A positive tipping cascade in power, transport and heating

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Key messages

01

Regulatory mandates are the most powerful policies for bringing forward positive tipping points where clean technologies become cheaper than fossil fuels in power, heating, light road transport and heavy road transport.

02

Mandates can bring forward the tipping points in these sectors by up to 3 years globally, significantly more than carbon prices or subsidies. With global emissions needing to be roughly halved in the remaining five years of this decade, such acceleration is essential.

03

Policies to advance the transition in one sector also tend to bring forward positive tipping points in other sectors, given reinforcing interactions between sectors.

04

A coal phaseout policy brings forward positive tipping points in the heating and heavy road transport sectors by up to 4 years in some countries, acting as a super-leverage point in the transition.

05

A zero-emission vehicle mandate in light road transport brings forward the positive tipping points in heavy road transport by nearly 2 years in some countries, and up to a year for power and heating, also acting as a super-leverage point in the transition.

06

Countries should work together to accelerate deployment of clean technologies to drive down costs and enable them to outcompete fossil fuels across all major emitting sectors.

Introduction

In 2018, the Intergovernmental Panel on Climate Change advised that CO_2 emissions must be roughly halved by 2030 to limit global temperature rise to 1.5°C.[1] Six years later, with CO_2 emissions still rising[2], governments face the question of how best to cut them by half in the remaining five years of this decade.

The relative cost of clean technologies and fossil fuels is a critical factor in the pace of the low carbon transition, affecting affordability for consumers, profitability for businesses, and political feasibility for governments. A cost-parity threshold between clean technologies and fossil fuels in a sector of the economy can be seen as a good proxy for a tipping point. At this stage, the new technology becomes more attractive than the old, and the transition acquires its own self-propelling momentum. In the leaders' statement on the Breakthrough Agenda at COP26, governments of 45 countries committed to work together to reach these tipping points, making clean technologies more affordable, accessible, and attractive than fossil fuels in each of the emitting sectors by 2030.[3]

In the power sector, the first such tipping point has already been passed – solar and wind power are cheaper forms of electricity generation than burning coal or gas, in most of the world – and the rate of progress is dramatic. In 2023, solar and wind accounted for over 80% of global power capacity additions,[4] and countries committed at COP28 to work together to triple the world's installed renewable energy generation capacity by 2030.[5] How can that target be met, and this acceleration of progress be extended to other sectors?

Governments know that meeting climate goals requires many policies simultaneously. In practice, all policies involve expenditure of political capital, public money, and administrative time, none of which are in infinite supply. It is useful to know which policies are likely to be the most effective: Where can governments get the most value for their money?

It is often stated that carbon pricing is the single most cost-effective policy for decarbonization, but recently empirical research and studies with dynamic models have challenged this assumption, suggesting that well-targeted clean technology subsidies and regulations could often be more effective and efficient.[6] Currently, detailed comparisons of policy options tend to be applied to individual sectors, but the clean energy system will be interconnected in multiple ways, and these offer additional opportunities to accelerate progress.

In this study we use a dynamic model to address two questions: first, which policies are most powerful for accelerating progress towards the clean technology tipping point in each of the individual sectors of power, heating, light road transport (cars), and heavy road transport (large trucks)? Second, given the connections that exist between sectors, which policies in any one of these sectors are most powerful for bringing forward the tipping points in the others?

1 IPCC (2018) Special Report on Global Warming of 1.5 degrees. (45% reduction from 2010 levels required by 2030).
2 Global Carbon Budget globalcarbonbudget.org/fossil-co2-emissions-at-record-high-in-2023
3 Leaders Statement on the Breakthrough Agenda climatechampions.unfccc.int/cop26-world-leaders-summit-statement-on-the-breakthrough-agenda For more information, see breakthroughagenda.org
4 IRENA Renewable Capacity Highlights 2024
5 Global Renewables and Energy Efficiency Pledgecop28.com/en/global-renewables-and-energy-efficiency-pledge
6 eeist.co.uk/eeist-reports

Modelling approach

The Future Technology Transformation (FTT) models that we use in this study simulate the process of technology diffusion in four greenhouse gas-emitting sectors of the economy.[7] In each sector FTT represents investors or consumers who choose between alternative technologies. Investment decisions are based on technology availability (more widely used technologies can spread more rapidly), cost estimates (which differ for different investors) and historical preference by county and technology. It simulates the process of learning-by-doing, where technology costs fall in response to increasing deployment. It includes specific representation of different countries, markets, and technologies, and is calibrated on the best available data.

These characteristics make the model well suited to testing the effects of alternative policy options in the low carbon transition. Even so, many of the model's inputs are subject to uncertainties, and its outputs are best interpreted in comparative terms ('policy A is likely to outperform policy B on criterion X') rather than treated as precise predictions.

Interactions between sectors

For this study, we established links in the model to represent some of the real-world interactions between the transitions in the four sectors mentioned above. These were:

- Growing uptake of electric cars, large electric trucks, and heat pumps increases demand for electricity. In some smaller countries, this results in deployment of renewables coming close to estimated technical limits imposed by land and sea area.
- The transition in the power sector influences the electricity price, which affects the relative cost of clean technologies and fossil fuels in the other sectors.
- Increasing deployment of batteries in cars brings down their cost as it stimulates innovation, making them cheaper for use in trucks and in the power sector (for energy storage).
- Faster deployment of electric vehicles makes more second-hand batteries available for use in the power sector, bringing down the cost of short-term storage and tending to reduce electricity prices.
- Increasing deployment of electric vehicles with vehicle-to-grid charging technology provide more support for system balancing in the power sector, reducing the need for energy storage. [8]

These interactions are illustrated in Figure 1.

7 e3me.com/what/ftt

8 V2G is modelled similarly to second-hand batteries. We assume a small share of larger EVs is available for storage, and that storage costs are half of those of new batteries.

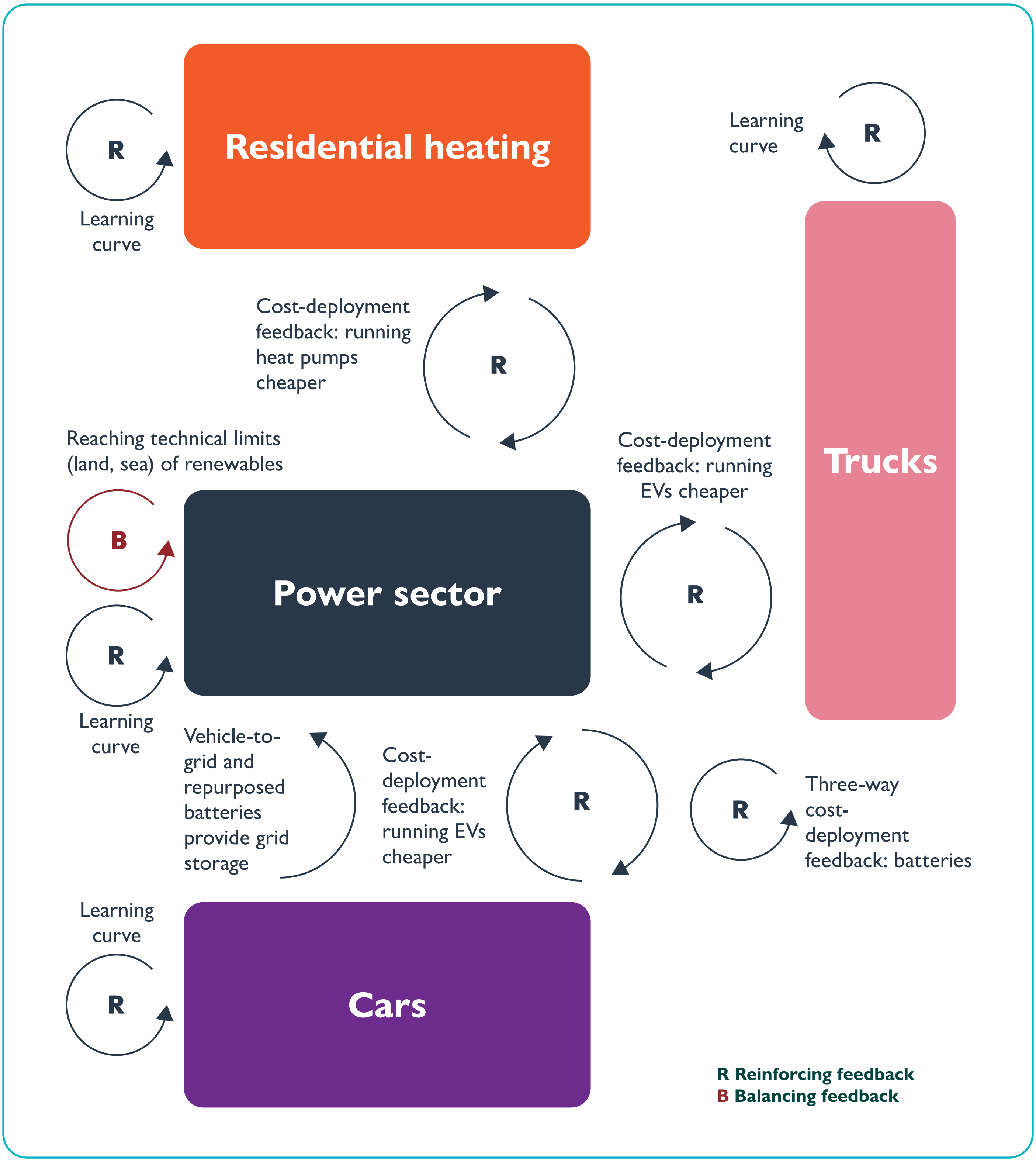

Figure 1: Reinforcing feedback loops within and between sectors considered in our modelling.

How close are the tipping points on our current trajectory?

With the model calibrated to represent current policies, we can see how long it will take for cost-parity thresholds between clean technologies and fossil fuels to be passed, for an illustrative selection of countries with large economies. The thresholds are defined as follows.

- **Power sector:** Since new solar or wind power is already cheaper than new coal or gas power in most of the world,[9] we look ahead to the next tipping point to cross: when new solar power with battery storage costs less than only the operational costs of existing coal or gas plants (whichever is cheaper in a given country).

- **Heating:** We compare the total (levelised) cost of ownership of gas boilers with that of heat pumps, using whichever of three heat pump technologies (air-air, air-water, or ground-source) is currently dominant in each country.

- **Light and heavy road transport:** We compare the total cost of ownership of electric vehicles with that of petrol cars and diesel trucks, respectively.

The model's projections, shown in Figure 2, show that the time of crossing the tipping point in each sector can vary widely among countries. In the power and heavy road transport sectors, all countries in this sample cross the tipping points in or before 2035, but in the heating and light road transport sectors, the tipping points are crossed later, and in some cases are still not crossed by the year 2050.[10]

9 IRENA (2023) – RENEWABLE POWER GENERATION COSTS IN 2022

10 The reason for heavy road transport reaching the tipping point earlier than light road transport is that trucks tend to be more intensively used than cars, and consequently benefit more from the lower operating costs of electric vehicles.

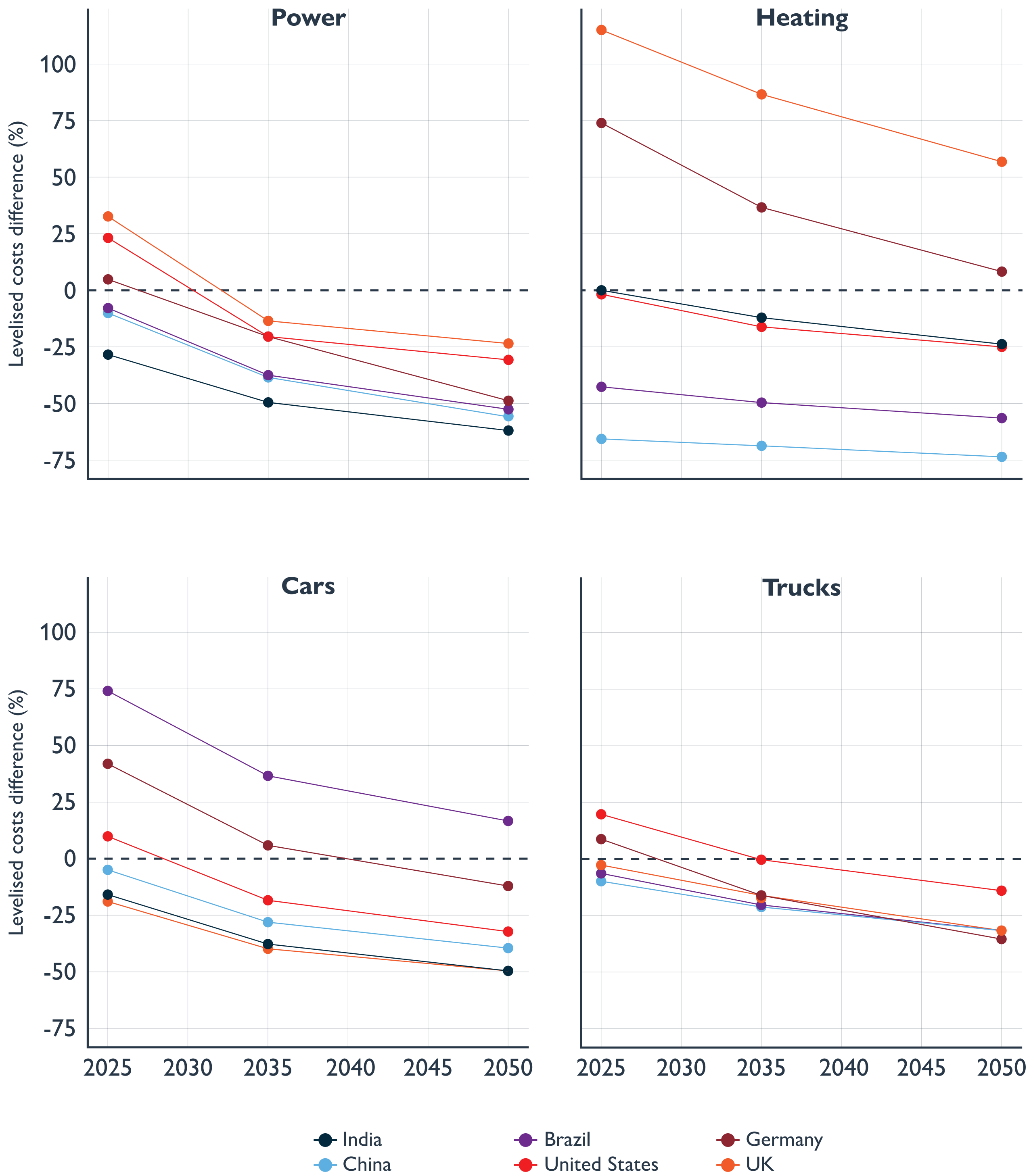

Figure 2: Evolving cost difference between clean and fossil fuel technologies in key countries across the four sectors, in the absence of further policies.

Policies tested

In this study we compare the effect of a carbon tax, a clean technology subsidy, and a mandate, in each of the four sectors. There are numerous examples of all three being used by governments in the low carbon transition, but their effectiveness can differ substantially.

The specifications of these policies are set out in Table 1.

The carbon price was set at a level matching the high end of expectations for the price the EU Emissions Trading System could reach by 2035.[11] Most existing carbon prices are much lower, typically between 0 and $60/tCO_2e$.[12] For subsidies, we chose a substantial level, which fell within the range of current policies. Real subsidy levels vary widely across regions and sectors. For instance, the UK heat pump subsidy of £7,500 can represent 75% of a heat pump cost[13], whereas the subsidy for electric trucks in India from late 2024 will represent some 20-25% of upfront costs.[14] The mandates were specified to match commitments on the pace of the transition[15] such as the Global Coal to Clean Power Transition Statement[16] the Zero Emission Vehicles Declaration[17] and the Global Memorandum of Understanding on Zero-Emission Medium and Heavy Duty Vehicles.[18] Since the policies are equalitatively different, there is no way to specify them with exactly quivalent stringency. These are illustrative values, chosen to enable a comparison between strong versions of the three policies.

For simplicity, we model each policy as being implemented by all countries simultaneously. The cost of clean technologies depends on their cumulative global deployment, so the effectiveness of a policy in any one country depends on the context created by the actions of other countries.

	Tax	**Subsidy**	**Mandate**
Power	A constant carbon price of €200/tCO_2 from 2025.	Subsidy at 30% of upfront cost for all renewable technologies from 2025 onwards	Phase-out of coal power by 2035 for developed countries and by 2045 for developing countries (with linear reduction in installed capacity beginning in 2025, representing a policy of gradual forced retirement of coal power plants).
Heating	A constant carbon price of €200/tCO_2 from 2025.	Subsidy at 30% of upfront cost for all heat pump types, from 2025 onwards	Mandate requiring a rising proportion of heating appliance sales to be heat pumps, from 2025, reaching 100% by 2035.
Light road transport	A constant carbon price of €200/tCO_2 from 2025.	Subsidy at 30% of upfront cost for fully electric cars from 2025 onwards	Mandate requiring a rising proportion of car sales to be zero emission vehicles, reaching 100% by 2035.
Heavy road transport	A constant carbon price of €200/tCO_2 from 2025.	Subsidy at 30% of upfront cost for fully electric trucks from 2025 onwards	Mandate requiring a rising proportion of truck sales to be zero emission vehicles, reaching 100% by 2040.

Table 1: Policy options tested in the model

11 about.bnef.com/blog/eu-ets-market-outlook-1h-2024-prices-valley-before-rally
12 World Bank, State and trends of carbon pricing 2024. openknowledge.worldbank.org/entities/publication/b0d66765-299c-4fb8-921f-61f6bb979087
13 gov.uk/apply-boiler-upgrade-scheme/what-you-can-get
14 financialexpress.com/business/express-mobility-e-trucks-will-get-govt-subsidy-as-part-of-a-new-scheme-3507549
15 Where available. We are not aware of any such commitment having been made for heat pumps.
16 webarchive.nationalarchives.gov.uk/ukgwa/20230313120149/https://ukcop26.org/global-coal-to-clean-power-transition-statement
17 acceleratingtozero.org/the-declaration
18 globaldrivetozero.org/mou-nations

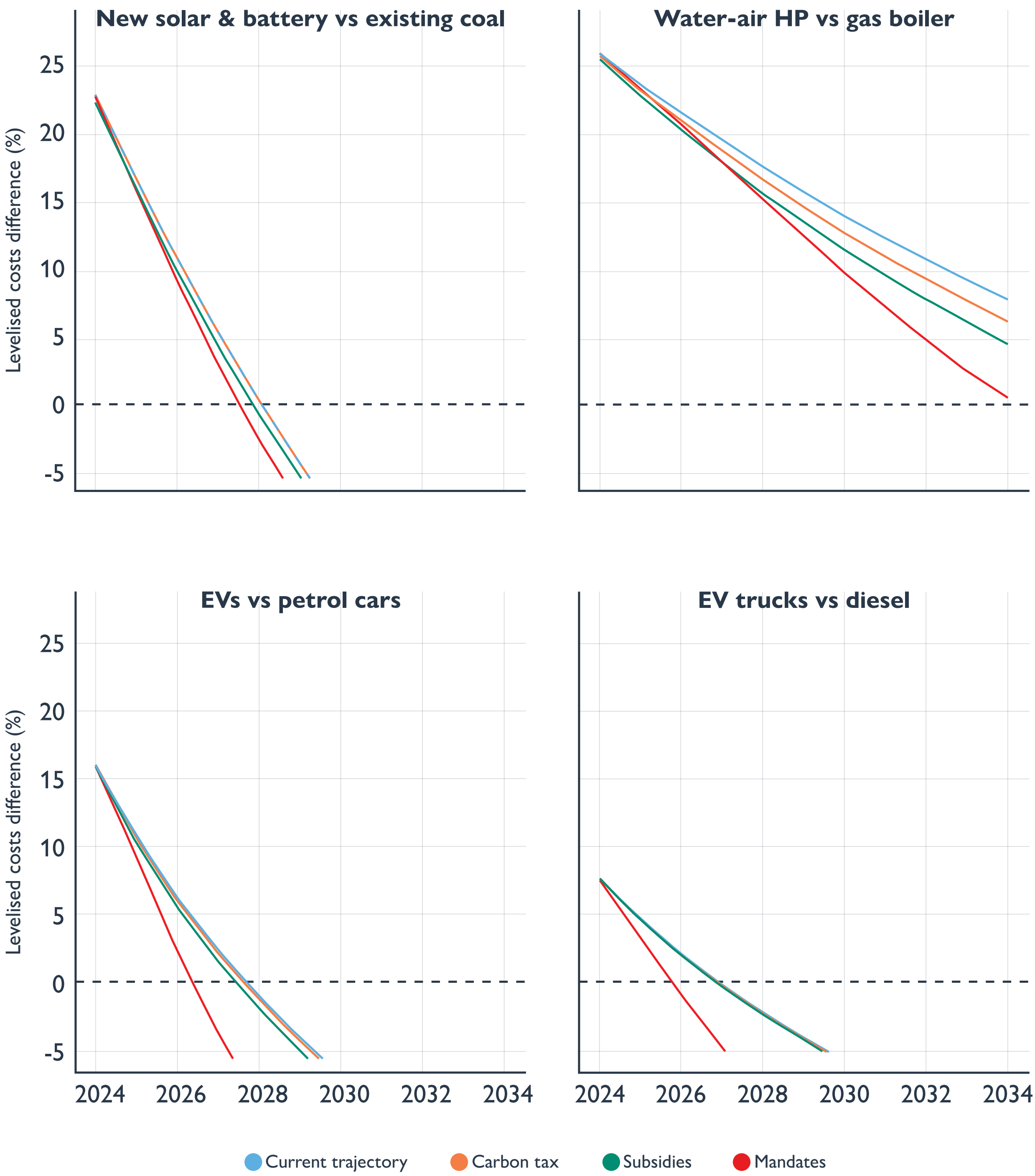

Figure 3: Effect of different policies on the global average levelized cost difference between clean and fossil technology across the four sectors.

Policy comparison

In each sector, the mandate brings forward the tipping point more than any of the other policies, as shown in Figure 3, which compares the policies' ability to bring forward the global average cost-parity tipping point in each of the four sectors. This reflects their ability to force a rapid and large-scale reallocation of investment towards the clean technology, accelerating technology learning and cost reduction.

The effect of the subsidies is weaker. Subsidies incentivize rather than force a reallocation of investment towards the clean technology.

Outside of the power sector, the effect of the carbon tax is weaker still, as the cost of carbon relative to other capital and operating costs is modest in these sectors. Moreover, the carbon tax can divert investment towards more efficient fossil fuels or biofuels, for which there is no strong relationship between deployment and cost reduction. In the power sector, carbon taxes make onshore and offshore wind more competitive with coal, and have a large effect on emissions.

Policies in the heating sector make the greatest difference to the timing of the tipping point (especially between air-water heat pumps and gas boilers) as the tipping point on our current trajectory is furthest in the future. Air-air heat pumps are already cheaper over their lifetimes. The smallest difference in timing is seen in the power sector, where the cost reduction achieved by faster deployment of solar and wind power is partially offset by the increased need for energy storage.

Figure 4 shows the effect of the different policies on changing the global technology mix in each sector. The carbon tax has relatively little effect in isolation, except in the power sector. The subsidies are more effective in the heating sector. The mandates are significantly more effective, especially in the two road transport sectors where they overcome the lock-in to internal combustion engine technology and force manufacturers to supply electric vehicles. In the heating sector, the mandate drives growth mainly in deployment of air-to-water heat pumps.

Combining all the policies drives further growth of clean technology particularly in the power and heating sectors.

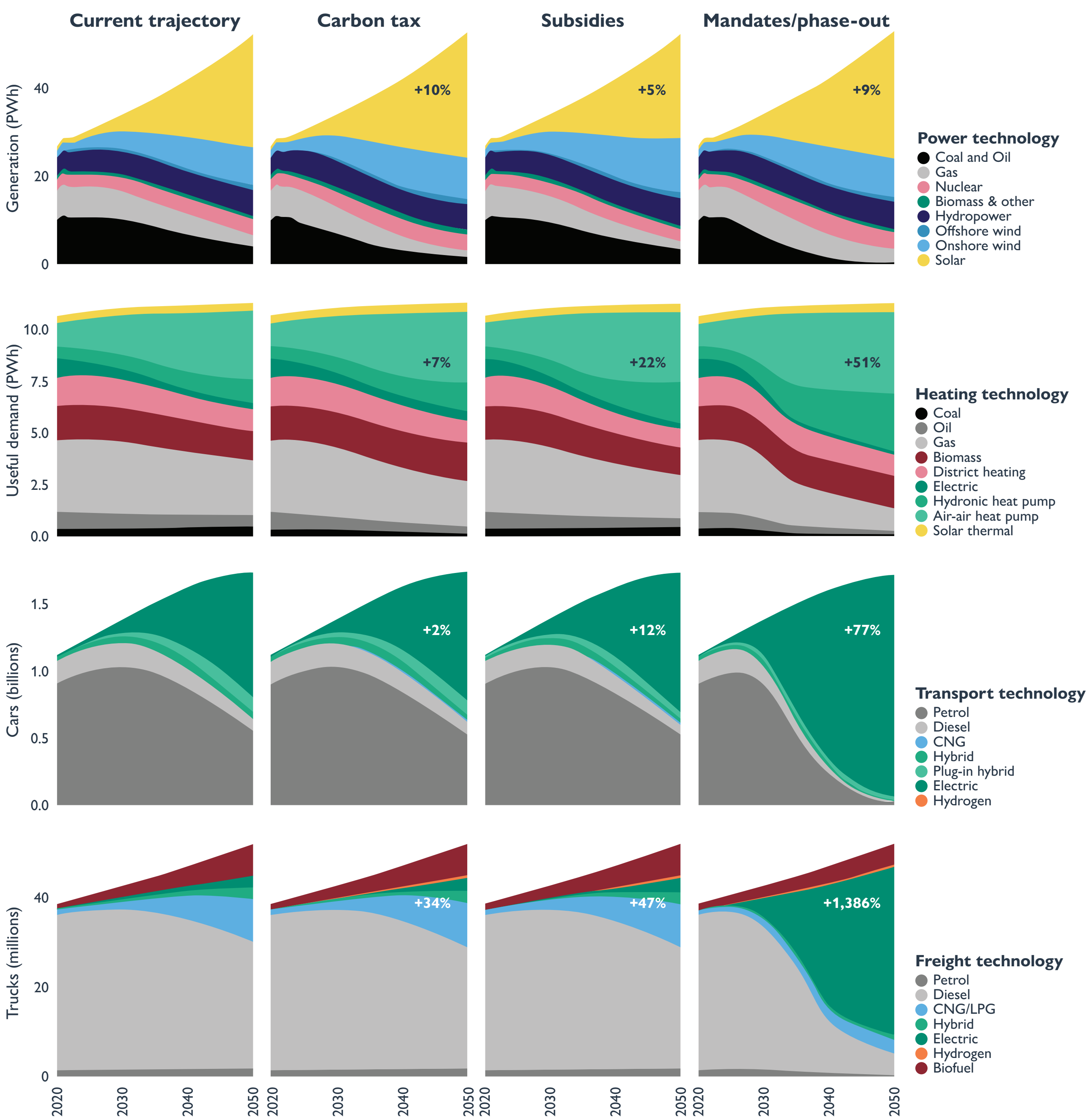

Figure 4: Effect of different policies on the global technology mix in each of the four sectors. The percentage growth is shown of selected green technologies: in the power sector, it is the sum of wind and solar, in the heating sector all types of heat pumps and in the transport sectors all types of full electric vehicles.

The effects of policies across sectors

Policies to advance the transition in any one sector generally help bring forward the tipping point in each of the other three sectors. This is because of the interactions described above. Increased use of clean electricity or energy storage technologies in one sector drives innovation and brings down the cost of these technologies, enabling the transitions in the other sectors. In addition, the increasing electrification of heating and transport provides new options for balancing the power system, reducing the cost of clean power.

One exception is the carbon price in the power sector: a moderately high carbon tax tends to increase the price of electricity, which depends at least to some extent on the cost of coal or gas power,[19] and the increased price of electricity can slow the transitions in road transport and heating.

The zero emission vehicle mandate in light road transport shows perhaps the best potential to be a 'super-leverage point' for the global transition – a policy that is not only the highest leverage action within its own sector, but also has a significant positive influence on the transition in other sectors.[20] The coal phase-out policy in the power sector also strongly influences other sectors, and could also be a super-leverage point. These results are shown in Table 2, which compares the effect of the mandate policies in each sector on the timing of the tipping point in each of the four sectors.

In the context of needing to halve global emissions in five years, bringing forward a clean technology tipping point by a year, or even by a few months, would be valuable - but even more than this is possible. Our global average weighs countries by their market size and so is most strongly influenced by countries with the largest economies, which tend to be those that are already furthest ahead in low carbon transitions. By breaking down the global average into data points for 71 countries and regions, Figure 5 shows that in many places, mandates in the four sectors together can bring forward tipping points in heating, light and heavy road transport by two, three or four years, and in a few cases, by over eight years.

When it comes to reducing emissions, implementing the full policy packages in all sectors together achieves more than the sum of their effects in each individual sector. As shown in Figure 6, this 'combination gain' is an additional reduction of 2% of cumulative global emissions over the period 2025 to 2050, and 2.3% of global emissions in the year 2050 (around 343 $MtCO_2$, equivalent to the current annual emissions of Vietnam). This is on top of the 43% savings in cumulative emissions between 2025 and 2050 in the four sectors, and 75% reduction in 2050 emissions from the policy packages individually.

	Power sector	Heating	Cars	Trucks
Coal phase-out	5 months	9 months	1 month	3 months
Heat pump mandates	0 months	1 year, 11 months	0 months	0 months
EV mandates	3 months	2 months	1 year, 3 months	5 months
EV truck mandates	1 month	1 month	1 month	2 years, 3 months
All mandates	8 months	2 years, 8 months	1 year, 4 months	2 years, 5 months

Table 2: How much can mandates and phaseouts in one sector bring forward the tipping point in the others

19 The degree of dependence depends on market design. In power systems where the price reflects the cost of the marginal unit of supply, coal or gas power can set the price of electricity even when solar and wind contribute a large share of generation. In systems where the electricity price is closer to reflecting the weighted average levelised cost of all generating technologies, the dependence is less.

20 www.systemiq.earth/breakthrough-effect

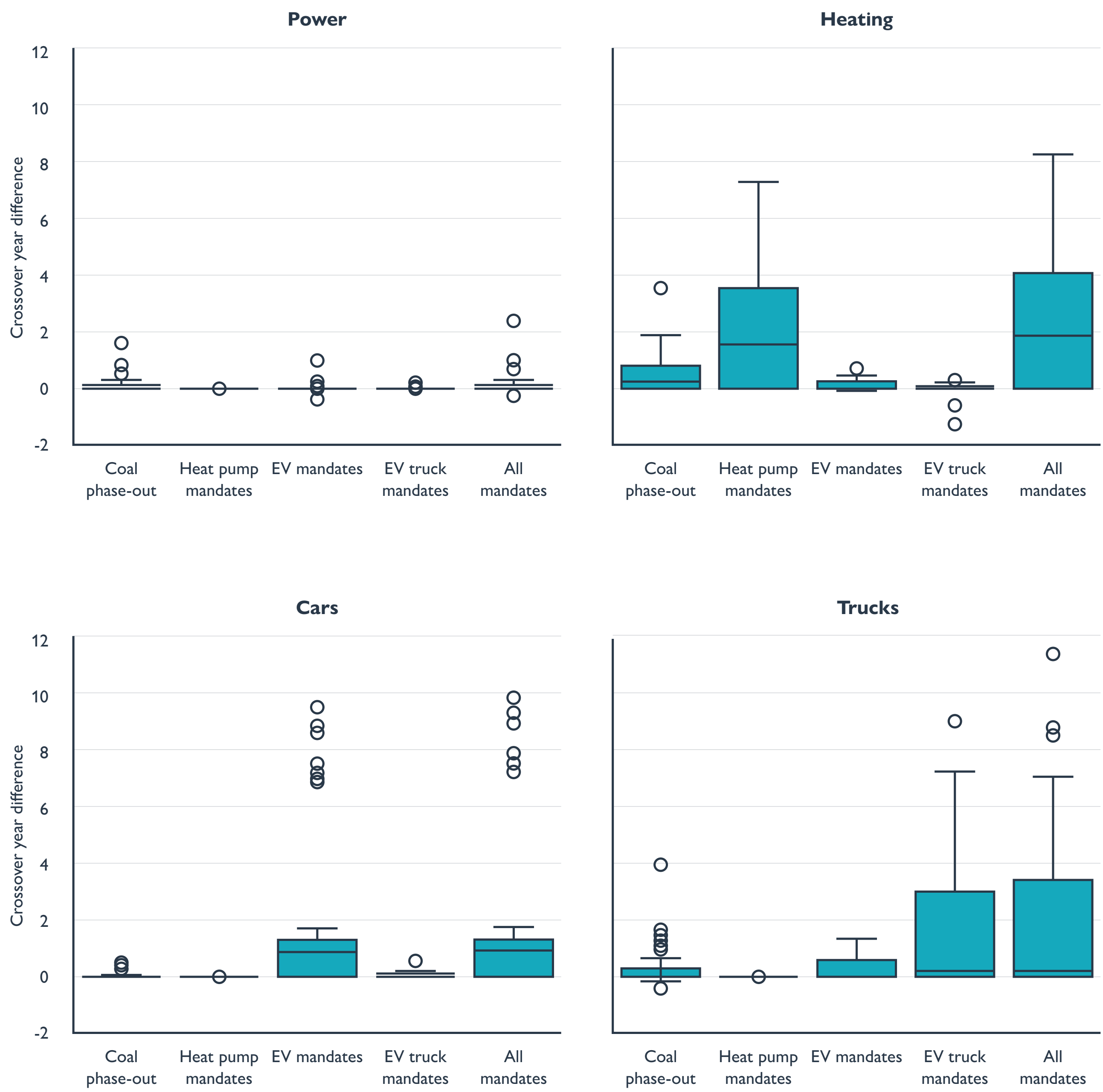

Figure 5: Country-level effects of mandate policies in each sector on the timing of the cost parity tipping point across sectors. Boxes show the interquartile range (so that half of regions fall within the box); whiskers show 1.5 times the interquartile range; regions outside this range are plotted separately.

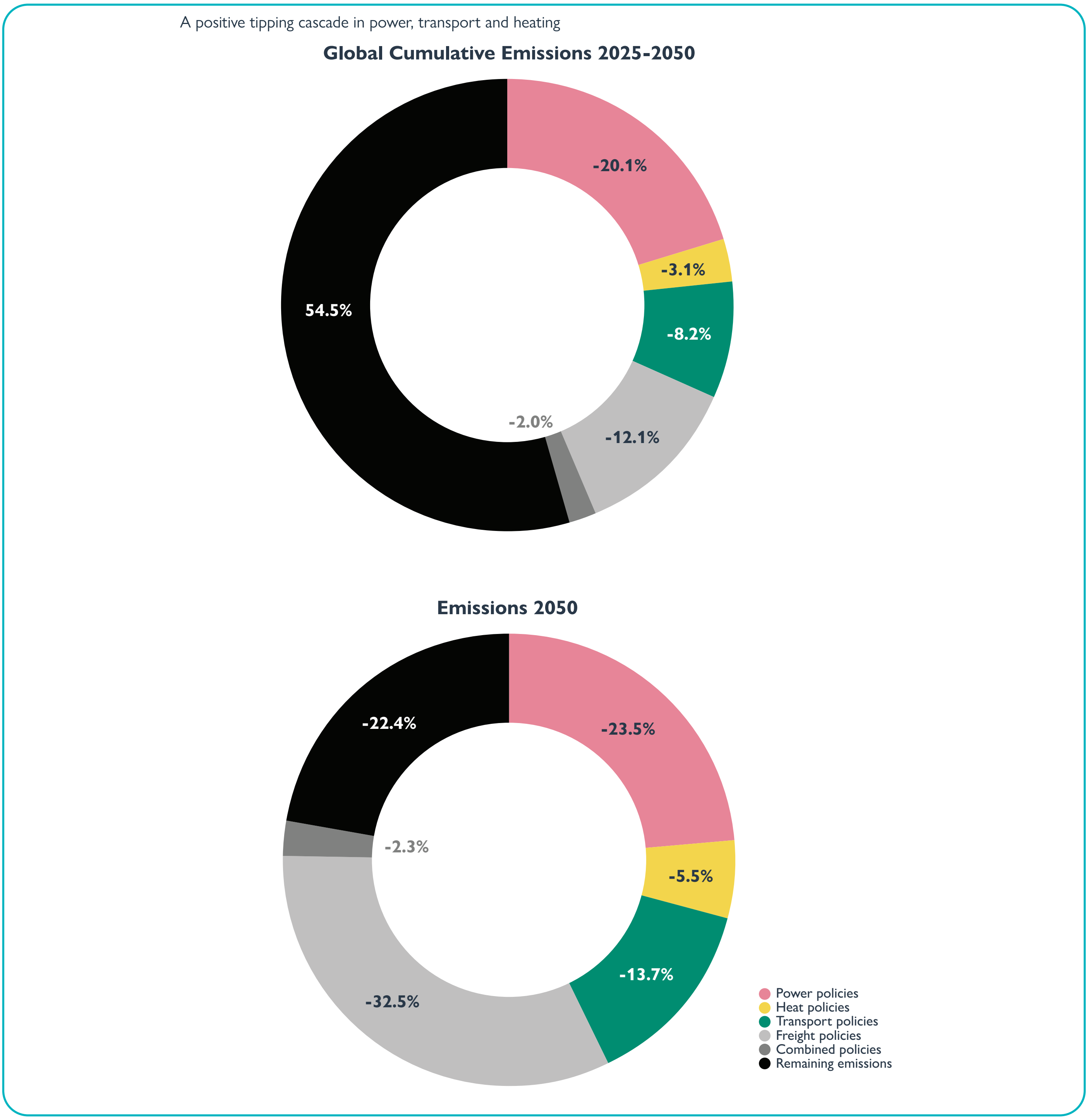

Figure 6: Cumulative emissions (top) and 2050 emissions (bottom) across four sectors are shown. The full circle represents total emissions in the baseline without additional policies in the four sectors. A rapid, combined transition across all sectors reduces emissions more effectively than individual sector transitions. This combined approach results in additional emissions savings, exceeding 2% of total emissions. Total cumulative emissions in the current policies baseline are 497 $GtCO_2$; 2050 emissions are 15 $GtCO_2$/yr.

Recommendations

Mandates are likely to be most effective in driving faster progress towards clean technology tipping points. This is consistent with the idea that reinforcing feedbacks are the engine behind the acceleration of the transition: mandates reallocate investment from fossil fuels to clean technologies; investment drives innovation and cost reduction; falling costs lead to higher demand and increased investment. However, in sectors that are still in the early stages of transition, targeted subsidies might be required initially to support the first deployment of clean technologies, before mandates can then promote their broader adoption.

Countries acting individually cannot use the policies described here to bring forward tipping points as much as we have shown. Clean technology cost reduction is proportionate to cumulative global production, so for the greatest gains, coordinated international action is essential. As the International Energy Agency has indicated, without this, the transition to net zero global emissions could be delayed by decades.[21] Countries with the largest economies can do the most to reduce clean technology costs for themselves and for the world, especially if they align their actions with each other.

Other policies are also important, especially in the power sector. The three deployment policies have a relatively small effect on the rate of growth of renewables in the power sector (see Figure 4), because solar and wind power are already outcompeting the fossil fuels on cost, and the policies that are now most important for the pace of the transition to clean power are to do with changes to the wider system: grids, permitting, flexibility technologies, and for developing countries, the cost of capital.[22] In our modelling we found that assumptions around these issues – such as the future cost of inter-seasonal energy storage, or the extent to which the growth rate of renewables is constrained by permitting processes – could determine whether a faster transition to clean power is projected to increase or decrease electricity prices. This underlines the importance of policies such as development and demonstration of long-duration energy storage (and other flexibility technologies) and speeding up approval processes for new clean power investments. In contrast, the price of fossil fuels is a highly uncertain variable affecting the timing of tipping points that is largely outside governments' control.

Policies not represented in our model can further increase the effectiveness of technology deployment policies of subsidies, taxes, and mandates. There are opportunities to deepen integration between sectors beyond the interactions we have simulated here. These include the use of demand-side response to support power system balancing at the national level and the triple impact of insulation in lowering heating & cooling demand, more efficient heat pumps, and the use of houses as thermal batteries. Smart vehicle charging can reduce peaks in power demand, whereas unmanaged charging increases peak demand, posing challenges to electricity grids. Other policies that can increase the effectiveness of clean technology deployment policies include investing in infrastructure (extending electricity grids, installing electric vehicle chargers); policies to deploy complementary technologies such as long-term energy storage; and social policies such as workforce training.

There are also important links with sectors not modelled here. Lower-cost clean electricity can support industry decarbonization, directly through electrification and indirectly through green hydrogen production. The use of green hydrogen in one sector, such as fertilizer production, could bring down its costs, enabling its use in others, such as steel or shipping.[23]

21 www.iea.org/reports/breakthrough-agenda-report-2022
22 eeist.co.uk/download/927
23 www.systemiq.earth/breakthrough-effect

Conclusion

The low carbon transition in each sector will need a range of policies, not a single one. However, governments often choose between deployment policies, and when they do so, they should be careful to prioritise those most likely to drive rapid deployment and cost reduction of clean technologies. These are likely to be clean technology mandates.

Governments should aim to move forward the transition in each sector simultaneously, to benefit from the reinforcing feedbacks between them, and should strengthen these feedbacks wherever possible – through policies such as enabling vehicle-to-grid charging, supporting the repurposing of electric vehicle batteries for use in the electricity grid, and promoting smart energy systems and energy efficiency within buildings.

Major economies should coordinate their actions to shift investment in global markets towards clean technologies, helping more countries make faster progress towards the tipping points where clean technologies outcompete fossil fuels. The faster the transition, the earlier countries can reap the benefits of cheaper energy, socially, economically and environmentally.

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