct.org/publications/ldv-co2-stds-eu-2030-update-jan2019.

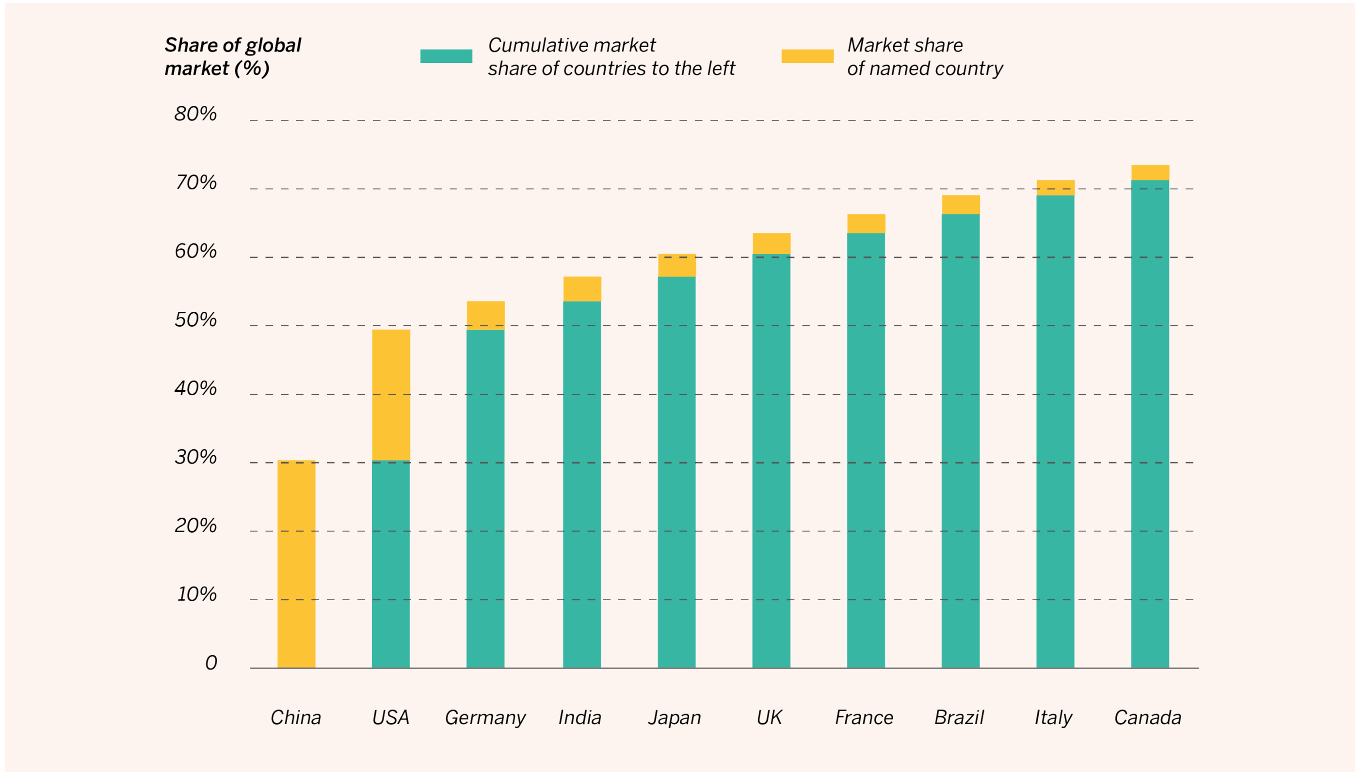
of the largest markets have already set quite similar trajectories for reducing the emissions intensity of vehicles (see Figure 19), and as noted above, these are increasingly driving a shift to ultra-low and zero emission vehicles. A coordinated move could expand global demand significantly, catalyse investment, and reduce the threat (whether actual or perceived) of industry relocation, enabling governments to pursue a faster pace of transition than they would have the confidence to do alone.

This effect could be achieved by coordination among a relatively small group of countries or regions. Ten countries account for around three quarters of global car sales (see Figure 20), and all of these already implement some form of emissions standards. Just three regions – the EU, China and California – account for over half of global sales. Strong economy-wide emissions reduction targets in California, and several of the largest European countries, create a high level of willingness on the part of their governments to pursue a fast transition. China also has good reason to forge ahead, with motivations including taking a larger share of the global market by leading in new vehicle technologies, reducing oil imports, and improving urban air quality. Such coordination among the leading large economies would accelerate the shift in industry investment that is already under way, over time increasing the incentives for more countries to follow suit.

Coordinated procurement is an additional measure to accelerate diffusion that can be taken by both governments and businesses. Most simply, any government or business that owns a large fleet of cars – which could include public utilities, taxi services, or firms that provide employees with company cars – can commit to buying only zero emission vehicles. This will accelerate the growth of the market, the reduction of costs, and the transition of zero emission vehicles towards profitability. Members of the EV100[139] initiative have committed to making their fleets 100% zero emission by 2030. The initiative currently has 59[140] corporate members worldwide. There is scope for many more companies to join, and for governments to make similar commitments.

Mutual learning can be valuable for supporting effective implementation of all the diffusion policies mentioned above. Rates of deployment in the leading countries and regions (Norway, the Netherlands and California) are more than ten times higher than the international average.[141] This suggests that there is

FIGURE 20: CUMULATIVE SHARE OF GLOBAL CAR SALES (ALL CARS) BY COUNTRY.



The top part of the bar indicates the additional share of each country. The total height of the bar represents the cumulative share of countries up to and including that country (from left to right).

Based on data from https://focus2move.com/world-car-market/.

much to gain from sharing policy expertise and market information. The International Zero Emission Vehicles Alliance (IZEVA)[142] is a leading forum for such exchanges between national and regional governments. It currently includes only four national governments (three of the top ten car-buying countries), so there is great potential to scale it up. With an expanded membership, in future this could potentially go beyond the sharing of expertise, and support discussions on coordinated regulatory trajectories. The Clean Energy Ministerial has broader participation. It previously initiated the '30 at 30' campaign, for governments to aim for at least 30% of new car sales to be electric vehicles by 2030. But it has limited capacity to support sustained engagement. At the city level, the C40 Cities[143] network facilitates exchanges of expertise on transport decarbonisation, as well as on the related issue of urban planning.

The politics of the diffusion phase will in many countries be influenced by perceptions of whether a '**just transition**' is taking place. The car industry supports high quality jobs, and the future of these jobs is likely to be a primary concern in any country with a significant manufacturing industry. Within the motor industry, retraining can support workers in the shift to the manufacture of zero emission vehicles. Electric vehicles are less labour intensive than conventional vehicles, so the car industry may support fewer jobs in future. But more broadly, the transition to electricity and hydrogen is expected to create more new jobs in related manufacturing and services sectors than are lost in the production of combustion engines and the supply of their petrol and diesel fuels.[144] Government investment in skills and adult education could be important in enabling motor industry workers to take up equally high-skilled jobs in the growth sectors of the low carbon economy.

For society more broadly, the transition presents a major opportunity for cleaner air to improve public health. Outdoor air pollution, of which cars are a major cause, currently leads to over four million deaths per year according to the World Health Organization,[145] most of which are in the developing world.

ACTIONS TO ACCELERATE PROGRESS TOWARDS RECONFIGURATION

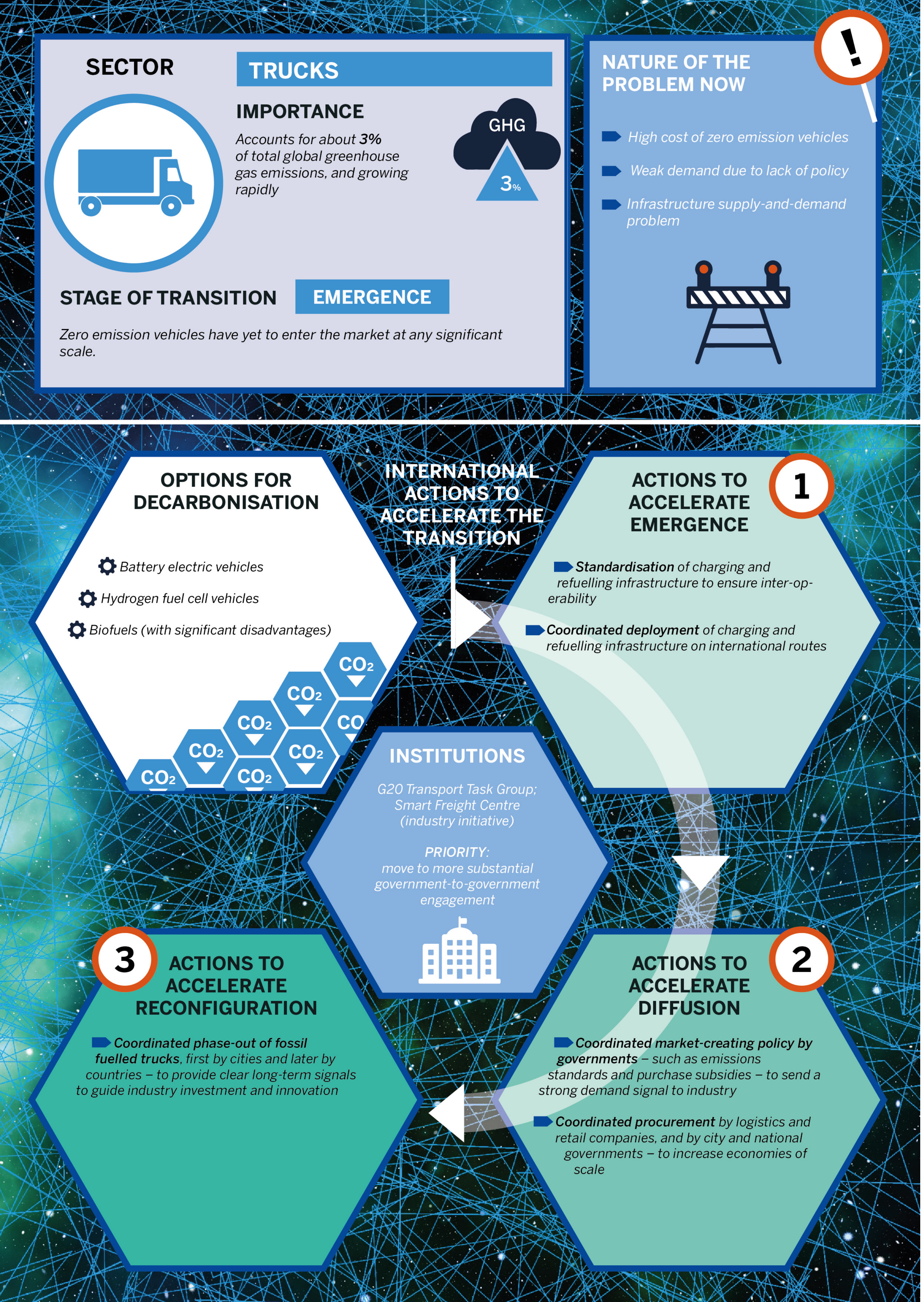
Several countries including the UK, France and Norway have already set phase-out dates for the sale of fossil fuelled vehicles. This supports the current stage of diffusion by providing a clear signal of the direction and extent of change required in the industry. Translating these commitments into regulation or law – which for the most part has not yet been done[146] – would bring the trajectories of emissions standards to their logical conclusion. A **coordinated approach to phase-out** by some of the largest economies could transform the outlook for the global market, accelerating progress towards reconfiguration. This may become increasingly possible as diffusion gathers pace, industry begins to profit from selling zero emission vehicles, and governments become more confident in their ability to handle the infrastructural implications.

The **development and deployment of complementary technologies** is likely to be important in supporting this stage of the transition. A major challenge will be to ensure electricity grids integrate the vehicle charging network as efficiently as possible, benefiting from its energy storage capacity, as well as managing the additional demand for power. Importantly, this integration could also support the reconfiguration of the power sector, by helping to manage large amounts of intermittent renewable power supply. Smart charging and vehicle-to-grid charging technologies are already being tested. A coordinated international effort could accelerate their development. Progress in battery recycling may be needed to limit vehicles' overall lifecycle emissions. In addition, the development of advanced materials could help to improve performance and range (by reducing vehicle weight) while reducing vehicles' embodied emissions. The shape of the sector could be further transformed by other technologies that are being developed in parallel, such as those for connected and autonomous vehicles.[147]

Over the long-term, the reconfiguration of road transport around zero emission vehicles could be a major factor in global oil demand moving from growth to contraction.[148] This could result in more workers in the oil and gas industry facing the job losses already being experienced in regions, such as the North Sea, where supply has peaked. The industry's expertise in extraction and mechanical, chemical and offshore engineering can be valuable for the low carbon transition. It may be used in the mining of minerals for clean energy technologies, the development of advanced biofuels, the development of electrolysis, and installation of hydrogen transportation and distribution networks. As well as in the deployment of offshore wind, carbon capture and storage, and geothermal energy. Gas itself, as a feedstock for hydrogen, could be a fuel supply for low carbon industry and heating, if accompanied by carbon capture and storage. Foresight, planning and diversification on the part of companies, as well as support for retraining and investment in infrastructure on the part of governments, are likely to be important in realising these opportunities.

On a larger scale, the transition presents risks to countries and regions that rely heavily on oil and gas for government revenues. A long-term strategy for economic diversification, supported by investment and political dialogue, is likely to be essential for managing the risks in these cases.

TRUCKS (HEAVY ROAD TRANSPORT)



Importance to emissions

Heavy duty road transport – trucks and buses – currently contributes around 3% of global greenhouse gas emissions. Emissions from the sector are growing by over 2% per year, with trucks accounting for more than 80% of this growth.[149] Road freight is increasing, driven by rising prosperity, especially in emerging economies. If no action is taken, the sector is projected to contribute as much to global emissions growth between now and mid-century as coal use in the power sector and all industry sectors combined.[150]

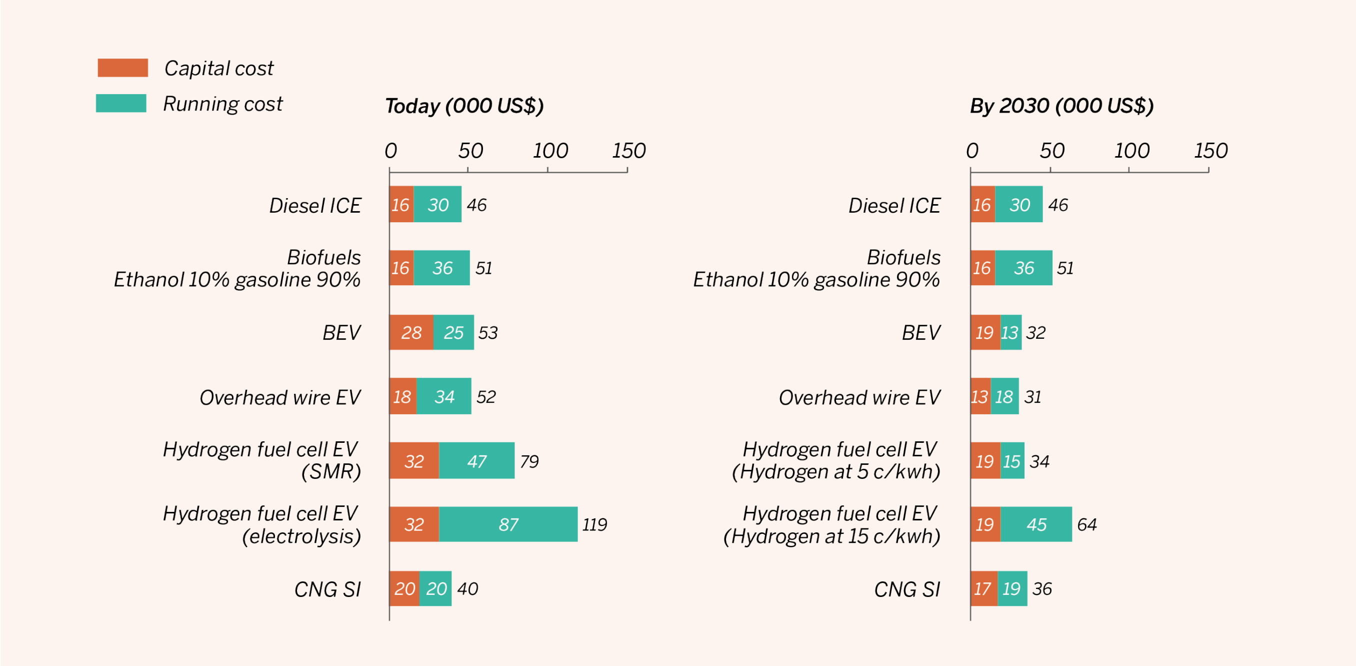
This section is mainly about trucks, because of the very large share of heavy road transport emissions that they account for. Buses will be considered too, for the important role they could play in creating a niche for zero carbon heavy road transport technologies.

Stage of the transition and technology options

Options to reduce emissions from heavy goods vehicles include reducing demand and increasing efficiency. A modal shift to rail or water-borne freight could reduce CO_2 emissions by up to 85% on shifted traffic. Yet road freight is currently increasing, and is likely to remain important for many countries, so a transition to zero carbon vehicles appears essential to meet long-term climate goals. The rest of this section considers the nature of that transition and how it can be accelerated.

The transition to zero emission trucks is in the emergence stage: zero emission models are under development and in testing, but have yet to enter the market at any significant scale. Buses are somewhat ahead: all-electric vehicles are already on the roads, and if that electricity were fully decarbonised these vehicles would be zero emission.

FIGURE 21: CURRENT AND ESTIMATED FUTURE COSTS OF HEAVY DUTY VEHICLES USING DIFFERENT TECHNOLOGIES AND FUELS



*12% first year depreciation for all technologies and vehicle elements.
SYSTEMIQ analysis for the Energy Transitions Commission (2018), based on IEA, ICCT, press research.

Adapted from the Energy Transitions Commission, 2019, Sectoral Focus on Heavy-Duty Road Transport: http://www.energy-transitions.org/sites/default/files/ETC%20sectoral%20focus%20HeavyRoadTransport_final.pdf.

For heavy road transport as a whole, it appears highly likely that electric drivetrains will emerge as a dominant technology, given their inherent efficiency advantage over internal combustion engines. They have an additional advantage over biofuels of being zero emissions at point of use and so better for air quality in cities. A further strategic consideration that governments may take into account is that with a limited global supply of sustainable biofuel sources, it makes sense to prioritise their use in sectors where the alternative clean technologies are technically difficult or very expensive (such as aviation). This is not the case for road transport.

Uncertainty remains over how much of the market will be taken by battery electric vehicles (BEVs), and how much by hydrogen fuel cell electric vehicles (FCEVs). At this stage, it seems likely that the currently-cheaper BEVs could dominate the short-haul market segment, and the FCEVs – with a lighter form of energy storage, and faster refuelling – could dominate the long-haul. Power by electric wires is an alternative option that could compete with FCEVs in the long-haul market. The medium distance segment could go either way. Ultimately, the answers depend on the performance and cost of each technology system, and the availability of its necessary supporting infrastructure.

Trucks and buses with electric drivetrains are expected to become a lower cost option than diesel or petrol vehicles during the 2020s. Even for hydrogen fuel cell trucks, this could happen by 2030, depending on the cost of hydrogen (see Figure 21).

Nature of the problem now

Truck manufacturers face a similar dilemma to car manufacturers: their incentive to accelerate the transition is limited, since petrol and diesel trucks are currently more profitable, but at the same time they need to be competitive in the technology of the future.[151] Within a context of weak demand signals, only a small number of new entrants (Tesla, Nikola) and a few incumbents hedging their bets (Daimler, Toyota, and some Chinese manufacturers such as BYD) are making serious investments in developing zero emission models. Most of these leading companies have already invested in battery and electric engine technologies for light vehicles, which gives them an important head-start and a greater incentive to drive the transition. Most of the industry as a whole, especially those companies without this advantage, appears to lack the confidence to shift its investment in this direction, meaning that while some small niches for zero emission trucks are opening up, the development of the transition has relatively low momentum.

Truck fleet owners and operators have little incentive to make an early move to zero emission trucks, for several reasons. Firstly, the costs (which for many will include the installation of charging or refuelling infrastructure in depots) are not yet in favour. Secondly, and more importantly, they will need to feel confident in there being sufficient charging or refuelling infrastructure in place before they can make the switch. Meanwhile, private investors are unlikely to invest heavily in infrastructure networks – although some initial investments are planned – until they have enough confidence in market demand. Thirdly, even if these first two obstacles are overcome, there will still be significant logistical challenges associated with making the switch across an entire fleet.

How coordinated action can accelerate the transition

Most of the world's heavy road transport takes place within national borders, and significant amounts take place at a regional or local level. This means that national and even city governments can take the critical first steps to give impetus to the transition to zero emissions vehicles. Given their need to invest in road infrastructure, and to recoup the costs through taxes, it is inevitable that governments are heavily involved in road transport and have many levers with which to influence its development. While lack of international coordination is not the dominant constraint, coordinated efforts could yield important gains in terms of shared learning and economies of scale. The latter will become increasingly important as the transition progresses.

ACTIONS TO ACCELERATE EMERGENCE

Cities and regional planning authorities acting individually can create essential first markets for zero emission heavy vehicles through the procurement of publicly owned fleets such as buses and rubbish trucks. China's fleet of one million urban buses, almost all to be electric by 2025, is an outstanding example.[152] The city of Shenzhen in particular has shown leadership, becoming the first city to move to an entirely electric-powered bus fleet. These initial markets provide manufacturers with the incentive to invest in the development of zero emission models, and provide policymakers with lessons that can be shared with others. **Coordinated learning** through international networks such as C40 Cities can accelerate the sharing of this knowledge, encouraging more regions to follow.

The deployment of charging and refuelling infrastructure is equally essential, to enable the initial deployment of zero emissions trucks and buses. The most viable options for early deployment will be along important freight corridors, and within major cities. Public investment is likely to be necessary for ensuring enough facilities are available. Planning this in consultation with fleet operators, fuel providers, and truck manufacturers can ensure infrastructure development is well aligned with patterns of use. This will give greater clarity to manufacturers about market demand for different technologies, as well as greater confidence to fleet operators and investors.

Cities, states or provinces on the same freight routes acting together can create the initial niches for long distance zero carbon road freight by coordinating their infrastructure investments. **International coordination** of infrastructure investments can play an important role in regions where a significant proportion of trucking is international (such as the EU, where this is a third of the total).[153]

Coordination on standards for charging and refuelling infrastructure will be important at all of these geographical scales, to ensure its interoperability. International coordination will be especially important in regions such as Europe with high levels of international road freight.

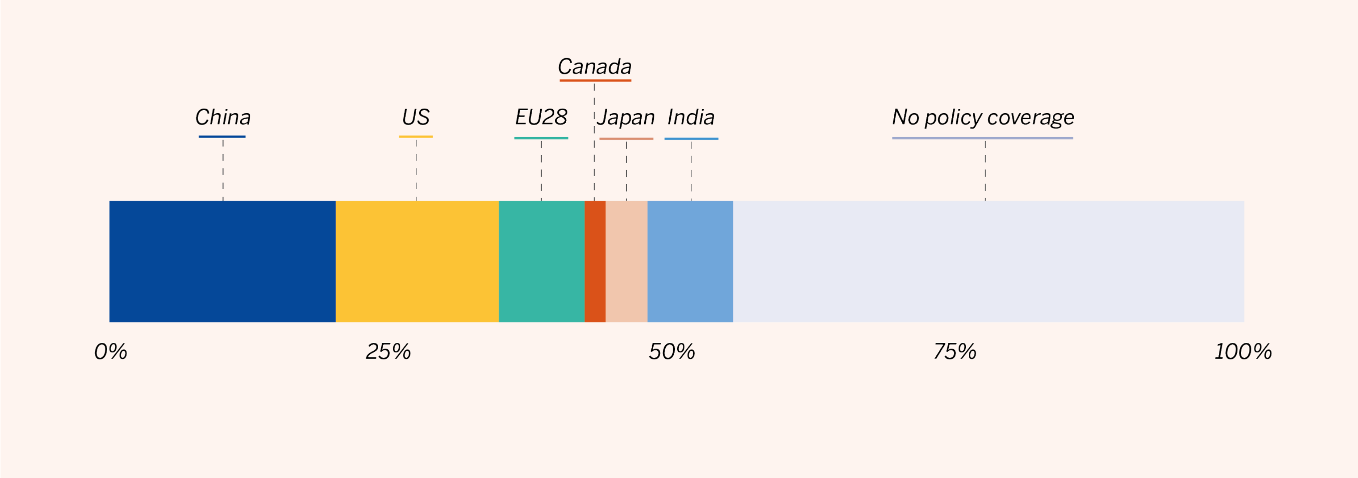
ACTIONS TO ACCELERATE DIFFUSION

Trucks are traded across borders much less than cars, and the nature of demand varies significantly between countries, so manufacturers are used to designing very different product lines for different regions.[154] This means that, compared to the car industry, there is less potential for standards in one country to shift investment patterns internationally. However, truck exports globally were worth US$138 billion in 2018,[155] and manufacturers with a presence in more than one of the large markets, such as Daimler, Paccar and Volvo (all in the US and EU), are likely to be influenced by developments in each of these markets as they decide how to allocate their investment in new technologies and models. This presents two opportunities for coordinated international action towards accelerating diffusion:

- **Coordinated market-creating policy**: two sets of policy can be especially powerful in creating a market for zero emissions heavy road transport: Firstly, mandatory emissions standards that tighten over time,[1] so that eventually they can only be met through a shift to zero emission vehicles. Secondly, subsidies for the purchase of zero emission vehicles and depot infrastructure, and taxes (or carbon prices) on diesel and petrol, to create cost parity at an earlier date. The more countries that apply these measures and move their markets in the same direction, the stronger the demand signal to manufacturers, and the greater the economies of scale – leading to cost reductions – from which the whole global market will benefit. Five countries, plus the EU, make up over half of the global market (see Figure 22). China, Europe, and some US states are well placed to lead the transition, given their access to low cost clean energy, their automotive industries, and their concerns about air pollution and climate change.

1 Currently only about half of the global market for heavy-duty vehicles is covered by efficiency standards. This compares to 85% for cars and light commercial vehicles. Note that efficiency standards will only drive the transition to zero emission models if they are tight enough to eventually become difficult to meet by any other means. (Source of data: https://www.iea.org/tcep/transport/trucks/)

FIGURE 22: SHARE OF GLOBAL HEAVY DUTY VEHICLE SALES BY COUNTRY, 2019 ESTIMATE, ADAPTED FROM IEA



Estimates adapted from IEA Mobility Model, May 2019 version, https://www.iea.org/tcep/transport/trucks/.

Coordinated learning can support this approach. In 2015, the G20 established a Transport Task Group[156] to share policy best practice on increasing efficiency and reducing emissions in the transport sector, especially for heavy duty vehicles. Institutional processes such as these need to be strengthened if they are to go beyond information-sharing and effectively support the coordinated market-creating policy and coordinated infrastructure investments described above.

- **Coordinated buying power**: Major international logistics providers, such as DHL and UPS, and large retail companies, own large fleets of heavy-duty vehicles and so hold significant buying power. Coordinated commitments to procure zero emission trucks (e.g., as for the EV100 initiative for cars)[2]could provide a stronger demand signal to manufacturers, and so accelerate the scaling up of the market and the reduction in cost of the vehicles. As noted above, national and city governments could also contribute through the procurement of zero emission trucks and buses for the fleets they control.

An industry initiative that could enable coordinated buying power is the **Smart Freight Centre**[157] set up by the Global Logistics Emissions Council, which works with industry to develop guidelines for measuring, reporting and reducing freight emissions, and advocates for industry uptake and aligned government policy. An increased engagement from governments with this industry-led initiative could be one way to strengthen coordination and accelerate decarbonisation of the sector.

ACTIONS TO ACCELERATE RECONFIGURATION

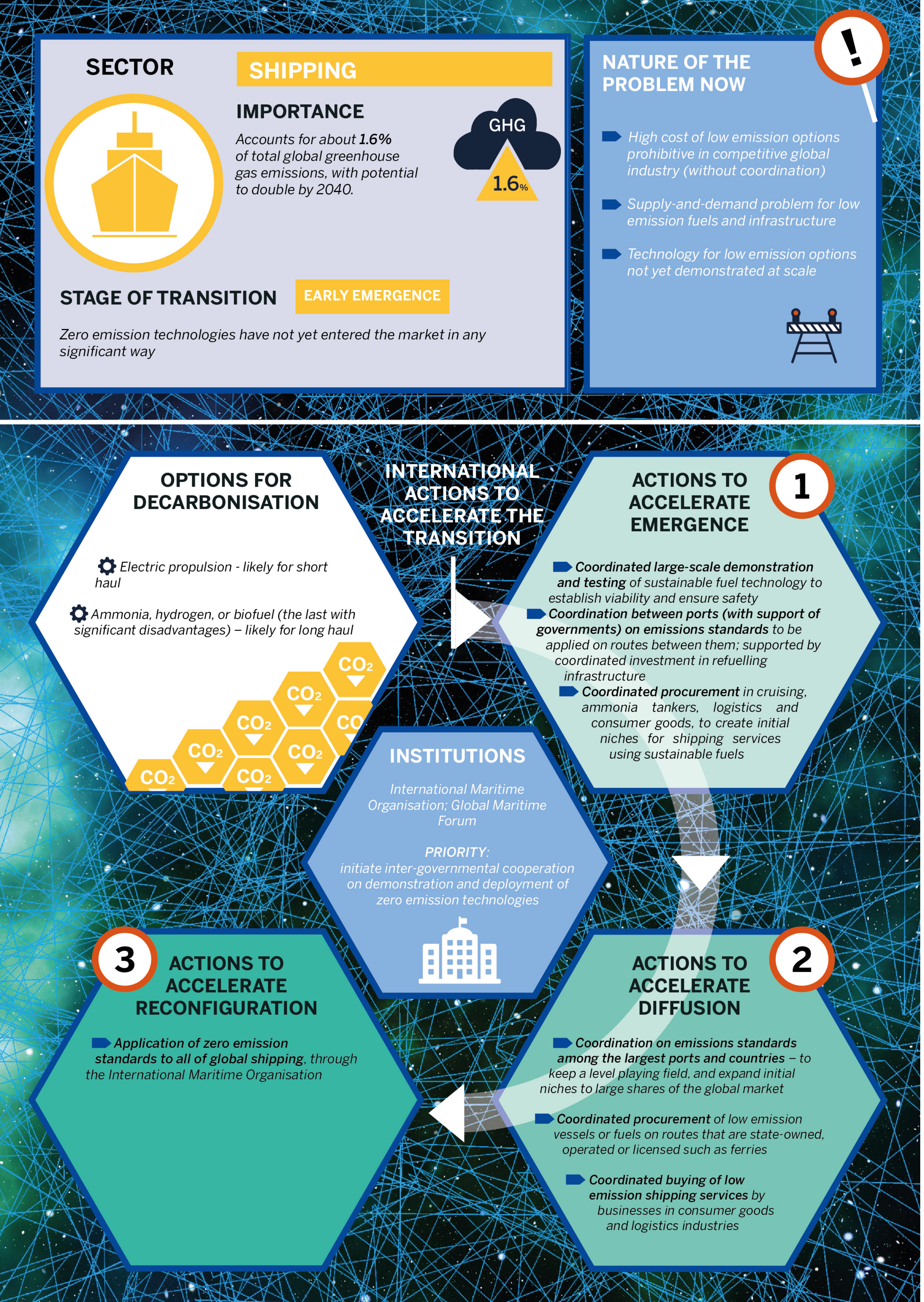
Coordinated phase-out: While reconfiguration of the road freight sector is a long way off, eventually petrol and diesel heavy duty vehicles will need to be phased out, in order to reach zero emissions. The cities of Mexico City, Paris, Madrid and Athens have already committed to end diesel engine use by 2025. Further coordination on phaseout between cities and countries, especially those on the same freight routes, could be instrumental in accelerating reconfiguration.

As reconfiguration gathers pace, the transition will affect an increasing number of countries. In developing countries, the health gains from less polluting road freight could be significant, but the costs and challenges of deploying the new infrastructure could stand in the way. One risk could be that an accelerated shift to zero emissions trucks in developed countries leads to an influx of second-hand high-emitting, high-polluting vehicles elsewhere. International discussion of plans, coordination of actions, and well-targeted assistance could be important in ensuring all countries benefit from the transition.

The cities of Mexico City, Paris, Madrid and Athens have already committed to end diesel engine use by 2025. Further coordination on phaseout between cities and countries, especially those on the same freight routes, could be instrumental in accelerating reconfiguration.

2 Members of the EV100 initiative commit to making their fleets 100% zero emission by 2030.

SHIPPING



Importance to emissions

Shipping accounts for about 1.6% of total global greenhouse gas emissions. The sector is growing at a rate closely linked with global economic growth, and unless a transition to low carbon technologies takes place, its emissions could almost double by 2040.[158] The International Maritime Organization (IMO) has agreed a target of reducing shipping emissions by at least 50% below 2008 levels by 2050, as well as the ultimate aim of phasing out emissions from the sector entirely. Meeting global climate goals would require something closer to full decarbonisation by mid-century. How, in practice, to embark on this transition is the challenge facing the sector.

The vast majority of the sector's emissions (87%) come from its role as the main carrier of internationally traded goods – through the combustion of marine bunker fuels in containerships, bulk carriers, and oil, gas and chemical tankers. Since the heavy fuel oil (HFO) burned in ship engines is the dirtiest fuel left over in the refinery after everything else has been taken, shipping also accounts for 15% of global nitrogen oxide emissions, and 8% of global sulphur gas emissions,[159] although these emissions are beginning to be addressed by measures aimed at reducing air pollution. The shipping sector's demand for oil is roughly equivalent to that of Germany, France and the United Kingdom put together.

Stage of the transition and technology options

The industry has already made moves to improve efficiency, with the IMO mandating a fleet-average 1% per annum energy efficiency improvement between 2015 and 2025. Larger improvements in efficiency are likely to be possible – around 30 - 55% for new ships,[160] and 15% for retrofitted existing ships – but given that the industry is growing at over 3% per annum,[161] it will be difficult for any efficiency improvements to make much of a dent in the sector's overall emissions. A transition to zero emissions technologies will be necessary, to meet climate goals. The rest of this section considers the nature of that transition, and how it can be accelerated.

The transition to zero emissions shipping is in the earliest stages of emergence. Zero emissions technologies have not yet entered the market in any significant way. Several options are being considered by the industry,[162] for both short- and long-distance transport:

- For river and coastal transport, and short-haul ferries and cruising, the most likely option appears to be electric propulsion, with either batteries or hydrogen fuel cells. These have the advantage of higher energy efficiency than combustion engines, but the disadvantage of lower energy density in terms of weight (batteries) or volume (hydrogen).
- For long-haul containerships, bulk carriers and cruising ships, options include biodiesel, hydrogen or ammonia (with each of the latter two used either directly in combustion engines, or in fuel cells for electric engines). Batteries appear unlikely to be viable for these segments of the market because their weight and space requirements – barring a major breakthrough in battery chemistry – are too large to be economic.

The debate on which of these options will prevail remains open within the industry. Their relative attractiveness will vary between market segments – depending on relative concern about weight, volume and range – and will depend on fit with existing assets, as well as cost. However, given the long lifetime (20 - 30 years) of vessels, fuels such as biodiesel and ammonia that can be used in existing engines with limited retrofitting are likely to be preferred over those that would require more extensive changes, such as hydrogen – which would need the retrofitting of expensive and voluminous fuel tanks.[163] Since biodiesel is likely to be limited by a scarce supply of sustainable biomass, and will be consequently more expensive, this leaves ammonia looking like a tentative front-runner for long-haul shipping.

A transitional option available to the industry could be dual-fuel engines, allowing for an incremental shift to zero carbon fuels. These are already available commercially for use with gas – in the form of Liquified Natural Gas (LNG) and Liquified Petroleum Gas (LPG) – in combination with HFO. They could be used for biodiesel with HFO, but have not yet been developed for use with hydrogen or ammonia. One engine manufacturer, MAN, aims to have an ammonia variant ready by 2022.

Some in the industry are currently considering a switch to LNG itself as a transitional solution, partly driven by the short-term need to comply with limits on emissions of nitrogen oxides and sulphur oxides. But this is unlikely to be helpful, since LNG's emissions are not significantly different from those of HFO – perhaps only 9 - 12% lower – when upstream methane leakages from gas production are accounted for. Given that LNG does not represent a long-term decarbonisation option, switching to it risks creating either high-carbon lock-in, or stranded assets in the forms of both ship engines and fuelling infrastructure, unless additional investments are made now to ensure these assets are adaptable and capable of handling zero carbon fuels in the future.

Nature of the problem now

The international shipping industry is highly competitive, and relies on a well-established infrastructure that supplies it with high carbon fuel at low cost. This makes the transition to zero emissions difficult in three ways:

- **Cost and competition**: Heavy fuel oil is by its nature one of the cheapest fuels available, and all decarbonisation options are likely to be more expensive. Switching from HFO to zero carbon fuels could increase operating costs for a typical bulk carrier by around 180 - 240%.[164] Ship operators cannot feasibly make this switch individually, given the highly competitive nature of the sector. The cost of ammonia-powered shipping could fall considerably if there is low cost hydrogen from electrolysis, but even then it is likely to be around 60 - 70% more expensive than HFO when the capital cost of ammonia fuel tanks and the opportunity cost of their extra volume are taken into account. Ports are similarly held back by competitiveness concerns: many have imposed 'green port fees' to put a price on shipping emissions, but these are mostly trivial compared to the estimated US$150 - 300/t$CO_2$ cost of decarbonisation. Imposing fees of that magnitude would risk re-routing shipping to other ports, unless done in coordination at an international scale. One advantage long-haul shipping has is that it faces relatively low risk of losing its business to other modes of transport. So, the costs of decarbonisation could be passed on to the consumer, if a level playing field could be created within the sector.

- **Supply and demand**: There is no large-scale production of low carbon shipping fuels today, whether in the form of biofuels or 'green ammonia' (from either renewable powered-electrolysis or steam methane reformation with carbon capture and storage). Potential suppliers have little incentive to produce these fuels, given the current lack of demand. But demand is held back by cost. As a result, the system so far remains locked in to high carbon fuels and infrastructure.

- **Technology**: The use of hydrogen or ammonia to power shipping has not yet been demonstrated at scale, and still raises safety concerns. For hydrogen, space constraints for fuel storage systems on vessels present an additional technical challenge. Although ship and engine manufacturers are confident that these technologies will be viable, many uncertainties exist around the exact engineering solutions needed for engines and fuel tanks, which need further testing to resolve. For electric propulsion options, the main uncertainty is around how much the energy density of batteries can be improved. The industry has some incentive to test these various technologies, given the IMO's agreed aims for reducing emissions, but this is weakened by the competitive structure of the sector and the lack of market-creating measures to ensure future demand for their use.

How coordinated action can accelerate the transition

Coordinated international action is likely to be important in the shipping sector's low carbon transition, both to take advantage of opportunities of scale, and to overcome the barrier of international competition. Unlike most other sectors, shipping is governed by a global body – the International Maritime Organization (IMO) – which sets the rules for the industry and its global market. This creates an opportunity for coordinated action at a global scale. At the same time, smaller groups of leading actors may be able to play important roles in accelerating the transition.

ACTIONS TO ACCELERATE EMERGENCE

- **Coordinated large-scale demonstration and testing**: This is a critical step towards introducing low carbon fuels to shipping. A series of demonstration projects is needed, particularly for hydrogen and ammonia, to i) pilot and prove the technology at scale; ii) resolve questions related to fuel storage and safety; and iii) refine the economic assessment of different technology options for different sub-segments of the fleet. Many industry groups are encouraging their members to undertake such projects.[1] Strong engagement from governments and the IMO could help to consolidate this landscape, focus efforts on resolving priority questions, and – with investment – incentivise greater participation.

- **Coordination on standards and infrastructure investment**: To create the initial niche for low emissions long-haul shipping, two problems have to be overcome: competition concerns, and the chicken-and-egg problem of fuel supply and demand. This is likely to require coordination from ports and national governments at either ends of a major shipping route, as well as ship operators and fuel providers. A small group of highly interconnected ports could jointly agree an emissions standard to be applied on the routes between them, while also committing to ensuring the availability of low carbon fuels, which would create the necessary demand signal for producers. Options for these first "green freight corridors" could include:
  - Between Asia and North America – the world's busiest shipping corridor (see Figure 23). North American companies may be able to exert demand for low carbon shipping through their supply chains, and low-cost green ammonia could conceivably be produced from renewable power in China, or on the US West Coast.
  - Between Europe and North Africa – where EU Member States and their neighbours could cooperate, using cheap hydropower from Nordic countries, or solar power from Mediterranean countries, for fuel production.

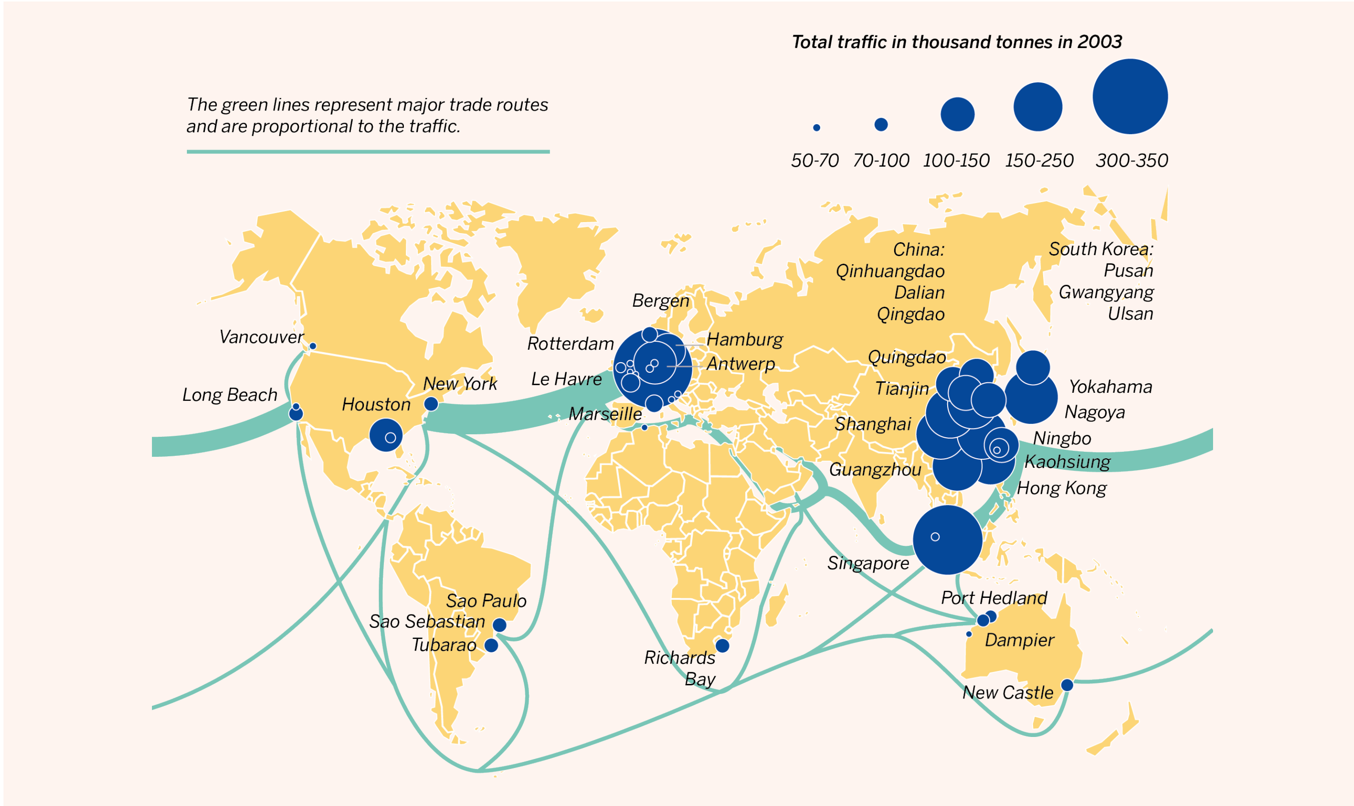
A limitation of this approach is that most vessel operations involve ships trading internationally on multiple routes, and ships adapted to run on ammonia in the routes where it was supplied would not be able to operate on routes where it was not – unless equipped with dual fuel engines. The application of standards might therefore need to be limited to route-dedicated trades (for example, car carriers), at least until a greater scale of participation is achieved. The more the technology is demonstrated, the more it should be possible to expand participation.

The **Global Maritime Forum**,[165] an international not for profit organisation, is beginning to catalyse discussions on this kind of coordinated action. Ports involved in the **World Ports Climate Action Program**,[166] which has so far focussed mainly on knowledge sharing, could be instrumental in taking the lead. These seven ports – Hamburg, Barcelona, Antwerp, Los Angeles, Long Beach, Vancouver and Rotterdam – together control around 6% of global shipping freight. Stronger government engagement in these initiatives could be important to ensuring industry leadership is supported by the necessary policy measures.

Ship operators will respond to regulatory incentives to the extent that they address competitiveness constraints, but some could also use their presence in the market to help bring about the necessary coordination between multiple actors. It may help that the market is highly concentrated: the five leading containership operators own over half of the total capacity of the world fleet.[167]

Without international coordination, governments may be able to create initial niches on a smaller scale by regulating at port level to require the use of low carbon fuels or technologies in certain segments of the market. The cruising segment could be a viable initial niche, since ports in highly-visited tourist cities could regulate

FIGURE 23: GLOBAL SHIPPING FREIGHT ROUTES AND VOLUMES



Adapted from Atlas du Monde Diplomatique, http://textbook.ncmm.no/index.php/textbook-of-maritime-medicine/32-textbook-of-maritime-medicine/3-the-shipping-industry/647-major-ports-cargo-handling-and-turnaround-time.

1 These include the Global Maritime Forum, the Sustainable Shipping Initiative, the Clean Cargo Working Group, Green Marine, Green Ship of the Future, the Clean Shipping Project, and the Getting to Zero Coalition.

with less risk of re-routing. In addition, they could offer consumers cleaner air on board and in ports, as well as a 'greener' service offer. Governments can enable industry to meet such requirements by investing in infrastructure to help ports provide electric charging or low carbon refuelling facilities. They can also ensure other necessary conditions are in place, such as electricity grid capacity and connections, and refuelling operation and configuration standards.

Without policy support from governments, it is likely to be difficult for industry leaders to solve the simultaneous problems of competition and demand-supply coordination that stand in the way of decarbonisation. However, industry leadership could be instrumental in creating niches for low emission shipping in some areas. Potential options include:

- **Cruise shipping**: Consumer concern about the sustainability of air travel has risen recently, and similar concerns about cruising could conceivably follow. Cruise operators could offer a clean shipping option to passengers, creating a niche for low emission technologies.
- **Ammonia tankering**: Ammonia is already transported by ship in significant volumes (albeit in small numbers of ships), mainly for use in fertilisers. Since the ships in this business are already fitted with ammonia storage tanks and covered by relevant safety regulations, they face lower barriers to adopting ammonia as a fuel. In addition, their owners and operators – some of whom are also ammonia producers – have a strong incentive to develop a new market for ammonia beyond fertilisers.
- **Logistics and consumer goods**: Although decarbonisation could double or triple costs for ship operators, as discussed above, its impact on the final cost of shipped products is likely to be very low: for example, less than 1% extra on the cost of a US$60 pair of jeans shipped from Southeast Asia to the US West Coast.[168] Consumer goods companies, and the logistics providers that service them, could therefore offer a sustainable shipping guarantee to consumers with only a minimal cost difference. This would require more detailed data on the emissions of shipping fleets, which the IMO is working to obtain, and which consumer goods and logistics firms could usefully put pressure on the shipping industry to provide.

ACTIONS TO ACCELERATE DIFFUSION

Success in any of the above approaches to creating a niche for low emission shipping would enable new technologies to take hold, allowing them to be scaled up and progressively reduced in cost. This would make low emission shipping feasible and attractive to a broader range of actors, setting the stage for diffusion.

- **Coordination on standards**: In the diffusion phase, a larger number of the big players will need to be involved, to accelerate the scale-up of low emissions fuel production and infrastructure at a rate consistent with climate goals. It will be especially important to involve the largest ports. The top 20 ports, located in just 12 countries and jurisdictions, control 45% of global container freight. Fifteen of these are in Asia, and eight are on the Chinese mainland.[169] Government policy support in conjunction with the IMO in the form of emissions standards is likely to be essential, given the need to create a level playing field.
- **Coordinated buying power:** Governments can accelerate diffusion by procuring low carbon vessels or fuels on routes that are state-owned, operated or licensed. For example, there are state-owned ferry services operating in countries including Canada, Scotland, Finland and Indonesia. On short-haul routes, these services provide a good opportunity to create initial niches for electric-propulsion ships. Governments can take this action individually, but a coordinated approach would have even greater impact. Similarly, a buyers' alliance of consumer goods and logistics firms could help to accelerate diffusion by scaling up demand for zero emission shipping, similar to the RE100 and EV100 initiatives in the power and transport sectors.

The top 20 ports, located in just 12 countries and jurisdictions, control 45% of global container freight.

ACTIONS TO ACCELERATE RECONFIGURATION

In the long term, meeting climate goals will require all shipping to become zero emissions. Standards set by the industry's global governing body, the International Maritime Organization, would be the best way to ensure coverage of the whole sector. Existing IMO standards are already effective in driving efficiency improvements. In future, zero emission standards could play the same role. For the transition to happen at a pace consistent with climate change goals, the sector would need to aim for net zero emissions by around mid-century, in line with the trajectory required of all sectors,[170] instead of the 50% emissions reduction (from a 2008 starting point) agreed by the IMO in April 2018. Such a goal will in any event be difficult to achieve. Even setting it is likely to be difficult to agree, until the actions to accelerate emergence and diffusion have brought the interests of the sector's actors more closely into alignment.

While shipbuilding is largely concentrated in developed countries, the reconfiguration of the sector presents an opportunity for economic benefits to be spread more widely. A total investment of around US$6 trillion in renewable energy and low carbon ammonia production plants could be required to decarbonise a large share of international shipping freight by mid-century. Developing countries with plentiful renewable energy resources could be well placed to attract this investment, and to create jobs through the establishment of supporting supply chains and services.[171]

Existing IMO standards are already effective in driving efficiency improvements. In future, zero emission standards could play the same role.

AVIATION

SECTOR: AVIATION

IMPORTANCE

*Accounts for about **1.5%** of total global greenhouse gas emissions, growing at 4% per year.*

GHG 1.5%

STAGE OF TRANSITION: EARLY EMERGENCE

Low emission technologies and fuels have not yet entered the market at any significant scale.

NATURE OF THE PROBLEM NOW

- *High cost of low emission options prohibitive in competitive global industry (without coordination)*
- *Supply-and-demand problem for sustainable aviation fuel production and infrastructure*
- *Low level of technological readiness for electrified and hybrid-electric aviation*

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OPTIONS FOR DECARBONISATION

- *Electric propulsion - likely for short haul*
- *Ammonia, hydrogen, or biofuel (the last with significant disadvantages) – likely for long haul*

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INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

ACTIONS TO ACCELERATE EMERGENCE (1)

- ***Coordination between airports (supported by governments) on mandates** for use of sustainable aviation fuel on routes between them – to create initial niches for deployment*
- ***Coordination on standards** to ensure genuine sustainability of low emission fuels*
- ***Coordinated development** of electrified aviation technologies, and deployment on short-haul routes*

INSTITUTIONS

International Civil Aviation Organisation; Clean Skies for Tomorrow initiative

***PRIORITY**: establish more practical cooperation between leading countries and airports, focused on testing and deployment of technology, fuels and infrastructure*

ACTIONS TO ACCELERATE DIFFUSION (2)

- ***Coordinated setting of sustainable fuel mandates** among the largest airports and countries - to keep a level playing field, and expand initial niches to large shares of the global market*
- ***Coordinated procurement** by business & travel agencies of flights using sustainable fuels (shifting spending away from offsets)*
- ***Coordinated reallocation of biofuels subsidy** from road to air transport*
- ***Coordinated investment** in airport charging and refuelling infrastructure at either ends of major routes*

ACTIONS TO ACCELERATE RECONFIGURATION (3)

- ***Application of zero emission fuel mandates** (or carbon prices achieving the same effect) to all of global aviation, through the International Civil Aviation Organisation*
- ***Adoption by ICAO and the whole industry of standards** to ensure genuine sustainability of low emission fuels*

Importance to emissions

Aviation accounts for around 1.5% of total global greenhouse gas emissions. The sector's emissions are growing at a rate of around 4% per year – faster than those of any other transport sector. Nearly 90% of aviation emissions are from passenger traffic, and the majority of these are from international flights. Passenger air travel is projected to triple by mid-century, meaning that emissions could rise significantly unless there is a transition to low-carbon flight.

Stage of the transition and technology options

Options to reduce aviation emissions include demand reduction – including through modal shifts to less carbon intensive forms of transport, such as high-speed rail – and increasing logistical and operational efficiency. A combination of these measures could potentially deliver a 15% reduction in aviation emissions by 2050.[172] However, global climate goals require a much faster rate of decarbonisation, eventually reaching net zero emissions. The rest of this section considers the nature of the transition to zero or near-zero emissions aviation, and how it can be accelerated.

The transition to zero-carbon aviation is in the early stages of emergence. Technology and fuel options are under development, but have not yet entered the market at any significant scale. There are two main options: sustainable aviation fuels, and electrification.

For long-haul flights, which contribute 80 - 85% of the sector's emissions, a switch to sustainable aviation fuels (SAF) is the only foreseeable option, at least in the short and medium term. These may be either biofuels, produced from biomass;[1] or synthetic fuels, produced from a combination of CO_2 (captured directly from the air or from flue gases) and hydrogen and ammonia (potentially from renewable powered electrolysis). Both kinds have already been developed by specialised new entrants and by conventional jet-fuel producers, although synthetic fuels have not yet been commercialised. These fuels would still emit greenhouse gases when used, but could in principle be close to net-zero CO_2 emissions over their lifecycles. Lifecycle assessments of existing SAF indicate on average an 80% emission reduction.[173] Other challenges, however, remain, including the emissions of other gases that are intrinsic to the combustion of fuels, such as nitrogen oxides (NOx), a precursor to formation of ozone (a powerful greenhouse gas); and water vapor, which under the right conditions can lead to the formation of contrails that could warm (or in some cases cool) the planet.

Two important advantages of SAF are that they can be used in existing aeroplane engines and fuelling infrastructure, and they can be blended with fossil jet fuel in any concentration between 0 and 100%. Blends of 100% have been demonstrated in highly controlled settings but have not yet been certified or made commercially available. Blends of up to 50% have already been certified,[2] meaning that there are no technical or legal barriers to immediately increasing their overall use in the jet fuel market.

For short-haul flights, electrification is an option. This can be with an electric engine driven either by a battery, or by a hydrogen fuel cell (which transforms hydrogen, stored in a tank, into electricity).[174] Over 170 projects on electrifying aviation are under development, mostly aiming to develop small aircraft with fewer than 20 seats, to enter the market for short haul flights in the early 2020s. The low energy density of batteries (1/40th of the energy that jet fuel contains per kg) and of hydrogen (1/3 of the energy per litre) is a constraint, and means that unless there is a fundamental breakthrough in battery chemistry, electric planes will be limited to relatively short ranges. However, in this market electric planes could potentially become the cheapest option from the mid-2020s if suppliers can deliver on promised cost and performance goals, although this is far from certain. As the technology improves, longer ranges or larger aircraft could become viable for electrification over the longer term.

Nature of the problem now

For sustainable aviation fuels, the main problem is cost. Certified SAF are currently 50 – 100% more expensive than conventional jet fuel (which is untaxed) even with the benefit of existing US and EU incentives, and between 3-6 times more expensive without. Full use of SAF would add roughly 10 – 20% to the price of a long-distance economy flight ticket.[175] In an intensely cost-competitive industry, this makes it impossible for any airline to accelerate decarbonisation without losing business. Similarly, airports cannot mandate the use of SAF without risking their business being re-routed to other airports that do not. Offsetting schemes — where users of aviation services buy offset credits to cover the emissions associated with their travel — tend to charge around US$10 – 20 per tonne of CO_2 – around a tenth of the carbon price required to incentivise switching from conventional jet fuel to SAF – and so currently do nothing to overcome this problem. The cost of SAF is likely to come down as their production is scaled up, but the industry expects it to remain higher than conventional jet fuel for the foreseeable future.

Like shipping, aviation has its own international rule-setting body – the International Civil Aviation Organization (ICAO). This body's 192 members have agreed a scheme aiming to offset the growth in aviation emissions from 2020 onwards (at least until 2035), with participation made mandatory from 2027. It remains to be seen whether this scheme might eventually generate implicit carbon prices high enough to incentivise switching to SAF, or indeed whether the offsets it provides for will actually reduce emissions.[176] One recent academic study concluded that 'existing international climate policies for aviation will not deliver any major emission reductions.'[177]

The second problem for SAF is supply. In principle, the world should be able to produce enough genuinely sustainable biofuel to decarbonise the whole of aviation without harm to forests and biodiversity. (Strict standards would most likely be needed to ensure sustainability in practice.) This would use around 30 – 60% of the world's total available sustainable bioenergy, a share that aviation could legitimately claim given its relative lack of other options.[3] However, getting to that share from today looks challenging. There is currently only one production facility in the world that is entirely dedicated to SAF jet fuel production (run by World Energy, in California), and there are only six airports that provide a regular supply of SAF (as well as jet fuel) through their refuelling systems.[4] Fuel production facilities have a lead time of at least 3 – 4 years to be constructed and to start producing, so investors have little incentive to invest in scaling up supply unless there is a clear advance commitment of demand – which at present there is not.

The supply availability problem is worsened by the fact that most biofuel and synfuel producers have to decide between producing fuels for the automotive, maritime, or aviation sectors, as all require the same feedstock, but different product qualities. Since significant subsidies exist for the use of sustainable fuels in road transport, most production capacity has been built for this application. As is discussed in the section on trucks, this reflects a lack of strategic prioritisation of limited biofuel resources on the part of governments – since for road transport, other cost-effective means of decarbonisation are readily available.

For electrified and hybrid-electric aviation, the main problems are technological readiness – especially in relation to batteries – and infrastructure. Competitiveness on short-haul routes will only be possible if testing and early deployment in niche applications proves to be feasible, if capital costs and the cost of hydrogen reduce considerably with economies of scale, and if the infrastructure for recharging (for battery electric planes) or refuelling (for hydrogen fuel cell planes) is in place. For a fleet of electric aircraft to operate with a reliable service infrastructure, investments would need to be made at either ends of a route, or across a route network. But airports may hesitate to invest in this infrastructure, given the uncertainty over which technology will become dominant, and by when.

How coordinated action can accelerate the transition

ACTIONS TO ACCELERATE EMERGENCE

Given the competitiveness constraints described above, airlines and airports agree that a scale-up of sustainable aviation fuel will only happen if either public policy creates a level playing field, or buyers of flights create the demand signal and accept paying the extra cost.

- **Coordination on standards, in terms of mandates requiring the use of SAF at a given blend**, is likely to be an essential measure in order to establish a niche for sustainable aviation fuels. Airlines will be able to use SAF if this is mandated by airports, so that they are on a level playing field. Airports will only be able to do this if enough of them coordinate for the risk of rerouting to be overcome. If the demand created this way is high enough, SAF producers will be able to come forward with supply.
- **Coordination on the standards for sustainability of the fuels** is equally important, otherwise biofuels may be supplied that are profitable for their producers, but no less high emitting than fossil fuels over the course of their lifecycle. The ICAO has attempted to agree global sustainability standards for SAF, but those agreed to date are not sufficient to ensure either reduced emissions or the avoidance of other negative environmental, social or economic impacts. Robust standards currently exist only in regional or voluntary schemes. The development

1 Five production pathways are currently certified for aviation: Fischer-Tropsch hydroprocessed kerosene (FT-SPK), Hydroprocessed esters and fatty acids kerosene (HEFA-SPK), Iso-paraffins from hydroprocessed fermented sugars (HFS-SIP), Alkylation of light aromatics from non-petroleum sources kerosene (FT-SPK/A), Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK); and many others are under development.

2 The ASTM (formerly known as the American Society for Testing and Materials) has presently certified blending up to 50%. Blends up to 100% have been demonstrated by constructors, but are not yet certified by ASTM and are not commercially available. Source: Aviation benefits without borders – Beginner's Guide to Sustainable Aviation Fuel.

3 A range of analyses on the maximum supply of sustainably sourced bioenergy exists, reaching widely different results (from near zero to >200 EJ). Based on IEA estimates, the Energy Transitions Commission recommends considering that about 70EJ of bioenergy could be available from waste and residues only (municipal waste, agricultural residues, wood residues) without creating a risk of any land use change. To decarbonise the whole of aviation, between 20-40EJ of bioenergy might be required, which would represent a 30 – 60% share of this budget.

4 The six are: Oslo Gardemoen, Bergen, Stockholm Arlanda, Seattle-Tacoma, San Francisco International, and Brisbane. State owned airlines such as Avinor and Swedavia, subject to SAF mandates, played a role in developing some of these airports' leading positions on SAF supply.

of sustainability standards will need to proceed together with further testing and development of the fuels themselves, to explore options for minimising contributions to climate change through emissions of non-CO_2 greenhouse gases and water vapour.

Countries acting individually could require a proportion of SAF to be used in fuel for domestic flights. The ten busiest air routes in the world (by frequency of departures) are all domestic – see Figure 24. If governments require the same standards to be applied to domestic flights from all airports within their countries, there will be minimal risk of re-routing, and this could create a substantial niche for SAF to begin scaling up. In large countries, even action at the sub-national level (e.g., the Western US, or Eastern China) could be enough to create a significant niche. The mandate could be introduced first for business flights, where the additional cost will be proportionately less.

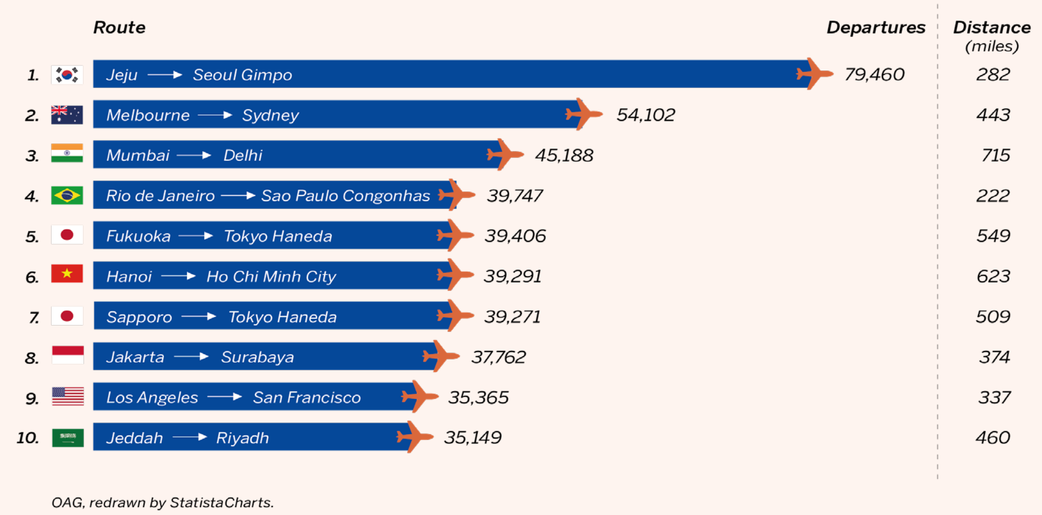
Individual countries could also follow the lead of Norway and Sweden by mandating initially very small blends of SAF in all international flights departing from their territories (0.5% in Norway by 2020). Governments that lead in this way may succeed in attracting the early establishment of biofuel production capacity in their countries. But as higher blends will increase costs and therefore the risk of re-routing, real progress on international flights will need international coordination.

International coordination is likely to be most viable initially either between several major airports operating within a regional zone (e.g., Western Europe), or between those at either end of a high value long-haul route. This will be much more achievable with policy support, with mandates to guarantee demand, and with these applied broadly enough to remove the risk of re-routing. But even without policy support, coordination between airports, airlines, and corporate customers jointly agreeing to increase use of SAF could achieve the same effect. The **Clean Skies for Tomorrow**[178] initiative aims to do exactly this, and is in the early stages of developing plans for pilot projects in the US, Europe and India. These would focus on routes heavily driven by corporate passengers, and involve a commitment from corporate buyers to pay the price difference.

The minimum size of a new greenfield sustainable aviation fuel refinery is typically >100,000 tonnes per annum, which represents about 10% of the annual traffic between London and New York. So it may need several coordination projects to go ahead in order to catalyse a significant creation of new production capacity.

For electrified aviation, the main action to accelerate emergence may be the creation of assured demand for early deployment. All major aircraft manufacturers and several start-ups are already undertaking research and development projects. Government support to R&D can help, and governments that subsidise large manufacturers, such as Boeing and Airbus, can encourage them to invest more heavily in this effort. An even stronger incentive, however, could be provided by procuring electric aircraft, or requiring their operation on certain routes. Initial niches could be short routes within island nations or regions, such as the UK or Indonesia; and in countries where geography limits modal shift opportunities for short haul flights and where strong carbon emission reduction targets are already in place, such as Sweden or Norway.

FIGURE 24: BUSIEST AIR ROUTES WORLDWIDE



Adapted from OAG via https://www.statista.com/chart/12598/the-worlds-busiest-air-routes/.

ACTIONS TO ACCELERATE DIFFUSION

To accelerate diffusion of sustainable aviation fuels, similar patterns of coordination need to take place, but on a much larger scale. The International Energy Agency's Sustainable Development Scenario suggests a 5% SAF share of aviation fuel globally by 2025 would be roughly consistent with climate goals. This would need 15Mt of annual production, which is about a thousand times the current dedicated SAF production capacity,[179] and some 12 times as much as the current pipeline of production facilities could realistically supply by that time. A strong demand signal is needed.

- **Coordinated standard setting** on SAF mandates, as described above, is likely to be the most powerful means to accelerate diffusion. To scale up quickly, this will need to involve the 5% of airports that host more than 90% of international flights. For the same reasons described above, this will be more feasible with government support in countries at both ends of major routes. The International Civil Aviation Organization could be well placed to encourage this, as a complementary and stronger measure to add to its current offsetting scheme.

- **Coordinated buying power** can also be scaled up, for example through a buyers' alliance of business travel, uniting major global corporates and travel agencies. These businesses could make a joint commitment now to purchasing premium green flights by a given date within the next few years, shifting their spending from offsets (which may help plant trees, but do nothing to decarbonise aviation) to 'green tickets' powered by SAF. Airlines can support this by making such 'green ticket' options available, as KLM and Lufthansa already have.

- **Coordinated reallocation of subsidy**: Governments could further support SAF diffusion by agreeing to end the subsidy of biofuels for road transport, where better options for decarbonisation exist, and reallocating any available budget to SAF subsidy. This would change incentives for biofuel producers, helping to bring more SAF to market.

For electrified aviation, diffusion can be accelerated by support for charging and refuelling infrastructure in airports, or public co-financing of initial aircraft acquisitions. These support measures can be most effective in places where electrified aviation is closest to commercial competitiveness – such as the short routes in island nations mentioned above.

ACTIONS TO ACCELERATE RECONFIGURATION

In the long term, meeting climate goals will require all aviation to reach net zero emissions. While for short-haul flights this may be possible through electrified aviation on a commercial basis, for long-haul flights it is likely to require policy measures applied to the whole sector – if industry expectations of SAF remaining more expensive than conventional jet fuel prove correct. This full-scale application of SAF would require regulation by the International Civil Aviation Organization (ICAO), the body that governs the industry at the global level. Regulation could be in the form of either SAF mandates, or carbon pricing high enough to ensure a switch away from fossil jet fuel. To be fully aligned with climate goals, the industry would need to achieve net zero carbon emissions by around 2050, as is needed in all sectors,[180] instead of the 50% net reduction by that date that the global aviation industry (through the Air Transport Action Group) has currently agreed.

Meeting the demand of fully decarbonised long-haul aviation would require around 500-570Mt of SAF production by mid-century – thirty times more than the target production capacity for 2025, and equivalent to roughly 10% of the current worldwide oil refining capacity. Government support for investment in converting traditional refineries to SAF production could be one way to bring forward the reconfiguration of this sector. The scaling up of this new SAF production industry represents a significant opportunity for job creation, on which developing countries with large biomass and other renewable energy resources could be well-placed to capitalise. Considering its high price volatility and negative impact on the balance of payments, an additional benefit for any country that establishes its own SAF production supply chains could be reduced reliance on imported oil. As this production capacity is scaled up, however, it will be critical to apply standards to ensure the genuine sustainability of the fuels. Otherwise, the industry could cause environmental and social harm while failing to reduce emissions as much as intended.

BUILDINGS

The authors are grateful to the Global Alliance for Buildings and Construction (GlobalABC) for their contributions to this section.

SECTOR: BUILDINGS

IMPORTANCE

*Accounts for about **6%** of total global greenhouse gas emissions directly, plus roughly half of the emissions from the power sector, and roughly half of all steel and cement.*

GHG 6%

STAGE OF TRANSITION: EMERGENCE/DIFFUSION

Design and construction of high efficiency buildings is in the emergence stage; some low emission heating & cooling technologies are entering diffusion.

NATURE OF THE PROBLEM NOW

- *Weak demand for efficient buildings*
- *Low innovation in construction industry*
- *Technical difficulty and cost of low emission cooling options*
- *Cost of high efficiency low emission heating options, and lack of skills for their installation*

INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

OPTIONS FOR DECARBONISATION

- *Design and construction of new buildings to minimise emissions embodied in construction and maximise energy efficiency in use*
- *Retrofitting of existing buildings to improve energy efficiency*
- *Cooling: improving efficiency of air conditioners; moving to refrigerants that are not greenhouse gases; reversible heat pumps*
- *Heating: heat pumps; solar thermal; hydrogen; biomass (with disadvantages)*

1 ACTIONS TO ACCELERATE EMERGENCE

- ***Coordinated research, development and demonstration** of high efficiency building designs; low emission refrigerants and high efficiency cooling; and less developed clean heating options*
- ***Coordinated government procurement** of zero emission buildings, to create initial niches*
- ***Coordinated standard-setting** by leading cities, to grow initial markets for high efficiency designs*
- ***Mutual learning** on policy best practice*

INSTITUTIONS

Global Alliance for Buildings and Construction; World Green Building Council

PRIORITIES: strengthen government engagement; expand participation of emerging economies

2 ACTIONS TO ACCELERATE DIFFUSION

- ***Coordination on measurement and standards for buildings efficiency** and emission savings (including embodied emissions and actual performance emissions) to enable greater flows of finance to genuinely low carbon buildings*
- ***Coordinated refocussing of policy support for low emission heating** towards options with greater potential to scale up, such as heat pumps and solar thermal, and away from biomass*
- ***Coordination on product efficiency standards** for heating and cooling technologies*

3 ACTIONS TO ACCELERATE RECONFIGURATION

- ***Coordinated regulatory trajectories** toward net zero emission buildings – to guide industry innovation and investment*
- ***Coordinated development and demonstration of complementary technologies** including energy storage, demand-side response, smart meters and smart grids*

Importance to emissions

Buildings account for around 6% of global greenhouse gas emissions directly, and considerably more indirectly: over a third of global energy-related CO_2 emissions,[181] as they account for roughly half of the emissions from the power sector, as well as roughly half of all steel and cement. More than half of all buildings' direct operational emissions come from space heating, while cooling accounts for some direct emissions and a large part of their indirect emissions through the power sector.

The total floor area of buildings globally is projected to double by 2060, which is equivalent to a new Japan every year. Energy demand for space cooling – emissions from which have already tripled between 1990 and 2018 – is currently around one sixth of energy demand for space heating, but is growing rapidly and is expected to triple by mid-century.[182] Building emissions could therefore rise considerably unless a low carbon transition takes place.

This section considers two major components of the transition to zero emission buildings. Firstly, a transition in design and construction of buildings is needed to reduce their embodied emissions, and to dramatically increase the energy efficiency of their operation. In developed countries especially, this needs to be accompanied by a retrofitting of existing buildings to increase their efficiency. Secondly, a transition to high efficiency electric systems is needed for both heating and cooling. These two components are closely linked, since greater building efficiency can reduce demand for heating and cooling and allow a greater range of zero emission technologies to become viable.

Stage of the transition and options for decarbonisation

Design and construction: While the construction of 'green buildings' is increasing markedly, this transition is still in the emergence phase. Very high efficiency building designs, such as the 'passive house concept', have been demonstrated, but the industry has not yet stabilised around a consistent set of standards, designs, materials or construction processes. Two-thirds of countries still have no mandatory building energy codes. Modern methods of construction such as offsite manufacturing and modular construction, which may have a high potential to reduce both operating and embodied emissions, and alternative construction materials such as timber (instead of steel), have yet to take off. In developed countries, the main task for emissions reduction is the retrofitting of existing buildings: few have begun to seriously address this challenge, with typical renovation rates at 1 – 2% of the building stock per year.

Cooling: The dominant technology for space cooling in buildings is electric powered air conditioning. This produces emissions directly through its use of refrigerants, and indirectly through power generation. Emissions can be reduced by:

a. Reducing demand through effective building designs (incorporating thermal design, and orientation), including those that are adapted to their local environments;
b. Decarbonising the power sector (see the section on this sector);
c. Replacing inefficient electric air conditioners with much more efficient ones, which can include reversible heat pumps, or with alternatives such as solar cooling; and
d. Moving to the use of refrigerants in air conditioning that are not greenhouse gases.

A holistic approach to reducing cooling emissions is likely to require all of these methods. A transition to new technologies – in the form of either (c) and/or (d) is likely to be needed for cooling emissions to reach zero. At present, the high cost of non-greenhouse gas refrigerants is a major barrier to their adoption. Reversible heat pumps are already available, and accounted for most of the growth in global heat pump sales between 2010 and 2018.[183] However, the energy intensity of space cooling globally is rising, reflecting increasing use of relatively inefficient air conditioning. The transition to new technologies is at an early stage.

Heating: More than three quarters of new heating technology sales globally are accounted for by fossil fuel technologies (such as gas boilers, and in some places coal and oil) that produce emissions directly from combustion, and conventional electric equipment that causes emissions indirectly through the power sector. In poorer countries, widespread use of traditional biomass contributes to air pollution and deforestation. As is the case with cooling, heating emissions can be reduced through demand reduction (in more efficient buildings or in district heating networks that make use of waste heat), decarbonisation of the power sector, improving efficiency of conventional technologies, and shifting to much more efficient zero emission technologies. The last of these is likely to be essential for full decarbonisation. Efficiency is an important consideration: conventional electric heating can in principle be zero emission. Its low efficiency, however, leads to high energy demand, high emissions for as long as the power sector is not fully decarbonised, and high costs. A range of low and zero emission and high efficiency heating technologies exists, at various stages of emergence and diffusion. For example:

- **Biomass combustion** is by far the largest source of low carbon heating in the EU. Its potential to be scaled up globally, however, may be constrained by the limited supply of sustainable biomass. As discussed in other sections, it may make sense to prioritise biomass resources for use in sectors where alternative low emission technologies are particularly difficult or expensive, such as in aviation. Further disadvantages include its negative impact on air quality and health, and the likelihood that with costs highly dependent on land requirements and fuel supply, there may be limited potential for cost reduction.

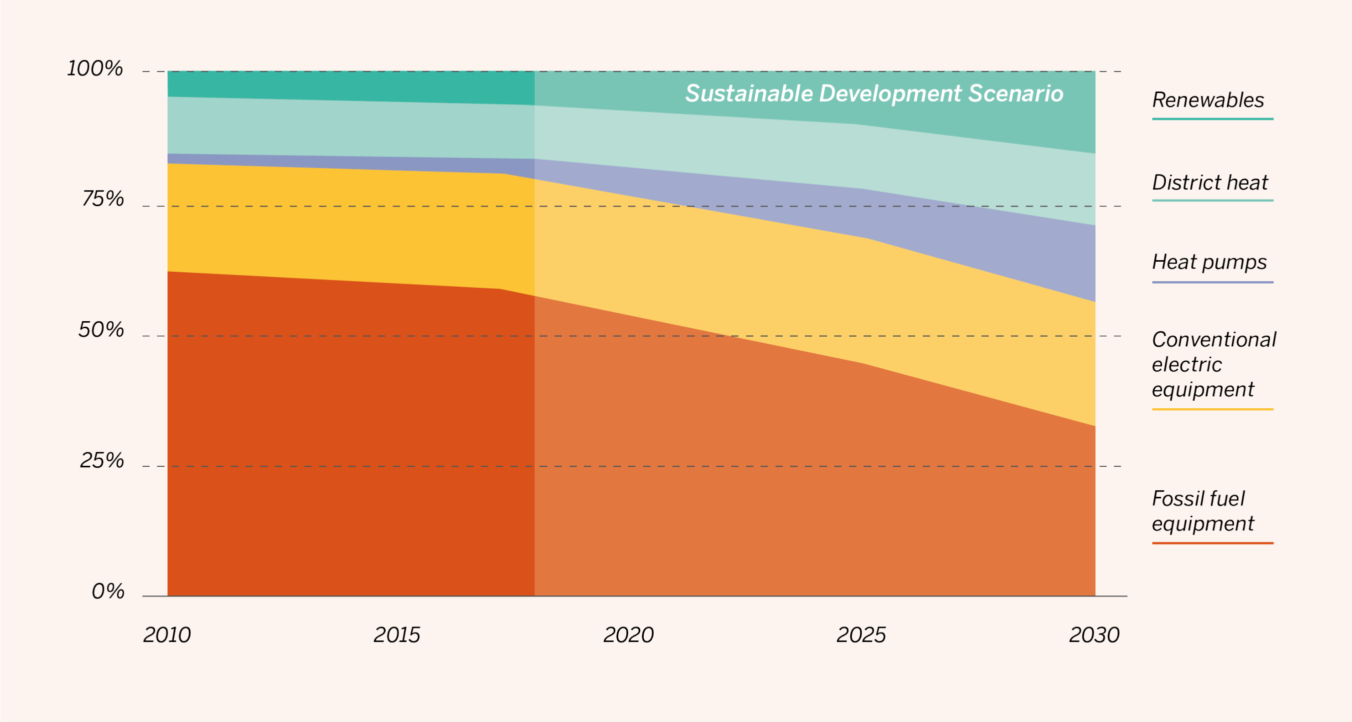
- **Heat pumps** have the great advantage of being around three times more energy efficient than conventional electric heating (and even up to four or five times more efficient in mild climates).[184] This means that they can significantly reduce emissions while the power sector is in transition, as well as being zero emission once the power sector is decarbonised. Heat pumps currently meet less than 3% of global heating needs, but their sales have increased by around 5% per year since 2010, reaching 20 million in 2018.[185] As noted above, most of this growth has been in sales of reversible heat pumps. The ability of this technology to provide both heating and cooling with high efficiency and zero emissions (once electricity is also decarbonised) suggests there is significant potential for scaling up its deployment. While the highest rates of heat pump market penetration are in Scandinavia, most of the global growth is now in China, Japan and the USA.[186]

- **Solar thermal** technology provided around 2% of global space and water heating demand in 2018, and is growing robustly – with a 250% increase over the last decade – though still some way short of the rate of expansion consistent with meeting climate goals.

- **Hydrogen** heating technologies are being demonstrated in countries including Japan, France, the Netherlands, and the UK, but have not yet entered the market commercially. For the small minority of countries that have extensive gas grids, hydrogen may be a less disruptive option than heat pumps, since it requires fewer changes to buildings. As an alternative fuel (rather than technology), it can be used in boilers with relatively minor modifications, and in existing mechanisms for heat conveyance within buildings such as pipes and radiators – significantly reducing the cost of retrofitting. For other countries, the need to create a hydrogen distribution infrastructure could be a strong barrier to uptake.

The most appropriate zero carbon heating and cooling options will vary between countries, depending on

FIGURE 25: HEATING TECHNOLOGY SALES



Note: excludes traditional use of biomass. 2018 estimated
Adapted from IEA, Tracking Clean Energy Progress (TCEP), "Heating", www.iea.org/tcep/buildings/heating.

their local climates, available resources, skills and infrastructure. On a global scale, the International Energy Agency anticipates heat pumps and renewable heating (including solar thermal and bioenergy) becoming the most important growth areas, with their market shares needing to triple by 2030 to be in line with its Sustainable Development Scenario – as illustrated in Figure 25.

Nature of the problem now

Design and construction: The dynamics of housing markets and the construction sector are significant barriers to the transition to highly efficient buildings. In many countries, property developers face high costs of land acquisition, while their sale prices must compete with those of existing buildings. This creates a strong pressure to reduce the costs of construction. Meanwhile, consumers provide only a weak demand signal for efficient buildings, since the costs of operation of a building are not as easily visible as its purchase price. The construction sector responds to demand, and so has little incentive to innovate. A critical action that can overcome these barriers is the imposition of mandatory efficiency standards, also known as building energy codes. These can drive innovation and reduce costs for building owners, as well as cut emissions. But governments are often deterred by concerns – sometimes encouraged by the industry – that standards could slow the rate of housebuilding or undermine housing affordability. In developing countries, lack of skills and administrative capabilities can impede both the design of standards and their effective implementation. For countries with large informal construction sectors, wide application of standards is particularly difficult.

Where retrofitting is required, the main challenges include cost and lack of financing options. In addition, it is difficult to persuade homeowners to upgrade the efficiency of their buildings, given the inconvenience and in some cases long payback periods.

Heating and cooling: while reducing demand for heating and cooling involves the problems described above, there are additional challenges involved in the transition to low and zero emission technologies. For cooling, there are technical difficulties in increasing the efficiency of air conditioners, and technical and cost challenges in moving to non-greenhouse gas refrigerants. For high efficiency zero emission options,[1] cost is a barrier: heat pumps, and their reversible versions used for cooling, are significantly more expensive to buy than fossil fuel technologies – and to operate – unless used in highly efficient buildings. There is also room for improvement in their performance and reliability. In most countries, skills and supply chains for their installation and reliable operation are under-developed. Consumers and housebuilders can both be reluctant to invest in a new and unfamiliar technology, especially one that has significantly greater space requirements than traditional alternatives. Where gas boilers are the incumbent technology, their low cost, flexibility and convenience make them difficult to dislodge without a strong push from policy. For national governments, a long-term challenge is likely to be the upgrading of electricity grids to cope with the increased demand from electrified heating and cooling. This is especially so in colder countries where demand for heating peaks in the winter when the supply of electricity from renewables is relatively low. Here lies one reason why improving building energy efficiency is so important.

1 As noted above, heat pumps (including reversible ones) will only be zero emission when the power sector is also zero emission, but their high efficiency means they can reduce emissions significantly during the transition. They also often contain refrigerants with a high global warming potential which can be released through leakage or in decommissioning and disposal. Research continues to reduce the impact of refrigerants in newer models.

How coordinated action can accelerate the transition

ACTIONS TO ACCELERATE EMERGENCE

The buildings sector, with its relatively localised supply chains and lack of exposure to international trade, highly differentiated needs in relation to geography and climate, and multiple options for decarbonisation, may be one of the most difficult sectors in which to accelerate the global transition through coordinated international action. Many of the priority actions to support emergence will need to be taken by countries individually. These actions will include developing skills in efficient building construction and in the installation of high efficiency electric heating and cooling technologies, implementing standards for new buildings, and incentivising the retrofit of existing buildings. However, there are opportunities for countries to reinforce each other's efforts.

- **Coordinated research, development and demonstration**: Government support for industry innovation – in collaboration with architects, engineers and developers – can be valuable in many areas of this transition. Innovation priorities include high efficiency building designs (including locally adapted solutions), high efficiency air conditioners and low global-warming potential refrigerants, new cooling options such as solar cooling, and less developed clean heating options such as hydrogen. Coordinated international efforts can accelerate the identification of viable options, and build practical knowledge through the sharing of experience gained through demonstration projects. Notable fora that already support such efforts include the Mission Innovation Affordable Heating & Cooling challenge,[187] the Kigali Cooling Efficiency Programme,[188] and the Cool Coalition.[189]

- **Coordinated procurement**: Government procurement could play a powerful role in creating a niche for zero carbon buildings, and for process options such as digital methods of design, including Building Information Modelling, and Modern Methods of Construction, such as offsite manufacturing. Countries acting individually can have a significant effect on their domestic markets, while a coordinated approach could help to increase the incentives for investment in the more internationally-connected parts of the sector.

- **Coordinated standard-setting by cities**: Cities are sometimes able to experiment with bolder policies than national governments, since their smaller scale helps reduce the political risks. Those with particularly high-value property markets can wield greater leverage over the real estate and construction sectors. A few cities, including Brussels, New York and Vancouver, are now setting regulatory trajectories consistent with climate goals, and supporting these with financial incentives. Coordination between these leading cities on the standards they apply could help achieve an earlier stabilisation of high efficiency building designs. The **C40 Cities**[190] partnership facilitates the exchange of best practice between its members, and is one of the leading fora for such discussions to take place.

- **Coordinated learning**: Given the wide range of policies practiced in different countries, there is a real opportunity to accelerate uptake by learning from best practice. The **Global Alliance for Buildings and Construction**[191] supports the exchange of best practice between governments, and the **World Green Building Council**[192] does the same between industries. This can be complemented by assistance in areas where it is especially difficult for change to propagate internationally – for example, in developing skills and raising standards in the informal construction sector.

ACTIONS TO ACCELERATE DIFFUSION

Design and construction: The most powerful policy measure to accelerate diffusion of high efficiency buildings is standard-setting in the form of mandatory energy codes for new buildings. This is a higher point of leverage than any policy measure aimed at retrofitting, since it can begin the scaling up of high efficiency designs, materials and skills without involving such high upfront costs or inconvenience. In countries where energy codes for buildings are in place, they are less effective than they could be. There is wide variation between the multiple mandatory and voluntary standards in use, but for the most part mandatory standards (or codes) share four weaknesses: i) they apply only to operating emissions, and not to emissions embodied in construction; ii) they apply only to the intended operating efficiency, assessed on the basis of building design, rather than to the actual operating efficiency, assessed on the basis of performance; iii) they are not aligned with emission reduction trajectories consistent with climate goals; and iv) they do not apply to the whole of the sector (e.g., applying to only residential or only to commercial buildings).[2]

The potential for **international coordination on standards** to help scale up finance and technology is constrained by the diverse needs of countries with different climates. Significant opportunities remain, however, and could be taken as part of a move to address the shortcomings described above:

- A coordinated approach to the **measurement of emissions savings from existing standards and accreditation schemes** would provide a significant opportunity to make the landscape more intelligible to investors, enabling greater financial flows to genuinely low carbon buildings, and scaling up the market.

- Many countries are now considering following Australia in moving to performance-based standards, which measure actual operating efficiency and require buildings to operate as efficiently as they are supposed to. This creates a window of opportunity to develop a common approach to the **measurement of building efficiency performance** that would support regulatory convergence in future. Similarly, there is an opportunity for **standards and measurement of embodied emissions** in building construction to be developed in a consistent way, since almost no countries have these at present.

In addition to standard-setting, many countries will need to support the development of new skills throughout industry supply chains so that higher efficiency buildings can be built, and will need stronger systems of enforcement to ensure that any standards imposed are actually met. Other complementary policies can include continuing investment in innovation, and support for the development of 'green mortgages' that offer lower interest rates to buyers of highly efficient buildings.

For countries where retrofitting is the priority, it will be important to identify ways to make this affordable, and to leverage private finance in ways that make this an attractive option to consumers. The Energiesprong programme, now active in four countries – France, Germany, the Netherlands and the UK – is one example of such an approach. Ireland's Deep Retrofit pilot programme, supported by the Irish government since 2017, provides homeowners with up to 50% of

2 Different parts of the buildings sector may naturally require different standards. The issue here is coverage – whether the whole sector is subject to standards or not.

the total capital costs for a deep energy retrofit, and up to 95% in the case of housing association homes.[193] In Alingsås, Sweden, long-term financing with low interest rates has been used to retrofit an old housing estate to passive house standards, with lower energy and maintenance costs expected to result in a payback period of only ten years.[194] An additional policy option to accelerate the rate of retrofitting could be to mandate energy efficiency upgrades to be undertaken as part of any major building renovation. Most countries will also want to ensure that as they make a transition to new building designs and standards, they are also preparing for resilience to further climate change.

As in the emergence stage, so also for diffusion, **international exchange of best practice** can play a valuable role in highlighting essential policy measures, sharing information on what works, developing new solutions for tough policy problems, and coordinating action. The need for this is perhaps indicated by the fact that most countries' Nationally Determined Contributions under the Paris Agreement mention the buildings sector, but most of these do not mention any specific policy actions. Among those that did include policies, areas such as building design, cooling, and links to urban planning received notably little attention. The **Global Alliance for Buildings and Construction**, supported by the UN, is emerging as the leading forum for government-to-government exchanges, and is developing regional roadmaps (based on a Global Roadmap[195]) to highlight priorities for transforming the sector and guide governments on where to start. Expanding the membership of this organisation, particularly among the emerging economies, where the future growth of new buildings is expected to be highest, could greatly benefit effective coordination.

Heating and cooling: As an important measure for reducing emissions in the medium term, regulatory standards for the efficiency of air conditioners can ensure the deployment of the best available technologies, and set a course for continual improvement. Japan's Top Runner programme is a world-leading example of such an approach, achieving efficiency improvements of around 16% in just five years.[196] Since there is international trade in electric systems for both heating and cooling, **coordination on product efficiency standards** could help to drive improvement through the global market. The Kigali amendment to the Montreal Protocol already effectively coordinates standards for the use of hydrofluorocarbons (HFCs) in cooling (and other) technologies, and has set a target to cut their consumption by at least 80% over the next 30 years.

To accelerate the diffusion of the high efficiency zero emission technologies needed for the full decarbonisation of heating and cooling, the central challenge of cost reduction can best be addressed through policy support for their deployment. This will increase incentives for investment in the improvement of these technologies, and increase the economies of scale in their production. Policy options in use include subsidies for clean heating and cooling technologies, taxes on fossil fuels, and regulatory standards that require decreasing carbon intensity over time.

In providing this policy support, a certain amount of technology choice is inevitable, and it can be useful to make this choice deliberately. As noted above, some countries are subsidising biomass for heating in large quantities, despite its limited scope for cost reduction and potential strategic conflict with decarbonisation needs in other sectors. A c**oordinated refocussing of policy support** towards options with greater potential to scale up – such as heat (and cooling) pumps and solar thermal heating – on the part of countries where these are appropriate, could benefit many countries by accelerating their performance improvement and bringing down their costs. In countries where the market for heat pumps is in the early stages of development, subsidies for deployment can usefully be complemented by providing suppliers with training in installation and maintenance, and by communications campaigns to familiarise the public with the product.

Businesses and governments can help accelerate this transition by committing to buying low emission heating technologies for their buildings. A coordinated procurement campaign – such as a heat pump equivalent of the RE100[197] and EV100[198] initiatives (for businesses that have committed to buying renewable power and electric vehicles) does not yet exist, but could usefully be created.

ACTIONS TO BRING FORWARD RECONFIGURATION

The full reconfiguration of the buildings sector globally is likely to be possible only when most of it is subject to regulations requiring that no fossil fuels are used in construction and operation. Twenty-three cities and six regions, including California, Catalonia and Scotland, have already committed to making all new buildings net zero carbon by 2030, and all existing buildings the same by 2050.[199] The more cities, regions and countries join this group, **coordinating regulatory trajectories** to net zero and **implementing regulations to meet those targets**, the sooner industry expectations and investment will change, and the earlier new technologies and business models will be scaled up, bringing down costs for all. The coordinated learning described above is likely to be critical in giving more governments the confidence to make these commitments.

For the full decarbonisation of heating and cooling, progress in the deployment of their individual technologies will need to be matched by progress to incorporate them efficiently not only into buildings, but also into national energy systems. Complementary technologies such as inter-seasonal energy storage, demand-side response, and smart meters and grids are likely to be important in supporting this reconfiguration. **Coordinated development and demonstration** of these complementary technologies can therefore play an important role.

The chances of a successful reconfiguration of the sector will be greater if the transition benefits from widespread social support, and this may depend on how the economic benefits are seen to be distributed.

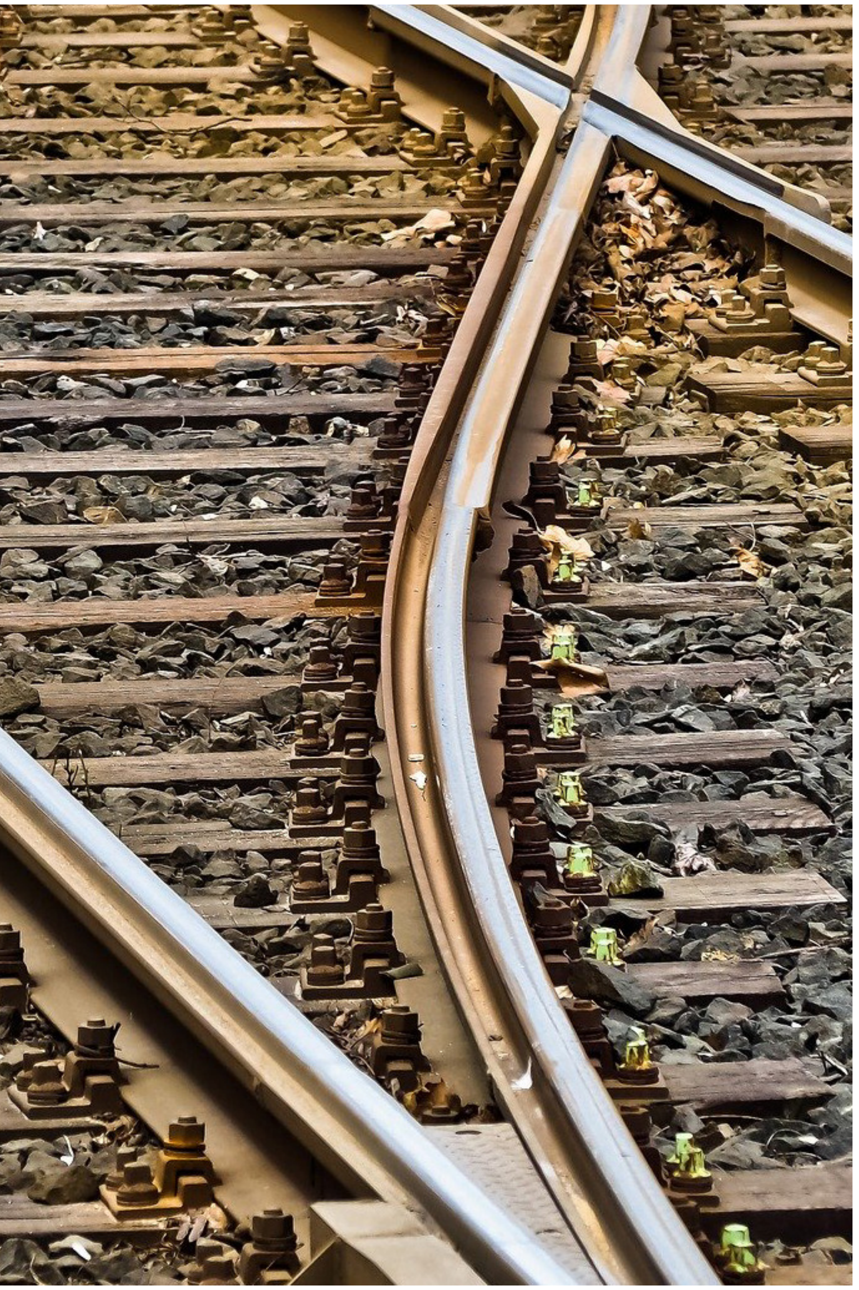
The construction sector globally supports at least 110 million formal jobs, as well as a much larger number of informal labourers. The construction of new energy efficient buildings will require new skills, and the retrofitting of existing buildings has the potential to create large numbers of new jobs. (One study found that a faster pace of building renovation could create 0.5 – 1.1 million jobs each year in the EU.)[200] The new jobs could be highly distributed between countries, given the opportunities to use local value chains for building materials, technologies and construction processes, and the potential for small- and medium-sized enterprises to contribute to each stage of a building's life cycle.[201] Capitalising on this opportunity could help to generate social support for the transition, and so bring forward the reconfiguration of the sector.

Early experiences of transition in the sector suggest that a concerted effort on the part of employers and governments may be needed to support workers in developing the skills that low emission buildings require – skills in planning, design, construction and maintenance – and that are currently in short supply.[202] In Belgium, strong energy efficiency standards and rapid innovation in the building sector have made it difficult for workers to keep their skills up to date. In response, employers and trade unions have jointly assessed training needs and developed training programmes, which government agencies then implemented.[203] In the city of Toronto, Canada, the City Council supported a programme to encourage building owners to carry out energy efficiency retrofits, backing it with loan guarantees for construction work and help with preparatory building audits. This collaborative effort catalysed action across the sector – with trade unions offering training on new heating, cooling and renewable power systems; and developers, architects and engineers experimenting with new designs and adopting new standards. This in turn lead to strong job creation while reducing emissions, and put the workforce in a strong position to compete for future opportunities.[204]

For many countries, a 'just transition' in the building sector goes beyond the need for jobs: providing sufficient housing fast enough to meet the population's needs is an absolute priority. Ensuring a healthy and safe living environment is also a primary concern.[205] Clear regulatory signals to industry, announced well in advance of taking effect, can ensure the transition to low emission buildings proceeds without affecting the rates of housebuilding. Perhaps most importantly, highly efficient buildings can be cheaper to run[206] – a crucial advantage, since it is the least well-off people who can least afford to live in an energy inefficient building.

> The more cities, regions and countries that coordinate regulatory trajectories to net zero emissions and implement regulations to meet those targets, the sooner industry expectations and investment will change, and the earlier new technologies and business models will be scaled up, bringing down costs for all.

STEEL



SECTOR: STEEL

IMPORTANCE

*Accounts for about **4%** of total global greenhouse gas emissions, with potential to grow nearly by half by mid-century.*

GHG 4%

STAGE OF TRANSITION: EARLY EMERGENCE

Zero emission technologies have yet to enter markets at significant scale.

NATURE OF THE PROBLEM NOW

- *High cost of low emission production processes is prohibitive in competitive global commodity market*
- *Highly fragmented industry with intense product differentiation makes application of common standards difficult*

OPTIONS FOR DECARBONISATION

- *Recycling of scrap steel*
- *Switching from blast furnaces to electric arc furnaces*
- *Using hydrogen as the reduction agent, instead of natural gas*
- *Carbon capture and storage*

INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

1 ACTIONS TO ACCELERATE EMERGENCE

- ***Coordinated testing and demonstration** of low carbon production plants at full industrial scale – to identify and prove viable technologies*
- ***Coordinated government procurement** and other policy actions to create assured markets for low carbon steel, and provide an incentive for investment in production*

INSTITUTIONS

None significant that are focussed on emissions reduction

***PRIORITY**: create a forum for international government-industry coordination of actions on steel decarbonisation*

2 ACTIONS TO ACCELERATE DIFFUSION

- ***Coordinated market-creating policy** to ensure rising demand for low carbon steel, incentivising greater investment in production*
- ***Trade measures**, based around standards or carbon prices, to maintain a level playing field for low emission producers*
- ***Standardising measurement** and information sharing on lifecycle emissions of steel-containing assets (such as buildings and cars)*

3 ACTIONS TO ACCELERATE RECONFIGURATION

- ***Policy support** for zero emission technologies and processes expanded to cover the whole industry*
- ***Trade measures** to create a level playing field expanded to cover the whole industry*

Importance to emissions

At present the iron and steel industry emits about 2.3Gt CO_2 per year, or around 4% of total global greenhouse gas emissions. Without new policies this figure will grow by nearly half, to 3.3Gt by 2050, representing 34% of the industry sector's emissions.[207]

Stage of the transition and nature of the problem now

From the perspective of making deep cuts in CO_2 emissions, the industry is in the early stages of emergence.

There are two main ways to produce crude steel, one of which is based on mining and processing primary ore – an industry that is in the earliest stages of development. Methods for low-emission virgin steel have been identified: experimentation is under way in a few countries, but support for creating niche markets for green steel are virtually non-existent. For most zero-carbon technological processes, initial pilot plants are announced for the early-to-mid 2020s. Industrial-scale pilot plants are currently planned for the late 2020s/early 2030s. **More decisive national green steel policies are needed that involve earlier and larger support for a wider range of demonstration projects, along with market creation. International coordination of these policies – including subsidy support, regulation, and market creation** – is essential, because steel is traded internationally. There will be a substantial cost differential between zero-carbon and high-carbon virgin production processes, making it impossible for any given player to engage in the decarbonisation of virgin production without losing to competitors. **Coordinated policy measures are needed to create a level playing field and/or a differentiated market for zero-carbon steel.**

The second method for steel production is recycling of scrap. Here the industry is potentially much further along in developing the technologies needed for decarbonisation because the required actions lie mostly outside the sector. Most emissions from scrap processing are related to electricity used in arc furnaces: decarbonising the electric supply decarbonises the steel. Modest reduction in total emissions from steel are possible with more recycling, but recycling rates are already high. For the scrap industry, **national policies to decarbonise the power sector are essential. Here too though is a need for international coordination to create level playing fields if decarbonisation raises the cost of power and thus the cost of steel recycled from scrap**.

Any policy strategy for decarbonising steel must contend with the industrial organisation of the sector. While the global industry has become more concentrated over time the firms that dominate production and trade in steel remain highly dispersed with the top ten producing firms accounting for only one-third of the global total.[208] Dispersion creates large challenges for coordination across the industry, which are amplified by the highly competitive and global nature of steel markets. Half of today's steel industry is located in China, which offers an opportunity for concentrated innovation, but Chinese firms and policy makers have not yet invested much in testing green steel options. This is why, from a low-CO_2 technology perspective, Chinese producers lag behind leaders based in Europe. (By contrast, China is at the frontier in other carbon-intensive industries, such as cements and the power sector.) Moreover, the fleet of Chinese steel mills is younger than those in western countries, with a longer useful lifetime – suggesting that in China the options for retrofitting production processes, rather than building greenfield mills, will be of particular relevance.

The products of this industry are themselves highly differentiated. Steel can be sold and bought in over 3,500 different grades, ranging from bulk steel – such as rebar and construction steel – to a host of high-quality speciality steels. (Speciality steel contains larger amounts of alloying elements in order to change the properties in a desired way, for example into stainless steel.) The price difference between bulk steel and speciality steel (which is manufactured from bulk steel) is substantial, with bulk steel costing between US$400-600 per tonne and speciality steel sometimes costing more than US$2,000 per tonne.[209] As the impact on the total cost is a smaller fraction of the total, speciality steels may prove to be an important early niche for green products. However, it is hard to achieve much total leverage on emissions from the sector without reconfiguring bulk steel supply, for this is the product that is traded in the largest volume and is the feedstock to essentially all forms of steel.

Technology and process options for decarbonisation

Reducing emissions from the sector requires pulling four levers, probably in tandem. One lever is improved energy efficiency – something that is already in the interest of many steel producers seeking to improve margins. This offers modest potentials for emission reductions. For example, improving energy efficiency in today's virgin steel production methods allows perhaps a 15 – 20% opportunity for emission reduction.[210] A second lever is to use less steel through demand reduction and material efficiency in a more circular economy – for example, by 'lightweighting' cars with different materials and greater material efficiency. The potential for demand reduction is hard to quantify, but the best studies suggest that decarbonising iron and steel aggressively in line with the Paris targets will mainly require a focus on primary production.[211] Demand reduction alone will have a modest impact. Moreover, these actions are outside the scope of the steel industry itself, which has neither the incentive nor the means to implement demand reduction programmes.

The third and fourth levers involve production methods – the recycling of scrap steel and production of new, virgin steel.

Recycling of scrap offers the quickest way to reduce emissions, but its potential is limited. Today, around 26% of total steel production is recycled scrap. At the end of its original life, steel can be recovered and then the method for recycling is straightforward: melting in electric arc furnaces. The carbon intensity of the electricity largely determines the carbon intensity of the scrap steel product.

Today, around 85% of discarded steel is collected for recycling. That recovery percentage varies massively across application: for example, 95% of industrial steel waste is captured and recycled because the waste product is valuable and easy to repurpose. By contrast, only half of structural steel (which is often embedded in concrete and tangled in building remains) is recycled. Fuller recycling – including better quality control during recycling – could, by 2050, allow scrap to account for half of global production, which would lower projected total emissions from the iron and steel industry by around one-fifth.[212]

The other mode of steel production is virgin steel, which is made by reducing iron ore. Today, nearly all virgin steel (90%) is produced via reduction of iron ore in a blast furnace-basic oxygen furnace (BF-BOF), with coal as the source of heat (for melting) and the carbon in the coal as the reduction agent. The emission factors for this mode of production vary from 1.9 – 2.3 tonnes of CO_2 per tonne of steel.[213] Reducing these emissions is possible by at least four routes. These are:

- The use of natural gas as a reducing agent, followed by processing in an electric arc furnace (DRI-EAF), which already accounts for perhaps 10% of world production, has an emission factor of around one tonne of CO_2 per tonne of steel. This route is attractive in places with low cost natural gas provision and decarbonised electricity, but does not fully decarbonise the steel.
- Production in an electric arc furnace, but using hydrogen as the reduction agent. This option, if scaled, could make steel mills one of the largest users of hydrogen. It could anchor both the customers for a new hydrogen economy – with hydrogen produced via zero emission methods – and the infrastructure (e.g., pipeline systems) required for that economy.
- Production in a blast furnace with coal, but capturing the carbon emissions via CCS. This method is known but not presently used anywhere and looks unlikely to be cost-competitive with direct hydrogen reduction in most locations.
- Direct electrolysis of iron ore, in the same way as other metals like aluminium are currently produced. This option is among the least ready technologically, but one firm (ArcelorMittal) is investing heavily in its R&D.[1]

At present, there has been extensive mapping of the options (along with many hybrids) and it is not possible to pick a winner. Indeed, it is likely that multiple solutions will co-exist, depending on the location-specific circumstances such as electricity prices. There is a lot of attention to direct reduction with hydrogen and multiple demonstration projects are focussed on this option. However, the most competitive options depend on many factors, including the cost of electricity. Where green electricity is inexpensive (<40 $/MWh) hydrogen (made from electricity) or direct electrolysis are likely favoured. Where costly, CCS is likely to represent a lower cost production pathway. Still other options, involving biomass, may be highly cost effective, where biomass supplies are available and scalable.[214] T**his plethora of viable options underscores why policies must be sure to explore the full diversity while not, at the same time, slowing down investment because of uncertainty about which option will perform best at scale**. Moreover, some of the options are particularly important for retrofitting existing sites: for example, CCS retrofitting is the only practical option for many existing sites with long operating lifetimes.

How coordinated action can accelerate the transition

ACTIONS TO ACCELERATE EMERGENCE

Decarbonising steel production – beyond what is achievable with decarbonising the electricity supply for the scrap industry – requires an active policy strategy that simultaneously tests a diverse supply of options, while also creating robust and sustained demand signals.

1 Beyond these four there are other methods, such as reduction using biomass (as is used in some Brazilian mills). Neither of these options look as promising to scale for high quality product as hydrogen or CCS.

For supply, initial pilot plants (on a scale of several hundred thousand tonnes per year) are planned for the early-to-mid 2020s and industrial-scale pilot plants (on the scale of two million tonnes per year, the minimum size for integrated primary steel facilities), are scheduled for the late 2020s/early 2030s. These projects are concentrated in the EU and Japan, because governments in those markets have offered reliable innovation support, along with more credible decarbonisation policies that have created expectations for further incentives for decarbonisation in the future. **Accelerating this process would require front-loading national policies that provide this support – initially to pilot demonstration projects, and then to ramp up full scale industrial demos**. From current plans, that process might be advanced by five to seven years with more active support for demonstration plants. Direct support for pilot projects must back a range of technologies and systems, since the best routes are, at present, unknown. That means road-mapping for the industry – something that has already been done[215] – and then **aligning the investment in pilots with the range of roadmap destinations. Coordination of national pilot project support could ensure that the total international effort is at an appropriate size and scope**.

The slowness in the emergence of pilot projects reflects how technological risks are multiplied by a host of infrastructural planning and supply chain challenges. For example, in Sweden, SSAB (a steel producer), LKAB (an iron ore pellet manufacturer) and Vattenfall (a power company), formed the HYBRIT joint venture to explore the feasibility of hydrogen-based ore reduction. Currently at pilot phase, the first commercial plant is expected in 2036.[216] Of the US$147 million estimated cost of the pilot plant, the Swedish Energy Agency will provide US$56 million, with the joint venture partners contributing the rest.[217] This approach helps diversify cost sharing, but it also means that the entire effort hinges on the stability of the alliance.

Assuring demand for this product is critical and has received less policy attention. On the current trajectory, a market of ~20 Mt per annum would be required in the early 2030s to sell the output of the first ten industrial-scale zero carbon pilot plants. **The critical actions needed today require the joint efforts of national governments and the steel supply industry, which at present have no institution for reliable coordination of purchases of low-carbon steel, and one incumbent organisation (The World Steel Association) focussed on supply. These unreliable institutional arrangements will make it harder to assure that demand for this product will rise with supply – unless key governments step in and provide this function**. The long lead times and risks in pilot supply projects mean that reliable demand for the 2030s must be created today. **These actions could take the form of differentiated public procurement, border adjustments, voluntary buyer alliances, internationally coordinated pricing, or other actions. These could be organised in technology neutral ways – according to carbon intensity – to allow some competition in the fledgling green steel industry**. But careful attention by government, coordinated amongst first movers internationally, must ensure that adequate demand for low-CO_2 steel ultimately exists, even if some options (e.g., voluntary buying or carbon pricing) does not materialise at the scale needed to create demand. It must also ensure that uncertainty about performance in pilot projects does not undercut the incentive to invest in those projects, even if a level of demand for green steel is assured. There are many candidates for early adoption of green steel: for example, two million tonnes of steel could be used, alone, in the production in 14,000 large onshore wind turbines.

The cost of steel decarbonisation in the long-run is uncertain and probably unknowable, but is expected to be cost-adding. The best estimates today suggest the premium will be 20% – 50% on the price of a tonne of bulk steel (US$100 – 200 on a tonne of steel currently sold at US$400-600) once decarbonised production reaches the full-scale industrial pilot stage. As these costs could be proportionally much lower for speciality steel, it is likely that governments and early adopters will establish the early markets for green steel in specialised products where customer demand might be higher and the impact on prices smaller.

ACTIONS TO ACCELERATE DIFFUSION

Moving from the first ten plants to more widespread diffusion will require plans to deploy hundreds of plants. For example, achieving just one-third of the total green steel capacity needed to meet Paris goals would require approximately 200 facilities by the late 2030s to early 2040s – with the rate of deployment dependant on the reliability of policy support and the lessons learned from earlier projects. (At two to four million tonnes per facility, those 200 plants would deliver about 600 million tonnes of steel annually.)[218]

On the supply side, the processes of diffusion will involve continuous industrial improvement, including the identification of superior production methods, supply chains and infrastructure. The infrastructural planning will be particularly important if zero carbon electricity is to be used for electric arc furnaces and direct reduction by hydrogen becomes the dominant production method. **This kind of industrial planning – which is probably premature at present but will be needed within the next decade – will require industry and government alliances, and coordinated deployments**. Success in these efforts could emerge from coordinated earlier-stage testing of decarbonised steel production, and from the market creation that is needed now.

The major challenge for diffusion will be demand. A few governments and firms working together can assure demand for the first 20 million tonnes of zero carbon steel – as discussed above – but **demand on the scale of 600 million tonnes will be a completely different matter. Creating that demand will require stronger decarbonisation policies along with, most likely, border measures, to keep a level playing field. Diffusion of low-carbon steel production methods can be encouraged to ensure competitive pressure to reduce emissions, and in technology neutral ways – e.g., via carbon intensity metrics.**

Diffusion will benefit from **better and more standardised information about the carbon emissions from steel**. Many industries that are planning on low carbon futures are largely unaware of the lifecycle emissions associated with steel infrastructure – for example, the wind industry. Better data will make it possible to combine traceability with incentives in some markets to pay a premium price. Such data is also essential to a system of border incentives that are aligned with the emission intensity of diverse production methods, and considered acceptable under the WTO and other trade agreements.

As diffusion proceeds, so must policy attention to ensuring that the transition does not unduly harm already vulnerable segments of societies. The steel industry is already grappling with technological change, such as reduced employment due to automation, and the geographical shift of production from the western nations to the developing world. Since 1990, production of metals in the U.S. has retained a rough constancy, but the number of people employed in the industry has fallen steadily. Decarbonisation is unlikely to alter this trend, but if decarbonisation becomes linked politically with the unemployment already appearing in the sector, this could erode political support for deep decarbonisation. Trade measures and industrial policy will be crucial to managing this process, since steel is central to national development. Least-developed countries (such as those in Africa) will be especially sensitive to these costs during the early stages of diffusion of new technology and business practices.

ACTIONS TO ACCELERATE RECONFIGURATION

The entire process of emergence and diffusion must be evaluated against the prospects for complete reconfiguration of the steel market by the late 2040s. This entails essentially zero life-cycle emissions everywhere through ubiquitous recycling of scrap and zero emission virgin production. Although planning today for reconfiguration in the 2040s is impossible, at least two elements of the process must be kept in mind.

Firstly, the industry goes through cycles of booms and busts, with long periods of excess supply. Strategies for retiring or retrofitting old plants – or hybrids of retrofits and new technologies – could greatly help the broader transition, because they will expand the options for existing plants.

Secondly, the extent to which reconfiguration will require active policy support depends on the speed and extent of technological improvement in the overall system for low-carbon steel production. If low carbon steel remains more expensive than high-emission options – which is likely – then decarbonisation incentives and trade policy supports will be needed for complete reconfiguration.

A few governments and firms working together can assure demand for the first 20 million tonnes of zero carbon steel, but demand on the scale of 600 million tonnes will be a completely different matter. Creating that demand will require stronger decarbonisation policies along with, most likely, border measures, to keep a level playing field.

CEMENT

SECTOR **CEMENT**

IMPORTANCE

*Accounts for about **3%** of total global greenhouse gas emissions.*

GHG
3%

STAGE OF TRANSITION **EMERGENCE**

Technologies for deep decarbonisation are yet to enter markets on a significant scale.

NATURE OF THE PROBLEM NOW

- High costs of decarbonised production are prohibitive in competitive global industry
- Demand for low emissions cement is non-existent without policy signal

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OPTIONS FOR DECARBONISATION

- *Switching primary energy source from fossil fuels to electricity, hydrogen or biomass*
- *Carbon capture and storage for chemical process emissions*
- *Alternative clinker chemistries with low to negative process emissions*

CO_2 CO_2 CO

INTERNATIONAL ACTIONS TO ACCELERATE THE TRANSITION

ACTIONS TO ACCELERATE EMERGENCE (1)

- ***Coordinated testing and demonstration** of low carbon cement production technologies including hydrogen and electric furnaces, and low emission clinker options – to identify viable options and accelerate learning*
- ***Coordinated government procurement** of low carbon cement in public works projects, buildings & infrastructure – to provide initial demand with enough scale to make investment in production viable – supported by joint definition of 'green cement'*

INSTITUTIONS

Global Concrete and Cement Association

PRIORITIES:
expand participation from industry to governments; focus coordination on practical experiments and creation of markets

ACTIONS TO ACCELERATE DIFFUSION (2)

- ***Coordinated market-creating policy**, in the form of regulation or carbon pricing, to ensure growth in demand for low carbon cement*
- ***Trade measures** to maintain a level playing field for low carbon production*
- ***Coordination on building standards** to ensure they are drivers of the transition (e.g. using lifecycle emission standards) and not blocking new cement technologies from entering markets*

ACTIONS TO ACCELERATE RECONFIGURATION (3)

- ***Trade measures** to ensure zero emission standards expanded to cover whole of global market*
- ***Support from multilateral development banks** for transition to zero (or ultra-low) emission cement technologies in developing countries*

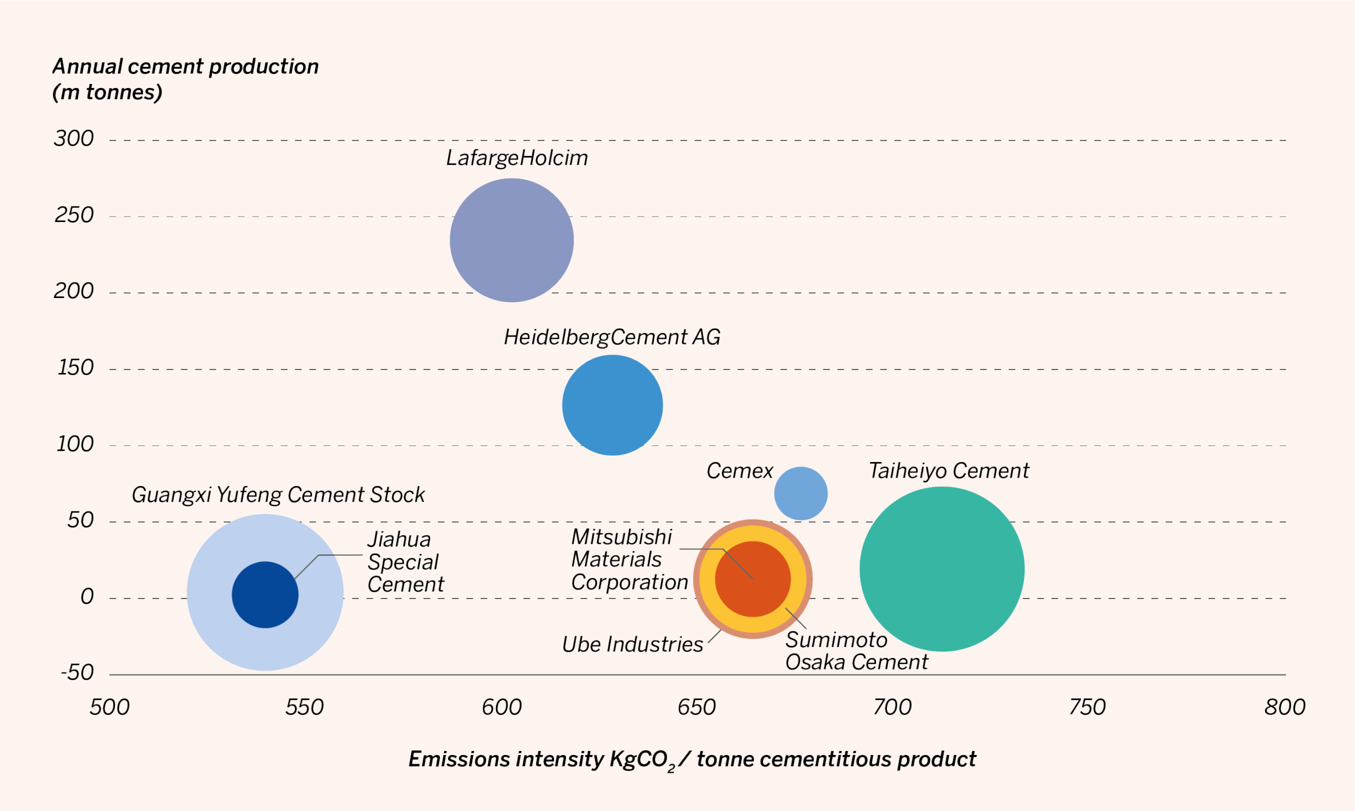
Importance to emissions

Cement, the binding agent in concrete, accounts for about 2.2Gt of current CO_2 emissions, or about 3% of total global greenhouse gas emissions. Emissions come mainly from the chemical process of making and curing cement (1.2Gt) and from the high heat inputs needed for production (0.75Gt) with the rest of emissions indirectly stemming from other industrial processes associated with production (e.g., power for grinding and crushing). In contrast with other carbon-intensive commodities, such as steel and plastics, consumption of cement is not growing quickly – total demand for cement may grow about 12% from current levels by mid-century.[219] On current policy trajectories, total emissions from that growth will rise more slowly – as less carbon intensive feedstocks get used, and energy efficiency rises – with total emissions expected at about 2.3Gt per annum by 2050. The geography of these emissions will shift substantially toward the developing countries that will account for most industrial growth and infrastructure needs in future.

Nature of the problem now

The central challenges to the decarbonisation of cement are rooted in incentives and industrial structure. Most cement – and concrete, the main ingredient of which is cement – is sold as a commodity. The industry is highly competitive and sensitive to cost, and all the options that would allow deep emissions reductions will be a lot more expensive than conventional cement for the foreseeable future. Cutting emissions will be easier in newly built cement plants, but nearly all the growth in the industry is in countries that are least willing to spend their own resources on climate emission controls, such as in Africa and India. The industry is highly concentrated and integrated, which reinforces the position of incumbents. Breaking this deadlock requires opening niche markets where new techniques can be applied and improved, and then diffusing those practices more widely. Diffusion will hinge on improved technology and direct incentives to cut emissions, along with other policies aimed at creating demand for low emission cement.

FIGURE 26: CEMENT PRODUCERS: TOP ASSIGNEES BY PRODUCTION VOLUME AND EMISSIONS INTENSITY



Adapted from: Making Concrete Change. Innovation in Low-carbon Cement and Concrete, Chatham House Report, June 2018.

Already today, there is room for improvement: Figure 26 shows the extent to which the carbon intensity of cement production varies among the world's largest producers. This variation stems mainly from a combination of (i) differing levels of adoption of best available energy efficiency technologies, (ii) the carbon-intensity of the energy input from primary heat sources (coal vs. gas, but also different qualities of coal) and electricity (which varies widely in carbon intensity), and (iii) some variation in feedstock blending (in particular with fly ash).

The industry is highly concentrated, with the three largest producers (LafargeHolcim, Anhui Conch and Heidelberg) holding more than half of the global market. LafargeHolcim alone holds a 25% global market share.[220] The capital intensity of cement production reinforces this concentration, creating stronger lock-in effects that make it difficult for smaller actors to enter the market and compete with larger firms.[221] Advantages of scale – vertical integration of upstream concrete into downstream operations of direct sales, along with supply chain efficiencies – further explain why the industry is becoming even more concentrated through cross-border holdings. Only 3% of global production trades across borders, and that mostly occurs among geographically close neighbours.

In other words, the big firms thrive while the small simply survive. The highest-performing cement companies (who occupy the top quintile) capture almost the full economic profit of the industry, whereas the next 60% of companies (quintiles two to four) create returns just above or below the cost of capital.[222] In addition to a large number of poorly performing firms, overall the global industry periodically suffers from over-supply, such as in China today. These factors help explain the huge industrial barriers in shifting toward higher cost products. Fully decarbonising cement may roughly double the cost of the product and raise the cost of concrete by about 30%. The structure of the industry is not favourable to any form of change. Commodity competition is intense, demand for low carbon cement is currently almost non-existent, and deployment of radically different technologies is risky and capital intensive.

Traditionally, the global industry has not been well organised. Firms have focussed on competition around a commodity product where price played the central role. Recent years, however, has seen the emergence of the Global Concrete and Cement Association (GCCA), which has aspirations to provide an active coordination role on emissions reduction across the sector. This organisation, which now includes all major producers, picks up the task of coordination following the pioneering work of the Cement Sustainability Initiative (CSI), an organisation that, a decade ago, assembled around one-fifth of the global cement producers. Vertical integration means that schemes which include both cement and concrete will have, in theory, greater leverage in the market. Though new and untested, the GCCA is promising. To be successful as a coordinating institution it will need to obtain more involvement of the governments that will be the first movers in green cement policies.

Stage of the transition, and technology options for decarbonisation

The cement industry is at the very early stages of a tentative transition to deep decarbonisation. The use of low carbon energy sources and higher energy efficiency is already diffusing widely in places where there is an incentive, such as high costs of energy and local pollution concerns.

Some of the effort to reduce emissions from cement requires reducing demand and making the applications that utilise concrete more circular.[223] One way to achieve this is through optimising the design of structures to require less supply of cement and concrete, including, for example, building retrofits that make more extensive use of existing materials. Another involves substitution with other materials that have lower or even negative emissions in production, such as the use of bamboo and other woody materials within the construction sector. Since the energy input in manufacturing timber is less than 30% that of cement, and the process emissions are nil, total emissions from timber production represent less than 15% of those that arise from using cement in similar applications. There are also opportunities to reduce emissions from the cement and concrete industry by raising energy efficiency through more widespread application of best practices. Overall, such demand reduction, fuel switching, and energy efficiency measures, allow for significant reductions in emissions: compared with today's levels, if more circular approaches were adopted, emissions from cement could be reduced globally by 45% by 2050.[1] Some of these measures are likely to entail negative abatement cost per tonne of CO_2 saved: for example, by shifting to best energy efficiency practices, which are still not widely shared within the industry. Such demand reduction and energy efficiency measures could achieve large emissions reductions and reduce the cost and technological challenge in decarbonising the emissions that remain.

1 Energy Transitions Commission Mission Possible report. Note that there are varied sources of leverage for full circularity. In the calculation presented here, 35% reduction could come from a combination of (i) recycling, (ii) greater materials efficiency and (iii) materials substitution – which are not things that the cement industry itself can easily influence. The rest (10%) comes from energy efficiency measures – which the cement industry can influence.

Deep decarbonisation requires new processes and switching to new sources of primary energy, the opportunities for which lie broadly across three complementary fronts. Most likely, an optimal strategy will involve working all three simultaneously, because the best combinations will depend on technological progress and local factors, such as the cost of energy.

Firstly, the carbon intensity of primary energy sources must be reduced, ideally to zero or negative. That means switching from coal to other sources of energy, such as gas that has been decarbonised by blending or replacing with green hydrogen or energy sources that come from various biological sources. It may also entail switching from direct combustion of primary energy sources for heat onsite to the use of clean energy carriers of electricity or hydrogen. The electric route is theoretically feasible but has not been tested at industrial scale and would require redesigning furnaces (which is likely to be impractical for existing plants). The hydrogen route is feasible too, in principle, but would also require redesigning furnaces, and will hinge on the cost of producing green hydrogen. The utilisation of waste or biomass in existing kilns is a proven technology, already used on an industrial scale and requires only a modest retrofit to existing kilns. It is unlikely to be scalable across all markets, however, given constraints on total supply of waste and sustainable biomass. (Every major option for decarbonisation must be assessed by its potential not just for cutting emissions but also for scaling.)

Secondly, pollution from energy sources and chemical processes at cement kilns, which are among the world's most highly concentrated sources of CO_2 already, could be captured and sequestered underground. Carbon capture would reduce or eliminate the need to switch away from carbon-based fuels and would also reduce or nearly eliminate the chemical process emissions from cement production. This is an important option, discussed in more detail below, if there is no scalable breakthrough in cement chemistry allowing for the elimination of process emissions of CO_2. Even if new cement chemistries are used, carbon capture would still be needed to capture likely remaining process emissions. A challenge for carbon capture is sheer cost, which is likely to be higher for cement than for other industrial sectors, in part because sources are dispersed and will require the infrastructure to gather CO_2 emissions and concentrate them at a point of CO_2 injection underground. Compared with iron production or steam methane reforming (a means of making hydrogen), the first few carbon capture operations on cement plants may be double the cost (about US$110 per tonne of CO_2), with costs declining modestly (perhaps to US$90 per tonne) for nth-of-a-kind plants). The higher costs reflect the relatively low concentrations of CO_2 streams on cement plants.

Thirdly, the chemistry of cement could be shifted from conventional clinkers – the binding agent, which today is made principally by heating limestone and other ingredients – to other chemistries that don't intrinsically release CO_2. (Limestone is $CaCO_3$ and heating it to make clinker transforms it chemically to CaO and released CO_2.) There are many options with varied impacts on emissions. Belite or Calcium sulphoaluminate have been proven, but they offer only modest reductions (10% to up to 30% respectively). (Some of these options require mineral inputs, the supply of which is uncertain.) The scalability of some other options is challenging. The most promising pathway forward today is Alkali/Geo-polymer-based-cements known as Pozzolan. This is an attractive option because they allow deep cuts in emissions (70% compared with conventional clinkers) and utilise minerals which are widely available across all continents. Although this is considerably more carbon-frugal, complete decarbonisation will still require capture of all remaining process emissions.

How coordinated action can accelerate the transition

ACTIONS TO ACCELERATE EMERGENCE

Emergence requires demonstration and experience with decarbonised cement technologies, which at present are at varied stages of testing and exploration:

- With regard to reducing primary energy intensity and switching away from carbon-based fuels, the industry has almost no practical experience beyond straightforward 'best practice' approaches to energy efficiency. **Roadmapping work is needed to understand whether biomass fuel switching – which has been tested – is scalable and relevant. Demonstration plants (or at least designs) are needed for hydrogen and electric furnaces, and these options must be costed against opportunities in carbon capture and decarbonisation of cement chemistry.**

- With regard to carbon capture, **multiple demonstration projects that explicitly explore a broad landscape of opportunities for decarbonised production will be needed**. A system perspective is important because to make Carbon Capture and Storage (CCS) effective, for example, it must be integrated with process heat and chemistry operations, so that the system, overall, is reliable and cost-effective. Also needed are infrastructures to collect and dispose of CO_2. Decisions will be needed around the interplay between energy and chemistry choices and CO_2 capture technologies. For example, several technologies are being developed to increase purity in the CO_2 flow and therefore reduce the cost of capture while enabling higher capture rates. Innovative kiln design could separate exhaust gases from fuel combustion (low in CO_2) from the exhaust gases of the clinker chemistry process (known as calcination, which generates almost pure CO_2), allowing the latter to be captured at a lower cost. Burning fossil fuel input in pure oxygen rather than air (oxy-combustion) would also increase the percentage of CO_2 in the heat-related emissions. A similar story about system integration can be told for every other major element of a decarbonised cement kiln – energy feedstocks, and decarbonised clinkers.

- With regard to decarbonised clinkers, Pozzolan cement is commercially available and has already been demonstrated at scale in various settings, including underwater and underground structures, as well as both state and federal highways in the US. These first projects have confirmed the competitive cost structure and technical performance of this chemistry and have created a small market. (About 500,000 tons of new production capacity was brought online in 2018 alone in North America.) In tandem, the biggest producers of traditional cement have invested in R&D and demonstration on small scales, but at this stage it is hard to assess the seriousness of these efforts by the incumbents. Some startups with new chemistries and processes have emerged (and some have already failed, because it is hard to master new production methods while also finding markets for costlier green cement). **What's missing in this process is a concerted effort to test a full range of decarbonised clinker options.**

Making progress on all these fronts requires direct support for R&D, along with policies that create reliable and growing markets for green cement. Put another way, a coordinated "push" and "pull" for the technology into the marketplace will be needed. **As a matter of national policy, larger and more reliable support for pilot projects is also needed. In addition, there is the need for international coordination through a larger parallel R&D programme across multiple countries to ensure that there is more intense testing of diverse approaches to producing decarbonised cement, along with a more active coordinated cross-border effort to compare lessons learned. No single pathway, be it fuel switching, carbon capture, and/or decarbonised clinkers, is a clear winner. This strategy, therefore, must not only map the landscape but also promote learning, based on real world pilot projects, in order to discover which systems are most practical.**

Since the dissolution of CSI, there has been no sustained international coordination of R&D on cement. One option for international coordination would be to have Mission Innovation take on cement as an additional area of focus for coordinated R&D.

The testing of diverse new technologies and systems will help, but it is also **essential in the creation of low-carbon cement markets: such as in procurement standards for public works projects, for example, as well as for ultra-green buildings where the extra cost of novel clinkers will be relatively small because the building overall is initially more costly.**[224] While decarbonisation may double the cost of cement, the total cost impact on, for example, green residential buildings might be around 3%.[225] **Much of this can be done by large national governments acting alone (and some large local and regional governments acting in tandem). Some joint cross-border procurement – for example, in EU infrastructure projects – can also play a role. A coordinated international effort could increase the gains from scale**, however, triggering cost reductions in new cement chemistries, alternative heat sources, and carbon capture technologies. A joint definition of 'green cement', and the ability to track this label throughout the value chain, would be a key enabler of this coordination. Investment in CCS infrastructure will also be needed for procurement of fully zero-carbon cement to be viable. Creating these markets requires not only direct financial incentives, but also adjustment of building standards that, currently, will consider nothing other than conventional cement-based products.

Success with a cement decarbonisation strategy requires that **governments (and other supporters of decarbonisation) figure out whether incumbent firms will be part of this solution, or a barrier to it. If the former, then the coordinated creation of markets could be helpful, because these firms are multinational and will thrive if similar activities are pursued in parallel. If the latter, then governments will need to focus incentives more surgically to navigate around incumbency**. A central challenge remains that the industry, despite its concentration, is poorly organised. Leading governments and firms will need a mechanism for coordination, so that technology and system landscapes can be mapped and lessons compared across national markets. These lessons will include not only industrial production but also the creation of new markets and the reform of building regulations. If the industrial organisation GCCA played a role, then this would be a key test of whether it will be relevant to the decarbonised future.

A critical question for emergence (and diffusion) will be how efforts in western countries relate to those in China. **China has emerged as a key cement innovation hub: perhaps more than half of all patents for new cement technologies are owned by Chinese companies and academic institutions, as the country now invests more than any other country in cement research and development (R&D).**[226] Two Chinas are emerging. In one China, firms must install advanced anti-pollution technologies to meet raised standards for the production of materials such as cement.[227] (These pollution standards focus on local and regional air pollution, but many of the technologies needed for decarbonisation will overlap.) **The reinforcement and engagement**

with this China will be vital to a global strategy. The other China is the one grappling with over-supply while pushing abroad – notably through the Belt and Road Initiative – making investments that are not held to the same standard. Eventually this China must be engaged, but doing that will require that governments establish a broader political framework for engagement.

ACTIONS TO ACCELERATE DIFFUSION

As new chemistries and systems are demonstrated, more widespread diffusion will hinge on incentives for supply and the availability of demand. On the supply side, **the most important incentives will involve a reliable direction for carbon pricing or regulation**. This is a familiar challenge for governments. The governments that lead in this process, and which are also seeding the emergence of new low carbon cement, **will need to use trade and investment measures to correct the unlevel playing field in the cement industry**. As there is little international trade in cement, this border adjustment approach will be much easier than for steel and plastics commodities where trade accounts for a much larger share of the global market.

For demand, reliable carbon pricing and regulation will create pressure, but all governments will need to do a lot more to help create these markets. **Public procurement can play a role because publicly funded infrastructure and other public works, such as buildings, are prodigious users of concrete**.

In addition, governments must engage in the careful mapping of how building standards and other procurement rules might be blocking low-carbon cement from markets beyond the early high-value and government procurement niches. They must engage too with how these same standards and rules could be changed to become drivers of the transition, for example through building lifecycle emission standards.

A government-supplier-user consortium, which does not currently exist, will be needed to compare best practices (including lessons learned in emergence niches) to help rewrite codes. **This effort probably would benefit from the central engagement of the professional societies in civil and mechanical engineering. National societies are looking at decarbonisation issues – mostly in other industries – but efforts are erratic and need to be organised and focussed on the problem of cement.**[228]

OPTIONS FOR RECONFIGURATION

Reconfiguration is a long way off and will be challenging, unless the technologies and systems integration needed for decarbonised cement prove highly successful and the cost premium is reduced nearly to zero.

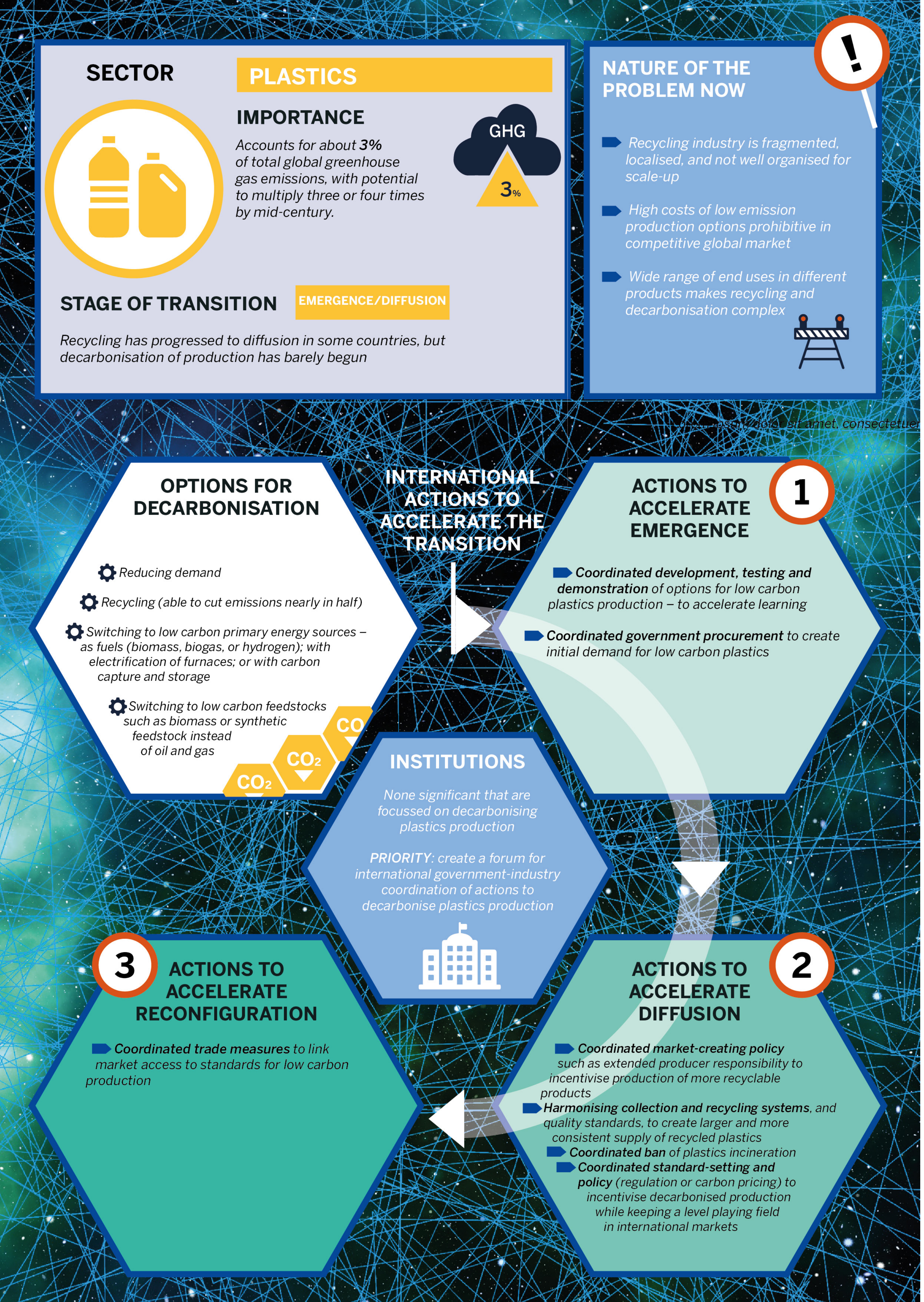
The scale of change needed for reconfiguration is massive. If the whole industry is to be decarbonised by 2050, more than 4500 low-carbon plants would have to be built between 2020 and 2050 – more than 150 per year, with older plants retiring at a similar rate. For comparison, in 2018 annual growth in cement production was 124 plants, and none with zero carbon systems.[229] An intermediary objective of 500 – 1000 plants (about 1,000 Mt of low-to-zero-carbon cement production capacity) by 2030 would appear to be in line with the longer-term objective. Among the many challenges will be extending decarbonisation to every corner of the industry. This will not be easy, what with the perennial overhang of excess supply and a reconfiguration of the global industry that is under way.

In fast-growing markets in Africa, Asia, and Latin America, a new champion of cement production has come to prominence: the regional producer.[230] In India, four regional players account for 44% of capacity.[231] In West Africa, the market is dominated by six producers, of which four are regional players.[232]

In principle, it will be easier to adopt low-carbon cement kiln configurations for greenfield producers, but essentially all the growth in the industry is in places where willingness to spend more is low (e.g., India and Africa, where urbanisation and industrial growth are accelerating). Thus, the early stages of complete reconfiguration of the industry will require accelerated turnover and retrofitting of plants in the markets where willingness to decarbonise is higher: such as in the more mature, western markets of Europe, North America and Japan. **From there the pattern will need to spread. In developing countries, support from multilateral development banks can help diffuse and reconfigure technology choices toward the best zero (or ultra-low) emission technologies. Some border adjustments may be necessary, especially if the role of trade rises as cement production globalises even further, eventually reaching the rest of the global market. Indeed, the role of trade will rise if not all countries adopt comparable emission standards. China will be pivotal to this process given its sheer size and its expanding presence through the Belt and Road Initiative.** For the near term, decarbonising a rising share of the cement in the Belt and Road Initiative is politically and economically impractical. The demonstration of technologies and policy support could determine whether green cement remains stuck in some early niches, and so halts diffusion, or in fact becomes ubiquitous.

PLASTICS

This note is heavily based on Energy Transitions Commission (2019), Reaching net-zero carbon emissions from plastics and Material Economics (2018), The circular economy – a powerful force for climate mitigation.



Importance to emissions

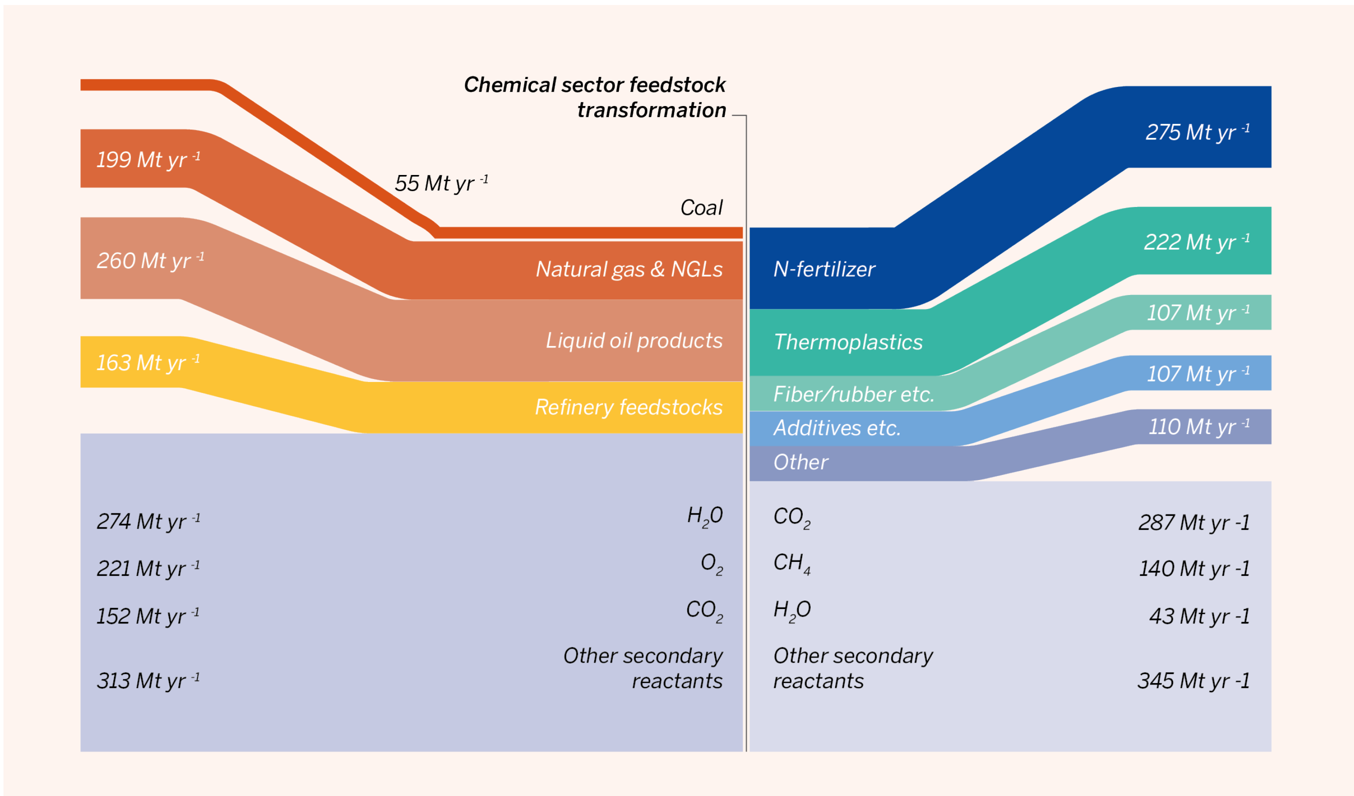
Plastics are one of the main outputs of the chemicals industry, which in total accounts for around 3% of global greenhouse gas emissions. The chemicals industry converts feedstocks (drawn primarily from fossil fuels) into valued end-use products, such as fertiliser, fibres, rubber, and of course plastics. Figure 27 shows the global flow of feedstocks (left side) and final products (right side).[233]

Today, the International Energy Agency (IEA) estimates that plastics production accounts for 0.5 – 0.7Gt CO_2 of emissions per year.[234] Without profound changes in the plastics value chain, growing demand will cause a rise in carbon emissions from plastics, which could represent 2Gt per annum by mid-century. Those emissions from production of plastics arise mainly because large amounts of energy are needed for the chemical and physical processes that yield thermoplastics (e.g., plastics moulded into food service containers), rubber, and other forms of plastic. Accounting for the emissions associated with the disposal of plastics – for example, incineration – could bring total plastics emissions to as much as 4.2Gt by mid-century.

Stage of the transition and nature of the problem now

Decarbonisation of plastics production has barely begun. The central challenges are technological and industrial structure. It is possible to cut emissions from plastics nearly in half through more recycling, and for some products and in some countries the recycling of plastics has progressed beyond niche emergence stages into more widespread diffusion. However, the industry for recovering plastics after use is fragmented, localised and not well organised for large scale-up. Technologically, it is also possible to shift energy supplies and chemical feedstocks away from traditional oil and gas towards other energy sources, including bioenergy or synthetic feedstocks, that have low or negative emissions. However, these technological routes must be tested and markets for decarbonised plastics created. This is a challenging task when oil and gas prices are relatively low. It makes new technological routes more costly than conventional production in an industry that is already highly global and competitive.

FIGURE 27: GLOBAL FLOW OF FEEDSTOCKS AND FINAL PRODUCTS IN THE CHEMICALS INDUSTRY



Adapted from Environmental Science and Technology, 2018, Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products.

Plastics is one of the most complex sectors to decarbonise because of diversity and fragmentation. More than 30 types of plastics are in common use. Production is highly concentrated and tied closely to the oil and gas industry: plastics are an attractive way to monetise oil and gas production, and the chemical engineering processes used in making plastics align well with the chemical engineering skills of petroleum refining. Production is also concentrated in major economies and internationally traded: 50% of the worlds' plastics are produced in Asia (30% in China); the rest is split between Europe (19%), NAFTA (18%), and the rest of the world (<15%).

While production is concentrated, utilisation is highly fragmented due to the many different end-use products. Collection of used plastics for recycling is extremely complex, as is sorting and reprocessing. As in the steel industry, co-mingling of different products means that recycled products are often lower grade. Many plastics find their fate with other trash that, in some countries, is incinerated – a process that sends all the carbon embodied in the plastic into the atmosphere as CO_2.

Technology and process options for decarbonisation

There are four main routes to decarbonising plastics.

The first route is to reduce demand. Global plastics production has grown from trivial levels in the 1950s to reach over 320Mt today. Of that, 222Mt are thermoplastics, the use of which is forecast to rise significantly, reaching perhaps 800Mt per annum by 2050. More than one-third of global plastic polymers are used for packaging (36%). Reducing these uses offers opportunities, but is problematic because secure packaging is vital to so many industries (e.g., the food service). Even dramatic reductions in some of the more discretionary single-use items could only reduce total carbon emissions from plastic by about 10%, with the biggest potential contribution coming from bottles and food containers. Most 'single-use plastics' are necessary for food conservation. Moreover, many uses of plastics – such as in the automotive industry, which accounts for 7% of global demand (9% in Europe) – are attractive because they substitute for even more carbon intensive (and expensive) materials such as steel and aluminium.

The second route is recycling: making the plastics economy circular thanks to mechanical or chemical processes. This is widely regarded as the largest source of leverage on emissions. The challenges here are not technological but industrial structure. The central challenges are limiting the quality downgrading, due to product contamination by additives and incomplete sorting, along with a lack of coordination across the value chain that limits collection rates.[235]

The third and fourth routes to decarbonisation involve technologies for production of virgin plastics. As it is improbable that 100% of end-of-life plastics can be collected and recycled, some level of virgin plastics production will be needed. Virgin plastics entail two streams of CO_2 emissions: the energy inputs needed during the production process produces on average 2.5 tonnes of CO_2 per tonne of plastics; while the decomposition of plastics at end-of-life produces about 2.7 tonnes of CO_2 per tonne of plastics.[236]

The third route involves decarbonisation of primary energy sources. A variety of options exists at very different stages of technology development. These include a switch to low-carbon energy sources (e.g., biomass, biogas or zero-carbon hydrogen), direct electrification of furnaces, and carbon capture and storage (CCS) techniques applied to fuel combustion. A switch to low-carbon energy sources (e.g., sustainable biomass, sustainable biogas or zero-carbon hydrogen) may not require major retrofitting of existing installations. However, the biomass and biogas routes are unlikely to be scalable given constraints on sustainable biomass supply. Electrification of primary energy is in theory also feasible but, while high-temperature electric furnaces have been built in laboratories and used in other applications, they are not yet commercially available for ethylene cracking.

A variety of methods that would alter the source of primary energy along with the plastics production methods, such as direct production electro-chemical processes, may lie further in the future.

Carbon capture could be applied to the capture of exhaust gases from furnaces in which feedstocks are decomposed into the materials that become plastics (a process known as "pyrolysis"). The carbon would then be either stored underground or used in several applications, potentially within the chemical sector itself. Plausibly, a fully green virgin plastics plant could apply CCS to fossil (or biomass) primary energy sources alongside pyrolysis.

The fourth route – reduction of emissions associated with eventual end-of-life decomposition – requires a switch in the feedstocks from which plastics are made. Options include using low-carbon alternatives, such as biomass or synthetic feedstock, rather than traditional oil and gas. This approach could yield plastics that are carbon neutral or even negative. Synthetic feedstock, for example, could be made from carbon captured from the air along with zero emission green hydrogen.

Profound decarbonisation of the plastics industry requires, most likely, working all four routes: the first two to reduce the need for virgin plastic, and the latter two to decarbonise the virgin supply.

How coordinated action can accelerate the transition

ACTIONS TO ACCELERATE THE EMERGENCE OF A DECARBONISED PLASTICS INDUSTRY

Recycling has diffused widely for a few plastic products in a few markets (e.g., Europe, Japan and in Berkeley, California), and in the next section we will discuss how to achieve wider diffusion. **The critical emergence challenge concerns production of virgin plastics in places with little experience.**

At present, none of the routes to decarbonised virgin plastics is being explored in reliable niches. In order to do this, governments will need to work with industry to build early-stage demonstration and first industrial-scale pilots for production decarbonisation techniques. These might include, carbon capture innovation on pyrolysis furnaces, or the use of hydrogen, or direct electrification to provide for industrial heat. In tandem, these governments could develop zero-carbon feedstocks (in particular, synthetic feedstock whose deployment would go hand in hand with the deployment of electrochemistry). These new feedstocks could have value in many different sectors. **Building these early stage testing programmes is mainly an activity for national policy working with firms. Governments and industry must engage in international cooperation, however, to ensure that the size of these demonstration projects is adequate, that the full landscape of technological opportunities is mapped, and that lessons are learned across borders about which systems are promising. At present, there is no international institution (or institutions) that offers a logical venue for this cooperation.**

As in the steel industry, **it is likely that support for pilot projects will need support, in tandem, for reliable markets for green plastics, such as through government procurement, or voluntary standards for high value products. This will require a measure of international coordination, because green plastics will be more expensive and not competitive in commodity markets without trade measures.**

ACTIONS TO ACCELERATE DIFFUSION OF A DECARBONISED PLASTICS INDUSTRY

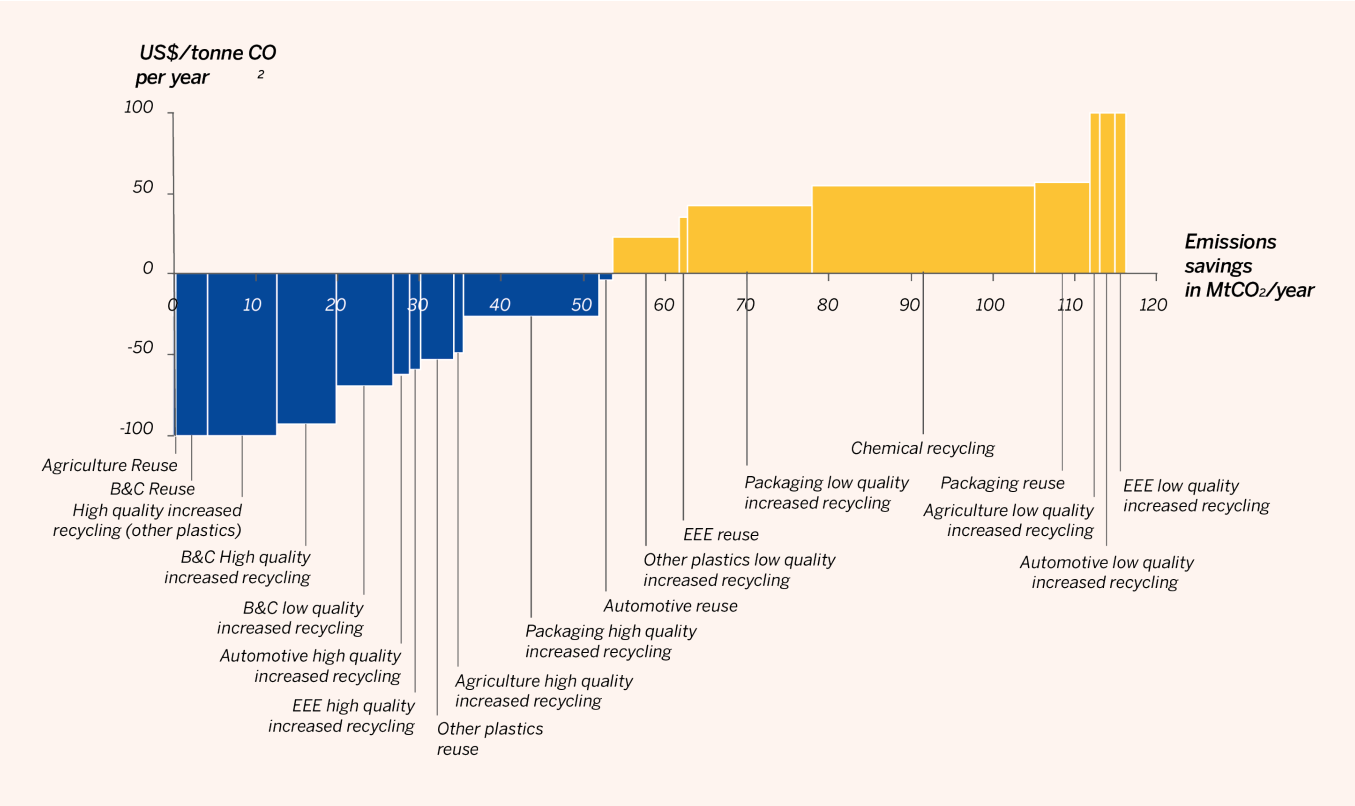
Some elements of recycling are already at the stage of widespread diffusion, and that process can be accelerated to make plastics more circular. **Governments and the industry can focus on actions that pull these four major levers in the following ways**:

- By providing information about the full costs and benefits of circularity, and by identifying areas where incentives are mismatched. For example, about 50 million tonnes of plastic-related emissions can be reduced at negative cost (see Figure 28).
- By strengthening extended producer responsibility (EPR) to create incentives for production of plastics-based products that will be more easily recyclable: in particular, by limiting the diversity of specialised plastics used and the contamination by other additives, like solvents and inks.
- By harmonizing collection and recycling systems on large enough geographical areas, through greater collaboration between local authorities (either voluntary or mandated by central governments), leading to large-scale public service delegation contracts.
- By creating quality standards for secondary plastics at national/regional level.

Currently, efforts on all these fronts are fragmented because they are mainly the effort of national governments and a few firms. A more coordinated international strategy has not emerged as recycling industries remain local. There is a chicken-and-egg dynamic at work, where a fragmented and small-scale recycling industry cannot produce the consistent quality and volumes required for large-scale use, while lack of demand for recycled products holds back the investment that would enable such production in the first place.

All four of these actions could be advanced with a large measure of international coordination to ensure that circular plastics markets are big enough to be economically viable. The likely lead for these coordinated efforts is the EU, since all four of these levers align with existing EU institutional capabilities. In tandem with all these actions will be the necessity to curtail incineration of plastics – an action that hinges on government policy and is an area where leverage in Europe is largest, because the use of incineration is largest in Europe.

FIGURE 28: ABATEMENT COST FOR PLASTICS DEMAND-SIDE DECARBONISATION



Adapted from Material Economics (2018), The circular economy: a powerful force for climate change.

Looking beyond recycling, diffusion of decarbonised or zero-carbon virgin plastics production will likely be more challenging once the corresponding technology and business development reaches that stage. To some degree, diffusion can accelerate through voluntary commitments, such as by large purchasers of products and firms that are motivated to provide greener products. The leverage of these voluntary actions is probably small, however. In addition, such actions will require prior steps, such as regulations that ensure the traceability of materials input, using two potential indicators: a materials-intensity indicator (per use or per square meter) and a carbon-intensity of materials used indicator (per tonne of materials).

Achieving widespread diffusion of decarbonised or zero-carbon virgin plastics will require active policy support that is rooted in policy frameworks in the major producer and consumer nations. These frameworks are needed to stabilise markets where decarbonised plastic must take a larger market share. Elements of this support will include **clear incentives for shifting to low carbon plastics and practices, such as carbon pricing and regulation**. They will also include **guidelines, developed through industrial collaborations, that define best practices along the value chain**. Creating these guidelines, embedded more deeply in policy as they are perfected, will require participation of major user groups, such as the buildings industry, represented by the World Green Buildings Council. In the automotive industry, the International Organization of Motor Vehicle Manufacturers (OICA) would have the representative weight and geographical scope, but complex governance and tendency to fall back on the lowest common denominator could get in the way. In short, **wider diffusion will require internationally coordinated standards and best practices, and at present there are no mechanisms for coordinated setting of standards for the full value chain of plastics**. Without stronger coordination, only large markets, such as the EU, can set standards that affect market demand and thus influence producers, and even those large markets are a fraction of the larger global total.

ACTIONS TO BRING FORWARD RECONFIGURATION

The industry is a long way from worrying about the problem of reconfiguration. Other problems, such as the rapid rise in public concern about plastics in the food chain and in ecosystems command much more attention. Those concerns may yet draw more attention to collection and recycling, which could help with decarbonisation, but widespread public concerns have not yet motivated the industry to plan for complete reconfiguration in ways that would achieve deep decarbonisation.

Looking to the future, attention will be needed on at least two fronts.

Firstly, as with any globally traded commodity, trade measures may be important, especially if decarbonised plastic is more costly to produce than higher emission products. Standard setting (as envisioned during widespread diffusion) is a vital first step, because the appropriate best practices must be identified and agreed before trade measures can be applied. Those standards will be the foundation for internationally coordinated trade measures. The recycling industry needs to shift from a low-quality, low-price model to a high-quality, high-value model. The harmonisation of collection processes, or even their standardisation, would facilitate the diffusion of recycling facilities and ensure higher-quality flows reach the recycling industry. Reconfiguration to lock this into place probably requires penalties for firms that don't align in this high-quality industry.

Secondly, reconfiguration will benefit from a broader normative shift – something that engages all of society. Big shifts in plastics consumption are already underway as society, in some markets, rethinks acceptable uses and disposal. Doing this through the lens of carbon will help establish and reinforce the political support needed for sustained government action and industry commitment to decarbonised plastic.

> It is likely that support for pilot projects will need support, in tandem, for reliable markets for green plastics, such as through government procurement, or voluntary standards for high value products. This will require a measure of international coordination, because green plastics will be more expensive and not competitive in commodity markets without trade measures.

5. CONCLUSIONS

In the first part of this report, we looked at how system transitions have happened in the past, in sectors as diverse as road transport, agriculture, aviation, water and heating. Our clear conclusion is that **well-targeted action can accelerate a transition**. Support to research, development and demonstration, and the creation of niches through procurement, can accelerate the emergence of radical innovations. Market-creating policies and investment can accelerate diffusion; while wider institutional and infrastructural changes can bring forward reconfiguration. **To accelerate the low carbon transition, we should look to use all of these levers, applying each at the appropriate point in each sector**.

In the second part of this report, we considered how the roles for international cooperation depend on the nature of the problem at hand – how well the problem is understood, and how much agreement there is on the actions to be taken. Our conclusion is that for accelerating transitions, **coordinated action can achieve more than the sum of its parts**. Experimentalist learning can accelerate emergence of new ideas and interest groups that want further action; coordinated diffusion can scale up new technologies and improve them more quickly; and a contracting approach can lock new practices into place, allowing reconfiguration of whole markets and ensuring a transition is sustained. While there are important roles for all-inclusive global cooperative institutions, because they are legitimate and help forge global goals and consensus, much of the history of cooperation for problem-solving occurs in more focussed institutions that are dedicated to specific industrial activities, functions or subsets of the global community. Traditionally, international cooperation has been focussed on relations between governments, but in a growing number of cases effective cooperation engages business and other elements of civil society in tandem.

Looking at the history of technology and at the practices of international cooperation leads to a view of policy action, including by leaders, that varies by stage. As the low carbon transition proceeds from emergence to diffusion to reconfiguration, the modes of international cooperation and the critical policies and government-business interactions will vary. In the early stages – where we find ourselves today – a few governments with large markets and a willingness to invest with firms in new technologies can make a big difference, which is fortuitous because the willingness to invest heavily in decarbonisation will vary a lot across the international system. **Forming 'coalitions of the willing' is therefore essential. Waiting for consensus among all governments, as required in most formal global agreements, will put the climate in jeopardy**. As the evolution of the technology proceeds it becomes more important that more governments are involved, that market "pull" (e.g., through regulations and market incentives) be in place, and that trade distortions be addressed. Eventually, countries representing a critical mass of the global market in each sector will be needed to complete the transition.

In the final part of this report, we applied these principles to ten broad sectors that account for around four fifths of the world's emissions of climate-warming gases. Transitions in these sectors are essential to the complete global decarbonisation of the economy that is needed to protect the climate. They also pose some of the greatest challenges for technology development, policy, industry and society.

Coordinate action within sectors

Looking across all these sectors, there are recurring patterns and mechanisms in transitions: for example, patterns in the role of government procurement policy in creating markets for new products. However, there is no single playbook for transition in each sector. Instead, there are ten broad playbooks, and within each sector there are many sub-playbooks for different segments and opportunities for decarbonisation. Many opportunities depend on progress in other sectors, which is why it is difficult to draw crisp boundaries around each sector. An example of this is the role of decarbonised electricity or hydrogen in enabling deep decarbonisation in the production of materials such as steel, plastics and cement. The central message that emerges from looking across all these sectors is that **solving the climate problem requires looking far beyond the broad concepts of "ambition" and "cooperation." What is needed are concrete plans and coordinated action bespoke to each sector's situation, stage of transition and its relevant actors.** Progress toward deep decarbonisation requires a new way of thinking and acting – one that combines the skills and resources of multiple actors, e.g., government, organised firms, users, and civil society.

In each of these sectors it is striking that the processes of transition to eventual deep decarbonisation are in the early stages. In every sector – with the exception perhaps in some countries of the power sector and light duty vehicles – the experience with technologies, processes and business models is at the stage of emerging in new niches. We have identified promising technological and behavioural options in every sector, but nearly everywhere those efforts are being tested. Experiments are under way, though often, from a global perspective, erratically. Some lessons are being learned, but usually not in a systemic fashion. Real transition has barely begun. **In every sector there are opportunities for stronger and more coordinated action to accelerate progress in each of the three transition phases.**

Accelerating emergence

In the sectors at the earliest stages of transition – such as shipping, aviation, heavy road transport, steel, cement and plastics, there is an urgent need for more support for demonstration projects. In most sectors, that support requires working simultaneously on the following multiple fronts: direct government support, the creation of transformative coalitions focussed on decarbonisation (including industrial frontrunners), reduced barriers to novel ideas, such as from startups, and the reliable creation of new markets for decarbonised products, so that when firms respond they have a market to serve. It is striking that at this early stage of decarbonisation there is a very wide range of options in many sectors, and the best choices are unknown (and highly contingent upon other unknowns, such as the price of feedstocks). This means that experimental demonstration programmes must use portfolio approaches that explore a wide array of opportunities, and lessons about which work and which fail must be learned quickly.

Few, if any, national governments and firms will or can invest in all the needed experimental exploration on their own. **Coordinated international efforts can identify, develop and demonstrate viable options more quickly, and coordinated procurement can create larger niches that attract greater industry investment.** In a few sectors, such as aviation, institutions to help achieve that cooperation exist, but even there the effort at experimentation and learning can be accelerated radically. In most of the sectors we considered, there are no tested institutions that can foster the needed international coordination between multiple actors, including leading governments and firms. Building these institutions and investing in niche experimentation must be an exceptionally high priority.

In addition to experimentation with supply technologies, we find that nearly every sector requires, in tandem, concerted efforts to create market demand at reliable levels that are sufficient to encourage niche supplies. Those market-creating measures can include voluntary uptake (e.g., users that want green cement or green freight), but voluntary efforts alone are unlikely to drive any of the necessary transitions at a pace consistent with climate change goals. **Government procurement can play a critical role in providing assured demand, and in overcoming the chicken-and-egg problem of supply and demand both waiting for each other.** This tandem dance between supply and demand will extend far beyond emergence to the more widespread diffusion of decarbonised products and services.

Accelerating diffusion

In sectors where low carbon innovations are already demonstrated and technically viable, the urgent priority is for market-creating policies to diffuse and scale them up. Critical to diffusion is economic viability and performance. In power, light road transport, and buildings, clean technologies, products and designs are already entering the market in various countries. A diverse array of policy measures – including subsidy, tax, investment, procurement, and regulation – can accelerate their wider take-up, strengthening the feedbacks that improve their quality and reduce their cost. **Coordinated action on market-creating policies, especially between the larger markets in each sector, can accelerate this process, bringing cheaper low carbon options to all countries at an earlier date.** In many cases there will also need to be coordinated investment in infrastructures, such as in heavy duty electric recharging at airports on both ends of electric aircraft routes, at similar locations with respect to electric road freight (or via transmission lines along freight routes).

Regulatory standards are especially important for determining whether (and how) decarbonised products can enter markets. Standards set closest to the point of use have the greatest potential to propagate decarbonisation through the whole value chain of relevant sectors. For example, lifecycle emission standards for buildings and cars can help to drive transitions in the steel, cement and plastics industries, as well as reducing the emissions that come from heating the buildings and powering the cars. This is a high point of leverage, since the additional cost of a low carbon final product is often minimal, whereas the extra cost of producing low carbon materials is often prohibitive. Similarly, standards for the sustainability of agricultural commodities can lend powerful support to efforts in producer countries to protect forests from destruction. In shipping and aviation, standards for fuel appear essential to enabling decarbonisation in these internationally-competitive markets.

As governments and firms that produce decarbonised products look beyond curated niche markets, they will pay close attention to whether leadership on decarbonisation creates competitive disadvantages. Most of the products considered in this study are traded on international markets. (Cement is an exception. Little of that product moves across borders, except in some compact regions, although the role for its trade is rising.) In these settings, with intense competition over increasingly global commodities, **trade and investment measures, such as linking market access to product standards, may be needed to avoid punishing early adopters whose decarbonised products are understandably more costly**. Although in most sectors the need for trade measures is not immediate, international discussions will take time, so there is already a need to start putting in place the processes and institutions that can enable these.

Bringing forward reconfiguration

Reconfiguration will make the transitions to deep decarbonisation ubiquitous. So far, no sector has arrived at this stage. Although, in a few countries (and in markets within countries), the shift to zero carbon renewable power is reaching the point of reconfiguration. Meeting internationally-agreed climate goals will require accelerating the processes of emergence and diffusion and then bringing forward reconfiguration as soon as possible. The key to this stage is broad economic performance along with norms of acceptability. **With more experience in early adopter and diffuser markets, costs and performance will improve. Active policy support, such as carbon pricing and regulation, can help reinforce new low-carbon practices.**

Most global sectors are far from this point, which makes it is difficult to plan in detail, but it is likely that international institutions will be needed on many fronts: to set and enforce standards, to allow trade measures so that markets that avoid carbon limitations do not gain an advantage, and to prevent the market-entry of new high carbon technologies and practices.

The need for and the nature of international cooperation for reconfiguration will vary significantly between sectors. That innovation in new technologies and systems makes decarbonised products more competitive than high carbon alternatives will make reconfiguration easier – this is one of the lessons of the Montreal Protocol. This goal appears within reach in the power sector, and achievable in several other sectors over the medium-term. So far, the experience with deep decarbonisation suggests that even in these sectors strong incentives are needed to reconfigure systems around ultra-low emission technologies at the pace required to meet internationally-agreed climate change goals. In sectors where technological change does not make new low-carbon systems superior to incumbents on their own, stronger incentives and alignment of actions internationally will be needed – including emission taxes, regulations, and trade measures where products are traded – so that free riders see no advantage to avoiding change. **New norms of appropriateness will also be important, meaning that civil society can be instrumental in creating pressure to decarbonise**, just as it was instrumental in the movement to take public health seriously in nineteenth century Europe.

As the low carbon transition moves beyond small niches and begins to have broader impacts, special and growing attention must be paid to how the transition affects justice, including inequality, within societies. System transitions on an unprecedented scale could have profound implications for the distribution of jobs, opportunities, and wealth. Governments have a crucial role to play in supporting a 'just transition'. Clear policy frameworks and investment for decarbonisation in relevant sectors can help businesses, workers and communities to plan for the future. Investment in skills and retraining can ensure workers' expertise is brought to bear on the transition, and not lost from the economy. Labour standards can ensure new jobs are good jobs, and where government procurement is used to accelerate the transition, it can set an example in this respect. Social protection can ensure the risks of change are shared by society. Businesses have a role to play too: in planning for competitiveness in a low carbon future, investing in skills, and giving workers and their unions a seat at the table in developing their plans. Bringing together all of these approaches will be needed where communities have everything at stake.

Cross-cutting technologies

A few technologies have vital cross-cutting importance because they are relevant to the decarbonisation of multiple sectors. Clean electricity can help to decarbonise heating and cooling, many forms of transport, and some industrial processes. **Energy storage** is a critical technology for enabling electricity to be used more widely, especially when it is generated by intermittent renewable power. **Hydrogen** is important as an alternative carrier of clean energy with different characteristics – lighter weight, more easily stored, and closer in similarity to existing fuels – that make it a leading option for the decarbonisation of heavy transport and industrial processes. Improvements in electrolysis and other technologies are needed to bring down its cost. **Sustainable bioenergy** is likely to be needed in aviation and plastics, and potentially more widely. **Carbon capture and storage** will be needed for the decarbonisation of many industrial processes – including some of the processes used to make hydrogen – and perhaps in future for industrial facilities that remove CO_2 directly from the atmosphere, or sequester it while producing energy from biomass. **These technologies should be high priorities for coordinated international development and demonstration, and for action to create the initial niches that give them a foothold in the economy.**

Bioenergy, however, should not be supported indiscriminately. As the low carbon transition progresses, broader constraints such as land availability will come into play. Anticipating these constraints now can avoid creating lock-in to systems that will not be sustainable. Priority use of bioenergy should be given to sectors where it is most needed, such as aviation. Reducing support in sectors where there are viable alternatives – such as road transport and heating – can help ensure that investment in production of biofuels goes to where it will be most valuable.

New and strategic institutions are essential

The view of cooperation outlined here is different from the standard diplomatic experience that has focussed on cooperative intergovernmental needs, and participation in global institutions, such as the UN Framework Convention on Climate Change. These institutions play crucial roles, but creating a rapid transition to deep decarbonisation will require a lot more. **It will require us to build on the Paris Agreement and to look far beyond it, and to focus much more narrowly on specific sectors, technologies and actors: to break down a broad, global problem into smaller units amenable to practical action.**

It is striking how under-developed and uneven the institutions and processes are that could support effective coordination between multiple actors and activities. In some sectors, institutions already exist with competence across the whole sector, such as the International Civil Aviation Organization. In others, institutions have been formed and now reformed: cement and concrete, for example. In many sectors there are institutions that address part of the opportunity: the International Renewable Energy Agency (IRENA), for example, helps to coordinate insights and policy research around renewable power. Some institutions engage only businesses (e.g., the Oil and Gas Climate Initiative) while many others focus more on government. In many cases, institutions are emerging that purport to organise industry and government activity within a sector, yet have little tangible impact.

We have highlighted some of the most promising examples that do exist, but many of these lack the participation of crucial countries, the serious engagement of governments, or the focus on meaningful coordination that goes beyond simply sharing information. **For governments and businesses there are important actions to be taken in each sector, but the single most important activity that "leader" governments can undertake is to combine their interest in action on climate change with a clear, strategic commitment to institution-building.**

These leaders must articulate well-defined standards, so that it is clear when institutions are working and when they are simply talking and diverting attention. They must also back their leadership with resources for the institutions themselves, as well as for creating niche markets for new technologies and expanding incentives for decarbonisation. **Crucially, this effort must be sustained and continuous: governments and businesses should invest in strengthening the most effective existing institutions in each sector, not to create multiple new ones – except where there are clear institutional gaps that must be filled.** It is with these kinds of actions that leadership – which today comes from countries and firms that account for a small fraction of global emissions – can translate into the followership needed for diffusion and eventual reconfiguration around deep decarbonisation.

Political interest in addressing climate change is rising, as is social concern, as well as an awareness within business of the need to act. Many initiatives are under way, but without focus and coordination, these positive forces are dissipated without impact. **To have any chance of meeting the goals set out in the Paris Agreement, we must focus on the points of greatest leverage, and coordinate action for system transitions.** If we act strongly and intelligently, a sustainable economy can be achieved, and a stable climate may yet be preserved for the future.

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ACCELERATING THE LOW CARBON TRANSITION

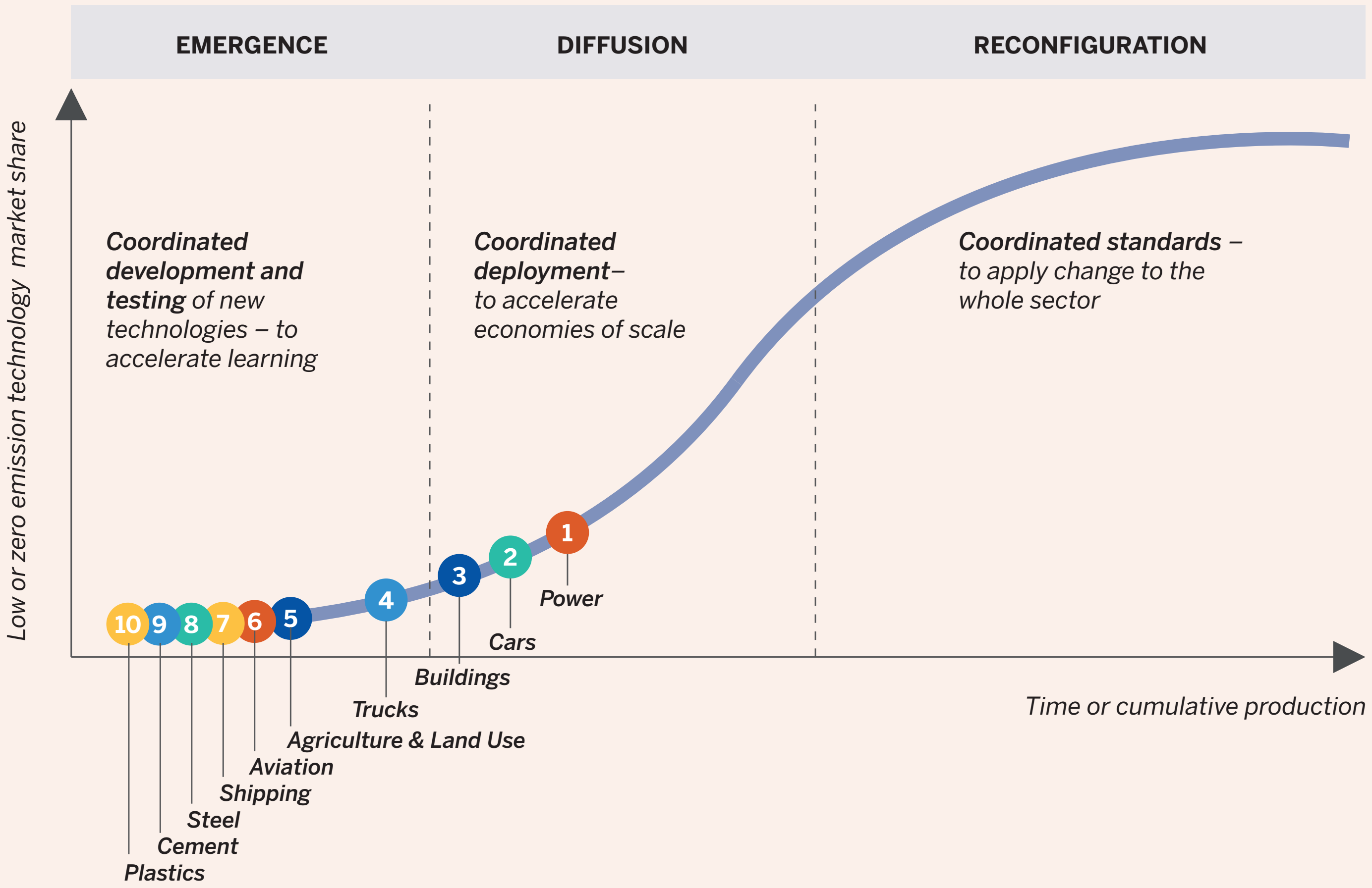
KEY MESSAGES OF THE REPORT

NATIONALLY: FOCUS POLICY ON SYSTEM TRANSITIONS. *Stopping emissions requires fundamental innovation, rapid diffusion of new technologies, and the reshaping of markets and socioeconomic systems. This requires actions far beyond simply putting a price on carbon or adopting bold emissions goals. A more targeted, hands-on and strategic approach to policymaking is required to reconfigure the technologies, business models, infrastructure and markets in each of the greenhouse gas-emitting economic sectors.*

INTERNATIONALLY: COORDINATE ACTION WITHIN SECTORS. *It is within economic sectors or systems that new technologies can be created and diffused eventually to reshape the social and economic activities of which they are a part. This process depends on the actions of policymakers, firms, consumers and civil society actors who, in today's economy, are connected globally. Coordinated international action, appropriate to the phase of the transition, can accelerate this process: by identifying viable technologies more quickly; by increasing incentives for investment and economies of scale; and by levelling playing fields so that first-movers are not held back by the constraints of competitiveness. This means that while formal climate diplomacy tends to be organised around countries, the real focus both for governments and for industry should be coordinating actions in sectors or systems.*

Much more effort is needed to convene the key actors in each sector in order for the goals of the Paris Agreement to be met. Alongside the policy actions for decarbonisation, ***a strategic commitment to institution-building*** *is therefore the single most important activity that can be undertaken by any government wishing to lead the global response to climate change.*

PROGRESS OF SECTORS' LOW CARBON TRANSITIONS



PRIORITIES FOR COORDINATED INTERNATIONAL ACTION

1 POWER

25% of global GHG emissions

DIFFUSION

Renewable technologies diffusing rapidly; others at earlier stages

Coordinated financing and assistance *to provide developing countries with a better clean power offer.*
Coordinated phase-out of unabated coal power*, to send clear signals to global markets.*

2 CARS

7% of global GHG emissions

EARLY DIFFUSION

Innovation has stabilised around electric vehicles Alternative technologies (fuel cells) much earlier stage

Coordinated tightening of regulatory trajectories *towards zero emissions, to send a strong signal of demand and accelerate the shift in industry investment*

3 BUILDINGS

6% of global GHG emissions

Construction:
EMERGENCE

Heating & cooling:
DIFFUSION

Coordination on standards *for efficiency of buildings and heating and cooling technologies.*
Coordinated refocussing of policy support *for low emission heating away from biomass.*

4 TRUCKS

3% of global GHG emissions

EMERGENCE

New technology yet to enter market at scale

Coordinated market-creating policy *– such as emissions standards and purchase subsidies – to send a strong demand signal to truck manufacturers.*

5 AGRICULTURE & LAND USE

24% of global GHG emissions

Agriculture:
EARLY EMERGENCE

Land use:
DIFFUSION

Coordination on standards linked to trade *to avoid deforestation in commodity supply chains.*
Coordinated development and testing *of low emission production techniques along with new methods for soil carbon absorption.*

6 AVIATION

1.5% of global GHG emissions

EARLY EMERGENCE

New technologies yet to stabilise or enter markets

Coordination by airports*, supported by governments, on* ***mandates for use of sustainable aviation fuel*** *on routes between them – to create initial niches for deployment.*

7 SHIPPING

1.6% of global GHG emissions

EARLY EMERGENCE

New technologies yet to stabilise or enter markets

Coordinated large-scale demonstration and testing *of sustainable fuel technology to establish viability and ensure safety.*
Coordination between ports on emissions standards *to be applied on routes between them,*

8 STEEL

4% of global GHG emissions

EARLY EMERGENCE

New technologies yet to stabilise or enter markets

Coordinated testing and demonstration *of low carbon production plants at full industrial scale – to identify and prove viable technologies.*

9 CEMENT

3% of global GHG emissions

EARLY EMERGENCE

New technologies yet to stabilise or enter markets

Coordinated testing and demonstration *of low carbon cement production technologies.*
Coordinated government procurement *to create initial demand.*

10 PLASTICS

3% of global GHG emissions

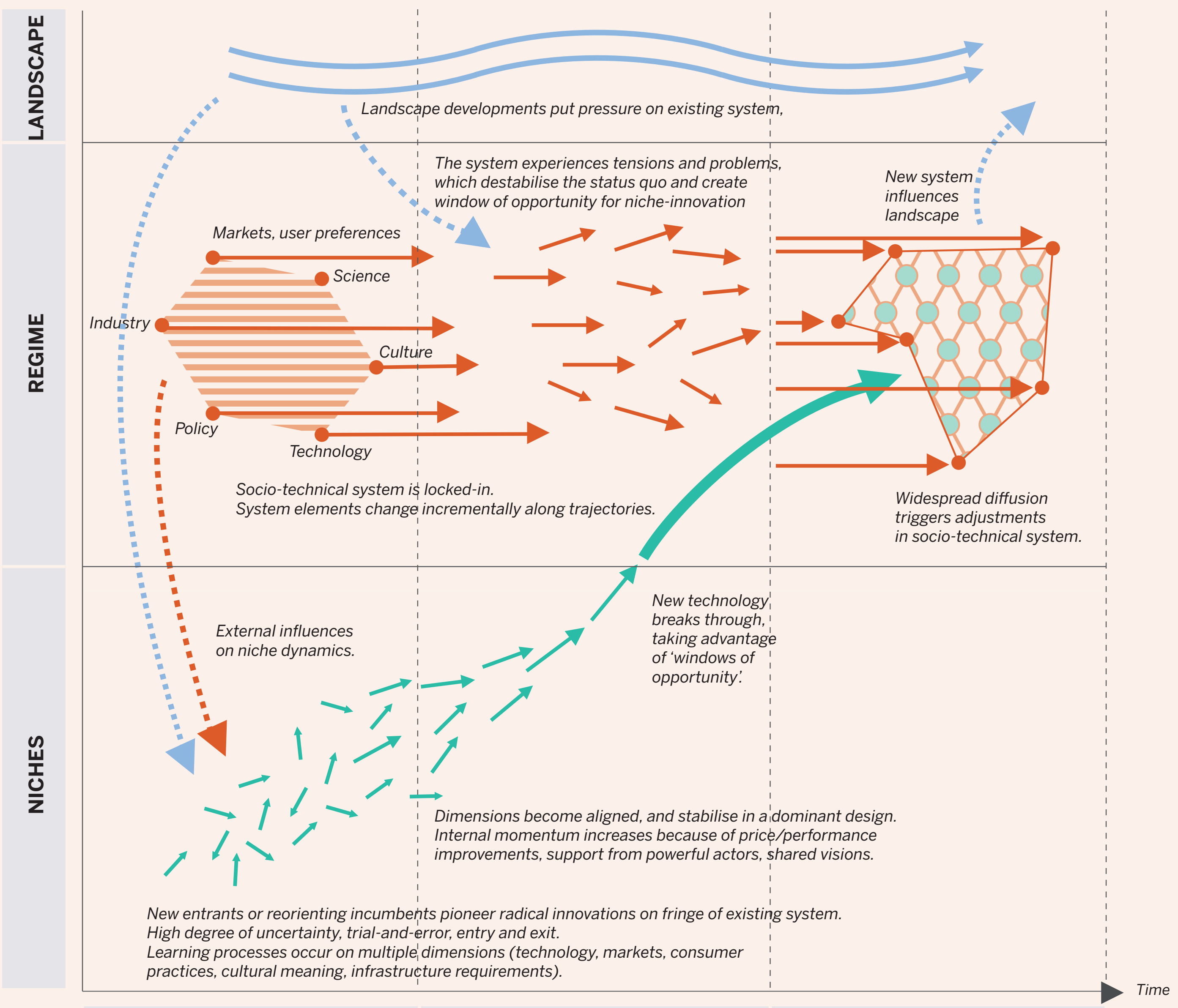
Recycling (in some countries):
DIFFUSION

Production:
VERY EARLY EMERGENCE

Coordinated development, testing and demonstration *of options for low carbon plastics production.*
Coordinated market-creating policy *such as extended producer responsibility to incentivise production of more recyclable products.*

SYSTEM TRANSITIONS AND INTERNATIONAL COOPERATION

THE MULTI-LEVEL PERSPECTIVE ON SUSTAINABILITY TRANSITIONS



Stage of the Transition	**EMERGENCE**	**DIFFUSION**	**RECONFIGURATION**
Dominant mode of international cooperation	**EXPERIMENTALIST LEARNING**	**COORDINATED DIFFUSION**	**CONTRACTING**

Emergence

- *Break problems down into manageable pieces that are aligned with how industries and policies are organised*
- *Create institutions to review the lessons from experiments and figure out what's working (and not)*
- *Coordinate action among a critical mass of willing actors to establish niches and give credible assurance to innovators*
- *Focus on bringing interests of key actors into alignment*

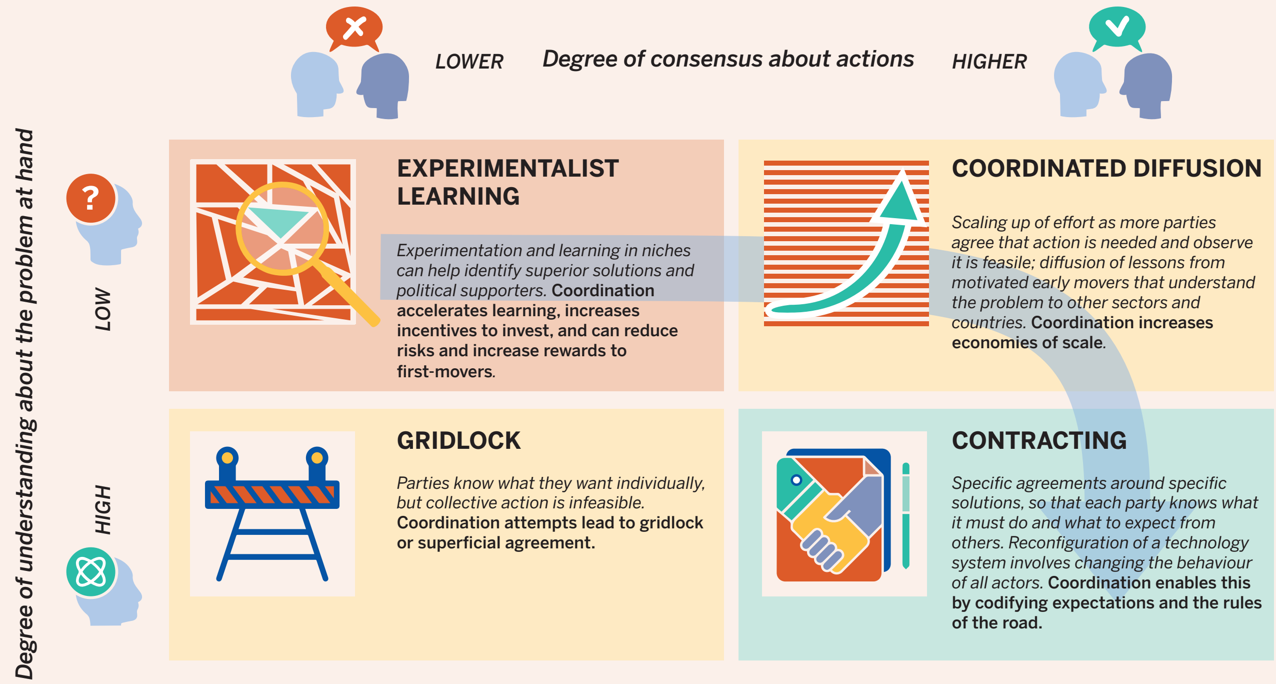
Diffusion

- *Coordinate action to scale up niches into larger market shares - work in small groups: coalitions of first movers*
- *Focus on markets where agreement is easier*
- *Focus on joint actions that, with experience and diffusion, can plausibly lead to reconfiguration of interests*

Reconfiguration

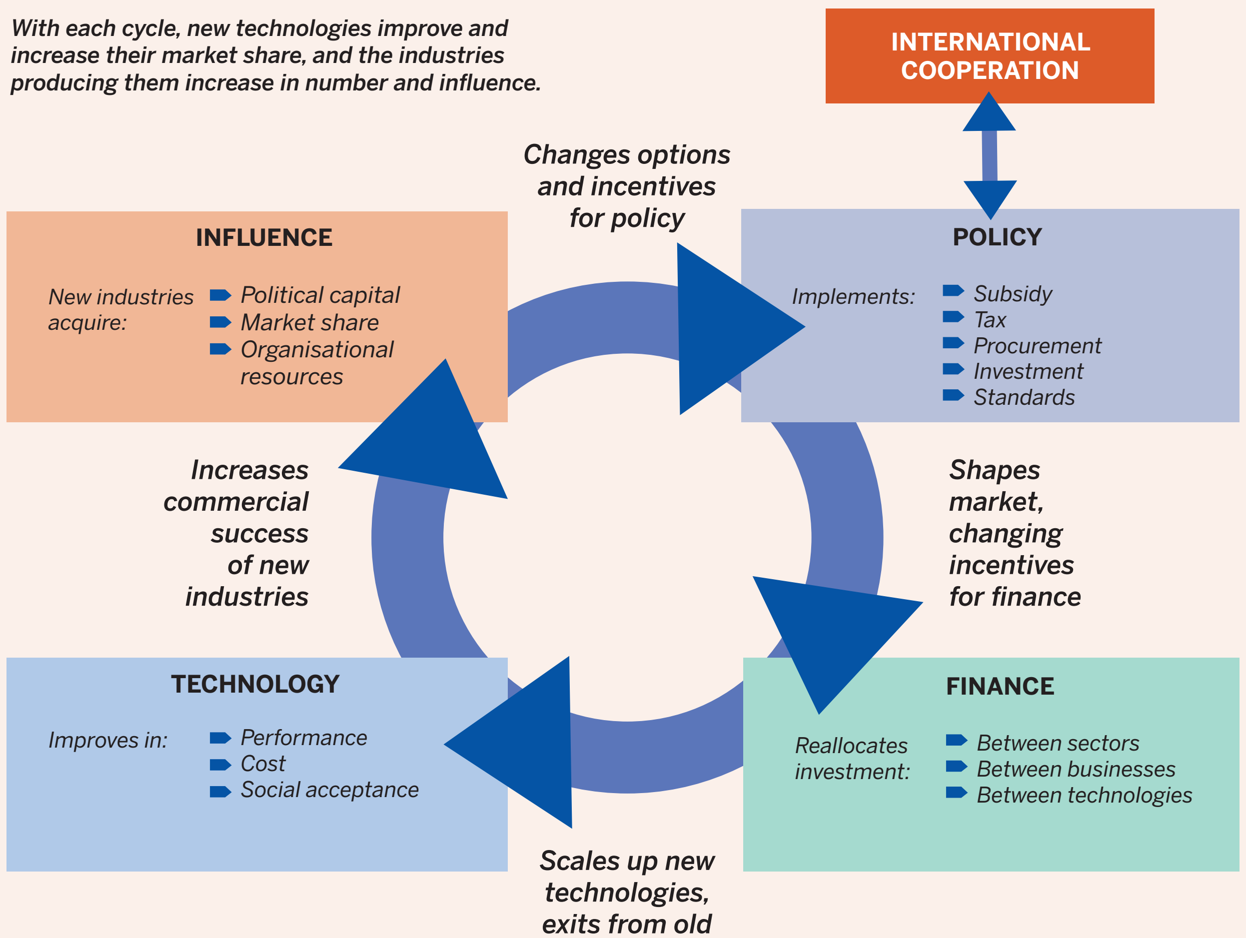
- *Create detailed, reciprocal agreements around known solutions that address known barriers to further application*
- *Negotiate among parties that constitute a critical mass of the market in the relevant sector*
- *Establish credible incentives for participation and compliance, and penalties for the reverse*
- *Set standards; monitor and verify compliance*

COOPERATION MATRIX



REINFORCING FEEDBACK IN THE DIFFUSION OF NEW TECHNOLOGIES AND GROWTH OF NEW INDUSTRIES

With each cycle, new technologies improve and increase their market share, and the industries producing them increase in number and influence.



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