Faster and Cleaner 2

KICK-STARTING GLOBAL DECARBONIZATION: IT ONLY TAKES A FEW ACTORS TO GET THE BALL ROLLING

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Climate Action Tracker

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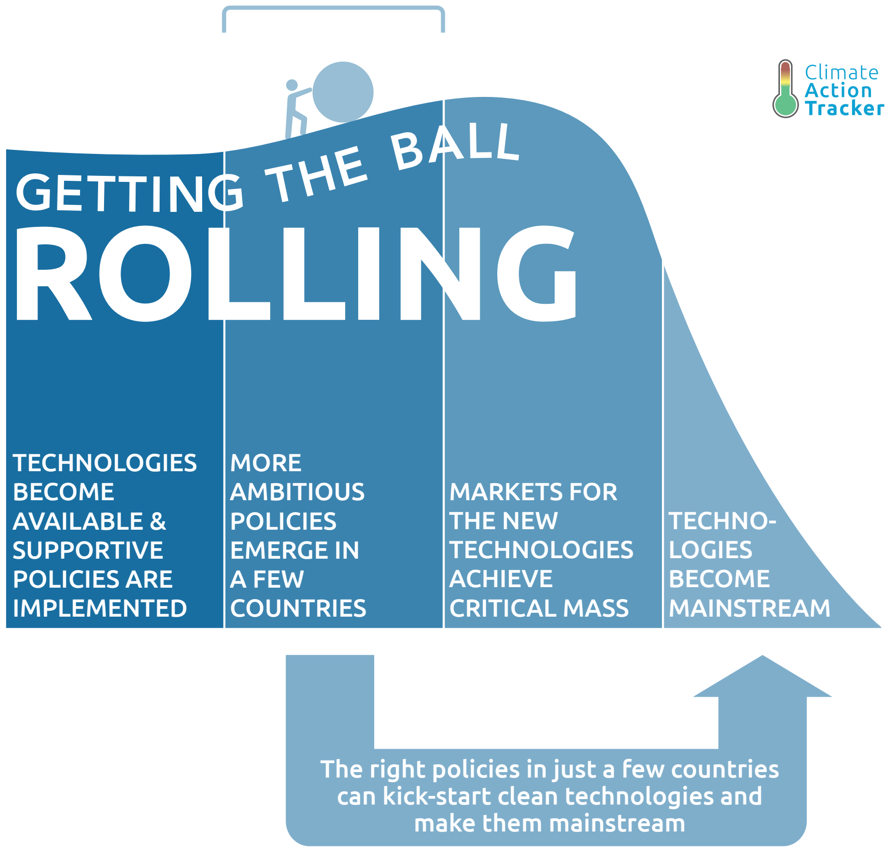
1. INTRODUCTION

Achievement of the Paris Agreement's long-term temperature goal requires an almost complete decarbonization of the major CO_2-emitting sectors, such as power, transport, and buildings, by mid-century (Rogelj et al. 2015). In this report, we look at technology trends in these three sectors that have seen very different degrees of transformational change. First, we assess how the current technology trends relate to the long-term temperature goal in the Paris Agreement. Second, we look at the drivers behind these technology trends, mainly in terms of policy making and innovation. Finally, we draw conclusions from the successes and apply them to future challenges in each sector.

We showcase how individual actors can drive change, providing a supportive environment for technological transformation. That environment consists, in large part, of policies that make it possible for new technologies, often financed by RD&D (research, development, and demonstration) funds, to enter the market. These policies create demand for products, which otherwise would not be competitive with the established technologies. Heightened demand pushes research to increase performance and decrease costs, making the new technologies more and more competitive, in turn leading to uptake in new regions or by new actors who form a transformative group of frontrunners. That group helps the new technologies achieve critical mass in the market and eventually to become mainstream technologies (see Figure 1).

Figure 1 — Stages of technology adoption.



This report starts with a summary of findings and goes on to examine the following:

- **Changes needed for Paris Agreement-compatible development in each sector.**
- **Past and projected trends as they relate to Paris Agreement-compatible development in each sector.**
- **Drivers of trends to date.** We highlight how a few actors have facilitated transformative change in one sector (power), examine the first signs of such change in another (transport), and explore the failure so far of yet another sector (buildings) to take advantage of well-established technologies to make Paris Agreement-compatible change.
- Acceleration of decarbonization through transformational coalitions. We explain how actors could quickly increase global uptake of new technologies by working together in formalized, high-ambition transformational coalitions.

2. EXECUTIVE SUMMARY

Meeting the Paris Agreement's long-term temperature limit requires a decarbonization of the global energy system by mid-century. Decarbonizing the power sector is the first step in the comprehensive transformation of the energy system (Rogelj et al. 2015). This requires transformational changes in each sector of the energy system before 2050.

This report looks at the technology trends driving decarbonization in three sectors—power, transportation, and buildings—along with empirical evidence on what can drive these rapid transitions.

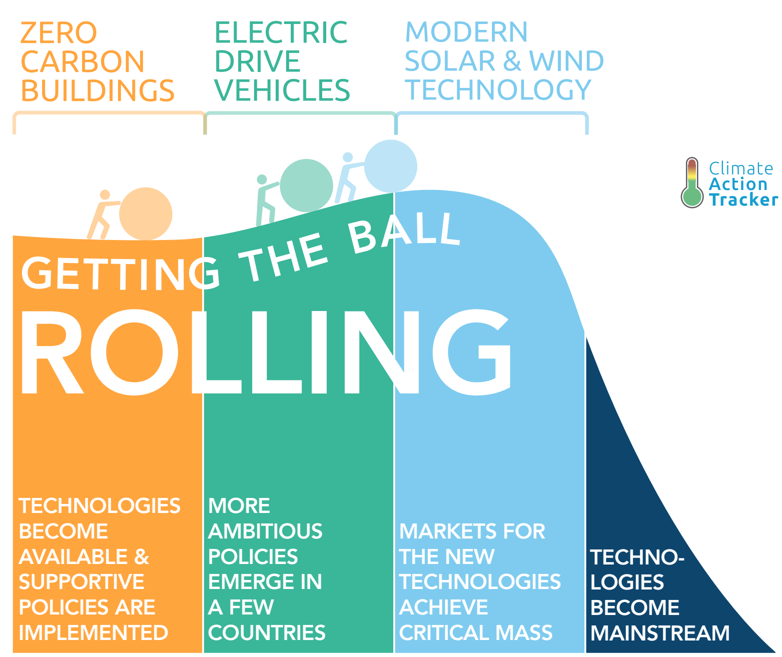
It identifies success factors that could support transitions in other areas to make the transformation scalable. The stringency of the Paris Agreement's aim to pursue efforts to limit global temperature increase to 1.5°C places significant additional pressure on the rate of transformation needed in each of these sectors.

Technological trends in these three sectors have experienced different levels of change, with the power sector witnessing the most transformation due to the rapid development of renewables that have far exceeded expectations. The accelerated uptake of electric-drive vehicles (EDVs) in the transport sector, if fully scaled, could trigger further transformation for that sector. The building sector, however, has seen limited progress and lags far behind its technological potential.

The transformational changes in the power and transport sectors have so far been triggered by policymaking efforts of only a few frontrunners —a small group of countries and regions with the right policy incentives—who have transformed the global market for the technologies and allowed the transition to move beyond the frontrunners to a wider circle. A transformative coalition of countries and sub-national actors in the building sector could accelerate the sector's decarbonization with approaches that take into account the considerable differences between the building stocks in various regions.

Lessons learned from these early-mover countries could enable these kinds of transitions to become mainstream, achieve critical mass—and transform not just the internal markets of countries participating but significantly influence development outside of those markets (Figure 1), eventually allowing for rapid global decarbonization.

Figure 2 — Stages of system change achieved by zero-carbon buildings, electric-drive vehicles, and modern solar and wind power technologies.



Major findings

Renewable energy technologies are transforming the power sector, which, in 2014, was responsible for almost 42 percent of energy-related CO_2 emissions (IEA 2016c), making it the largest single sector contributing to climate change.

The increase in installed renewable energy capacity, particularly wind and solar energy, has consistently exceeded mainstream expectations. Support mechanisms in a few first-mover countries (Denmark, Germany, Spain) and regions (California, Texas), with stable government policies and financial incentives, spurred RD&D and demand. Adoption of similar policies in other countries, notably China, and now in India, led to rapid growth of low cost renewable energy products and manufacturing at scale.

Should recent trends continue, future renewable capacity installations are set to dwarf what seemed ambitious forecasts a few years ago. Current progress is encouraging, and needs to be bolstered with policies to support the integration of high shares of renewables and replacement of CO_2-emitting fossil fuel-based electricity generation in order to meet 2050 deep decarbonization targets—in particular through corresponding grid and storage development as well as transforming electricity markets. A decarbonized power sector plays an important role in decarbonizing the transport and building sectors.

Electric-drive vehicles are now beginning to transform the transport sector which, in 2013, was responsible for roughly 23 percent of global energy-related emissions, of which three-quarters were attributable to road transport (IEA 2016c). There are three commonly accepted ways to reduce emissions in the transport sector: avoiding motorized travel, shifting travel demand to more energy-efficient modes, and improving the fuel and carbon efficiency of vehicle technology.

Although the first two have seen limited development, the third has shown progress. Increasing fuel efficiency standards for conventional internal combustion engine vehicles have played a role in this progress but are not sufficient for deep decarbonization—the solution lies in a rapid diffusion of zero-emission vehicle technologies.

Norway, the Netherlands, California—and more recently China—have developed markets for electric-drive vehicles (EDVs) that have contributed significantly to electric car sales reaching close to a million in 2016 (Kuramochi et al. 2016), but EDV uptake needs to accelerate significantly.

Climate Action Tracker analysis indicates that half of all light-duty vehicles on the road would need to be electric-drive by 2050 for 2°C compatibility, and for 1.5°C compatibility nearly all vehicles on the road need to be EDVs, implying that no internal combustion engine cars should be sold after roughly 2035 (Sterl, Kuramochi, et al. 2016).

The building sector has seen modest progress, but lags far behind its technological potential. It represented some 19 percent of global energy-related greenhouse gas (GHG emissions) in 2010 (Lucon et al. 2014) through heating and cooling, use of appliances (including lighting), and cooking. Energy use related to heating and cooling, in particular, has shown little positive movement.

Although there are proven technological solutions, they are applied primarily at the margin and in niche markets. If these solutions were effectively combined, they could result in zero-carbon buildings and, some argue, be cost-effective over a building's lifetime. They have failed to reach critical mass because of financial, geographical and other barriers.

The evolution and adoption of new financial mechanisms can help increase the rate of retrofitting of buildings across geographies, both in markets with sizable existing building stocks—such as the E.U. and the US—as well as in large emerging economies such as Brazil, China and India (Energy Programs Consortium 2017). By 2050, this sector would need to see a 70–80% reduction in 2050 emissions for a 2°C compatible pathway and 80–90% for a 1.5°C compatible pathway (Rogelj et al. 2015).

We conclude that single countries and a diverse set of actors within them taking action in parallel has, in some sectors, led to dynamics that are shifting global markets. Nevertheless, the pace of technology deployment is not sufficiently rapid to meet the Paris Agreement's goal of limiting temperature rise to well below 2 degrees Celsius above pre-industrial levels.

One way to speed up technology deployment are "transformative coalitions." Under the umbrella of such coalitions, countries and sub-national actors interested in advancing a particular low-carbon technology can work together to create similar market dynamics. Our research shows that an important base factor in creating such dynamics is the implementation of effective policy packages.

The success of low-carbon technology deployment in the power sector and partly in the transport sector would suggest that some polices may be particularly supportive. Transformative coalitions can identify and develop best practice policy packages that then can be tailored to the particular situation in each country. This strategy would ensure effective policy implementation in a number of countries, triggering a global market dynamic.

3. POWER SECTOR: MODERN SOLAR AND WIND TECHNOLOGY

The power sector was responsible for almost 42 percent of energy sector CO_2 emissions in 2014 (IEA 2016b), making it the largest single sector contributing to climate change. The increase in installed renewable energy (RE) capacity, particularly wind and solar energy, has consistently exceeded expectations. Should the recent trends continue, future capacity installations are set to dwarf even the seemingly ambitious forecasts from just a few years ago.

This increase in installed capacity has been driven by—and has led to—a significant fall in the costs of renewables, thus giving rise to a virtuous cycle wherein increasing capacity decreases costs, which facilitates an increase of capacity. This cycle has been initiated by the introduction of support mechanisms for renewables in a few countries (Denmark, Germany, Spain) and regions (California, Texas). The stable and predictable government policies and sufficient financial incentives triggered investment in RD&D and created a demand for new products. After similar policies were introduced by other countries, especially in China, and now in India, price decreases accelerated, increasing demand and leading to rapid growth in manufacturing at scale.

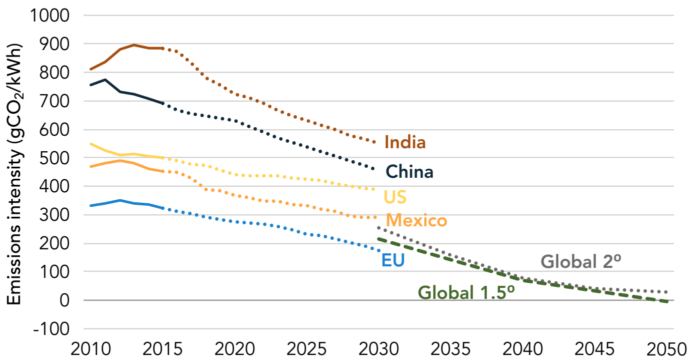
Even though trends in capacity growth suggest the power sector may be on track for 2°C-compatible pathways in key major economies (Cronin et al. 2015), an even faster and more dramatic transition from fossil fuels to renewables needs to take place at the global level so as to not exceed the Paris Agreement's long-term temperature limit.

3.1 What is needed for Paris-compatible development?

Despite the decreasing costs and accelerating capacity expansion of renewables, the speed of the power sector's transformation is not yet consistent with what is needed to achieve the Paris Agreement's long-term temperature goal. It needs to reach zero carbon dioxide emissions globally around 2050 (Rogelj et al. 2015). In addition to a clear vision accompanied by targets, that goal will require an immediate shift of investments toward renewables and other zero- and low-carbon alternatives. All fossil fuel-fired power generation without carbon capture and storage (CCS) will have to be phased out by 2050 and replaced with low-carbon options (Rogelj et al. 2015). Yet new fossil power plants with beyond-mid-century lifespans continue to be constructed and planned.

Development of renewable sources of energy, replacement of coal with gas, and the recent upsurge in nuclear energy in China have led to a decrease in the average, global carbon intensity of electricity from 641 g/kWh in 1990 to 567 g/kWh in 2014 (IEA 2016). But this speed of carbon intensity decrease is significantly lower than what is needed to fully decarbonize the power sector by mid-century. Figure 3 illustrates what is happening, what is expected, and what is needed with respect to the emissions intensity of electricity in China, the EU, India, Mexico, and the United States.

Figure 3 – Historical and projected emissions intensity of electricity (gCO_2/kWh) according to ClimateWorks Carbon Transparency Initiative (CTI) models.



Sources: Emission factor–ClimateWorks Foundation (2016); 2°C pathway (global) from Krabbe et al. (2015). Data for 1.5°C pathway adapted after Rogelj et al. (2015, 2013).

3.2 Past and projected trends

The decrease in power generation's carbon intensity has largely been the result of displacement of coal by natural gas and increased use of renewables. Over the last decade, modern renewable energy technologies, that is, solar and wind, have moved from niche products to mainstream solutions responsible for the significant majority of new capacity in many countries.

In the United States, renewables were responsible for almost two-thirds of the utility-scale capacity additions in 2015 and 2016. This capacity does not include the small-scale installations responsible for more than half of the installed PV capacity (US EIA 2017b). Even though renewables, especially wind and solar, generally have lower utilization rates than fossil fuels, the share of power coming from them increased from 10 percent in 2010 to almost 15 percent in the first 10 months of 2016 (US EIA 2017a). In the EU, more than three-quarters of all new installations were coming from renewables (EWEA 2016), which led the share of power from renewables to increase to 29.6 percent in 2016 (Agora Energiewende 2017). In China, installed solar capacity almost doubled in 2016 and reached 77.4 GW (CleanTechnica 2017), while wind energy capacity increased by 23.3 GW (GWEC 2017).

Globally in 2015, for the first time, new installed renewable energy capacity exceeded new installed coal capacity (IEA 2016g). Deployment of wind and solar energy is occurring at significantly higher rates than previously projected (Cronin et al. 2015). The installed capacity of these technologies grew 36-fold from 2000 to 2015 (IRENA 2015, 2016a). Growth is expected to continue: from 2015 to 2030, installed capacity of solar PV power is projected to increase sevenfold from 230 GW to more than 1,600 GW, while the capacity of wind power may more than quadruple from 400 GW to more than 1,800 GW (IRENA 2016c).

Simultaneously, continuous improvements reflecting economies of scale and increased knowledge about installation and operation of renewables led to a steep decline in the cost of renewables (IEA 2016h). For example, from 2010 to 2014 the levelized cost for solar PV decreased by half (IRENA 2014) and, in some cases, has fallen below that for wind energy (Bloomberg 2016d). In some US states, solar energy is already cheaper than coal (Bloomberg 2016c).

This cost decrease is expected to continue due to increasing economies of scale, more competitive supply chains, and technological improvements. Taken together, these factors could reduce the global weighted average cost of electricity from wind and solar energy by 26–59 percent between 2015 and 2025 (IRENA 2016). As a result, in many regions, renewables—as measured by their global average levelized cost of electricity (LCOE)—are becoming competitive with fossil-fuel-fired generation (IRENA 2014).

3.3 Explanation of the drivers

The initial push for growth of renewables in the power sector was driven by several factors, including concerns about the impact of fossil and nuclear sources of energy on the environment; grassroot movements to develop small-scale alternatives to established, large-scale conventional technologies; and the desire to increase energy security and reduce energy dependence by relying on domestic renewables (Bechberger et al. 2008; Lovins 1977; Yergin 2011). The policy efforts to stimulate this push to renewables can be broadly divided into support policies and targets.[1] The latter have been established to guide policy toward achieving a certain benchmark of renewables deployment and increasing security of investment in innovation, research, and development.

Our analysis shows that of the many factors that influenced renewables development, support policies and renewable energy targets were the most important. Together, they accelerated market uptake, drove down costs, and increased the number of actors involved in the energy sector. The predictability provided by long-term goals and targets and the simplicity of early-phase support mechanisms were key in advancing renewables development.

3.3.1 POLICIES AND TARGETS

Development of modern renewables goes back to the 1970s, when it was driven primarily by concerns about energy security and avoiding environmental pollution (Carter 1979). The introduction of generous tax credits in California in the National Energy Act from 1978 allowed for the early development of wind energy there (Righter 1996). But the technology did not work as planned and had to be replaced. That initial failure and a substantial reduction in financial support in the 1980s led to a slowdown in development and the subsequent collapse of the wind energy sector in the United States. Increased concerns about climate change in the 1990s led to the introduction of the production tax credit, which allowed the market to recover (Galbraith & Price 2013).

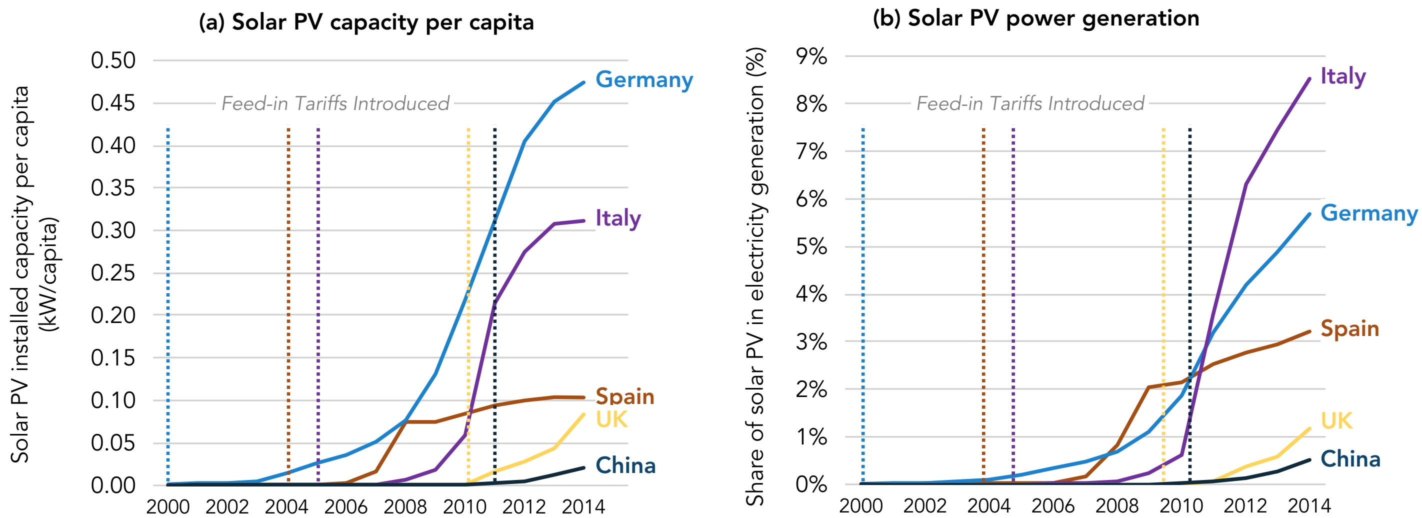
In the meantime, opposition to nuclear energy, especially in Germany, played a significant role in development of the nascent technology in some European countries (Meyer 2014). The uptake of renewable energy became notable at the turn of the century (Figure 4). The main driver was the introduction of renewable energy support schemes, in particular, feed-in tariffs (FiTs), which due to their simplicity and guaranteed return on investment allowed several new actors, such as cooperatives and individual houseowners ("prosumers"), to enter the market. Denmark and Germany played a major role. Introduction of differentiated feed-in tariffs for different sources of energy in Germany led to a rapid increase in the installed capacity of wind and solar energy (Bechberger et al. 2008; Volker Quaschning 2016).

Other countries in Europe and around the world followed suit. Notably, after having developed its manufacturing capacity (described in detail below), China also introduced feed-in tariffs for wind energy in 2009 and for solar energy in 2011 (Liu et al. 2015; Liu 2011). What followed was a substantive growth of installed capacity from these two sources of energy in China: from 45 GW wind and 1 GW solar energy in 2010 to 97 GW wind and 28 GW solar energy in 2014 (IEA 2012; IEA 2016i). According to preliminary numbers, by the end of 2016 the total installed solar energy capacity in China had tripled, reaching 77.4 GW (CleanTechnica 2017).

There is a clear correlation between the introduction of FiT and other support schemes and the increase in solar PV generation. Figure 4(b) shows the increasing share of solar PV in electricity generation after the introduction of feed-in tariffs. In Germany, the rapid growth of renewables was delayed by the still relatively high unit costs of renewables and by the lack of significant production capacities for renewable energy installations.

1 For example, aiming for a certain share of renewables in power generation or total primary energy supply, emissions reduction in particular sectors or decreasing carbon intensity of the economy, or quantitative targets on installed capacity generation, such as in India and China.

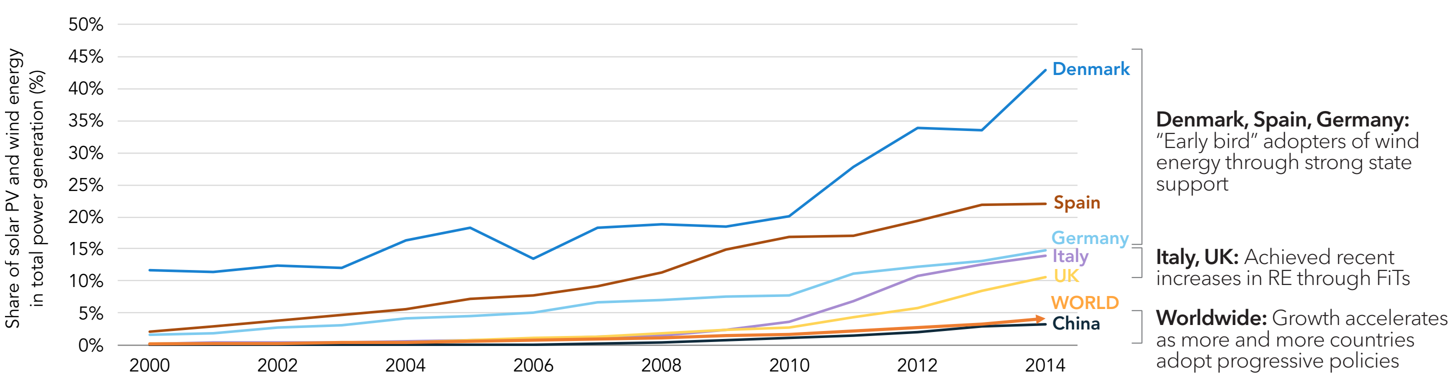
Figure 4 – Increases in solar PV capacity (a) and power generation (b) in several European countries after introduction of a nationwide feed-in tariff for solar PV.



Source: Capacity data from Eurostat (2015) and IEA (2016a); generation data from IEA Energy and Emissions database (IEA 2016c).

On the basis of renewables development patterns, countries can be grouped as shown in Figure 5; Germany, Denmark, and Spain focused on wind energy deployment starting in the 1980s and 1990s, whereas other countries achieved increased shares of renewable energy only after they incentivized solar PV in the late 2000s and early 2010s. These early, parallel movers were followed by a number of second movers that implemented similar support schemes with similar success. This trend resulted in a steep increase in the adoption of such support schemes in both developed and developing countries and, by 2015, 146 countries had some type of support scheme for renewable energy in place, compared with only 48 in 2004 (REN21 2014).

Figure 5 – Increase in modern renewable energy generation in selected countries.



Data from IEA (2016c).

In recent years, the growth of renewables has picked up in China and India, where significant potential for growth in power consumption and the size of the market will continue to drive the virtuous cycle of increasing capacity and decreasing costs—giving these two countries, and many other developing countries, an opportunity to use low-carbon sources to satisfy their energy needs. The relatively high costs of renewables made China initially turn to coal to satisfy these needs. The significant cost decrease in renewables and, in many cases, favorable weather conditions may allow India to leapfrog the coal phase of development and thus reduce the value of stranded assets, a challenge China will have to deal with in the future.

What these two countries have in common is the significant scale of their markets, further strengthened by long-term targets that increase the stability of investment: by 2020 China is planning to have installed 110 GW in solar and 210 GW in wind energy (Bloomberg 2016a). India is planning to increase installed capacity in solar energy to 100 GW and wind energy to 60 GW by 2022 (Government of India 2015b).

Though decisive for driving down the costs of renewables, China and India are only two of many countries implementing renewable energy targets. Between 2005 and 2015, the number of countries setting targets increased from 42 (mostly OECD) to 150, with nearly all the growth coming from non-OECD countries (IRENA 2016a). Targets send clear signals to investors by creating reliable financial and legislative conditions (Wei et al. 2016). A number of indicative examples are presented in Table 1. A comprehensive compilation of targets can be found in (REN21 2016).

Many other important policy trends directly or indirectly support renewable energy as an increasing number of countries are moving toward a fossil fuel phaseout. In the wake of the 22nd Conference of the Parties in Marrakech in November 2016, several countries announced they would completely ban coal-fired power: France by 2023 and Finland and Canada by 2030 (The Independent 2016 a, b, c). In addition, a coalition of 48 climate-vulnerable countries in Latin America, Africa, and Asia announced they would aim for transitioning to 100 percent renewable energy by 2050 (Climate Vulnerable Forum 2016a).

Table 1 – Countries and regions setting targets on renewable energy and electricity in various formulations.

Country/region	Target	Target year	Source
European Union	27% renewables in final consumption	2030	(European Commission 2016a)
Denmark	100% renewables in final consumption	2050	(Ministry of Foreign Affairs of Denmark n.d.)
Brazil	28%-33% renewables, excl. large hydro, in energy mix	2030	(Federative Republic of Brazil 2015)
Indonesia	23% renewables in energy mix excl. traditional forms of biomass	2025	(Climate Action Tracker 2016; Republic of Indonesia 2015)
	100 MW wind power capacity; 156.8 MW solar PV capacity	2025	(REN21 2016)
China	20% non-fossil fuel energy in TPES	2030	(National Development and Reform Commission 2015)
	250 GW of wind power capacity; 150 GW of solar power capacity	2020	(REN21 2016)
India	175 GW of renewable capacity	2022	(Government of India 2015a)
	40% of installed capacity non-fossil based	2030	(Government of India 2015a)
Morocco	52% share of renewables in installed capacity (20% solar, 20% wind, 12% hydro)	2030	(Government of Morocco 2016)

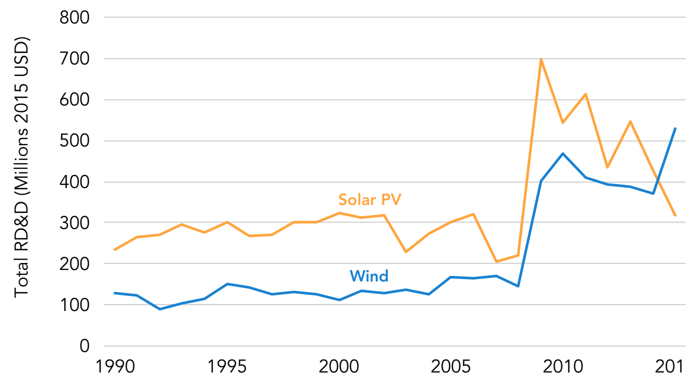
3.3.2 INNOVATION, RESEARCH, AND DEVELOPMENT

Continued technological and non-technological improvements are key requirements in overcoming the challenges resulting from power sector decarbonization. Investments in different kinds of RD&D—basic science, innovation, demonstration, prototyping, and smart deployment—help to accelerate renewables' grid parity with fossil fuels in different regions, facilitating, along with market incentives, renewables' massive global deployment (Nicholson and Stepp 2013; Breyer et al. 2010; Breyer and Gerlach 2013). The scalability of investment in renewables gives them a major advantage: their production, installation, and operation can be improved with every subsequent investment.

Public innovation expenditures on modern renewable energy technologies in IEA member countries (largely overlapping with OECD countries) changed little between 1990 and 2008. It was only in the run-up to the 15th Conference of the Parties (COP) in Copenhagen in 2009—and partly as a result of a strong push by the Obama administration (Congress 2009)—that these expenditures increased sharply, as shown in Figure 6. The Mission Innovation Initiative initiated during COP21 in Paris—whose 22 participating countries, including almost all OECD countries, have committed to double their governments' investments in clean energy RD&D—may contribute to a further significant increase in spending on innovation (Mission Innovation 2017).

A doubling of RD&D spending by Mission Innovation Initiative countries by 2021 would result in additional $35 billion investment over the next five years. Although each participant determines its own mix of technologies to be supported, all participants have declared investment in renewables and storage (Mission Innovation 2017). The Mission Innovation Initiative should ensure that money is invested wisely and that researchers from different countries cooperate to avoid duplication of efforts and instead build on one another's experiences. Policy instruments should ensure that the Valley of Death between basic research and product commercialization is bridged (Beard et al. 2009).

Figure 6 — Yearly public spending on RD&D for modern RE technologies in all IEA member countries.



Source: IEA (2016e).

As RD&D efforts have driven the virtuous cycle of higher production, leading to lower prices (Koseoglu et al. 2013), and the technology has spread, the levelized unit costs of electricity (LCOE) have decreased. From 1976 to 2010, every doubling of installed solar PV capacity worldwide resulted in a roughly 20 percent reduction in price per kilowatt-hour on average (Breyer et al. 2010). From 2010 to 2015, the costs of energy from solar PV dropped by more than 50 percent and reached the upper range of levilized costs of fossil fuel energy, a trend that has continued. The median LCOE for utility-scale PV technologies decreased approximately 11 percent in 2016 (Lazard 2016).

Increased market penetration of renewables and a corresponding decrease in price have further facilitated the virtuous cycle. In 2014, the average price per unit electricity from solar PV achieved grid parity with the global average price range of fossil fuels (IRENA 2016b). Solar and wind are now the same price—or cheaper—than new fossil fuel capacity in more than 30 countries. In a few years, solar and wind power prices will achieve grid parity with fossil fuel prices in two-thirds of all nations, even without subsidies (World Economic Forum 2016).

The growth of China's solar panel manufacturing industry has played a key role in the recent price decreases. The drive to increase manufacturing of solar panels in China initially occurred as a response to the increasing demand in countries such as Germany and Spain, the result of policies discussed above. Manufacturers of renewables in China benefited from state support, such as tax incentives and relatively cheap labor, both of which helped them to develop solar and wind energies into a strategic industry and made them a worldwide price leader (Fialka 2016).

Renewables' price reductions were possible thanks to various factors, including improvements in value chain steps from metallurgical silicon to PV modules; system design optimization; and increased productivity through modularization, standardization, and automation in solar module production (Aanesen et al. 2012; Breyer et al. 2010). The reductions can thus be viewed as a product of diffusion through policies combined with RD&D efforts focused on developing cheaper and more efficient PV modules.

In the case of wind energy, the virtuous cycle of increasing installed capacity and decreasing price began some two decades earlier: in 1980 the average price of wind energy in the United States was approximately 60 US cents/kWh (Office of Energy Efficiency & Renewable Energy 2016)—only slightly above the costs of solar energy in Germany in 2000. The benefits of scale, accompanied by technological improvements, have led to a continuous decrease in the costs of wind energy. In 2016, with an average price between 3.2 and 6.2 cents/kWh, it was the cheapest source of energy in the United States (Lazard 2016).

The increasing size and efficiency of wind turbines were key contributors to decreasing costs. In the mid-1980s, the dominant size of wind turbines was 50–100 kW, and the utilization rate was 11–13 percent. Interestingly, the utilization rate of larger wind turbines—more than 200 kW—was only 8 percent, because of defective turbine designs and flawed support schemes (California Energy Commission 1986).

In the subsequent three decades, the situation changed significantly: the average size of wind turbines installed in Germany in 2014 was 2,680 kW (Fraunhofer ISE 2015) and the average utilization rate in many regions, including the United States between 2008 and 2012, exceeded 30 percent (US EIA 2016). Both the size of the wind turbines and their utilization rate are expected to grow due to the increasing role of offshore wind. The lack of challenges associated with turbine transport allow for new records to be set, as in the case of the 9 MW Vestas turbine prototype, which produced 216 MWh power in 24 hours (Vestas 2017).

It has become clear that the recent increases in RE generation (Figure 5), spurred by progressive RE policy setting have, in the last few years, been synchronized with a marked increase in budgets (Figure 6) for RD&D and technological and non-technological innovation as well as with a marked reduction in costs of solar PV and wind power generation.

3.3 Achieving critical mass

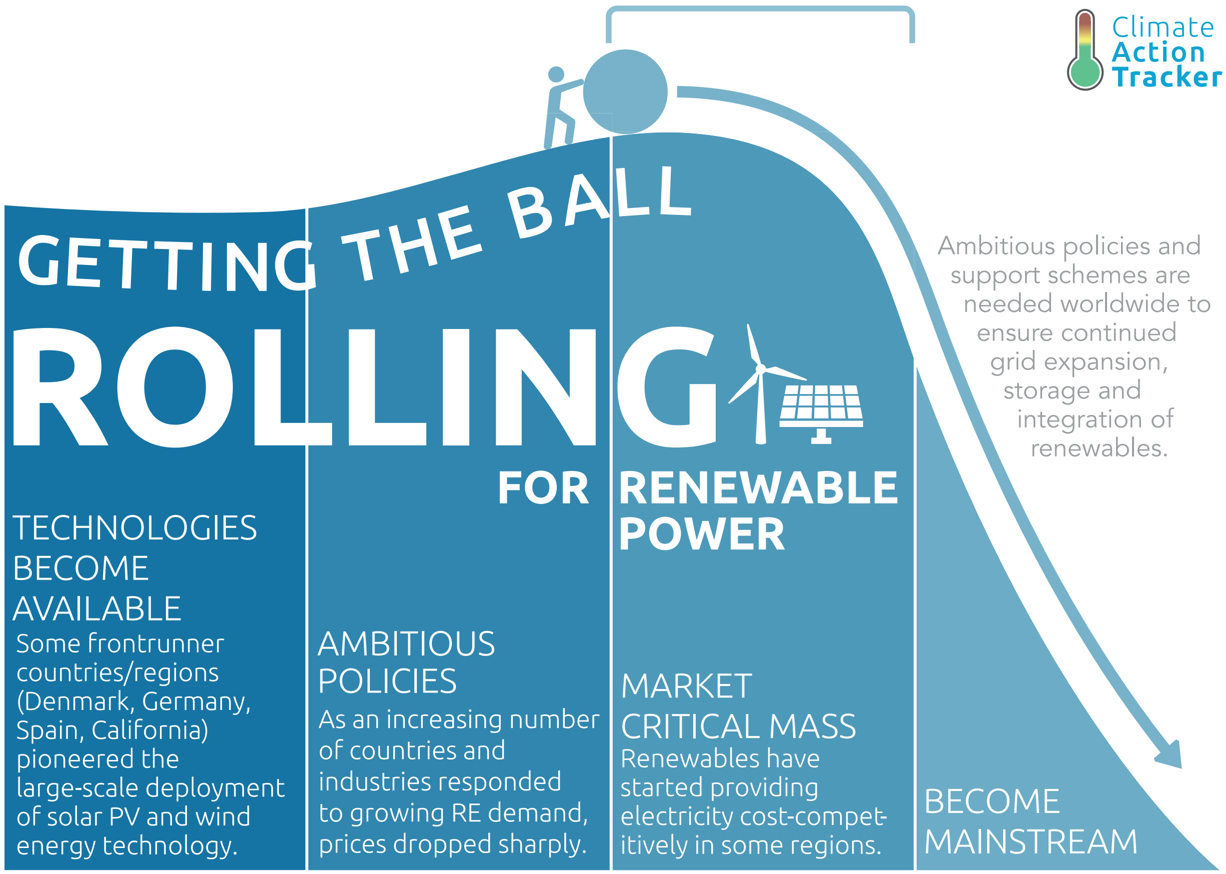
Today, renewables have become an important consideration in nearly all energy systems around the globe. Since 2000, a few countries acting independently but in parallel to implement ambitious policy frameworks involving renewables support schemes such as feed-in tariffs have been able to kickstart a virtuous cycle of technology development and market growth far exceeding predictions. We need not only to learn from—and mirror—this process, but also to find ways to accelerate it by integrating high levels of RE generation into the power sector as well as into other key sectors such as transport and buildings. The power sector will play an increasing role for these other sectors, as electrification plays an important role in decarbonizing them.

Despite its impressiveness, the renewables growth trajectory falls short of that needed to reach the long-term temperature goals of the Paris Agreement (BNEF 2017; The PV Market Alliance 2017; Phys 2017). The share of electricity production from wind and solar grew from less than 0.1 percent in 1995 to only 3.3 percent in 2013 (IEA 2016c) despite hundredfold growth in these sources' total generation during that timeframe. However, these trends in modern solar and wind technology, which have almost reached full market maturity and which have become the new normal in electricity generation, allow us to draw two important lessons:

1) Independent but parallel movers can initiate a virtuous cycle that makes a new technology viable around the world.

2) To achieve global decarbonization by mid-century, we need to find ways to accelerate this virtuous cycle. One promising avenue could be formal transformative coalitions focused on integrating high levels of RE generation into the electricity grid. Such coalitions could be supported by and themselves facilitate the exchange of expertise on grid integration politics, economics, and practice.

Figure 7 — Stages in the development of modern wind and solar.



In the power sector, accelerated penetration of renewables compatible with the Paris Agreement's long-term temperature goal will be challenged by a decrease in investment: the 2016 investment in renewable energies fell to $287 billion from the record level of $348 bn in 2015. Part of this decrease resulted from the lowered unit costs of renewables, which allowed for another record in installed capacity. To keep global warming below 2°C, an average of $900 billion must be invested in renewables every year between 2016 and 2030 (IRENA, 2016c).

Although the right policy mix, including phasing out direct and indirect subsidies for fossil fuels, ambitious renewable energy targets, support policies, and continuous investment in RD&D will speed renewables' market penetration, they must be complemented by innovative approaches to securing adequate financial streams. Because an increasing share of variable renewables will pose a challenge to the existing power infrastructure, new regulatory and technological solutions will have to be found. Finally, to fully decarbonize the power sector, many countries' renewables must replace existing fossil fuel generation in increasingly modern, flexible grids.

In 2015, coal consumption decreased for the first time since the 1990s (Eurocoal 2016), but at least 84 GW of new coal power capacity was added that year. The new capacity has been accompanied by a reduction in the utilization rate of coal-fired power plants, thus mitigating its negative impact on emissions (Shearer et al. 2016). Investments in that capacity likely represent future stranded assets in a decarbonized future, and they reduce the resources that could be directed to low-carbon alternatives and flexible grid infrastructure.

Therefore a change in the financial flows from fossil fuels to renewables requires a change in the mindset of investors and a lengthened planning horizon. The divestment campaign is a step in the right direction, but it needs to be accompanied by the strengthening of a campaign encouraging large-scale investments into clean sources of energy. As ambitious national long-term renewable energy targets help turn investment streams toward climate-friendly technologies, investors are increasingly offered certainty. A good example is the initiative of the Climate Vulnerable Forum, representing 48 countries that during COP22 in Marrakech jointly adopted a goal targeting 100 percent renewable energy "as rapidly as possible" and preparation of long-term low-carbon development strategies before 2020 (Climate Vulnerable Forum 2016b).

Drawing on the our lessons above, parallel efforts by a number of countries to create supportive investment environments can achieve a critical mass in the financial resources available for investment in renewables. That critical mass can, in turn, facilitate a decrease in renewables' unit cost and drive further investment, due to the competitive advantage over carbon-intensive alternatives. A more formal transformative coalition of countries that put in place conducive investor frameworks could be envisioned.

3.4.1 GRID INTEGRATION—CHANGING THE POWER MARKET PARADIGM

Renewable sources of energy play an instrumental role in decreasing the power sector's carbon intensity, but they also come with several challenges to successful grid integration, especially variability. As the role of wind and solar energy increases, an growing number of countries and regions will face the issue of relying on variable sources of energy. This requires a power market paradigm: Existing power systems must be adapted to provide flexibility for variable electricity sources and large numbers of distributed providers.

There are already several solutions for this issue. Increasing interconnection between countries and regions can balance changes in power supply and demand. Large- and small-scale storage—including that offered by e-mobility—is an effective option for dealing with the discrepancy between power demand and supply in any particular moment (Kempton & Tomić 2005; Tomić & Kempton 2007; Grahn 2013). The significant price decreases for batteries over the last few years driven by the benefits of scale for e-mobility, offer new opportunities in this regard (Clean Technica 2017). Demand-side management, especially in the case of large power consumers, offers new business opportunities to reduce the costs of power consumption, while contributing to grid stability. Finally, variable renewables can be complemented with dispatchable renewables, such as biogas or hydroenergy (as is the case in Norway and Vermont).

In addition to the emergence and policy support for technological solutions for matching demand and supply, policy mechanisms that focus on market design are needed to balance and increase system flexibility and to expand and improve grid infrastructure (e.g., energy storage and smart grids) (Müller et al. 2011). Lessons can emerge from the experiences of countries and regions, including Denmark, Germany, and California, that have already initiated energy transitions—experiences such as integrating an increasing share of variable renewable energy onto the grid and long-term planning towards an operation of a power market fully based on renewables. The latter is necessary to avoid certain costly investments, such as investments in new power lines or large-scale storage capacity that may turn out to be unnecessary if cheaper alternatives have not been taken into consideration. At the same time, lack or delay of such investments may threaten the security of energy supply. Insufficient infrastructure to transport energy may even slow down development of renewables, as is the case in China (Luo et al. 2016).

The mix of solutions will differ, depending on the local or regional circumstances: reliance on flexible renewables, such as bioenergy or hydro-energy, will be much higher in Brazil than in California. However, countries, regions, and states should be learning from one another about the effectiveness of different solutions and the policies needed to implement them. Such cooperation in the framework of transformative coalitions has the potential to significantly lower the costs of the global shift to low-carbon sources of energy in the power sector (Kuramochi et al. 2016) and options for integration of those sources into other energy sectors.

4. TRANSPORT SECTOR: ELECTRIC-DRIVE VEHICLES

The transport sector was responsible for some 23 percent of global energy-related emissions in 2013, of which three-quarters were attributable to road transport (IEA 2016b). The scientific literature has identified the transport sector as playing a key role in global decarbonization if the objectives of the Paris Agreement are to be met (Rogelj et al. 2015).

Emissions from transport can be decreased by lessening activity levels, facilitating the shift toward public transport, and reducing carbon intensity per distance traveled. The last goal can be achieved by improving vehicle efficiency as well as moving toward comparatively sustainable fuel sources, and thus it requires shifting to new technologies and helping these technologies to become market-ready.

Efforts to increase personal vehicles' fuel efficiency have reduced emissions intensities. However, efficiency improvements on their own are not compatible with a 2°C trajectory, let alone with a 1.5°C trajectory (Cronin et al. 2015). The solution lies in the rapid diffusion of zero-emission vehicle technologies. These technologies, such as electric-drive vehicles (EDVs), despite growing quickly, are still in the early stages of development and need further support to quickly attain critical mass in the market.

In this section, we show how the market for zero-emission, light-duty vehicles needs to develop to be compatible with the Paris Agreement's long-term goals, and what this alignment would mean for the car industry. We discuss in detail how the global market for electric-drive vehicles, both plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV)—which are substantially more efficient than internal combustion engine (ICE) vehicles (IEA 2016e) and which are zero-emission if powered by renewable electricity—has recently picked up speed in some countries (Cronin et al. 2015).

We review how governments have helped to increase EDV's competitiveness and discuss what needs to be done to facilitate decarbonization of the transport sector.

We examine what a policy package that addresses EDVs' main hurdles might look like and how a coordinated effort among countries might increase EDVs' market uptake.

We conclude by noting how a concerted and coordinated effort by a limited number of countries could lead to electric vehicles achieving critical mass in the global car market.

4.1 What is needed for Paris-compatible development?

The need for strong sectoral emissions reductions becomes evident when we consider what needs to happen to reach the Paris Agreement's long-term goals. Although the EU, US,[2] and Japan have set ambitious fuel economy or emissions intensity standards, research suggests that efficiency alone is insufficient to move to a 2°C-compatible, let alone a 1.5°C-compatible, pathway (Deng et al. 2012; IEA 2016e; Sims et al. 2014; Sterl, Kuramochi, et al. 2016).

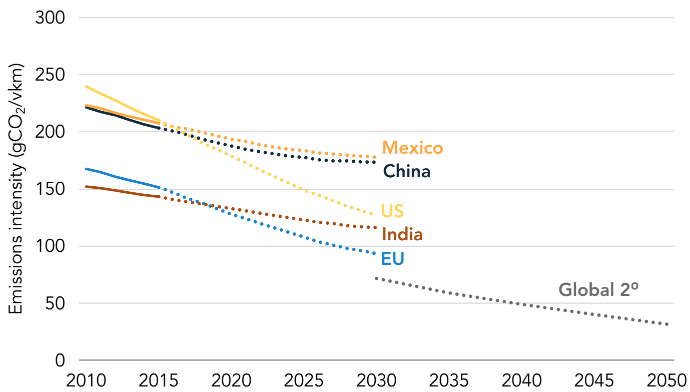
Given the expected increase in travel demand worldwide, a 2°C-compatible pathway cannot be attained with stringent fuel economy standards for vehicles with combustion engines alone. A recent study by the Climate Action Tracker suggests that roughly half of all personal car transport would have to have zero emissions by 2050—equivalent to an average emissions standard of nearly 70 gCO_2/vkm by 2030 and 30 gCO_2/vkm by 2050 (Sterl, Kuramochi, et al. 2016).

Current CO_2 emissions per vehicle-kilometer are more than five times higher than these averages (Tietge et al. 2015), and the EU standard, at 95 gCO_2/vkm starting in 2021, is approximately three times higher. At no more than 0.1 percent of the light-duty vehicle market, EDVs have a minimal impact on the emissions performance of personal transport today (IEA 2016e).

As shown in Figure 8, despite recent decreases in emissions intensity, the current fleet-average trends are neither 2°C nor 1.5°C compatible. Although sector-level 1.5°C pathways expressed as gCO_2/vkm do not yet exist in the scientific literature, preliminary analysis suggests that the last fossil fuel car would have to be sold in 2035 to make the transport sector compatible with the 1.5°C warming limit (Sterl, Kuramochi, et al. 2016).

2 As of March 2017, it appears likely that US Corporate Average Fuel Economy, or CAFE, standards may be weakened or rolled back in the future.

Figure 8 – Projected fleet-average emissions factor of LDVs in ClimateWorks' CTI model.



Sources: Emission factor–ClimateWorks Foundation (2016); 2°C pathway (global) adapted from Krabbe et al. (2015) with the methodology of Sterl et al. (2016). Data for 1.5 degree excluded due to lack of suitable analysis.

Note: Projections for China do not yet include Phase IV fuel consumption standards for passenger vehicles.

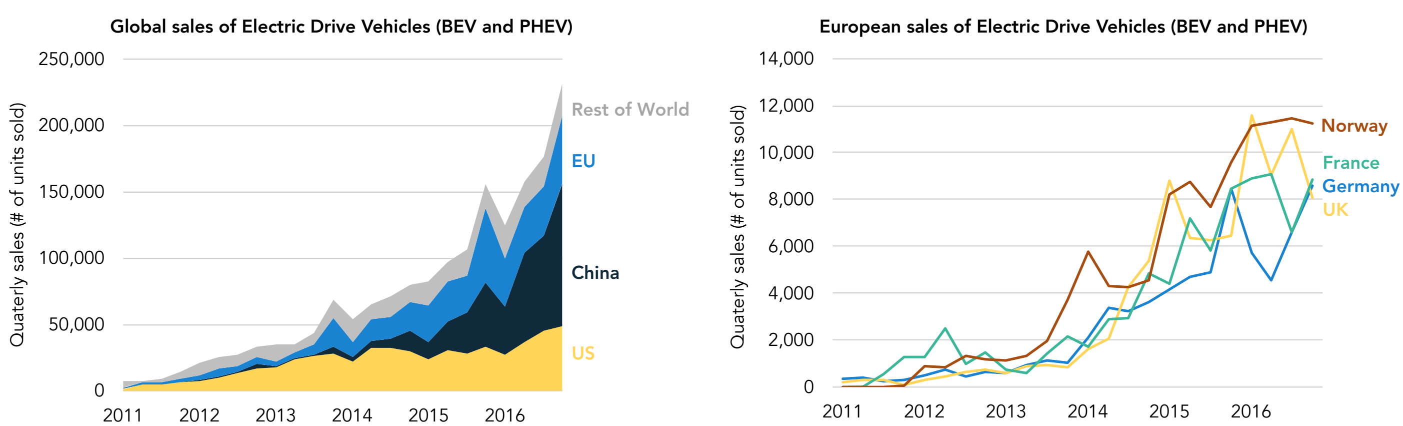
4.2 Past and projected trends

In recent years, demand for electric-drive vehicles has grown much faster than expected (Cronin et al. 2015).[3] Worldwide, the number of and infrastructure for electric-drive vehicles has increased rapidly (IEA 2016e). Some countries have realized high EDV sales much earlier than others. In the US (and particularly in California), EDV sales saw a big uptick in the 2011–2013 period; comparable sales were reached in the EU some two years later (Figure 9, left side). In the last two years, EDV sales in China have surpassed those in both the US and the EU.

3 We consider here both battery electric vehicles and plug-in hybrid vehicles.

Figure 9 – Differences in historical EDV quarterly sales worldwide and in major regions (left) and in several European countries (right).

Source: Data are from BNEF's Electric Vehicle Data Hub (BNEF 2016).

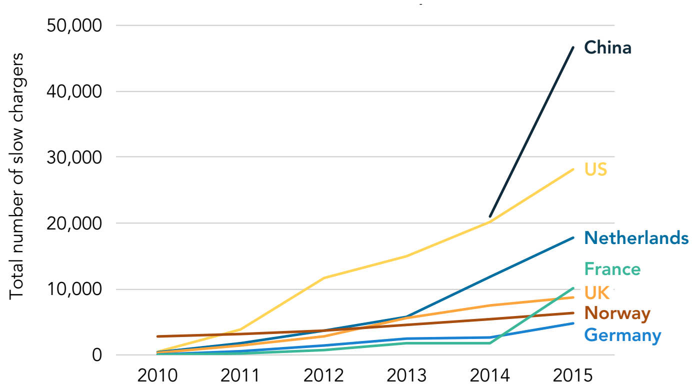


Within Europe, similar differences in timing can be seen (Figure 9, right side). For example, sales in Norway picked up earlier than those in the UK, Germany, and France—three of the four countries with the largest car fleets in the EU (the other being Italy, which has comparatively low EDV sales). The high share of EDVs in Norway's car fleet (which, as a whole, is some 10 times smaller than that of Germany, France, and the UK) is closely related to the Norwegian government's ambitious policies to incentivize EDV uptake; those policies include high purchase subsidies and an array of tax benefits. In the Netherlands, which currently has the EU's highest absolute number of (PH)EVs on the road, sales have not increased as steadily as in Norway, but instead have spiked when there are changes in tax incentives (see Figure 10).

Overall, EDV sales are concentrated in a few major economies. In 2009, the US accounted for nearly half the world's EDV stock; by 2015, about 80 percent of the world's EDV stock was in China, Europe, and the US (IEA 2016e). It is assumed that EDV market penetration will increase in several major countries and regions, where strong recent sales have exceeded expectations (Cronin et al. 2015), suggesting that future sales will continue to surpass projections from the Carbon Transparency Initiative (ClimateWorks Foundation 2016). According to those projections, the share of electric cars remains below 10 percent through the 2020s.

Along with increased sales of EDVs has come a strong push to increase supporting infrastructure. There are now almost 100 times as many EDVs on the road as there were in 2010, 50 times as many fast chargers, and 30 times as many slow chargers (the absolute worldwide number of slow chargers is still about six times larger than fast ones (IEA 2016e)). The number of slow chargers in various countries, together accounting for 76 percent of the global total, and their increase in the last five years, is shown in Figure 10.

Figure 10 – The total number of publicly accessible slow chargers in seven countries.



Source: IEA (2016d).

The recent surge in global EDV uptake has been spurred by a number of drivers. Policy actions (sometimes coupled with governmental targets) providing financial and non-financial incentives to potential buyers in countries such as Norway, the Netherlands, and China have played a critical role. At the same time, as markets grew, innovation and efforts in research and development, leading to improved manufacturing and economies of scale, have helped to improve EDV performance and drive down costs.

4.3.1 POLICIES AND TARGETS

Norway is currently the country with the highest share of EDVs in new car registrations worldwide: EDVs now account for nearly 30 percent of all new cars sold in Norway (EAFO 2017b). Norway has policies that provide incentives to EDV drivers, such as bus lane access and free public parking. In addition, financial incentives make EDVs competitive with fossil fuel cars (Transportøkonomisk Institutt 2016).[4] Because Norway's power sector is largely based on hydropower, EDVs already have had a substantial effect on emissions reductions beyond their improved efficiency compared to ICE vehicles.

Although the absolute number of EDVs on the road is roughly the same in the Netherlands as in Norway (Nijland et al. 2016), due to the former's much larger population, the Netherlands' share of EDV registrations in new sales is far behind Norway's—some 6 percent in 2016 (EAFO 2017c). Another significant difference is that most EDVs on the road in the Netherlands are leased, whereas in Norway private ownership of EDVs is much more widespread: many families are using an electric vehicle as a second car for short trips (Volkskrant 2016; Nijland et al. 2016). The emissions reductions associated with increased EDV uptake will grow as the Netherlands reduces the carbon intensity of power production, which still relies on comparatively low levels of low-carbon sources (Sterl, Höhne, and Kuramochi 2016).

The Netherlands' quarterly EDV sales figures provide a compelling example of the link between financial incentives and sales: tightening of the tax liability charges for leased low-emission cars in 2014 and 2016 led to extremely high sales numbers of plug-in hybrid electric vehicles in the last months of 2013 and 2015 (Figure 11), as attempts were made to profit from the incentives at the last moment (CBS 2015; Belastingdienst 2016). From 2017 onward, these incentives have been tightened again such that only all-electric vehicles—not plug-in hybrids—will profit from lower taxes on leased cars (Rijksoverheid 2016), resulting in another spike at the end of 2016. However, some sources also state that without the eventual implementation of purchase incentives—currently absent from policy—the Dutch EDV market may "sputter and stagnate" in the coming years (NOS 2016).

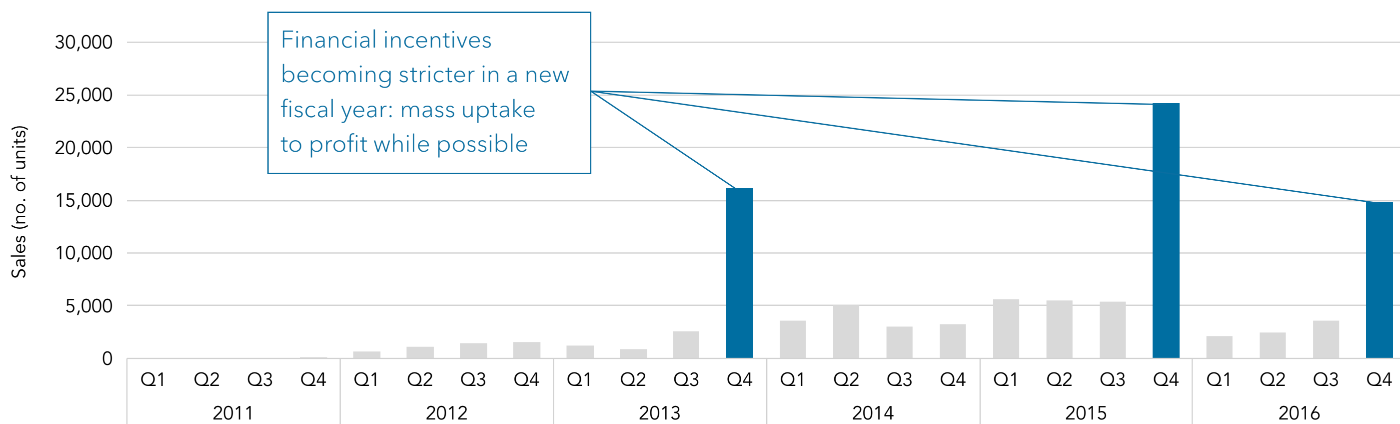
4 Norway's financial policies for EVs include a VAT exemption for private buyers; such a policy is currently not possible in EU countries because it conflicts with EU regulations on VAT (Nijland et al. 2016).

Examples of EDV support are also emerging from other countries. EDV sales in Chinese cities, with help from financial incentives such as free license plates, have exceeded expectation (Forbes 2016). There are purchase subsidies in Germany, France, Sweden, the United Kingdom, and the Flanders region of Belgium, and tax benefits are offered in Denmark, Italy, Austria, Spain, and Switzerland (Nijland et al. 2016). The effect of such financial incentives is comparable to that of feed-in tariffs in the EU and other regions on the competitiveness of renewable energy sources (Ragwitz et al. 2012; Nijland et al. 2016).

Apart from financial and behavioral incentives, the availability of charging infrastructure, measured in number of chargers per capita, plays a large role in driving or inhibiting EV uptake (Sierzchula et al. 2014). This number is again highest in Norway and the Netherlands. Charger density (number of chargers per surface area) is more than 10 times higher in the Netherlands than in France, Germany, and the UK, all of which have considerably lower shares of EDVs in their car fleet (Nijland et al. 2016).

Most EDV incentives are aimed at removing barriers. Table 2 presents approaches to these barriers in various countries and regions and, as a proxy for their success, overall incremental EDV market shares.

Figure 11 – Connection of EDV sales peaks in the Netherlands with tightening of financial incentives for leased EDVs.



Source: Data from BNEF's Electric Vehicle Data Hub (BNEF 2016).

Table 2 – Approaches to EDV barriers in Norway, the Netherlands, China, Belgium, and California

Type of Barrier	Norway	Netherlands	China	California	Belgium
Range anxiety: Availability of charging points	**High** Level of public chargers per capita (1.6 / 1,000 cap) higher than in all EU countries (ChargeMap.com 2017)	**High** Highest level of public chargers per capita (1.1 / 1,000 cap) and public chargers per square meter in EU (Nijland et al. 2016)	**Medium** Total estimated number of public chargers, 150,000, or 0.1 / 1,000 cap in 2016; plans to add another 100,000 public and 700,000 private chargers in 2017 (Forbes 2017)	**Medium/High** Average 0.3 public chargers / 1,000 capita (US Department of Energy 2017); in some cities on par with Norway (Searle et al. 2016); in 2017, California's utilities asked for more than $1 billion in funding to increasing number of charging stations (BNEF 2017)	**Medium** Total number of public chargers per capita close to EU average (0.2 / capita); more than five times lower than the Netherlands
High costs of EDV purchase	**High** Purchase incentives of up to €10,000; registration, ownership, company tax, and VAT benefits (EAFO 2017b)	**Medium** No purchase incentives; registration, ownership, company tax benefits (EAFO 2017c)	**High** Purchase incentives of up to $10,000; registration benefits in several cities; exemptions from ownership taxes (IEA 2016e)	**High** California offers incentives of $2,500 for EVs and $5,000 for FCEVs (or more for low-income consumers) (IEA 2016e)	**Medium** Purchase grant of €4,000 in Flanders; registration (in Flanders), ownership, company tax benefits (EAFO 2017a)
Behavioral preference for "conventional" cars	**High** Free parking; use of bus lanes allowed (EAFO 2017b)	**Low** No behavioral incentives programs (EAFO 2017c)	**Medium** Improved chance of obtaining license plates within annual quota (IEA 2016e)	**High** Major cities have programs, e.g., reserved parking at chargers, waived parking fees, electricity rate discounts (Searle et al. 2016); EDVs get access to carpool (HOV) lanes (California Environmental Protection Agency 2017)	**Low** No behavioral incentives programs (EAFO 2017a)
Overall penetration	**High** Number of EDVs in new car sales up to 30%; already more than 1% in 2011 (EAFO 2017b)	**Medium/High** Number of EDVs in new car sales some 6% in 2016, but down from nearly 10% in 2015 (EAFO 2017c)	**Medium** Currently largest EDV market, overtaking EU and US in last three years; share of EDVs in incremental market reached 1.45% in 2016 (EV-Volumes 2017)	**Medium/High** In 30 California cities, EDVs make up 6% to 18% of new vehicle sales; overall incremental share approx. 3% (Searle et al. 2016)	**Medium** Number of EDVs in new car sales approx. 1.7% in 2016, more than double the figure of 2015 (EAFO 2017a)

Several countries have, in parallel, set targets for EDV uptake. In Europe, for instance, Germany has set a target of one million EDVs on the road by 2020 and six million by 2030. The Netherlands aspire to have 1 million (PH) EVs on the road by 2025, which would represent a little more than 10 percent of the entire fleet (Sterl, Höhne, and Kuramochi 2016). The Dutch Parliament passed a motion in early 2016 calling for 100 percent EDVs in new car sales by 2025 (NRC 2016); legislative plans aim for 2035 (Ministerie van Economische Zaken 2016). Other countries with EDV targets are Austria, Denmark, France, Ireland, Portugal, Spain, and the UK (IEA 2016e).

Outside Europe, several US states have set EDV targets and supporting policies, as have South Korea, Japan, India, and China (IEA 2016e). The Chinese government's goal is that 30 percent of all government-owned cars be "alternative-energy" cars by 2016 (Bloomberg 2014). An 8 percent quota for electric vehicles in new car sales is under consideration. It would start in 2018 and ratchet up over time (Bloomberg 2016b). Given the size of the Chinese car market, this quota would likely spur carmakers from major car-producing countries, such as Germany, to expand their EDV offerings.

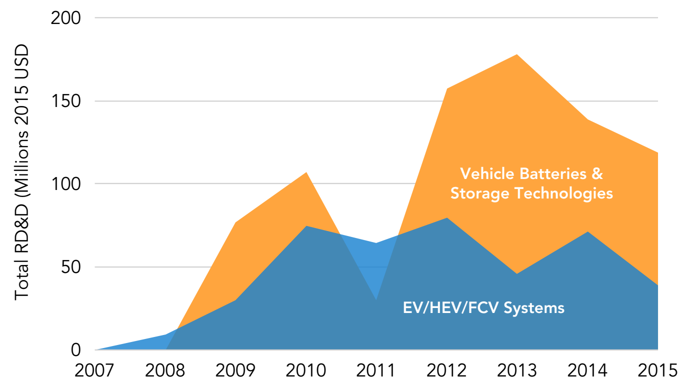
As in the power sector, targets signal governments' ambitions to investors and other actors and provide a benchmark for policies. Targets that are translated into actual laws and operationalized by incentives and requirements, as could be the case with the Chinese quota, will increase pressure on the automobile industry to comply and to invest in RD&D.

4.3.2 INNOVATION, RESEARCH, AND DEVELOPMENT

The cost of fuel, maintenance, and repair are significantly lower for EDVs than for combustion vehicles, but the purchase price for EDVs is higher due to the cost of the battery. That higher upfront cost presents a barrier to EDV uptake (Nijland et al. 2016).

To decrease this cost, several countries have established RD&D programs to help EDVs become more competitive (Schott et al. 2015). Public spending budgets for RD&D related to electric vehicles have grown substantially since 2008. Figure 12 shows public RD&D spending on vehicle batteries and storage as well as on EDV and other new vehicle technology systems. The figures cover only public spending; total private spending by manufacturers is likely to be orders of magnitude higher (*The Economist* 2017).

Figure 12 – Yearly public spending on RD&D for EDV technology in IEA member countries since 2007.



Source: IEA (2016e).

Together with expanding markets, supported in some countries by financial incentives for EDV uptake (BCG 2010) that lead to benefits of scale, RD&D leads to a decrease in price per unit. The price of EDV batteries (in cost per stored kWh) has decreased since 2008 by a factor of 4 to roughly $250 per kWh, a figure expected to drop (IEA 2016e) such that cost parity with conventional cars may be reached by 2020 (IEA 2013a). At the same time, the energy density (energy stored per unit volume) has increased by a factor of between three and four (IEA 2016e), reducing the space needed in the car and thus costs.

Directly related to the energy density and cost of car batteries is the driving range of EDVs, which, especially for first-generation vehicles, was regarded by many potential consumers to be too low in comparison to conventional cars (BCG 2010); in addition, consumers have concerns about EDVs' lifetime on the road, performance in varying weather conditions, potentially long charging times. Technological improvements in batteries thus play a major role in making EDVs more convenient and accepted as well as cheaper for customers. Such improvements are already under way; the best mainstream EDVs reportedly have 400-kilometer driving ranges (*The Guardian* 2016). As technology advances, applications beyond personal transportation, such as electrifying freight transport or providing balancing services to the electricity grid, can be targeted.

Electric-drive vehicles will substantially increase the worldwide demand for electricity. They could act as a flexible load in an ever-increasing electricity system in need of mitigating load variations (Kempton and Tomić 2005; Tomić and Kempton 2007; Grahn 2013). The transition to electric vehicles on the one hand and to renewable sources of electricity on the other must happen in concert if the transport sector is to decarbonize.

4.4 Achieving critical mass

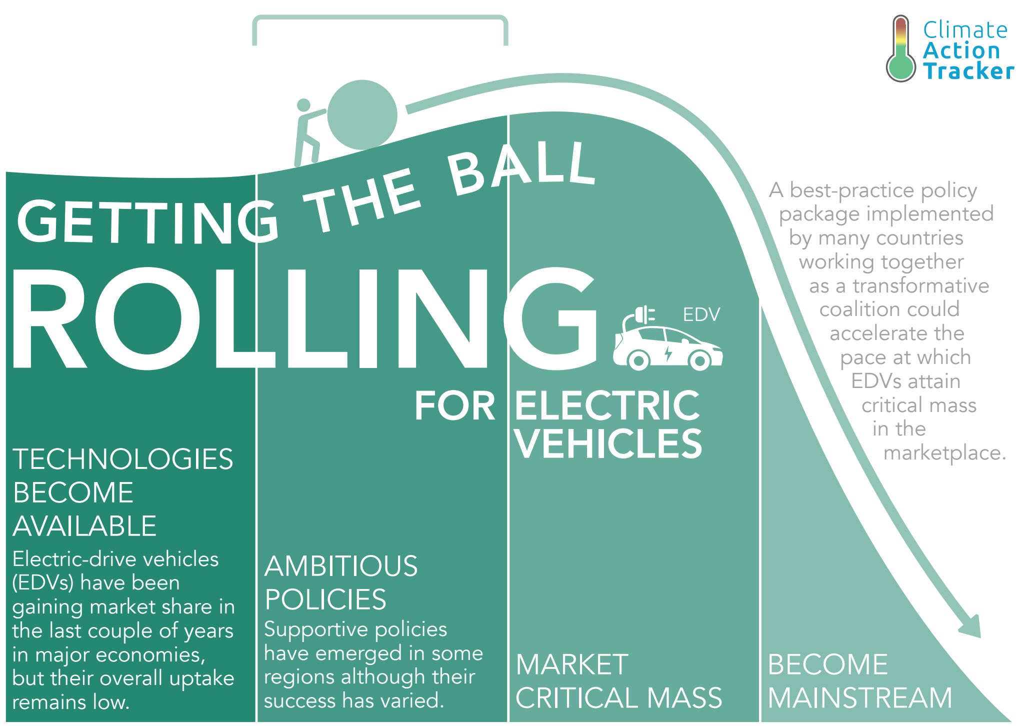
There are promising signs that EDVs will penetrate the transport sector just as renewables penetrated the power sector. Important drivers of RE development are starting to emerge in the transport sector: implementation of EDV-supportive domestic policy packages in some countries has led to EDV uptake and technology development that has surpassed expectations. Working in parallel, albeit uncoordinated, fashion, these countries appear to be creating an EDV dynamic similar to the modern renewables dynamic in the power sector. However, the EDV dynamic is in a nascent stage, and predictions about how fast and to what extent it will continue are extremely uncertain at the moment.

Our analysis indicates at least two approaches to ensure that this dynamic's potential is fully realized. First, because the success of individual policy efforts has varied, those that have proven effective—and that continue to prove effective—in more than one country should be replicated. Second, and somewhat related, countries should coordinate those efforts with one another. We discuss both approaches below.

4.4.1 DEVELOPING MORE EFFECTIVE POLICY PACKAGES

At the moment, relevant EDV uptake is limited to a small number of countries, each with its own policy package. Even within the European Union, individual countries are setting individual targets and creating unique policy packages to support the competitiveness of EDVs. The observation that EDV uptake is occurring in a few countries, each with its own supportive policies, with varying degrees of success, suggests that some combinations of policies are more effective than others. To accelerate EDV penetration of the global car market in line with 2°C- or 1.5°C-compatible pathways, countries should learn from one another, identifying and pursuing the most successful policy packages, a process represented in Figure 13.

Figure 13 – Stages in the development of EDV technology.



- Tax rebates for EDV drivers and financial support for EDV purchases
- Behavioral incentives for EDV drivers, such as access to EDV-only road lanes until EDVs make up a certain percentage of EDVs in the car fleet
- Support for continued expansion of EDV charging infrastructure
- Support for basic research into EDV batteries in order to improve EDVs' energy efficiency and performance
- Governmental targets and laws that guide policymaking and exert compliance pressure on industry—for example, zero emission vehicle requirements for manufacturers and increasingly stringent CO_2 emission standards.

4.4.2 IMPROVED COORDINATION EFFORTS

Working together in a formal transformative coalition, countries and regions could combine successful financial and behavioral incentives with continued support for RD&D and internal markets large enough to influence global demand for EDVs. A supportive policy environment in the participating countries could then drive investment in technology, leading to higher performance standards and lower prices worldwide, thereby accelerating global uptake.

Efforts to establish such coalitions already exist. For instance, the Zero-Emission Vehicle (ZEV) Alliance, a collaboration of the national governments of the Netherlands, Germany, the United Kingdom, and Norway and several sub-national governments in Canada and the United States, seeks to share existing targets for EDV deployment, a vision of zero-emission vehicles, and best practices to promote ZEV uptake. The UC Davis and the China Automotive Technology and Research Center recently established the China-US ZEV Policy Lab (UC Davis 2016). The member base of the Platform for Electromobility, which advocates acceleration of transport electrification in the EU, is formed by several companies and other organizations operating across the EU (Platform Electromobility 2016).

If these transformative coalitions were to implement policy packages in a coordinated manner, they would boost demand and accelerate investment and technological improvements. Such coalitions would push the global EDV market toward an "tipping point" beyond which the cost decreases are large enough to have a cascading influence on the rest of the world.

If a breakthrough coalition could also help novel technologies develop further such that they could spread to other parts of the transport sector (such as electric buses and electrified freight transport), emissions from the sector would reduce rapidly, provided that the power sector also decarbonizes in line with Paris Agreement goals. Bringing the transport sector in line with those goals should set the benchmark for the coalition's ambition.

5. BUILDING SECTOR: ZERO-CARBON BUILDINGS

While decarbonization is just starting in the transport sector and is well under way in the power sector, it has barely begun in the building sector. Progress lags far behind technological possibilities owing to a pervasive set of barriers. Overcoming these barriers requires a concerted effort to implement existing policies while also developing new mechanisms that enable transformation.

5.1 What is needed for Paris-compatible development?

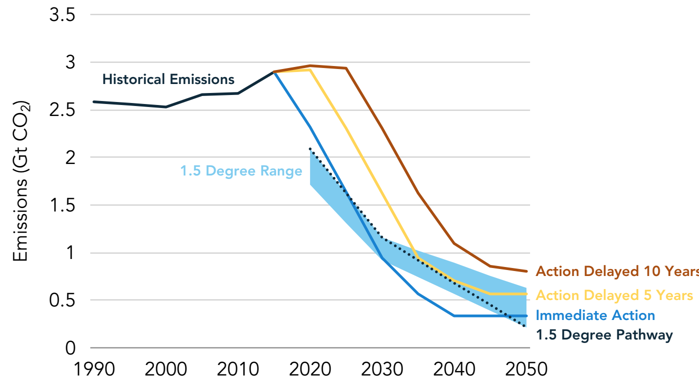
Greenhouse gas emissions from the building sector represent some one-fifth of global emissions (IPCC 2014a). Decarbonization in the built environment is one of the key factors needed to make the difference between 2°C of warming and 1.5°C of warming. Scenarios with a likely—or very likely—chance of limiting warming to less than 2°C require a 70–80 percent reduction of direct emissions from the building sector by 2050 (Rogelj et al. 2015). For scenarios consistent with no more than

1.5°C of warming, the required emissions reductions increase to 80–90 percent (Rogelj et al. 2015). Indirect emissions, primarily from electricity, are treated as part of the power sector in these scenarios and require full decarbonization by mid-century. However, energy efficiency measures in the buildings sector, coupled with on-site generation of renewable electricity, are important to curb the expected growth of electricity demand in the building sector as it electrifies. Curbing this growth reduces the stress on the power sector by reducing the simultaneous need to decarbonize existing capacity and provide for new and greater demands for electricity. Compared with indirect emissions, direct emissions are the most difficult emissions to reduce because they are subject to building infrastructure's lock-in effects.

Very ambitious efforts are required to steer the building sector toward a 1.5°C-compatible scenario (Wouters et al. 2016). An immediate-action scenario, in which all new buildings are zero-energy by 2020 in OECD countries and by 2025 in non-OECD countries, would bring direct emissions down to Paris Agreement-compatible levels if combined with an immediate scale-up of deep renovation efforts: 5 percent of floor space renovated per year in OECD regions and 3 percent per year in non-OECD regions (see Figure 14).[5] For comparison, renovation rates in the EU are currently some 1 percent per year (Renovate Europe 2017). Given the current policy outlook, the feasibility of such immediate-action scenarios is low, but they exemplify the importance of a rapid transformation in the building sector. Delay in ambitious action increases pressure to reduce emissions in other sectors and to implement negative-emissions strategies.

5 In this briefing we define a "zero-energy building" as a building that generates as much renewable energy on-site as it consumes annually. This can also be referred to as a "net zero-energy building". Zero-energy buildings are in general also zero-carbon buildings. Non-zero energy buildings can also be zero-carbon buildings through the use of renewable energy generated off-site.

Figure 14 – Comparison of direct building-sector emissions in three scenarios compared to 1.5°C-compatible range, 1990–2050.



Source: (Wouters et al. 2016). 1.5 degree pathway adapted from Rogelj et al. (2015, 2013).

5.2 Past and projected trends

From 1990 to 2010, emissions from the building sector have more than doubled to just more than 9 $GtCO_2e$. This growth has come overwhelmingly from indirect emissions, mostly from an increase in electricity use, which accounts for 6 $GtCO_2e$. Over the same period, direct emissions (i.e., emissions from fuel use in buildings, mostly for heating and cooking) have stagnated at 3 $GtCO_2e$ (Lucon et al. 2014). The majority of this growth comes from developing countries; the highest absolute growth is in Asia. Under current policies, energy consumption in buildings would continue to rise for decades—by an average of 1 percent per year. Electricity use sees by far the largest projected increase (at 2.5 percent per year), while coal and oil use for heating may slowly decline (IEA 2015). Both direct and indirect emissions need to decrease rapidly to be in line with the Paris Agreement.

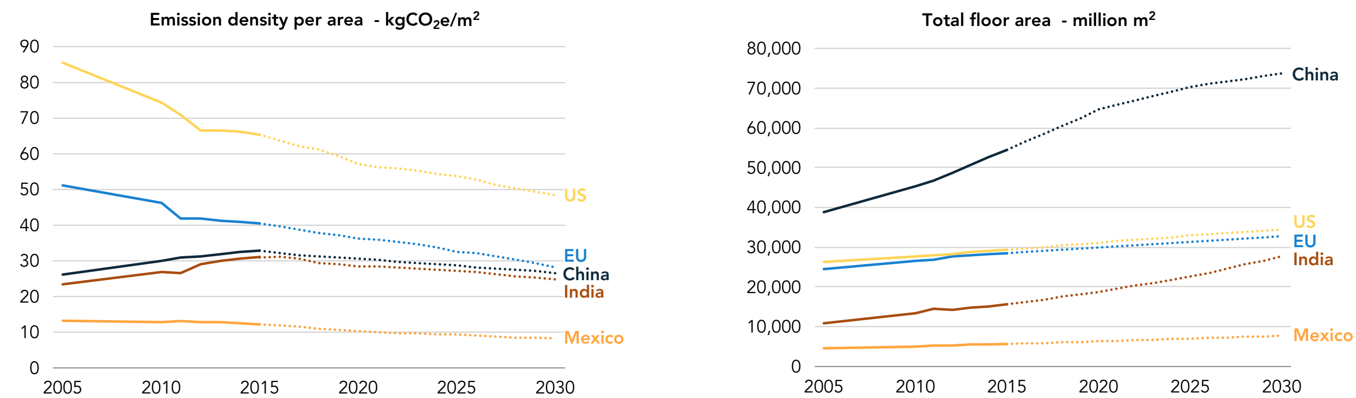
Moving beyond just energy and emissions in the aggregate, we can evaluate trends in a subset of countries to illuminate progress, but also the complexity of the problem. Take, for example, four metrics for China, the EU, India, Mexico, and the US: building emissions per floorspace area, total building floor area, building emissions per capita, and total emissions in the building sector.

In developed regions, such as the EU and the US, the emissions intensity per floor area and per capita exhibit a modest declining trend for the past decade that is expected to continue under a current development scenario (see Figure 15 and Figure 16).[6] By contrast, developing countries' emissions intensity per floor area is rising (and is linked with income and GDP growth). Although emissions per floor area are expected to plateau and potentially decrease after 2025 in both India and China, the growth in floor area per capita and population continues to drive total emissions upward (see Figure 15 and Figure 16.) Per capita emissions in China and India are projected to remain well below those in the EU and the US.

The situation in the EU and the US—and to some extent in Mexico—is very different from that in China and India, where building stock is still rapidly growing with economic expansion, giving rise to increased energy use and total emissions.

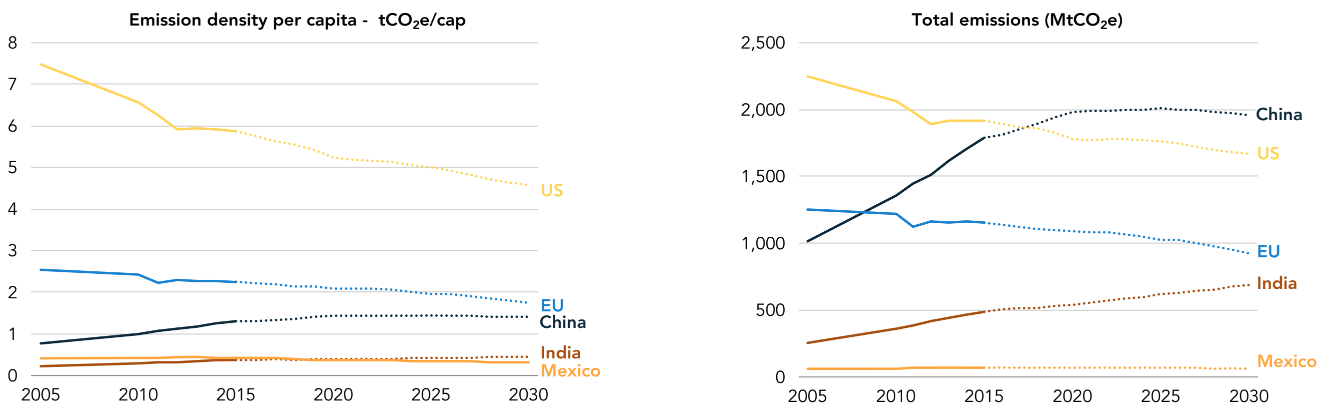
6 Emissions intensity includes both direct emissions related to fuel use in buildings and indirect emissions related to electricity use (for appliances, airconditioning, etc.). The current development scenarios (CDS) in the Carbon Transparency Initiative models is based on current policies, decarbonization trends, and energy-related investments. The CDS assumes continued efforts to implement policies and to support and defend current policies and legislation.

Figure 15 – Building sector emissions (direct and indirect) per floor area and total floor area.



Source: Data from ClimateWorks' CTI models (ClimateWorks Foundation 2016).

Figure 16 – Building sector emissions (direct and indirect) per capita and total building sector emissions.



Source: Data from ClimateWorks' CTI models (ClimateWorks Foundation 2016).

The slow decarbonization trends, both observed and projected, contrast starkly with the maturity of the technological solutions. For example, we have known how to build zero-carbon buildings for several decades. Between 1990 and 2010, more than 200 building projects claiming a net zero energy balance were realized worldwide. Small net zero-energy residential buildings were followed by bigger building types with higher energy demand (Musall et al. 2010). The vast majority of zero-energy buildings are located in Europe and North America, but the concept is taking root in other geographies. For example, the world's first zero-energy skyscraper is being constructed in Jakarta (SOM 2016). The number of net zero-energy buildings, although rising year after year, so far still represents a negligible share of total building construction worldwide.

5.3 Explanation of the drivers

There are targets and policies aimed at reducing emissions in the building sector in many countries, and there are some promising trends in some EU member states, Japan, and some US cities and states. But these policies and targets are insufficient to overcome the barriers to the sector's full decarbonization. To achieve the Paris Agreement goals, ambitious policies and best practices in policy implementation must be replicated in other geographies and adapted to local circumstances.

5.3.1 POLICIES AND TARGETS

Many policies in the building sector have resulted in the gradual downward trend in emissions intensity per floor area, as noted above. The IPCC (IPCC 2014b) categorizes the sector's policy instruments as follows:

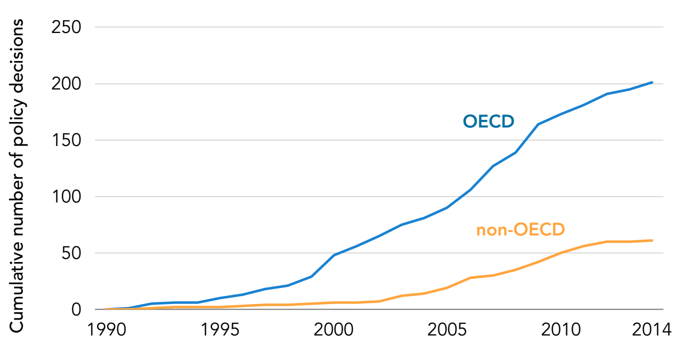
- **Regulatory measures,** such as building codes and standards.
- **Informational instruments,** such as energy labels and mandatory energy audits.
- **Direct market intervention instruments,** including public procurement.
- **Economic instruments,** such as tradeble permits, taxes, and financial incentives.
- **Voluntary agreements,** such as industry related agreements.

Any of these instruments—if tailored to local conditions and policy sectors and implemented and enforced well—can be (cost-)effective, but no single instrument will be sufficient to achieve the full potential savings in the building sector (IPCC 2014b). In a well-designed policy package, various elements can support and reinforce each other, thus increasing their overall effectiveness.

The most effective packages couple instruments that address different barriers (see the discussion below). For example, financing instruments are effective when informational instruments communicate the full scope of benefits they offer. Building-related policies reinforce broader energy sector instruments, and vice versa. Policies can act as substitutes for one another. For example, depending on the policy preferences of a given government, energy demand reductions can be achieved by financial support for energy efficiency technologies or by mandatory performance standards (Amecke & Neuhoff 2011).

Many policies and targets have been implemented in OECD countries, and non-OECD countries are following this trend (see Figure 17 below). The number of new policies in the building sector reached a peak in 2009, the year of the Copenhagen Climate Change Conference. Although the growing number of policies indicates that a response to the need to transform the sector is under way, it says little about the policies' effectiveness in realizing energy and emissions savings. The character and implementation record of these policies differ widely. Additional policies and further strengthening of existing policies, implemented in a coordinated manner within a country, could accelerate the decarbonization trend.

Figure 17 – Number of building sector policy decisions implemented globally.



Source: (NewClimate Institute 2016).

The EU is one frontrunner in terms of building sector policies and targets (although the number of buildings affected is small). Its main legislative tools for reducing the energy consumption of buildings are the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED). Both directives were revised in December 2016 to bring them up to date with the 2030 energy and climate goals (European Commission 2016c). The EPBD requires all new buildings to be nearly zero-energy buildings (nZEB) by December 31, 2020—public buildings by December 31, 2018.

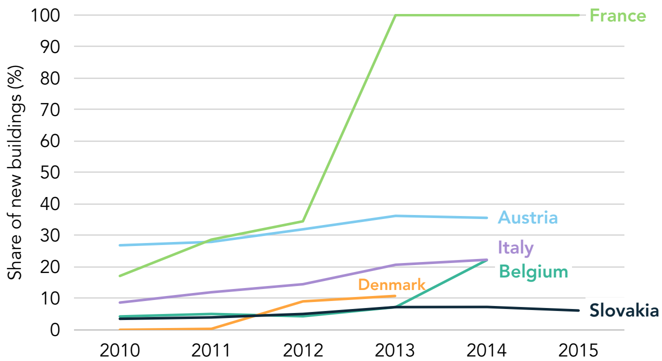
Additionally, the EPBD mandates standards for the renovation of existing buildings (European Commission 2016b). The revision of the EPBD incorporates provisions on long-term renovation strategies aimed at obtaining a decarbonized building stock by 2050 (European Commission 2016c). The EED aims to increase the rate of renovations to at least 3 percent a year of buildings owned and occupied by the central government (European Commission 2016b) compared to a current rate of renovations in the EU of approximately 1 percent (Renovate Europe 2015). This does not meet the 5 percent renovation rate required to reach the Paris Agreement goals, but it is a step in the right direction. The importance of building sector decarbonization was reaffirmed in the recent EU 'Winter Package'.

Adoption of the EPBD in 2010 has spurred construction of buildings that meet or exceed standards in the national nZEB definition. Several member states (such as France—see Figure 18) go beyond the minimum requirements of the EPBD and already meet the 2020 100 percent target. However, in many other EU member states, the share has so far remained negligible (Enerdata 2016), and some states have yet to establish an official nZEB definition. The EPBD establishes the framework definition of nZEBs, and member states create their own definition reflecting local circumstances and cost-optimal levels.[7]

Denmark and the Slovakia progressively tighten buildings' energy performance standards, whereas Denmark seeks to go beyond nZEB by constructing "positive energy" buildings. Most member states enforce the requirements of the EPDB as of 2021 (2019 for public buildings), but in 2013 France went a step further, requiring all new buildings to be nZEB. Similarly, the Brussels Capital Region (Belguim) defined nZEB requirements in 2011 and began enforcing them in 2015, allowing the building sector four years to adapt (BPIE 2015a). The nZEB definition of both member states is based on maximum primary energy demand: 40–65 kWh/m^{2}yr in France and 45 kWh/m^{2}yr in Brussels. These demand standards are fairly high compared to the Danish standard of only 20 kWh/m^{2}yr (BPIE 2015a). These standards should be strengthened to achieve zero-carbon buildings.

7 A nearly zero energy building is a building that has very high energy performance. The nearly zero or very low amount of energy required should be covered to a significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. However, the exact definition of this building standard varies in each member state.

Figure 18 – Share of new dwellings built according to a national nZEB definition or a more stringent standard in five EU member states.



Source: (Enerdata 2016).

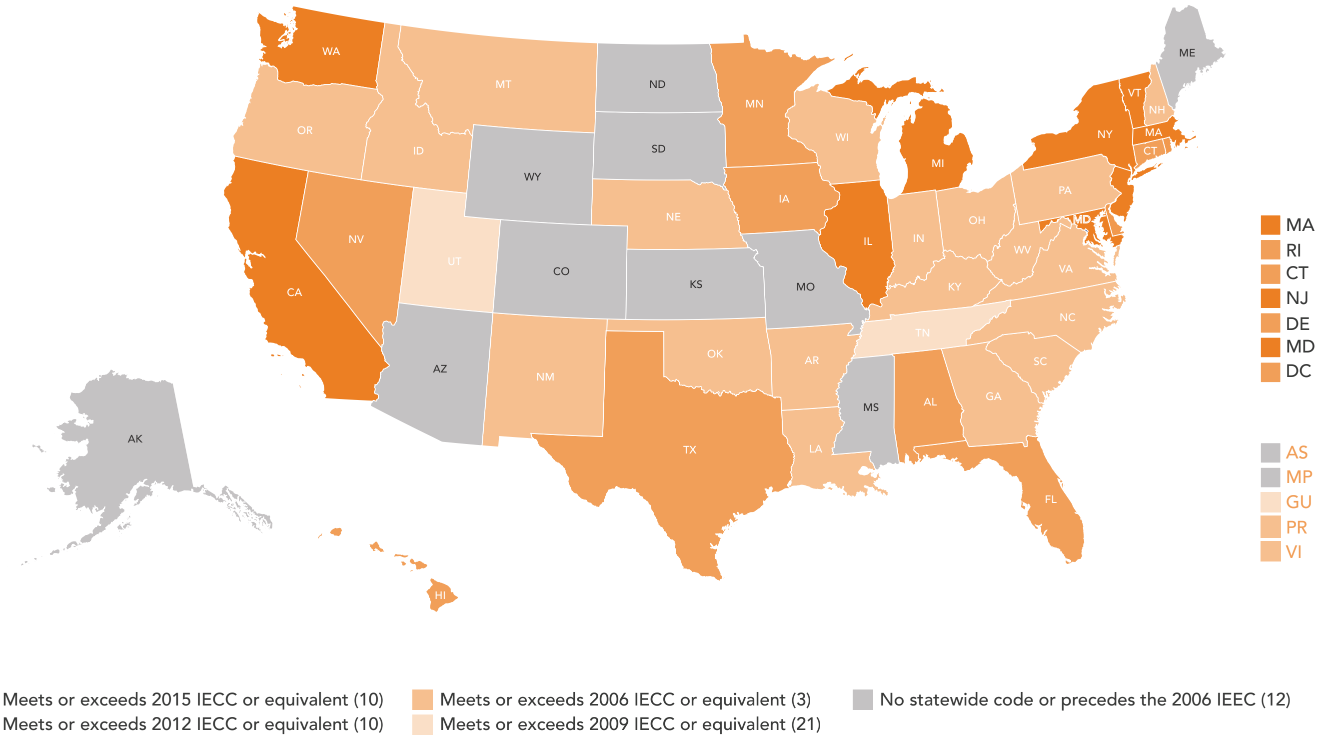
Note: Because definitions vary from state to state, numbers are not directly comparable.

Various financial support schemes exist in the EU, both at the EU level (e.g., the Cohesion Fund and the European Energy Efficiency Fund) and at the national level (mostly grants and "soft" loans, followed by tax incentives). Financial support measures vary significantly among member states (European Commission 2013). Financial support for energy efficiency in buildings will have to be improved for the EU to meet the targets specified in the EPBD and the EED, in turn requiring proper implementation of the regulatory framework, improved access to financing, and efforts to address key barriers and market failures (European Commission 2013). Additionally, enforcement and compliance are crucial and determine the true effectiveness of a policy (IEA 2013b).

Like EU member states, individual US states similarly have differing sets of policies for the building sector. Although the US has no exact parallels to the EU's EPBD or EED, the US Department of Energy (DOE) does support uptake of energy efficiency in buildings through support of policy guidance, research and development, elevation of codes and standards, and financial support through various grant, loan and financing programs. Program participation and policy adoption varies from state to state. For example, not all states adopt or fully implement the DOE's building codes, which are under the rubric of International Energy Conservation Codes (IECC) for both residential and commercial sectors (IECC codes exist for 2006, 2009, 2012, and 2015) (see Figure 19).

Figure 19 – Adoption of residential International Energy Conservation Codes in the US

Source: Adapted from Building Codes Assistance Project.



Note: Within some states, municipal governments have adopted codes exceeding standards adopted by their state governments.

Like EU member states, US states have differing targets and definitions. The 2008 and later California Long-term Energy Efficiency Strategic Plans (CEESP) have targets similar to some of EU member state targets. The CEESP aims for all new construction to be net-zero or net-positive energy producers. The CEESP wants all new residential buildings to be zero net energy (ZNE) buildings by 2020 (California Energy Commission 2015c) and all new commercial buildings to be ZNE buildings by 2030 (California Energy Commission 2011b). The CEESP also addresses renovations of existing buildings, aiming to reduce their energy consumption 40 percent by 2020 and to have 50 percent of existing commercial buildings become ZNE buildings (California Energy Commission 2016d). California is not the only state to adopt ambitious policies and targets, but as Figure 19 shows there also large gaps in policy uptake, highlighting the need for further ambition in the building sector in order to comply with any low-carbon, Paris Agreement-compatible pathway.

The checkerboard action among US states has allowed testing of various types of interventions. For example, states have taken a variety of approaches to a major barrier to energy efficiency implementation: the financing of energy efficiency measures. Implementation of the 2009 American Recovery and Reinvestment Act led to further funding and development of energy-related programs by earmarking more than $31 billion in investments through the DOE.[8] This investment has resulted in multiple studies that evaluate the effectiveness of financial programs. If and when others adopt more ambitious targets and policies, they will have ample examples of financial programs that might be tailored to fit their own circumstances (Leventis 2016).

China and India have building energy efficiency policies, but their ambition levels are far from the required ambition levels.

Since the 1980s, China has had national building energy efficiency codes, including mandatory and voluntary clauses, for new residential and public buildings. The building codes are not yet close to resulting in near-zero-

8 See the Department of Energy website: https://www.energy.gov/recovery-act.

energy buildings. China has also attempted to introduce market-based policies to popularize energy efficiency in buildings, implementing domestic rating and labeling programs in 2008: the Green Building Evaluation and Labeling Program (GBEL) and the Building Energy Efficiency Evaluation and Labeling program (BEEL) (Feng et al. 2015). However, both programs are voluntary in nature and have seen slow uptake. Retrofitting the existing building stock is the most challenging aspect of promoting energy efficiency in China's building sector. For the residential sector, policy efforts focus on setting energy efficiency standards and guidelines for the building envelope, external windows, heating systems, and lighting equipment and other electrical facilities and for the use of renewable energy. The residential retrofit rate exceeded expectations during the 11th Five-Year-Plan period (Li & Shui 2015). But given the total floor space, that rate does not approach the required renovation rate.

China's cities can take the lead in decarbonizing their building stock. An example is the International Low Carbon City (ILCC) program in Shenzhen. The initiative aims for urban transformation and low-carbon innovation through integrated efforts to preserve existing buildings with construction of high-standard new buildings. The project is driven by the city with extensive private sector involvement. Some ten major infrastructure and constructions projects have begun in the pilot zone and expansion area. They include upgrades of existing buildings to green building standards, design of all new buildings to meet the latest green design methods, and construction of an industrial park for advanced low-carbon industries. The environmental impacts of the ILCC program are expected to be vast. Substantial improvements have already been shown: 100,000 square meters have been renovated so far (Trencher et al. 2017).

In 2007 India's government adopted the Energy Conservation Building Code (ECBC) for new commercial buildings with a connected load of at least 100 kW or 120 kVA. India's state governments have the flexibility to modify the code to match their local needs. To date, 22 of 29 states are at different stages of what is for now voluntary implementation (Bureau of Energy Efficiency 2015). However, the majority of commercial buildings are not ECBC-compliant, and compliance is not systematically measured and verified (Yu et al. 2014). Moreover, there is as yet no nationally binding nZEB strategy in place (Global Buildings Performance Network 2013).

5.3.2 COSTS

Increasing evidence shows that new buildings can realize very high energy performance at little and sometimes even at negative additional lifetime costs. Cost-effective design and construction of zero-carbon commercial buildings is on the rise (IPCC 2014b; Leach et al. 2014). But in the residential sector, such design and construction is less cost-effective. Moreover, when assessing the cost-effectiveness of zero-carbon buildings, we should also take into account the cost of the required future renovation if net-zero energy use is not realized at the time of construction.

Regarding renovations, studies have highlighted the important distinction between conventional, "shallow" renovations that reduce energy use by only 10–30 percent, and aggressive, "deep" renovations that reduce energy use by at least 50 percent. Compared with deep renovations, shallow renovations can result in a lock-in of suboptimal energy efficiency levels and higher medium-term mitigation costs. There is considerable evidence that deep renovations can be cost-effective under many conditions (i.e., climates, building types, and cultures). Many examples show that deep renovations are not necessarily less cost-effective compared to shallow renovations (IPCC 2014b). When a multi-step approach is chosen, the deep renovation of a building must take place in a series of planned stages so that the costs of undertaking a particular stage do not preclude or increase the costs of carrying out subsequent stages (staged deep renovation) (Renovate Europe 2017).

The Dutch program called Stroomversnelling (meaning "rapid" but also translatable as "electricity acceleration")—part of the innovation program Energiesprong—shows that zero-energy-focused renovation of rental houses is feasible at cost-effective levels. This scheme addresses the principal-agent problem and high upfront capital costs by funding the costs from a social bank. The costs are to be paid for by the energy cost savings over a 30-year period, keeping the housing costs (rent plus energy) for the tenants the same (BPIE 2015b). The scheme is currently being replicated in France, the United Kingdom, Denmark, and the state of New York (Energiesprong 2017). This innovative approach to financing combines mechanisms to address one barrier, but there are multiple barriers in the building sector.

5.3.3 BARRIERS

Even though policies aimed at increasing the energy efficiency of the building sector are in place in many countries around the world, decarbonization of the sector is not yet accelerating. The reason? Uptake of the necessary technologies is stymied by considerable barriers.

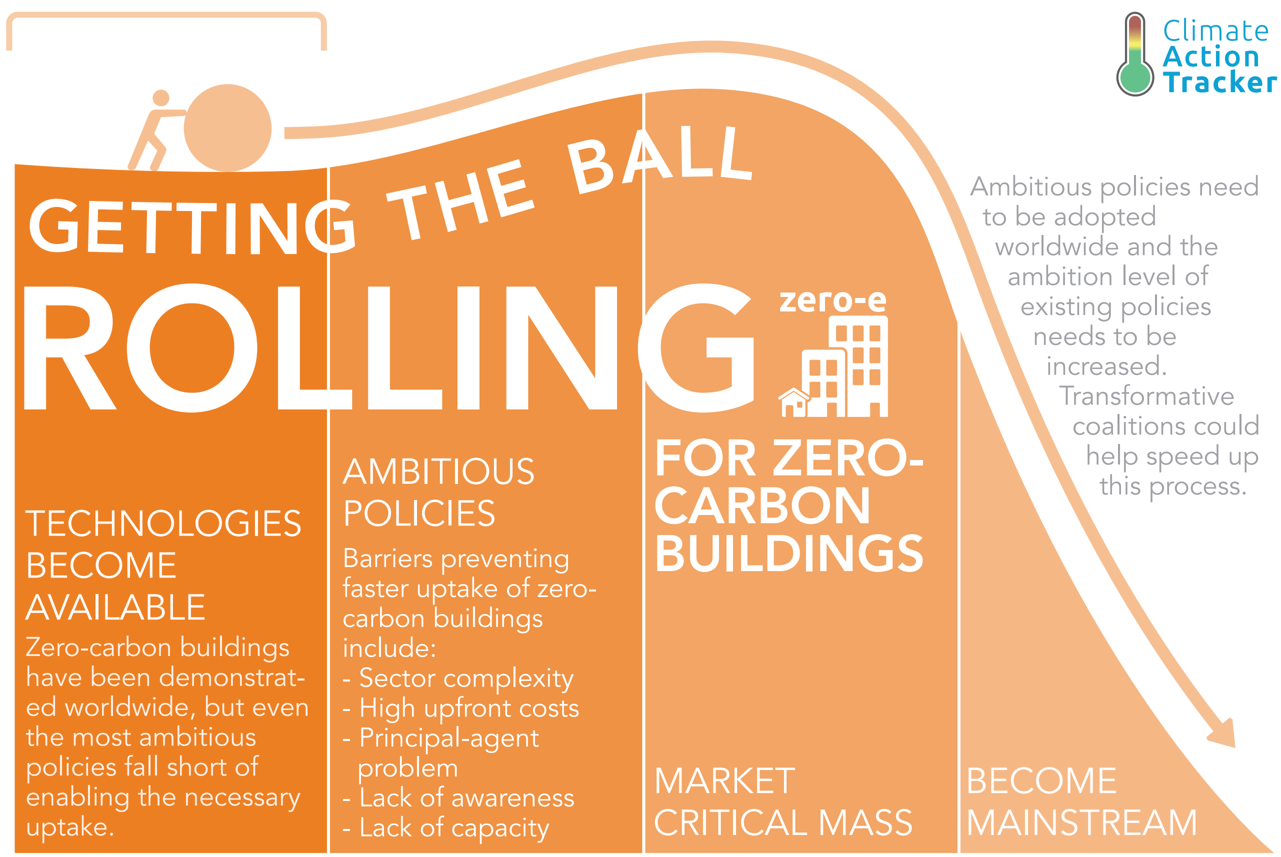
- Sectoral complexity barriers: In the building sector, pathways to spread decarbonization solutions from one region to other regions are often not as straightforward as in other sectors. The technology used for electric vehicles and photovoltaics can be applied worldwide, but space heating and cooling solutions need to be tailored to the local climate, culture, and geography. Whereas renewable power generation and electric vehicles replace incumbent technologies unit for unit, a multitude of technologies are needed to move buildings to zero energy use. Insufficiently ambitious standards for new buildings and renovations will need to change over time. Therefore today's renovation is but one in a series of renovations required by mid-century.
- Financial barriers: Although energy efficiency investments in the building sector tend to be cost-effective, they often fail to materialize for at least three reasons.
  - » High upfront costs and access to capital: Investment costs are often high and have to be paid up front, whereas the savings, even if they are substantial, occur over a relatively long period. Payback periods are often perceived as too long, even if they are short in comparison to the lifetime of the building or equipment. To encourage people to make energy-efficiency investments, financial incentives are needed—a particular challenge for countries with limited public finances. To overcome this barrier, Mexico created a "green mortgage" program, which has improved the energy efficiency of millions of buildings. The green mortgage has a low interest rate and is available from state-owned banks for buildings that can prove compliance with energy efficiency standards.
  - » The principal-agent problem: In many instances, the party deciding on the implementation of energy efficiency measures (e.g., the developer or the landlord) is not the one benefiting from the reduced energy bill (e.g., the buyer or the tenant). Therefore, that party has a limited financial incentive to implement measures, even if they are cost-effective overall. The split-incentive issue affects not only residential landlords and their tenants, but all economic groups as well as commercial groups.
  - » Duration of occupancy: Occupancies are often insufficiently long to benefit from the life of energy efficiency measures; current occupants only temporarily benefit from the measures. Therefore, they may not invest in deep renovations. This barrier is related to the principal-agent problem in that a current homeowner or occupant is making decisions for future occupants without their input.
- Lack of awareness: Decisionmakers often lack knowledge about the options and their benefits as well as have concerns about the reliability and lifetime of new technologies (IEA 2013b). Lack of awareness can result in low-ambition policies and measures, especially in developing countries, resulting in lock-in of suboptimal technologies and infrastructure—and high future costs (IPCC 2014b). However, lack of awareness is also a major hurdle in developed regions, such as the EU. Building owners will need to be convinced of the benefits of energy-efficient properties, not only lower energy costs but also co-benefits such as improved comfort and increased property value (European Commission 2013). To close the information gap the Retrofit Chicago Energy Challenge included one-to-one consultations with technical experts as well as networking events, engineer roundtables, and energy road maps. Participants were assisted in gathering and analyzing data and in creating a business case by identifying sequential actions and investments. Tokyo's Carbon Reporting Program provides annual training seminars to industry stakeholders, sharing carbon emissions trends, improvement strategies, and best practices from frontrunners (Trencher et al. 2017).
- Lack of capacity: Lack of skills to implement new technologies in emerging markets hinders the uptake of those technologies. Information, technology transfer, and capacity building play a critical role in addressing this barrier.

An integrated set of measures is needed to address these barriers, while combining various technologies in an optimal way.

5.4 Achieving critical mass

Any delay in ambitious action would mean that the building sector will overshoot the emissions reduction pathway compatible with the 1.5°C warming limit, putting additional pressure on mitigation efforts in other sectors (e.g., industry and transport). It would also increase the need for negative-emissions technologies in the second half of the century. Rapid action is also urgently required in the building sector because there lock-in effects—for example, of poorly insulated walls and windows—are much longer and consequential than in many other sectors. The needed transformation of the building sector is show in Figure 20.

Figure 20 – Stages in the development of zero-carbon buildings.



Although much can be achieved by individual countries or regions, a formal global commitment is likely to be beneficial (IEA 2013b). Transformative coalitions made up of non-state actors could accelerate the building sector's decarbonization. However, the considerable differences in regions' building stock mean that approaches need to be tailored to local circumstances.

Various decarbonization initiatives already exist in the sector:

- The World Green Building Council is a network of national green building councils, active in more than 100 countries. Its main purpose is to support new and emerging councils by providing them with the tools and strategies to establish leadership positions in their countries. In June 2016, the World Green Building Council launched a new project aiming to ensure that all buildings are net-zero-energy users by 2050. Eight councils take part in the project and Architecture 2030 (WorldGBC 2016).
- The Global Alliance for Buildings and Construction was launched at COP21 and signed by 20 countries and more than 50 organizations from the building and finance sectors (GABC 2016). The alliance's goal is to scale up ambitious actions in the building sector by bringing together relevant global players.
- Architecture 2030 issued the "2030 Challenge," adopted by 70 percent of the top 20 architecture, engineering, and planning firms in the US. Its aim is achieving carbon-neutral new buildings, developments, and major renovations by 2030. There are similar activities in China through the China Accord, where Architecture 2030 is working with Chinese architecture and planning firms. (Architecture 2030 2016).
- The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative is a voluntary collaboration among 17 governments working to promote the manufacture, purchase, and use of energy-efficient appliances, lighting, and equipment worldwide. The governments are working together to scale up the design and implementation of energy efficiency policies and related measures for appliances by providing knowledge, tools, and technical expertise as well as by raising awareness (SEAD 2016).
- The Carbon Neutral Cities Alliance (CNCA) is a collaboration of cities committed to achieving aggressive long-term carbon reduction. The CNCA aims to cut GHG emissions by 80 percent by 2050 and has initiatives related to net zero or renewable-energy-positive buildings (CNCA 2017).

Most of these initiatives are public-private partnerships. The existence of these and similar efforts shows there is support for voluntary collaboration. The private sector buy-in highlighted by these initiatives also provides a clear signal to governments that more ambitious policy action is welcomed.

Although these initiatives can form an important basis for cooperation, our analysis shows that the building sector lacks an important component for achieving critical mass for nZEBs: countries that are successfully implementing effective and integrated policy packages.

In many countries and states, building standards often lead to limited energy savings. Additionally, these standards are not often accompanied by appropriate financial support schemes. To be successful, a transformative coalition would need to work with governments to ensure implementation of ambitious and coordinated policy packages—including building codes and standards as well as financial and information instruments—in line with the coalition's objectives. Given the need to adapt packages to national or regional circumstances, close cooperation among public authorities, finance providers, and the building sector is critical.

Some US states and EU member states have set targets for nZEBs and renovation rates and have implemented supportive building codes and financial mechanisms. However, given the different characteristics of the building sector around the globe, these actions will not yet be sufficient to kick start global uptake of energy efficiency in buildings. The availability of many cost-effective technologies provides hope for that uptake.

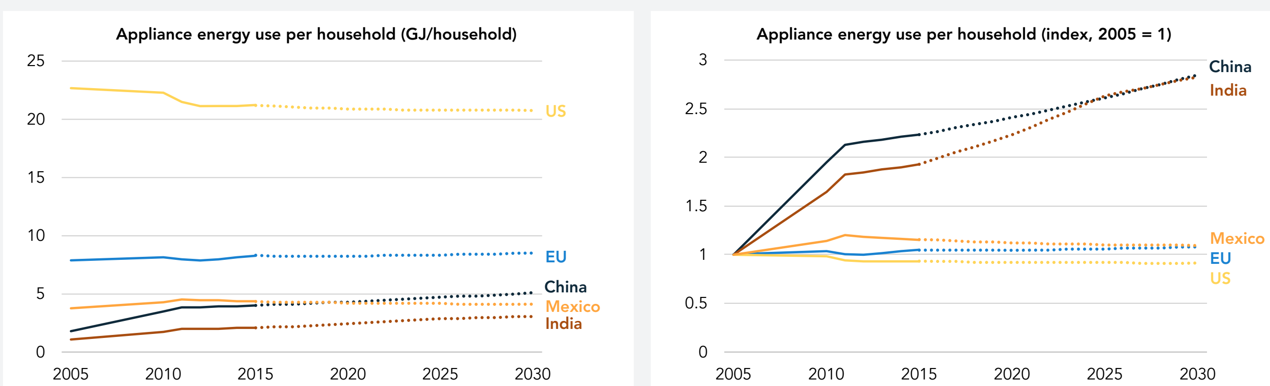
HIGHLIGHT: APPLIANCES AND LIGHTING

Appliances and lighting account for more than 60 percent of the building sector's electricity use. This category represented 20 percent of the sector's final energy demand in 2013, and it is projected to represent 30 percent of that demand by 2050 (IEA 2016d). The indirect emissions associated with electricity use from appliances and lighting can be phased out by full decarbonization of the power sector, but an increase in energy efficiency plays a critical role as well. Reducing energy consumption will speed transformation of the power sector by reducing the demand for renewable electricity.

Although total electricity demand in buildings has been steadily rising, improvements in energy efficiency have been achieved at the level of individual appliances. These improvements have averaged 3–4 percent per year over several decades in many countries (IEA 2016d). They are primarily driven by the implementation and enforcement of appliance standards. For example, a typical new refrigeration unit on the market in the US uses only a quarter of the energy it did in 1973, prior to the introduction of standards. Since 1990, the energy use of washing machines, dishwashers, and air conditioners in the US has fallen by 70 percent, 40 percent, and 50 percent, respectively (US Department of Energy 2016).

The continuation of this trend is expected to help stabilize energy use of appliances per household in developed countries (see Figure 21), even though the number of appliances per household is increasing. The situation looks differently in developing countries, where energy used by appliances is much lower, but is projected to continue to increase due to rising wealth and living standards.

Figure 21 — Appliances' energy use per household in GJ (left) and indexed to 2005 (right).



Source: Data from ClimateWorks' CTI model (ClimateWorks Foundation 2016).

Energy efficiency improvements in appliances are driven by appliances standards and labeling programs, which are in place in more than 80 countries. Two frontrunner policies are the EU's Energy Labeling Scheme and Japan's Top Runner Program.

The **EU's Energy Labeling Scheme** was established in 1992. Between 1996 and 2004, EU energy labeling has contributed to annual energy savings on the order of 3 Mtoe, corresponding to emissions reductions of some 14 $MtCO_2$ annually. According to some estimates, the energy label could lead to savings of some

22 Mtoe per year by 2020, corresponding to annual emissions reductions of some 65 $MtCO_2$ (bigEE 2010). These energy savings are generally considered cost-effective for consumers, meaning that they reduce the overall life-cycle costs of the appliance purchase and energy use over the average appliance lifetime.

Japan's Top Runner Program was introduced in 1999. It consists of a set of energy efficiency standards for energy-intensive products, such as home appliances. Energy efficiency targets are set to be achieved within a given number of years on the basis of the most efficient model on the market (the top runner). The Top Runner Standard effectively improved the efficiency of the high-end Top Runner product by 50 percent, but it has also almost doubled the efficiency of the low-end products (Kimura 2010). This development implies that the Top Runner Standard greatly contributes to eliminating low-efficiency products from the market.

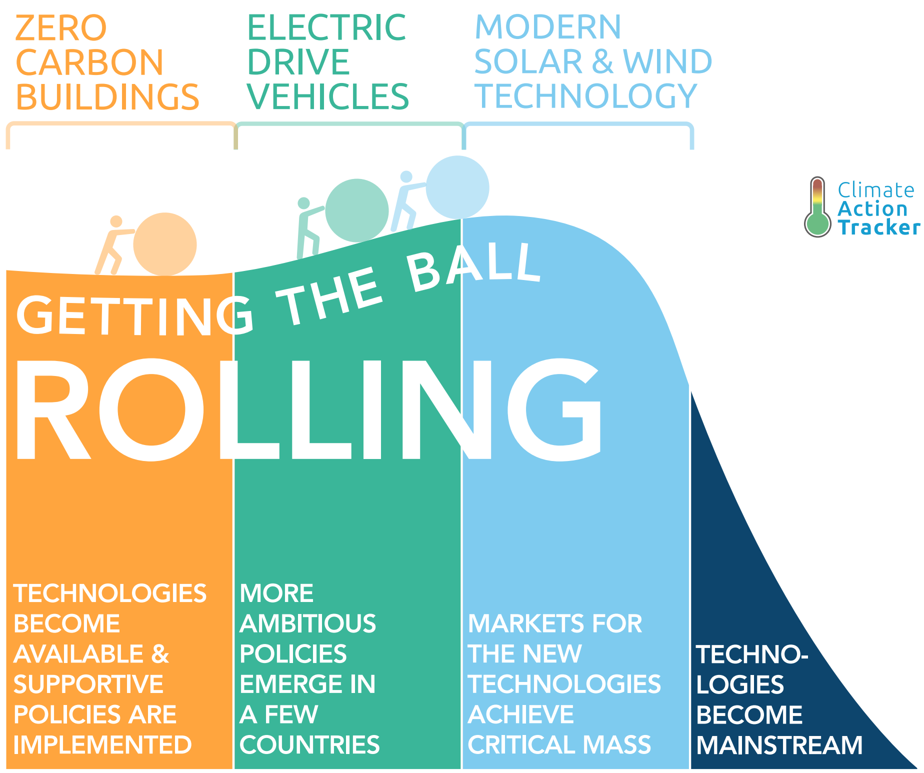
The success of energy efficiency policies for appliances suggests that all countries can and should adopt similar measures. The stringency of existing energy efficiency programs should be progressively increased. The programs need regular review to ensure that their requirements keep pace with rapid technological developments and that they remain in line with policy objectives (IEA 2016d). This review process is a key feature of Japan's Top Runner program.

6. DISCUSSION AND CONCLUSIONS

Strong sectoral transformations are necessary to reduce GHG emissions to the extent that global warming beyond dangerous levels can be avoided. Our analysis shows that governments in a few countries and sectors have implemented policy packages that, combined with market forces and research have decreased costs of low-carbon technologies making them increasingly competitive with carbon-intensive technologies. The result has been increased uptake of the former in other regions and by other actors, which has created a positive feedback loop. Eventually the new technologies have become the mainstream technologies. We argue that such a change could be accelerated if frontrunner actors coordinated their efforts in what we call transformational coalitions.

The mainstreaming of modern renewables in the power sector is well under way, the mainstreaming of EDVs in the transport sector is building momentum and the mainstreaming of zero-carbon buildings in the building sector has yet to truly begin, as illustrated in Figure 22.

Figure 22 – Stages of system change achieved by modern wind and solar technology (breakthrough well underway and market maturity within reach), electric-drive vehicles (currently at inflection point), and zero-carbon buildings (yet to take off).



Our analysis of modern RE development in the **power sector** shows that the right policy mix, including effective support schemes and targets complemented by RD&D investments, implemented by a number of countries has led to a global uptake beyond expectations. However, it also shows that this uptake, starting around the turn of the century, was predated by years of technology development in niches. Only when a number of countries decided to implement effective policy packages were they able to start a virtuous cycle that led to the development we observe today. These independent but parallel movers initiated a dynamic that allowed new technologies to mature and increase their market share in the respective sectors.

These movers included Denmark, Germany, Spain, and California. Each of them implemented financial support schemes for wind and solar energy. Since the turn of the century, more and more countries have implemented effective support schemes, including feed-in tariffs for renewable energy sources, leading to an increase in capacity and generation from these sources. Countries learned from one another's experiences, inspiring yet other countries to initiate their own schemes. Today more than two-thirds of countries worldwide have implemented RE support schemes and set RE targets. Electricity production from modern renewable sources keeps accelerating and has, in some regions, already become mainstream. Looking back, this change could have come about faster if frontrunner countries had formed a formal transformative coalition, together identifying and implementing a best-practice policy package for RE support.

The next challenge in the power sector is ensuring that existing power systems are adapted to increasingly replace fossil fuel sources with increasingly large shares of intermittent renewable power sources. Countries, regions, and states should be learning from one another about the effectiveness of different solutions and necessary policies. Cooperation in the framework of transformative coalitions could significantly lower the costs of the global transition to zero-carbon power sectors.

In the **transport sector,** uptake of electric vehicles began only in the last five years. Sales of electric vehicles, close to negligible before 2010, were initially supported in a few countries and regions such as Norway, the Netherlands, and California through a combination of financial and behavioral incentives. The EU and the US, combined, accounted for nearly two-thirds of global EDV stock in 2013 (IEA 2016e). Since 2014, however, sales in China have exceeded all expectations and have surpassed those in both the EU and US as the Chinese government pushes ambitious policies that favor (and possibly will mandate) EDV uptake. The strong effect that supportive policies have had on EDV uptake in these countries suggests that if countries started a coordinated effort to implement a best-practice policy package, the worldwide vehicle market could transform much more rapidly than initially expected.

In the **building sector,** progress has been much slower, and there are no signs that zero-energy or nearly-zero-energy building technologies will achieve critical mass anytime soon. One reason is the presence of geographical and socio-cultural barriers that inhibit the worldwide diffusion of these technologies without adaptation to local circumstances (i.e., there is no "one-size-fits-all" approach). Additionally, financial barriers and lack of awareness and capacity hinder uptake. However, we also observe that few countries are implementing ambitious and integrated policy packages. If supportive policies were to be taken up by transformative coalitions, our study suggests that the rate of uptake of zero-energy buildings could be substantially increased.

Such coalitions could accelerate the uptake of efficient **household appliances,** low-carbon **industrial products** such as steel and cement, and low-carbon **food products.** There is a potential global market for all of these: the one-size-fits-all concept applies to a certain degree to each of them, just as it does for modern renewable energy and electric-drive vehicles.

Tracking the progress of transformative coalitions will be essential to helping them strive and contribute significantly to achieving the Paris Agreement goals. Tracking progress toward nationally set targets and benchmarks requires us to look at appropriate indicators of decarbonization. Appropriate indicators are those that (1) can be linked back to emissions reduction efforts under the NDCs and illuminate what is needed to achieve the Paris Agreement's long-term temperature goals, and (2) provide sufficient detail to fully capture sector-specific trends.

In the power sector, the average emissions factor of electricity generation must show a big decrease through the growth of modern renewable energy sources replacing fossil fuel technologies.

In the transport sector, the fleet-wide emissions factor must be reduced by increased market shares of electric vehicles powered by renewable electricity.

In the building sector, indicators such as the emissions intensity of floor area or energy use per household can be used to track the effects of potentially transformative changes.

Differences in such indicators between regions inside a transformative coalition and those outside such a coalition can pinpoint how certain policies translate into measurable outcomes.

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