GROUP OF TWENTY

REACHING NET ZERO EMISSIONS

Prepared by Staff of the

INTERNATIONAL MONETARY FUND*

*Does not necessarily reflect the views of the IMF Executive Board

JUNE 2021

EXECUTIVE SUMMARY

Keeping global temperatures to safe levels requires governments to swiftly adopt comprehensive climate policy packages. A growth-friendly strategy consists of four building blocks: a green investment plan, carbon pricing, support to green R&D, and measures to ensure the social fairness of the transition. The green investment push would pave the way for a phased-in rise in carbon prices (by addressing network externalities and market failures), while also boosting demand and employment and helping the recovery from the COVID-19 pandemic. Carbon pricing or regulations are necessary to achieve a deep reduction in emissions, which green investments or R&D alone cannot deliver.

Aligning infrastructure with net zero emissions requires *additional* public investments in the range of 0.5 to 4.5 percent of GDP cumulatively over the next decade, with most estimates clustered around 2 percent of GDP. Investment has to shift away from the extraction and combustion of fossil fuels toward renewable energy, electricity networks and storage, electrification of end-uses, and energy efficiency. While the bulk of investment will come from the private sector in most countries, the public sector has a catalytic role to play through direct infrastructure investment and also through other support measures, such as co-funding for projects with large upfront investment costs, and risk-sharing through insurance and guarantees.

Carbon pricing is a cost-effective way of reducing emissions. Carbon pricing, which can take the form of a carbon tax or an emission trading system, is the least-cost option to deliver deep emission cuts. Moreover, it generates revenues that can be used to finance compensatory measures such as transfers to affected households or green infrastructure spending. Delaying action on carbon pricing by ten years would likely imply missing mid-century net zero emission targets by a large margin, since the prices required at that point to reach those goals would appear unviable. That, in in turn would unleash higher temperature increases than could be achieved with a swift introduction of carbon pricing, with potential irreversible damage to the climate and the economy. Where carbon pricing is not politically feasible, regulations can be used to limit emissions—but these would likely come with higher economic costs. In hard-to-decarbonize sectors such as transportation, agriculture, and land use, carbon pricing should be complemented with sector-specific policies.

The transition to a low-carbon economy needs to be just and create opportunities for displaced workers. The shift in investment can create a geographically concentrated loss in employment, for example in coal mining regions. Proven remedies include programs for retraining workers, support for geographic mobility, the active promotion of new industries, and investments in the quality of life in the region. Apart from funding such efforts, revenue from carbon pricing can be used to compensate affected households for higher energy costs. In advanced economies, this can take the form of reduced taxation or direct transfers to these households. In developing economies, providing basic infrastructure in education, health, clean water access, etc. might be the most effective.

Immediate and coordinated climate action, including transfers of green technology and climate finance for developing economies, is needed to prevent catastrophic climate change. Successfully mitigating climate change will require the participation of all countries, including developing economies where carbon emissions are expected to grow substantially. Joint action through a coordinated green investment push would create beneficial demand spillovers and lift global output and pave the way for higher carbon prices. In addition, a global carbon price floor among the G20—differentiated according to level of development to reflect the principle of common but differentiated responsibilities—would decisively curb emissions and limit carbon leakage among the participants. Bringing every country on board, however, will require financial and technological support for developing economies for which the transition costs are more difficult to bear, due to fast-growing energy needs and less fiscal space to finance green investments.

The note was authored by Florence Jaumotte and Gregor Schwerhoff under the general direction of Oya Celasun, with contributions from Weifeng Liu, Warwick McKibbin and Augustus Panton for model simulations and Jaden Kim for research support. Daniela Rojas provided administrative support. G-20 Notes are available on IMF.org.

REACHING NET ZERO EMISSIONS

Governments have a crucial role to play to bring about a transition from a high- to a low-carbon path, including through investing in catalytic green infrastructure, providing R&D incentives and carbon price signals, and ensuring a just transition. A front-loaded green infrastructure push would also help economies recover from the COVID-19 crisis.[1] This note outlines a pathway of achieving this policy mix in the G20 over the next several years.

A. Risks from Climate Change

1. **Climate change could destabilize economies and threaten global security as well as human welfare.** Unmitigated climate change is expected to increase global warming relative to pre-industrial levels to around 4°C, raising the average temperature on earth's surface to levels not seen in millions of years.[2] This would have significant detrimental effects on macroeconomic stability through lower productivity in agriculture, fishing, and work in non-climatized locations; more frequent disruption of activity and destruction of productive capital due to extreme weather events, natural disasters and rising sea levels; diversion of resources toward adaptation and reconstruction; and possibly increased morbidity and mortality due to more prevalent infectious diseases and natural disasters. According to IPCC (2019), climate change "may lead to increased displacement, disrupted food chains, threatened livelihoods (high confidence), and contribute to exacerbated stresses for conflict (medium confidence)".[3] Given the strong interconnectedness of the global economy, no country is likely to remain unscathed even if the worst warming impacts are initially concentrated in hotter regions. Scientists have also warned about the risk of reaching climate tipping points—such as the melting of glaciers and ice caps—which could not be reversed over human time scales and bring catastrophic consequences for life on the planet.[4]

2. **Ambitious climate action to reach net zero emissions is necessary to achieve the temperature goals set out in the 2015 Paris Agreement.** In the Paris Agreement, countries agreed to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels" to avert catastrophic outcomes. Keeping temperature increases below 2°C, in turn, will require bringing net greenhouse gas emissions to zero by mid-century.[5] This means that carbon emissions must be eliminated or that any remaining carbon emissions must be removed from the atmosphere by natural sinks (for example, forests and oceans) or artificial means (for example, carbon capture and storage).

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[1] IMF (2020a), Chapter 3.

[2] IPCC (2013).

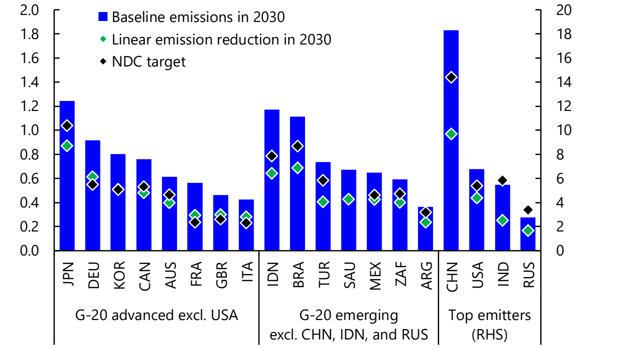
[3] A recent study found that absent climate mitigation policies, mean annual temperatures could be above 29°C in 19 percent of Earth's land surface by 2070 compared with only 0.8 percent currently, affecting a third of the global population and possibly leading to massive migration. Xu et al. (2020).

[4] Wunderling et al. (2021).

[5] Climate stabilization, at any temperature level, requires a reduction of emissions to net zero. Limiting global warming to 1.5°C is considered ambitious climate policy. Aiming at stabilizing global temperature at 2°C, 3°C or higher would allow for more delay, but also requires a reduction to net zero emissions. The reason is that the global average temperature depends on the stock of emissions. Therefore, as long as the emission concentration increases, global temperature will also increase.

Figure 1. Baseline Emissions and NDC Target

(GHG emissions in GtCO2e)



Sources: IMF Staff using the IMF's Carbon Pricing Assessment Tool

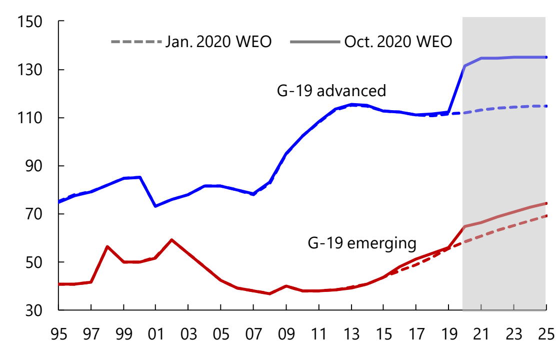
Note: Linear emissions are calculated from baseline emissions in 2021 to net zero emissions in 2050. NDC targets are the unconditional target or, where available, the average of the conditional and unconditional target. For EU countries, the EU commitment to reduce emissions by 55% is used. Saudi Arabia's NDCs could not be converted to emission reduction targets.

3. **Reaching net zero emissions will require much more ambitious policy than has been implemented so far.** Almost all countries have defined Nationally Determined Contributions (NDCs) to implement the 2015 Paris Agreement and are expected to adopt more ambitious NDCs over time, including in the 2021 United Nations Climate Change Conference (COP26) meeting in Glasgow, UK. Current NDCs are insufficient to reduce global warming to 2°C or below, being more compatible with 3°C warming by 2100.[6] A growing number of countries (58 to this day, covering 53 percent of global emissions) have since 2015 specified their long-term commitment by announcing "net zero emissions" objectives by mid-century. This includes the G20 members Argentina, Brazil, Canada, China (2060), the EU, France, Germany, Japan, South Africa, Korea, UK, and US. However, few G20 countries have put these targets into policy or law (as reflected in "baseline" emission paths being higher than what would be consistent with NDC targets for most countries in Figure 1). To implement the net zero emissions commitments, countries will need to ramp up action significantly and quickly on carbon pricing and investment in clean technologies from current levels (see below).

Figure 2. Government Debt and Green Recovery Spending by Country

Government debt

(percent of GDP)

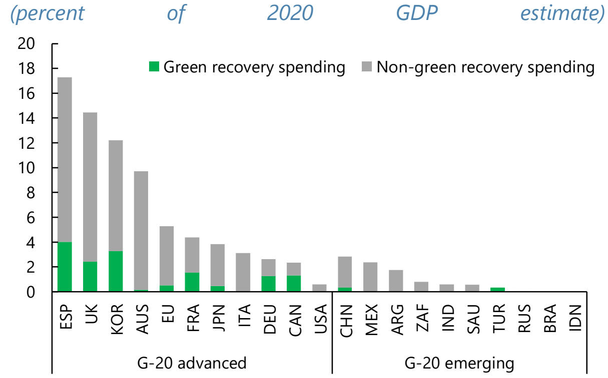


Sources: IMF, World Economic Outlook; and IMF staff calculations.

Note: Includes G-19 plus ESP. ESP is a permanent invitee.

Total and green recovery spending by country

(percent of 2020 GDP estimate)



Sources: IMF World Economic Outlook; Global Recovery Observatory (2021); and IMF staff calculations.

Note: The data on the website used update weekly. These numbers are from May 24, 2021. Funds that have been given a designated purpose by the EU but have not yet been allocated to a member country are counted under European Union (EU) spending.

[6] UNFCCC (2021).

B. The Opportunity to Reset Economies on a More Sustainable Path

4. The current recovery from the Covid-19 crisis presents a unique opportunity to reset economies on a more sustainable path. Where fiscal space is available—bolstered in many economies by historically low interest rates—governments are considering mobilizing large investments in infrastructure to help economies recover. The type of investments made will influence economies' carbon trajectories for decades. At the same time, debt has climbed to multi-decade highs in both advanced and emerging G20 economies (Figure 2), meaning that investment packages of the magnitude currently planned cannot be repeated any time in the near future. It is therefore best to use the existing fiscal space to meet multiple goals at the same time and in particular to make critical progress toward a low-carbon economy. While this note focuses on investments toward the latter goal, developing economies also face substantial investment needs in adaptation to climate change.

5. So far a moderate share of recovery packages was dedicated to green spending, but some large economies are acting more boldly. In 2020, announced spending on recovery measures (which are distinct from the immediate rescue packages) amounted to US$1.9tn. The low-carbon (or "green") share of the recovery spending increased during the year 2020 but reached only 18 percent by the end of the year[7] amidst other crucial needs to sustain livelihoods.[8] Recovery packages are very diverse in terms of their size and their greenness (Figure 2). The EU's earmarking of 37 percent of the total disbursement under the 2021/22 Recovery and Resilience Facility for climate-friendly investments and the proposed American Jobs Plan with substantial support to green the economy—if passed—are notable actions to set economies on more sustainable paths.[9]

6. Climate policy has important co-benefits through improved health and productivity.[10] Climate policy discourages the burning of fossil fuels, thereby reducing local air pollution. The latter caused 10 million deaths globally in 2012.[11] In South Asia, 7 percent of pregnancy losses can be attributed to local air pollution.[12] In addition to averting these incalculable losses, reducing local air pollution increases labor productivity and effective labor input.[13] By encouraging the use of public transportation over individual transportation, climate policy can also reduce congestion.[14] As a result, a considerable amount of climate policy is in the immediate domestic economic interest of countries.

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[7] UNEP (2021).

[8] The classification of recovery measures and the definition as "green" is based on the "subjective assessment" of Hepburn et al. (2020).

[9] The EU has also announced enhancements to the InvestEU program for sustainable infrastructure and a climate share of 25 percent of the EU budget.

[10] M. Li et al. (2018).

[11] Vohra et al. (2021).

[12] Xue et al. (2021).

[13] Graff Zivin and Neidell (2012).

[14] Parry et al. (2014).

C. A Comprehensive Policy Package is Needed: Combining Carbon Pricing with Green Infrastructure Investment

Box 1. A Comprehensive Mitigation Package to Reduce Emissions by 80 Percent

IMF (2020a) examines an illustrative comprehensive policy package scenario to reach close to net zero emissions by mid-century in a growth- and distribution-friendly way. The purpose of this analysis is to illustrate the role that a green fiscal stimulus can play in combination with carbon pricing for each country to reduce their emissions substantially. The 2050 objective is operationalized as a reduction in gross emissions by 80 percent, assuming that the remaining emissions are absorbed by negative emissions technologies.[1] In this scenario, each country/region is assumed to reduce independently its own emissions by 80 percent by 2050, except the group of selected oil-exporting and other economies which keep emissions at current levels (going beyond that goal would entail a further loss in output for fossil-fuel exporting economies already facing a substantial loss in income due to the fall in global oil and gas demand). The proposed policy package includes:

Green supply policies. These consist of a subsidy on renewables production and a 10-year green public investment program (starting at 1 percent of GDP and linearly declining to zero over 10 years; after that, additional public investment maintains the green capital stock created). Public investment is assumed to take place in the renewable and other low-carbon energy sectors, transport infrastructure, and services—the latter to capture investments in the energy efficiency of buildings.

Carbon pricing. Carbon prices are calibrated to achieve the 80 percent reduction in emissions by 2050 in each country/region, after accounting for emission reductions from the green supply policies. A high annual growth rate of carbon prices (7 percent) is assumed to ensure low initial levels of the carbon price given the post-crisis context. Carbon prices start at between US$6 and US$20 a ton of CO2 (depending on the country), reach between US$10 and US$40 a ton of CO2 in 2030, and are between US$40 and US$150 a ton of CO2 in 2050.[2]

Compensatory transfers. Households receive compensation equal to 25 percent of carbon tax revenues, which should protect the purchasing power of low-income households through targeted cash transfers.

Supportive macroeconomic policies. The policy package outlined above implies a fiscal easing that requires debt financing for the first decade and occurs amid low-for-long interest rates. The debt increase to finance green spending is only partly offset by the additional carbon revenues.

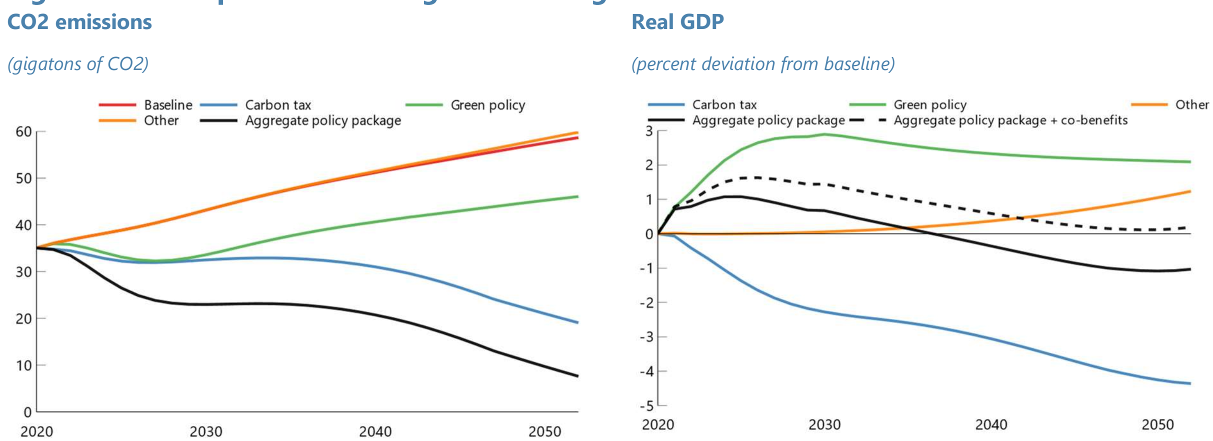
1/ IPPC (2018).

2/ The range of estimates of carbon prices needed to reach a certain level of emission reduction is large (see, for instance, (IPCC (2014), Figure 6.21.a; High-Level Commission on Carbon Prices (2017)). IMF (2019a), for instance, recommends a carbon price of $75 by 2030. The relatively low levels of carbon prices in simulations in IMF (2020a) reflect (1) the fact that carbon prices are combined with other instruments (green infrastructure investment and green subsidies) that achieve part of the emission reduction; (2) the high assumed growth rate of carbon prices, which back-loads their increases (which forward looking agents in the model perfectly foresee); and (3) the fact that the G-Cubed model embeds more substitutability between high- and low-carbon energy (based on econometric evidence) than engineering-based models, which means that a given amount of emission reduction can be achieved with lower carbon prices than otherwise.

7. **A growth- and employment-friendly transition toward net zero emissions would require a multi-pronged strategy.** A green infrastructure push would have the double benefit of supporting output and employment in the recovery from the Covid-19 crisis and putting in place the conditions to support the transition. At the same time, a green investment push alone is unlikely to reduce emissions to net zero. Carbon pricing is critical to mitigation because it incentivizes both energy efficiency gains and a reallocation of resources from high- to low-carbon activities. At the same time,

even a combination of investment and carbon pricing would need to be complemented by an active support of the development and industrial-scale deployment of new low-carbon technologies to achieve a full transition to net zero emissions, since in some sectors, no viable low-carbon technology exists at the moment. Last but not least, a fair transition requires compensating affected households for the impacts of higher carbon prices and supporting the transitions of workers from high- to low-carbon sectors; revenues from carbon pricing could be used to this end (see Section G). Box 1 provides an illustrative example of policy package[15] and its elements are discussed below. In addition to this package consisting of fiscal instruments, central banks and financial supervisors have an important role to play by ensuring that the financial sector takes climate-related risks into account[16] and increasing transparency on these risks.[17]

Figure 3. A Comprehensive Mitigation Package to Net Zero Emissions



Sources: IMF (2020a), Chapter 3; and IMF staff calculations.

Note: The "Aggregate policy package" is a combination of the "Carbon tax", "Green policy", and "Other" layers. The "Other" layer includes the compensatory transfers to households and the avoided damages from climate change resulting from the mitigation package. The carbon tax layer assumes that the tax is used for debt repayment. As a result, GDP losses are higher than they would be if the revenue were used for investments or to reduce other taxes. Co-benefits in the form of improved health (due to lower local pollution) and reduced congestion are additional benefits from carbon taxes and other mitigation policies. Their valuation is based on Parry, Veung, and Heine (2015).

Green Infrastructure Investments

8. Green public infrastructure can take various forms. In the transportation sector, the government can accelerate a transition to low-carbon options by providing the supporting infrastructure like charging stations for electric vehicles, supporting drivers' access to low-carbon transportation. Similarly, in the energy sector, more interconnected and reliable electricity networks would help increase the amount of (intermittent) renewable energy that can be integrated into the grid, catalyzing private investment in wind and solar electricity generation. Providing incentives for energy-saving building retrofits can also help overcome the misaligned incentives, between renters and landlords for example, in that sector.[18] Deploying green infrastructure will also facilitate more

[15] IMF (2020a).
[16] Bolton et al. (2020).
[17] NGFS (2021).
[18] Bird and Hernández (2012).

ambitious climate policy later by facilitating affordable low-carbon alternatives and forming a constituency in favor of climate policy.[19]

9. Green investments can have a significant stimulating effect on GDP and employment. By adding to demand and the productivity of the low-carbon private sectors, the green supply policies described in Box 1 could raise annual global output by about 2 percent compared to the baseline on average over 2021-30 (Figure 3), and total employment by nearly 1 percent on net —equivalent to 30 million additional people being employed over that period. The investment push reduces emissions by 22 percent in 2030 compared to the baseline. This is equivalent to a 4 percent reduction compared to 2021 emissions (in the baseline, emissions increase by 23 percent between 2021 and 2030).

10. Estimated multipliers of green investments are high. While the scenario analysis mentioned above embeds multipliers estimated for general infrastructure investment,[20] emerging evidence suggests that multipliers of green investment could be at least as large as for other energy investments. The median estimate of cumulated multipliers for sustainable energy investments (investments that don't contribute to emissions on net) is larger than one for the first five years and appears to be larger than those of energy investments that are not environmentally friendly.[21] In addition, job multipliers—defined as the number of jobs created by a certain amount of energy generation—are higher for renewable energy generation than for fossil fuels.[22] Taken together, these findings suggest that the output and employment effects simulated and described above could be a lower bound for actual impacts.

11. The economic and social outcomes of public investment depend crucially on the efficiency of spending, calling for strong public investment management practices. On average, over one-third of public investment value is lost due to inefficiencies, and better public investment management—that is strong public sector institutions that effectively plan, allocate, and implement public investment—can reduce losses by more than half.[23] According to the results of 60 conducted Public Investment Management Assessment (PIMA)—the IMF's tool to analyze the strength of public investment management practices—countries need to improve their project appraisal and selection capacities as well as maintenance funding which see the weakest scores in the public investment cycle. Integrating climate change perspectives in public investment management would enable countries to better design and implement climate relevant infrastructure. In this regard, the IMF is also developing the PIMA Climate Change Module (PIMA CC) with a particular focus on the resilience and sustainability aspects—PIMA CC integrates climate change issues into PIMA framework and helps strengthen governments' capacity to address risks related to climate and natural disasters in public investment.

Cost and Benefits of Carbon Pricing

12. Carbon pricing has several advantages as a tool for achieving rapid and substantial emissions reductions. Carbon pricing provides across-the-board incentives for shifting to cleaner

[19] Pahle et al. (2018).
[20] They are based on the results from Calderón, Moral-Benito, and Servén (2015).
[21] Batini et al. (2021) estimate fiscal multipliers for investments in renewables to be about twice as large as those for investments to extract and use fossil fuels.
[22] Wei, Patadia, and Kammen (2010).
[23] IMF (2021).

fuels and, by raising the cost of high-carbon energy, it also incentivizes higher energy efficiency. By contrast, green supply policies if implemented alone tend to lower the cost of energy and hence do not incentivize energy efficiency as much, making it harder to reach net-zero emissions targets. Moreover, a strong commitment to carbon pricing would not only boost the adoption of available clean technologies but also encourage the development of new ones.[24] The carbon price paths described in Box 1 can deliver an 80 percent reduction of global emissions by 2050 if combined with a green investment push (Figure 3). While carbon prices hurt economic activity by increasing the cost of polluting energy, when used in combination with a green investment stimulus, the net global output effects are simulated to be positive for the first 15 years (at about 0.7 percent relative to baseline) and moderately negative thereafter; when health and congestion related co-benefits are included, the effects are positive or neutral for global output throughout.

13. The costs from carbon pricing can be partially offset by benefits of reducing carbon emissions, which are not fully captured by the simulation analysis. These additional benefits include the productive recycling of revenues (instead of debt reduction as in the simulation), lessened informality, impacts on productivity from lower local air pollution, and induced technical change. Using carbon tax revenues to fund productive investment or lower distortionary taxes can partly offset the loss in GDP resulting from higher energy costs. It is preferable to tax things that are harmful to the public health and the economy (like CO2 emissions) and instead reduce taxation on things that are desirable, like labor input.[25] Such a strategy increases tax efficiency and produces a double dividend of less environmental damage and lower labor cost. In addition, as it is more difficult to avoid carbon taxes than most other taxes, a switch from labor to carbon taxation also motivates some firms to move from the informal to the formal sector, thus increasing productivity and formal employment.[26] Through lowering local air production, carbon pricing and other mitigation policies improve health outcomes and hence labor productivity.[27] Finally, carbon pricing will induce technical change in low-carbon technologies, further supporting the expansion of economic activity in low-carbon sectors. The empirical literature—albeit largely focused on advanced economies—currently suggests very small or, in some cases, positive impacts from carbon taxes on GDP and other estimates of economic activity.[28]

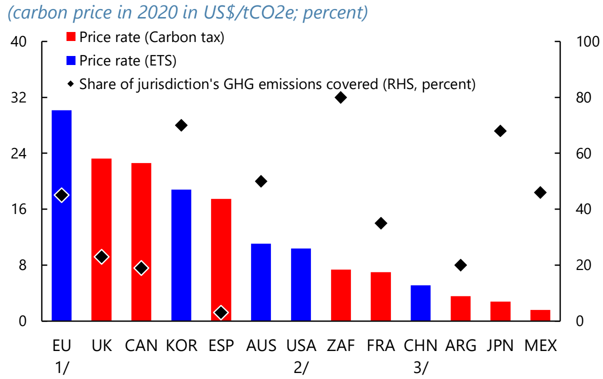
14. Where carbon pricing would not be politically feasible, regulations that limit emissions are an alternative policy tool. Regulation can be an entry point to climate policy. In many countries, carbon pricing, which ensures that carbon emitters and consumers internalize the cost of the climate externality, faces political economy obstacles. In these cases, regulation—which is an indirect form of putting a cost on carbon emissions—can help start the transition. This can improve the chances of

[24] IMF (2019b); High-Level Commission on Carbon Prices (2017).
[25] IMF and OECD (2021).
[26] Bento, Jacobsen, and Liu (2018).
[27] Graff Zivin and Neidell (2012).
[28] Pigato et al. (2020), Chapter 1. For example, Metcalf and Stock (2020) find no negative impact from existing carbon prices in Europe. (Metcalf 2019) and (Bernard, Kichian, and Islam 2018) similarly find no impact of carbon tax on GDP in British Columbia; (Azevedo, Wolff, and Yamazaki 2018) find there was no negative impact on jobs in British Columbia; and (Yamazaki 2017) finds a net increase in jobs from the carbon tax in British Columbia. (Cali et al. 2019) find an increase in energy taxes in Mexico and Indonesia increased firm-level productivity, likely due to inducing firms to invest in energy efficiency technologies at the frontier. Lastly, (Schoder 2021) finds a negative multiplier from environmental taxes of 1 to 1.8 at the peak, in many cases not significantly different from zero, and overall less than those of income taxes.

introducing carbon pricing later and be an important step in a policy sequencing approach.[29] However, in contrast to carbon pricing, which provides across-the-board incentives to agents to identify the least-cost way of reducing their emissions, regulations require the government to identify where and by how much emissions should be reduced, requiring complex and multiple rules for different sectors, and don't generate an income to support a just transition or finance the clean transition. Seeking to lower emissions through regulations would therefore be likely to be more costly for economic activity (though in the long run any successful policy for cutting emissions is likely to be better for global income than not acting at all).

Figure 4. Prices in Implemented Carbon Pricing Initiatives

(carbon price in 2020 in US$/tCO2e; percent)



Sources: World Bank (Carbon Pricing Dashboard); and IMF staff calculations.

1/ The bar contains three non-EU countries (Norway, Iceland, and Liechtenstein) due to data limitation.

2/ Simple average of carbon prices subnational ETS: CA, MA, and Regional Greenhouse Gas Initiative (RGGI).

3/ Simple average of carbon prices subnational ETS: Beijing, Chongqing, Fuijan, Guangdong, Hubei, Shanghai, and Tianjin. G20 countries not shown here do not have a carbon price.

15. The number of jurisdictions applying carbon pricing and the amount of emissions covered have increased every year. Both carbon taxes and emission trading have been used successfully: Sweden's carbon tax has been introduced in 1991 and has reached a level of US$120/tCO2. California's emission trading system was introduced in 2012 and now covers nearly 90 percent of its greenhouse gases (at a price of about US$17). In 2021, the total number of carbon pricing schemes globally has reached 61, and 23.2 percent of global emissions are covered by a carbon price (World Bank 2020). At the same time only three countries have a carbon price exceeding US$75—the price identified as compatible with the 2°C target[30]: Liechtenstein, Sweden, and Switzerland. Twelve G20 countries have a form of carbon pricing and the EU ETS covers all EU countries (Figure 4).

The Role of Technology and Innovation

16. Further technology developments are key to enable and facilitate the transition to a low carbon economy. The upside potential of supporting innovation in hydrogen technologies, batteries, and carbon, capture, utilization, and storage (CCUS) is very large. These technologies are available already and further innovations could make them competitive. Green hydrogen is an energy carrier that can be synthesized through electrolysis with renewable energy and can be used in industrial applications which are difficult to decarbonize otherwise (for example steel production) and heavy transport (for example in aircraft). Batteries in electric cars not only help decarbonize the transport sector, but—by expanding storage capacity—they can also help integrate variable renewables into

[29] Pahle et al. (2018).

[30] IMF (2019a).

electricity production. CCUS technology could be used to capture the emissions in the production from "blue hydrogen"[31] or to withdraw carbon from the atmosphere.

17. Early public support for the development and industrial-scale deployment of breakthrough innovations is key to make the transition to net zero possible. While a lot of emission reductions can be achieved with existing technology[32], additional innovation is likely needed for reaching net zero emissions globally. Supporting risky R&D with long lags to returns addresses the market failure (leading to suboptimal innovation) arising from the positive spillovers of technology development that innovators do not internalize. Public procurement can be used to increase the size of the market for clean technologies, thus incentivizing innovation.[33] Blue hydrogen, for example, uses CCUS, so that government demand for blue hydrogen supports the development of CCUS. In addition, supporting technology transfers from advanced to developing economies would accelerate decarbonization globally. Options to enhance technology transfers are de-risking mechanisms like loan guarantees, public equity co-investments, and political risk insurance for private investments in low carbon technologies in developing economies.[34]

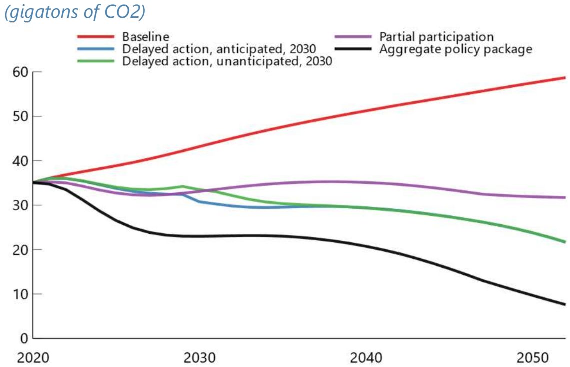
D. Need for Immediate and Universal Action

18. Delaying carbon pricing makes it extremely difficult to reach net zero emissions. In an illustrative "delayed action" scenario, the green stimulus investment is implemented in 2021, but the start of carbon pricing is delayed to 2030. It is assumed that the carbon prices applied in the "aggregate policy package" of Box 1[35] are simply shifted back by nine years. This delay implies that emissions are merely stabilized at today's level and are far from reaching net zero by mid-century (Figure 5). Moreover, the trajectory of economic activity is smoother when the introduction of carbon prices is anticipated (see blue line in Figure 5) than when it is unanticipated (see green line in Figure 5). An alternative would be to assume that the carbon prices increase more sharply after their delayed introduction. This might still make it possible to reach net zero emissions by mid-century, but the fast rate of increase in carbon prices can be expected to lead to large economic costs. While an economy can adjust smoothly to a moderate

Figure 5. Delayed Action and Partial Participation Scenario

CO2 emissions

(gigatons of CO2)



Source: IMF staff estimates

Note: In the "delayed action" scenario all countries implement a green stimulus package in 2021, but the introduction of carbon prices is shifted to 2030. "Anticipated" refers to the scenario, where economic actors anticipate the introduction of carbon prices in 2030 and adjust decisions accordingly. In the partial participation scenario, China, EU, Japan, and USA implement both a green fiscal stimulus and a carbon price, while the other countries do neither.

[31] van Renssen (2020). "Blue" hydrogen is produced from natural gas, but the generated CO2 is stored underground through CCS. Both green and blue hydrogen are zero-carbon fuels (Englert et al. (2021a)).

[32] Pigato et al. (2020).

[33] IEA (2020b), Section 2.7.

[34] Pigato et al. (2020).

[35] IMF (2020a).

increase in carbon prices[36], the capital replacement rate might be too slow to react without large losses to drastic increases.[37]

19. Global participation is needed to reach net zero emissions. Some of today's major carbon emitters (China, EU, Japan, Korea, and USA) have made pledges to reach net zero emissions by mid-century. This will reduce a large share of emissions. In addition, the transition in these countries will provide technology and policy solutions that will make it easier and more affordable for other countries to follow.[38] However, stabilizing the global climate will require global emissions to go to net zero. In the absence of climate policy, today's smaller emitters will become major emitters as their populations grow and per capita incomes increase. It is thus important that countries other than today's top several emitters follow quickly. An illustrative "Partial participation" scenario assumes that China, the EU, Japan and the US form a coalition to reduce their emissions to net zero, but none of the other countries act.[39] The reduction in emissions by the coalition countries does avoid the increase in global emissions seen in the baseline. But the absolute level of emissions declines only moderately compared to today's level, reflecting the continued increase of emissions in the countries that do not participate (Figure 5). In this case, global emissions will be far from reaching net zero, underscoring the need to ensure broader participation in mitigation strategies.

20. Coordinated green stimulus investments would generate positive demand spillovers, making the transition easier for all. Investing together in a green economy would spur the development and deployment of new carbon-saving technologies, by creating a larger market for them, enabling more learning-by-doing, and generating mutually beneficial knowledge spillovers (IMF 2020b). A coordinated green investment push would also boost global activity beyond what each country could do individually, especially in a context of accommodative monetary policy.

21. An agreement on a minimum carbon price among G20 countries would help scale up action while limiting negative spillovers. A common minimum carbon price among the G-20 economies would help protect firms in energy-intensive and trade-exposed sectors from losing competitiveness and prevent production from shifting to countries with lower prices within the group.[40] It could also avoid the use of potentially contentious and complex border-carbon adjustments by countries that plan to move ahead with carbon pricing. A minimum price system could embed a lower carbon price floor for countries with lower per capita incomes in recognition of the principle of common but differentiated responsibilities between countries, as well as the higher carbon intensity of their economies. A higher carbon intensity makes emissions more responsive to changes in carbon prices, requiring a smaller increase to achieve a given reduction in emissions.[41]

22. Financial support will be necessary for developing economies, which are expected to incur greater costs along the transition yet have little means to pay for it. The comprehensive policy package boosts output throughout in China, the EU, Japan and the US until 2050, especially when co-benefits are accounted for (Figure 6, left panel).[42] The net output effect is negative through

[36] Metcalf and Stock (2020).
[37] Luderer et al. (2016).
[38] Schwerhoff (2016).
[39] Korea was not modelled separately in G-cubed and hence could not be included in the illustrative coalition.
[40] IMF (2019a); Parry, Black, and Roaf forthcoming.
[41] IMF (2019a).
[42] IMF (2020a).

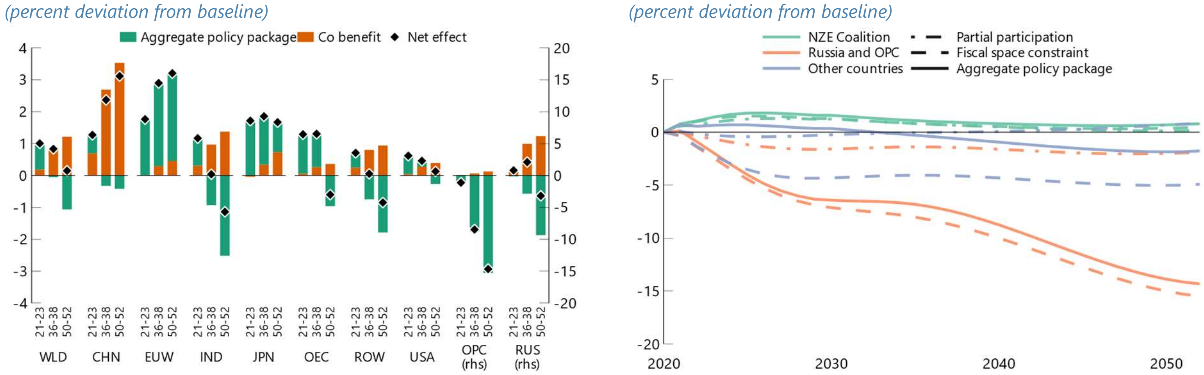
2050 for oil producers; while it is positive in the near and mid- term, and negative in the long term for non-oil producing developing economies apart from China. While the size of the net effect depends on policy design (the use of carbon pricing revenue, in particular) and how large the co-benefits are, the relative impacts are clear: the transition to a low-carbon economy is likely to be more costly for developing countries that have faster growing energy needs than advanced economies. In addition, developing economies typically have more constrained fiscal space, limiting the option of using a green fiscal stimulus to make the transition growth friendly. If developing countries were to only implement carbon pricing and not the green fiscal stimulus, their output would be lower than in the aggregate policy package (Figure 6, right panel). Climate finance—financing emission-reducing investments in developing economies—would allow for a more even burden sharing and help the global economy reach net zero emissions. Many developing economies are prepared to ramp up their NDCs conditional on receiving climate finance; and given that many of the world's lowest-cost mitigation opportunities exist in emerging and developing economies, it is in the global interest to make sure that these are pursued. Climate finance is also justified on the grounds that developing economies are likely to face much higher investment needs for adaptation to climate change, given that they are typically in regions of the world that are more exposed to damages from climate change.[43]

23. While oil exporters can expect a drop in demand for their main export commodity, there are also potential upsides from climate mitigation. Fossil fuel exporters are bound to experience the largest economic losses from the transition of the global economy to a low-carbon path. Even without a domestic carbon tax, the fall in global demand for fossil fuels would significantly lower these economies' fiscal revenues and economic activity. However, potential upsides are higher prices from

Figure 6. Regional Effects and Scenario Comparison

Real GDP and Co-benefits, three-year average *(percent deviation from baseline)*

Real GDP *(percent deviation from baseline)*



Source: IMF staff estimates

Note: "OEC" includes Australia, Canada, Iceland, Liechtenstein, and New Zealand. "OPC" includes Ecuador, Nigeria, Angola, Congo, Iran, Venezuela, Algeria, Libya, Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen. ROW includes the rest of the world. The "NZE coalition" includes China, EU, Japan, and USA. "Other countries" in the right-hand side panel include India, ROW, and OEC; however, OEC countries have a small weight and excluding them does not alter the results. In the "partial participation" scenario, the NZE coalition countries implement both green investments and carbon pricing in 2021, while the other countries do neither. In the "fiscal space constraint" scenario, the NZE coalition countries implement both green investments and carbon pricing in 2021, while the other countries do only carbon pricing. In the "aggregate policy package", all countries implement both green investments and carbon pricing in 2021.

[43] World Bank (2013). Hallegatte, Rentschler, and Rozenberg (2020) highlight that much of adaptation can be done in the form of enabling the population to become more resilient, through fighting poverty and building social safety nets. Infrastructure is only one (though important) aspect.

remaining oil sales (including through imposing an export tax on oil sales themselves as a replacement for carbon pricing abroad), lower climate damages and the potential to produce zero-carbon fuels with existing infrastructure for transporting, storing and exporting fossil fuels. Further options for oil exporters include the re-use of carbon emissions and their recycling.

E. Zooming into Green Infrastructure Investment Needs

24. A shift from fossil fuels toward low-carbon energy will require large investments to replace installed carbon-intensive capital with low-carbon capital. There is thus a need for a strong increase in total investments in the next 20 years and a change in the composition of investment. The total amount of investment should increase, because in some cases low-carbon technology requires more investment (Table 1). One reason for this is that a new network infrastructure needs to be constructed, like electricity grids or electric vehicle charging infrastructure. Also, in many sectors, reducing emissions means building infrastructure that has higher initial cost and lower operating cost due to a reduction in fuel consumption. An example for this is renewable energy, which costs more initially, but does not require fuel. Investments in energy efficiency have a similar structure. After the initial cost for setting up a low-carbon system, less investments are needed. As a result, the investment need is hump shaped, with an increase in the next 20 year and a decrease to recent historical levels after that (Figure 7).

Table 1: Additional Cumulative Investment Needs for the Decade 2021 to 2030

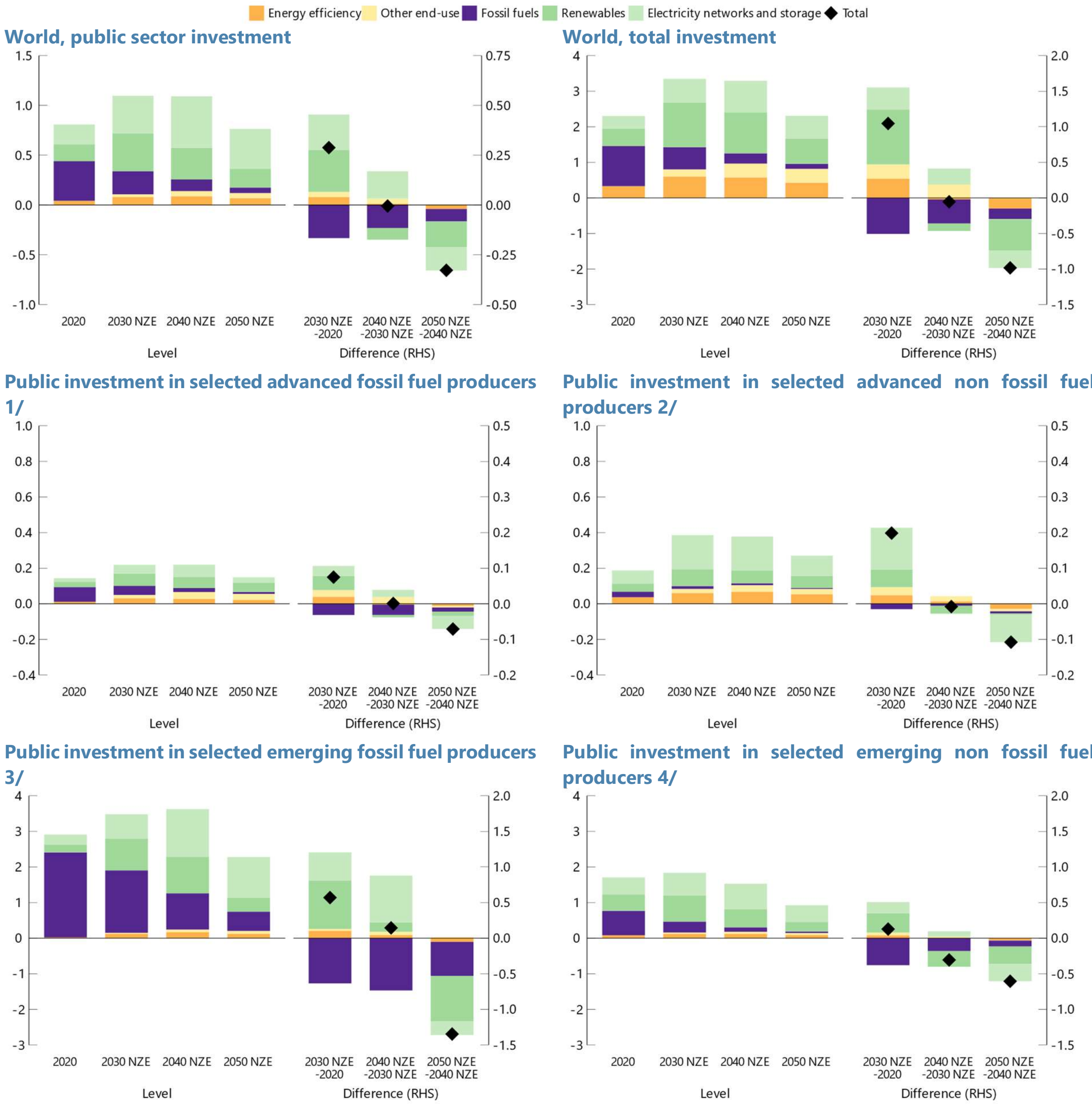
Source	**Sectors**	**Period considered**	**Public investment need** *(percent GDP)*	**Total investment need** *(percent GDP)*	**Climate target**
OECD (2017)	All	2016-2030	1. 9	6.3	2.0 °C
McCollum et al. (2018)	Energy	2016-2050	2.1	7.1	1.5 °C
Range of models			0.4 to 4.4	1.3 to 14.6	
IEA (2021b)	Energy+	2021-2030	2.7	9.9	NZE by 2050
EIB (2021)-EU only	All	2021-2030	2. 1	4.7	55% reduction by 2030

Source: OECD (2017), McCollum et al. (2018), IEA (2021b), EIB (2021) and IMF staff calculations.

Note: The investment need is the difference between the investment required for the climate change scenario less investment in the baseline. The share of public investments in total investments is based on the historical average split. The estimate of average GDP for the denominator is taken from the G-Cubed baseline scenario (IMF (2020a)). Percent of GDP for IEA (2021b) are calculated with each year's GDP separately. For the other sources average estimated GDP for 2021 to 2030 is used. (McCollum et al. 2018) compares six Integrated Assessment Models for which the average and, below, the range are reported. EIB (2021) refers to investment needs in the EU; all other publications refer to global investment needs.

Figure 7. Public Sector Investment in Energy-Related Sectors

(percent of GDP; annual average per decade)



Sources: International Energy Agency; and IMF staff calculations.

Note: First three bars represent the annual average over the decade except for 2020 (the average of 2015-2020); i.e. 2030: the annual average of 2021-2020. Last two bars show the difference between two decadal average, i.e. 2030 NZE – 2020 represents the annual average of 2021-2030 in NZE scenario – the annual average of 2015-2020 historical. NZE = Net Zero Emission scenario.

1/ USA and CAN,

2/ EU, GBR, JPN, KOR, AUS, and NZL,

3/ RUS and middle east countries,

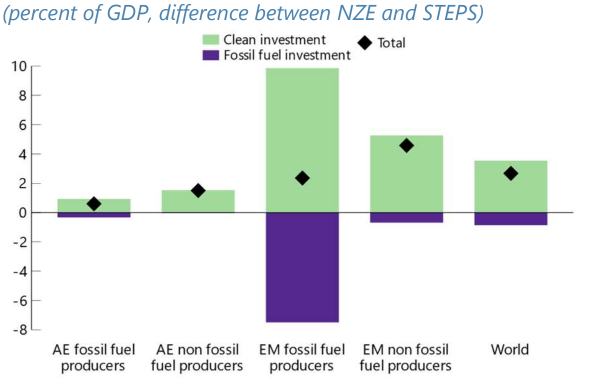
4/ BRA, CHN, IND, IDN, MEX, and ZAF

Size and Composition of Investment Needs

25. The net cumulative increase in public investment needed to support the low-carbon transition over the next decade is estimated to be between 0.5 and 4.5 percent of average GDP, with most estimates clustered around 2 percent.[44] Table 1 shows the additional investment need estimates from various sources and relates them to the climate target for which they were designed; the investment needs are cumulated over a decade and expressed as a fraction of one year's GDP. The additional investment is calculated as the difference between investment needs in a climate change mitigation scenario and investment needs in a baseline where no additional mitigation policy is implemented. Future energy demand is calculated based on projected GDP growth and specialized models of the energy sector. The additional public investment need is based on the historical share of public investments, and likely provides a lower bound, given the radical shift in energy systems that is required and the need to support substantial private investment in low-carbon sectors.[45] Given the differences in sectors covered, period considered, and emission reduction targets, the estimates from various sources are not immediately comparable, but they give a range of the investment effort required. Figure 7 shows the public sector investment needs in percent of GDP as well as the increments by decade, according to newly released IEA estimates.[46]

Figure 8. Cumulative Public Investment, 2021-2030

(percent of GDP, difference between NZE and STEPS)



Sources: International Energy Agency; and IMF staff calculations.
Note: The Stated Policies Scenario (STEPS) is the baseline scenario, the net zero emission (NZE) scenario is the climate policy scenario. For country groups, see Figure 7. Investments refer to energy related sectors.

26. Compared to baseline investments, most regions need to increase investments. All regions of the world need to decrease fossil fuel investments and increase clean investments, according to new IEA estimates of public investment needs to reach net zero emissions by 2050 (Figure 8). This is consistent with additional investments in existing oil and gas fields but no further exploration and development of new fields (IEA 2021b). Globally, cumulative public investments for 2021 to 2030 in the baseline (STEPS scenario) are at 8.1 percent of current GDP. Reaching net zero emissions by 2050 will require these investments to rise to 10.8 percent of current GDP. However, there are important regional differences. Fossil fuel investments are small in many regions, but clean investments need to increase strongly, implying strong net increases. In the emerging market fossil fuel producers (Russia and the Middle East), the level of investments is

[44] The policy mix assumed crucially influences estimates of overall investment needs (public plus private). For instance, greater reliance on carbon pricing incentivizes energy efficiency, which tends to reduce total energy demand, and the accumulation of capital. Another driver of differences across models are the assumptions relating to the transformation of the energy system. Switching from fossil fuels to intermittent, renewable power sources requires a more interconnected and flexible electricity grid. The cost of this extension is different across models.
[45] Investments by state owned enterprises are in some data sources also aggregated with investments of the private sector.
[46] IEA (2021b).

almost at the NZE compatible level, but a considerable shift from fossil fuels to clean investments is required.

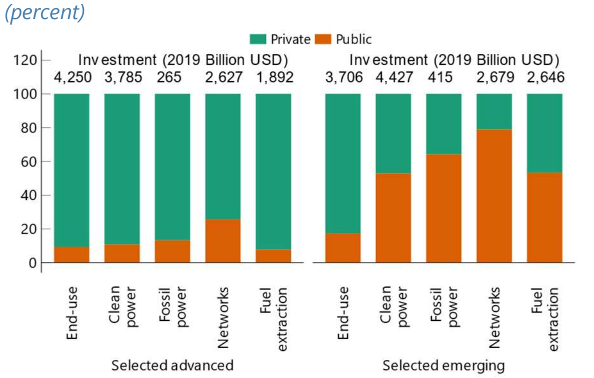
27. About 63 percent of the public investment needed in 2021 to 2030 on a path toward net zero emissions are in electricity distribution networks and generation from renewables. The IEA estimates provide a sectoral decomposition for the world and selected country groups (Figure 7). Renewable energy and electricity networks and storage are the most important categories, with estimated increases of about US$2 trillion and US$ 2.2 trillion, respectively in the decade 2021 to 2030 compared to the previous decade. In addition, investments into end-use are important. This includes end-use renewables (renewables directly used in buildings, transport, and industry, rather than connected to a grid), energy efficiency (mostly building retrofits) and other end-use investments (this includes mainly charging stations for electric vehicles).

28. Investing into lifetime extension for nuclear power plants can make an important contribution to the energy transition. Nuclear power stations can be adjusted to respond to seasonal fluctuations in energy demand to a certain extent. They can thus help manage output from renewables. However, nuclear power stations are on average 35 years old in the EU and 39 years old in the US. To extend the lifetime of nuclear power plants, key components need to be refurbished and that requires significant investments.[47] However, the desirability of expanding nuclear energy is controversial[48] so the extent of use of nuclear energy can be expected to vary depending on country preferences.

29. Hydropower capacity is expanding at a moderate pace, but environmental costs impede a large scale-up. Hydropower generation capacity has grown steadily in the past ten years, but at a slowing rate.[49] Actual capacity additions in hydropower have been far smaller than in solar and wind power. The reason is that in many cases the socioeconomic and environmental damages of large dams are large.[50]

Figure 9. Public/Private Investment Split, 2021-2030

(percent)



Sources: International Energy Agency; and IMF staff calculations.
Note: Selected advanced (emerging) group contain USA, CAN, EU, GBR, JPN, KOR, AUS, and NZL (RUS, BRA, CHN, IND, IDN, MEX, ZAF, and middle east countries).

30. Public investment needs for reaching net zero emissions differ across countries and sectors, in part reflecting different ownership structures. Private investment needs are estimated at about twice the level of public investment on average globally. The share of public investment in the energy sector is sizable in emerging market economies but generally small—except in electricity distribution networks—in advanced

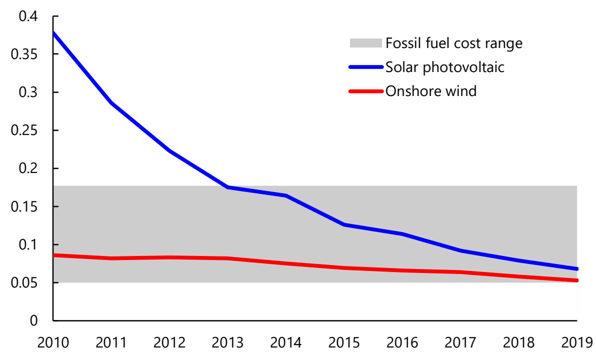
[47] IEA (2019).
[48] Sovacool et al. (2020).
[49] IRENA (2021).
[50] Moran et al. (2018).

economies (Figure 9). In emerging market economies, public investment needs have to do with the necessity of shifting from fossil fuel-based electricity generation to clean power in the current decade, and an attendant upgrade to electricity networks and storage (Figure 7). In advanced economies, where consumers are expected to shift toward electric vehicles earlier, public investment needs are mostly focused on electricity networks and storage and "other end-use", which mostly consists of electric vehicle infrastructure.

Figure 10. Trends in the Use and Cost of Solar and Wind Energy

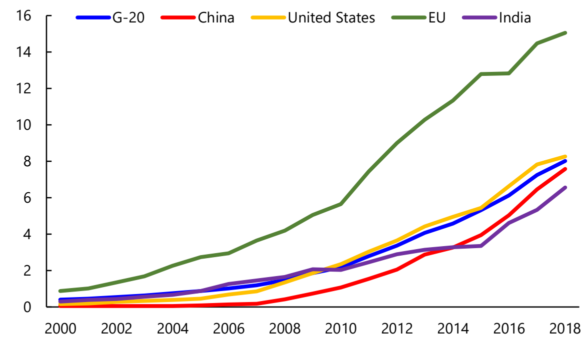
Global average price for solar photovoltaic and onshore wind

(2019 US$/kWh)



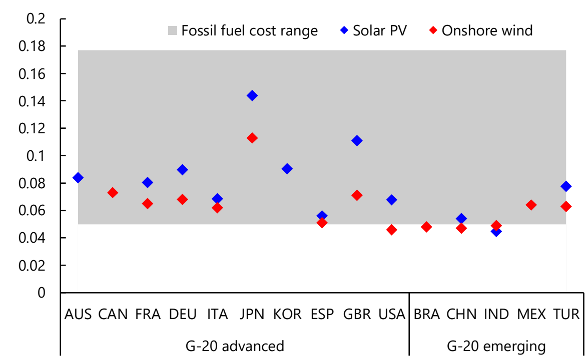
Weighted average share of wind and solar energy in electricity generation

(percent)



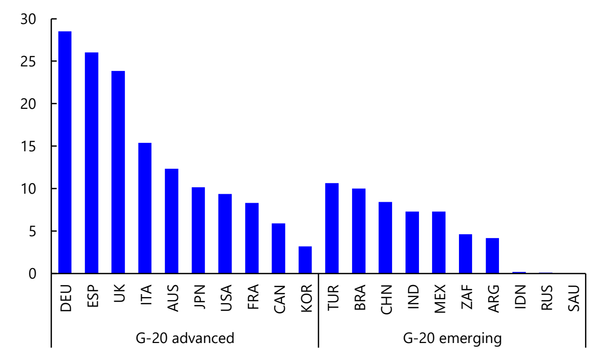
Average cost of solar photovoltaic and onshore wind

(2019 US$/kWh)



Share of wind and solar in electricity generation 1/

(percent)



Sources: International Renewable Energy Agency; International Energy Agency; and IMF staff calculations.
1/ 2019 is latest for all countries except for SAU for which 2018 is used.

31. Climate finance is needed to help developing economies finance investments required for the transition to low-emissions resilient economies. Advanced economies pledged to mobilize US$100 billion a year from 2020 for mitigation and adaptation in developing economies from private and public sources at the 2009 Copenhagen Summit. The Climate Policy Initiative estimates such flows at US$70-80 billion for 2017–18 from bilateral, multilateral, and privately leveraged sources—even though some public finance may reflect relabeling of existing funds, and systematic data on private flows is lacking. The UN's Green Climate Fund and the Global Environmental Facility were established to catalyze investment. Carefully costed, fiscally sustainable investment plans are needed to attract donor finance. Innovative instruments such as debt-for-climate swaps could, under certain circumstances, help attract financing, especially for adaptation.

Cost and Feasibility of Renewable Energy Investments

32. Decarbonization of the electricity sector—which generates 32 percent of carbon emissions globally—is a low-hanging fruit because alternative technologies have become competitive with fossil fuel technologies. The cost of adding new wind and solar energy capacity is below the upper end of the cost range for new fossil fuel capacity in all G20 countries, offering attractive investment opportunities (Figure 10). The cost comparison is done for the levelized cost of energy (LCOE) which is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. In fact, in most G-20 countries, the cost is at the *lower* end of the fossil fuel cost range. For instance, the cost for onshore wind is below the cost range for new fossil fuel capacity in Brazil, China, India, and the United States, and solar is below the range in India. Given the steady downward trend in the price of these technologies, more countries can be expected to see the cost of new renewable energy capacity falling below any possible new fossil fuel power capacity additions in the near future.

33. So far, the share of renewable energy has increased rapidly in the G20. Integrating renewable energy into the electricity system is a challenge, but so far, several European countries have pushed the limit continuously. The share of wind and solar energy in electricity generation has recently surged upwards in the UK, Spain, and Germany, exceeding 20 percent (Figure 10). Other G20 countries can benefit from the technology development and experience of these early movers. While conditions for renewable energy vary between countries and the pioneers are grappling with grid integration challenges (once again pointing to investment needs); no upper bound has been reached yet. Feed-in tariffs have proven very successful in increasing the share of renewable energy in many countries around the world.[51] Now that the technology has developed substantially, carbon pricing is an efficient option to increase the share of renewables in electricity generation without imposing large costs on end-users.

34. Technological advancements continue to improve the prospects for integrating variable renewable energy (VRE) into the electricity grid and even 100 percent renewable energy might be possible by 2050. The most prominent options for addressing variability, called "intermittency" in the technical literature, in the electricity grid are i) the adjustment of conventional power plants (hydropower and gas in particular) to more flexibility (to complement the intermittent supply of wind and solar electricity generation), ii) the expansion of transmission grids to pool different renewable energy sources, iii) making electricity demand respond to supply and iv) expanding storage capacity.[52] Connecting the electricity system with other sectors (sector coupling) provides further flexibility.[53] An important example of sector coupling is the use of excess electricity from renewable energy to produce zero-carbon fuels like green hydrogen. Exploiting such options fully would allow reaching much higher shares of VRE than what has been attained so far.

[51] Couture and Gagnon (2010).
[52] Pietzcker et al. (2017).
[53] Fridgen et al. (2020); Bogdanov et al. (2019).

F. A Sectoral Perspective on Climate Policy

35. As the low-hanging fruits in the power sector are being harvested, G20 countries are ready to move into transportation and other sectors. Reaching net zero emissions by mid-century requires efforts across all sectors, going beyond the electricity sector (combined with heat, electricity generation accounts for about a third of global carbon emissions). However, deep emission reductions in these sectors, unlike in the electricity/heat sector, would likely not be feasible with a combination of carbon pricing and public investment alone. They would require complementary sector specific regulations and other government interventions to develop technical solutions (building on existing ones that are not yet ready for scale-up) and to address certain sector-specific challenges. Setting sector-specific emission reduction targets can help to keep track of progress and identify need for further efforts.

Table 2: Sectoral Composition of GHG Emissions in 2018

Sector	G20		World	
	MtCO2e	% of Total	MtCO2e	% of Total
Total	**35,671.3**	**100.0%**	**48,939.7**	**100.0%**
Agriculture	3,576.3	10.0%	5,817.7	11.9%
Industrial Processes	2,274.7	6.4%	2,902.7	5.9%
Land-Use Change and Forestry	-592.8	-1.7%	1,387.6	2.8%
Waste	1,046.4	2.9%	1,606.9	3.3%
Energy	29,366.8	82.3%	37,224.9	76.1%
Building	2,383.9	6.7%	2,882.5	5.9%
Electricity/Heat	13,240.2	37.1%	15,591.0	31.9%
Fugitive Emissions	1,991.7	5.6%	2,883.4	5.9%
Manufacturing/Construction	5,263.9	14.8%	6,158.3	12.6%
Other Fuel Combustion	891.6	2.5%	1,452.0	3.0%
Transportation	5,595.5	15.7%	8,257.7	16.9%

Source: Climate Watch (2020), data from CAIT

Transport Sector

36. In ground transportation decarbonization is possible through public transportation and electrification. In 2018, almost 17 percent of global greenhouse gas emissions were emitted by the transportation sector (Table 2). In road transportation, electrification is developing dynamically[54], while the use of hydrogen in road transportation would exceed the production capacity, given that the green hydrogen production capacity is needed for aviation and shipping until 2050.[55] An important policy measure for vehicles are feebates, which are already used by several countries, including France, the Netherlands, and Norway.[56] For feebates, a tax is collected for highly emitting vehicles and the revenue is used to subsidize low-emission vehicles. Another option is to impose a ban on vehicles with internal combustion engines (ICE) as preannounced by seven G20 countries—typically for 2030-40) and under consideration in China (see Table 3). Boosting public transportation capacity is an

[54] IEA (2020a).
[55] Ueckerdt et al. (2021).
[56] Yan and Eskeland (2018).

important option since it is more energy efficient and less space consuming.[57] Supporting this mainly requires public investments.

37. Green hydrogen and ammonia are viable options to decarbonize aviation and maritime transport. In aviation and maritime transport, electrification is not possible with current technology. Instead, the industry could switch to synthetic fuels, like green hydrogen and ammonia.[58] Biofuels are not available at sufficient scale, synthetic carbon-based fuels are more expensive[59] and liquefied natural gas (LNG) has disadvantages such as methane leakage.[60] Producing the green hydrogen or ammonia required for aviation in 2050 would require solar panels of 140.000 km^2—about half of the area of Italy.[61] The raw materials for this much renewable energy are available, but a quick increase in demand requires a careful planning of supply.[62] Among the countries well suited for the production of zero carbon fuels are most of the current fuel exporters (because of favorable renewable energy conditions, available desert space in many cases, as well as existing infrastructure for exporting fuels), but also some others.[63]

Table 3: Bans on Petrol and Diesel Cars

Country	Start year	Applies to
Canada	2040	New vehicle sales
China	2035	New vehicle sales
Costa Rica	2050	New vehicle sales
Denmark	2030	New vehicle sales
France	2040	New vehicle sales
Iceland	2030	New vehicle sales
Ireland	2030	New vehicle sales
Israel	2030	New vehicle sales
Netherlands	2030	All vehicles
Norway	2025	All vehicles
Slovenia	2030	New vehicle sales
Spain	2040	New vehicle sales
Sri Lanka	2040	All vehicles
Sweden	2030	New vehicle sales
Taiwan	2040	New vehicle sales
United Kingdom	2030	New vehicle sales

Source: various newspaper reports.
Note: The table lists all countries that have a concrete government or climate plan to ban petrol and diesel vehicles. Additional countries are currently debating the introduction of bans or intend to use weaker policy instruments like incentives.

Manufacturing, Construction, and Industrial Processes

38. Many types of low-carbon technologies in manufacturing and construction are still comparatively expensive and require government support to be implemented. In addition to consuming electricity (for which the emissions are attributed to electricity/heat), some manufacturing processes use fossil fuels directly, contributing close to 13 percent of global emissions. Technologies to decarbonize these processes exist, but they are expensive and boosting take up would require government support. An example is steel. Steel is today mostly produced with coke-based blast furnaces, which can be coupled with carbon capture systems or replaced with a new and clean

[57] Gota et al. 2019; Brand et al. (2020).
[58] Englert et al. (2021a).
[59] Englert et al. (2021a).
[60] Englert et al. (2021b).
[61] Gössling et al. (2021).
[62] IEA (2021a).
[63] Englert et al. (2021a), Chapter 4.

technology called "direct hydrogen reduction".[64] These types of technologies remain expensive and their widespread adoption would require government support—similar to the support given to renewable energy in its early stages of development.

39. Emissions from industrial processes cannot be avoided altogether but can be reduced and compensated through negative emissions. This type of emissions results from chemical processes (most importantly the production of cement) and account for about 6 percent of global emissions (in addition to those associated by the electricity consumption and direct consumption of fossil fuels by the sector). Emissions from industrial processes can be lowered by increasing material efficiency[65], but within limits. The residual thus needs to be compensated through negative emission technologies to withdraw the emissions at source or from the atmosphere. As carbon storage options are limited[66], using it for these kinds of emissions, which cannot be avoided by other means, seems the most suitable. Re-using or recycling carbon are further options.

Agriculture

40. The largest part of agricultural emissions originates from livestock production and can be submitted to Pigouvian taxation. Agriculture contributes 12 percent to global emissions. Livestock production releases large amounts of methane, a potent greenhouse gas. Enteric fermentation (40 percent), manure left on pasture (16 percent), manure management (7 percent) and manure applied to soils (3 percent) are estimated to have accounted for two-thirds of global agricultural emissions from 2001 to 2011.[67] It is possible to determine the content of greenhouse gases in the products based on livestock. Meat and dairy products could thus be taxed in proportion to the climate damage they cause.[68] This would be an indirect extension of carbon pricing to agriculture.

41. Incentivizing low-carbon farming practices could mitigate the remaining emissions. The government can reduce emissions by incentivizing better farming practices, for example through new feed additives, better slurry management, and biorefining. Reducing fertilizer use can also contribute to reducing emissions, because the chemical input of nitrogen as fertilizer is an important source of greenhouse gas emissions. Reducing food loss is another obvious way to reduce emissions.[69] Supporting organic farming would sequester more carbon and thus withdraw it from the atmosphere.[70] Even reducing whaling has a positive effect as whales play a role in capturing carbon from the atmosphere.[71]

[64] Kushnir et al. (2020).
[65] Cao et al. 2020; Habert et al. (2020).
[66] Fuss et al. (2018).
[67] Tubiello et al. (2014).
[68] Batini, Parry, and Wingender (2020).
[69] Batini, Parry, and Wingender (2020).
[70] Lal (2004).
[71] Roman et al. (2014); Chami et al. (2019).

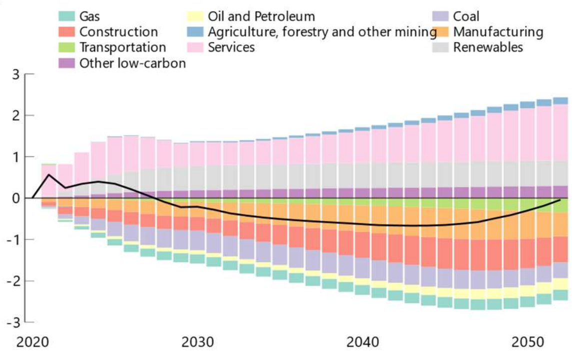
Other Sectors

42. Other sectors with smaller emission shares require specific approaches to decarbonization. Reducing emissions from the building sector (6.7 percent of emissions) requires retrofitting buildings, which means for example improving their insulation. Fugitive emissions (5.6 percent of global GHG) is the unintended leakage of emissions, mostly from handling fossil fuels. Reducing emissions from that sector will be automatic if less fossil fuels are produced. In addition, better maintenance and the detection of leaks would also help.

43. Land use change and forestry can be used to withdraw emissions from the atmosphere. Afforestation has a large potential to create negative emissions by withdrawing carbon from the atmosphere. This explains why the sector contributed a negative amount to emissions (-1.7 percent) in the G20 in 2018. One study estimated the potential to be as high as 200Gt[72], which is more than four times the global emissions of 48.9Gt in 2018. This amount can be absorbed only once because forests absorb carbon as they grow, but mature forests are carbon neutral. Using the negative emission potential requires stopping deforestation and using available land to increase afforestation. In addition to conservation policy, fiscal instruments can be very effective in protecting and expanding forests.[73]

Figure 11. Employment Effect of Climate Policy

(contribution to deviation of total employment from baseline, percent)



Source: IMF staff estimates

Note: The black line shows the aggregate effect.

G. Need for a Just Transition: Ensuring Equity and Creating Opportunities

44. Higher prices for energy and for other carbon-intensive products could raise poverty and be regressive in some countries. In many advanced economies and some developing economies, the direct effect of carbon pricing is regressive, meaning that low-income households would have to pay a higher share of their income than high-income households.[74] This is because many basic needs like heating and transportation are energy intensive. Even where carbon pricing would be progressive, as estimated to be in the case of India[75], higher energy prices could push some lower-income households into poverty. Moreover, in many countries, a phase-out of fossil fuels can create increased unemployment in regions where the industry is a major employer, for example in coal mining regions. In general, climate policy would lead some sectors to expand and others to shrink,

[72] Bastin et al. (2019).

[73] World Bank (2021).

[74] Dorband et al. (2019).

[75] IMF (2019a).

reducing employment in some sectors but creating new opportunities in others (possibly requiring a different set of skills) (Figure 11).

45. Revenues from carbon pricing can be used to reduce taxes in a way that benefits lower-income households and boosts jobs, or to boost spending to support low-income households. For advanced economies, reducing labor taxes for low-income households is a way of increasing their net income and supporting job creation.[76] The Canadian province of British Columbia, for example, uses carbon tax revenues to reduce distortionary taxes including personal income taxes and the corporate income tax. Both the tax and the revenue use are progressive.[77] A climate dividend paid to each household can support non-employed households.[78] Switzerland implements this idea by paying a "carbon dividend" to all households with the revenue from carbon pricing. Alternatively, a system of targeted cash transfers can be used to boost the net income of low-income households and protect them from a loss in purchasing power.[79] In some countries, providing access to basic infrastructure like health, education, and access to clean water might be the best way to support low-income households and help them move out of poverty.[80] Green infrastructure investments and reskilling/retraining programs financed with carbon revenues are also a way of supporting job transitions from high- to low-carbon sectors. If well targeted based on country characteristics, revenue recycling can help address political economy obstacles.

46. Climate policy can create geographically concentrated economic decline, but there are tested approaches for effectively supporting the transition in such areas. When coal mining areas were affected by mine closures in Japan starting in the late 1950s, the Japanese authorities introduced a set of targeted employment measures: "wider area" placement services, vocational training, and financial assistance for re-employment.[81] When coal mine closures affected a large part of western Germany, the government used similar employment measures as Japan did earlier and in addition attracted renewable energy producers and investments, for example in modern transport infrastructure.[82] The different levels of government cooperated to set up a deliberate strategy that included improving infrastructure, education, research facilities as well as cultural, recreational and environmental aspects to improve the region's attractiveness. This polycentric approach involving city, regional, and national governments and institutions aided success.[83] Awareness of the damages of pollution is not sufficient to motivate a mining region to transition into other forms of income generation. In combination with positive visions of low-carbon futures, however, the intentional exit from fossil fuels can find public support. In the UK for example, the awareness of pollution did not affect public opinion strongly. Only when a new vision of a "modern, clean, convenient, smokeless household" emerged, was there support for a transition away from coal.[84]

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[76] Klenert et al. (2018).
[77] Beck et al. (2015).
[78] Boyce (2018).
[79] IMF (2020a).
[80] Jakob et al. (2016).
[81] Li, Long, and Chen (2013).
[82] Oei, Brauers, and Herpich (2020).
[83] Oei, Brauers, and Herpich (2020).
[84] Turnheim and Geels (2012).

H. Conclusion

47. A green investment push can help lead the economy out of the COVID-19 crisis and make significant progress on mitigating climate change. Moving to net zero emissions will require a scaling-up of investment over the next decade and a reallocation away from fossil fuels and toward clean energy. The public sector has a catalytic role to play by providing critical public infrastructure and other support measures for private investment, and by promoting low-carbon technologies which are not yet competitive. Estimates of additional public investment needs to align infrastructure with net zero emissions range between 0.5 to 4.5 percent of GDP cumulatively over the next decade, with a cluster around 2 percent of GDP.

48. Carbon pricing is essential for reaching net zero emissions at a reasonable overall cost and can be phased in gradually. Carbon pricing is a very effective tool to reduce carbon emissions across-the-board by encouraging a reallocation of activity from high- to low-carbon activities and incentivizing energy efficiency. It also generates revenues which can be used to finance green public investments and support measures for households and workers affected by the transition. Hard-to-decarbonize sectors require additional sector-specific policies in addition to carbon pricing. Where carbon pricing faces political economy obstacles, regulations are an alternative tool to limit emissions, although they are likely to be more costly to the economy.

49. Stabilizing the global temperature by mid-century requires both immediate and global climate action, supported by financial and technology support for developing economies. Joint action in the form of a coordinated green investment push and an international carbon price floor agreement among the G20—with differentiated prices according to level of development—would be a valuable first step in putting the global economy on a path to net zero emissions. Financial and technology support to developing economies which are expected to experience growing emissions but have little means to pay for the transition will be key to stop global warming.

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