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TRANSFORMATION POINTS: ACHIEVING THE SPEED AND SCALE REQUIRED FOR FULL DECARBONISATION

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Climate Action Tracker

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KEY MESSAGES

- Staying within the Paris Agreement 1.5˚C temperature limit requires rapid, large-scale systemic transformations to fully decarbonise the global energy system by 2050.
- Transformations of the speed and scale required have occurred when systems reached a **transformation point:** the moment when a previously novel technology, behaviour or market model achieved critical mass, took off, and rapidly became the new normal.
- Policy action is key to kick-starting a rapid and wide-ranging transformation.
- A rapid switch to renewable energy, supported by a significant expansion of electricity storage is needed to decarbonise the power sector by the 2040s. By 2050, the world could need up to 475 times more storage capacity than installed today. To increase the likelihood of reaching a transformation point in **energy storage**, governments can modify market rules to make storage competitive, set targets for storage capacity additions, and invest in R&D for technologies with a focus on inter-seasonal storage.
- Electric vehicle sales worldwide will need to reach 100% of new sales by around 2035 to decarbonise the passenger transport sector by 2050. To make a transformation point in **EV deployment** more likely, governments can follow frontrunner examples like Norway and implement financial incentives, install charging infrastructure, and provide other benefits.
- Industrial emissions need to fall between 65–95% below 2010 levels by 2050 to stay within the 1.5˚C limit. Some zero-carbon solutions exist and will need to be scaled up significantly, while many new **zero carbon industrial technologies** will need to be developed. Governments can work with industry to demonstrate the feasibility of technologies at local level and provide financial incentives to invest in technology deployment.

PARIS AGREEMENT REQUIRES TRANSFORMING THE ENERGY SYSTEM INTO A NEW STATE

Staying within the Paris Agreement 1.5˚C temperature limit requires fundamental, rapid, and large-scale shifts that lead to full decarbonisation of the global energy system by 2050 (IPCC, 2018). The Paris Agreement is nothing less than a mandate to transform and move the global energy system into a new state supporting economic prosperity and sustainable development using zero-carbon technologies.

System transformations of this scale are possible and have happened before. Mobile phones, for example, soared from virtually zero to almost full coverage in less than two decades (Figure 1).

A slower transformation on a much larger scale is already happening in renewable electricity, where the costs of some sources have dropped exponentially over the last two decades, making renewables competitive with incumbent technologies. In this process, ***a transformation point marks the moment when a previously novel technology, behaviour or market model achieved critical mass, took off, and became the new normal*** (*Figure 2*).

In this paper we examine a number of such “transformation points” that must be reached as part of the zero-carbon transformation, and what is required to get to the ‘take-off’ phase. We then examine three of these in more detail: storage for renewable power, electric vehicles in passenger road transport, and decarbonisation of high temperature heat in cement production.

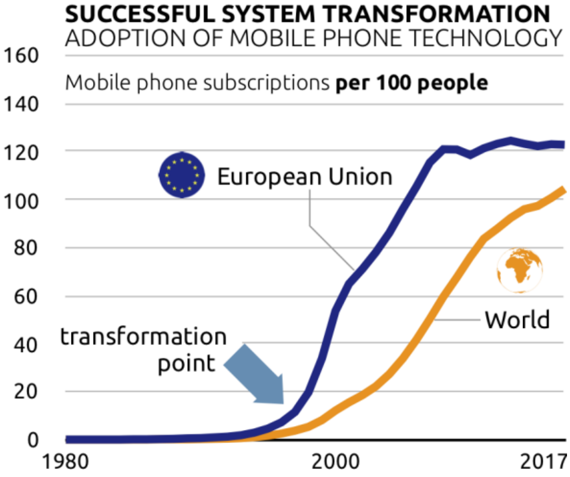

Figure 1: Data for mobile phone subscriptions showing the rapid transformation potential for a new technology. From World Development Indicators database, data series IT.CEL.SETS.P2 https://databank.worldbank.org/data/home.aspx

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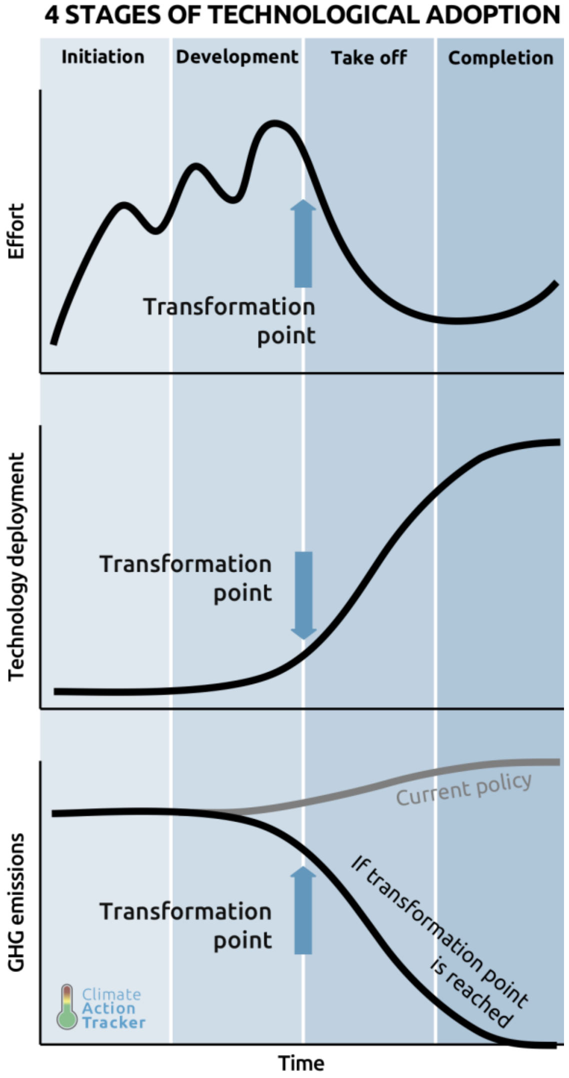

Figure 2: Concept of a system change which proceeds via 4 stages, including a "transformation point' where a noticeable change occurs.

Zero-carbon technology deployment will typically pass through the four following stages (top panel in Figure 2):

1 | **initiation phase** where a technology demonstrates feasibility at a project level;

2 | **development phase** overcomes the main barriers to adoption by putting certain building blocks in place. A moment of critical mass is reached (the "transformation point"), where the previously new state begins to be considered the new norm;

3 | **take-off phase** where the adoption rate increases rapidly. Further adoption still requires effort after this point, but this decreases over time until the final phase;

4 | **completion phase** involves continued effort to reach completeness / maximum market penetration.

Targeted policies can aid transformation in some countries: To facilitate the transition in the renewable energy sector, a small number of ambitious actors—in particular governments introducing policies such as feed-in tariffs—took the lead, and were followed by a critical mass of early movers (Climate Action Tracker and ClimateWorks Foundation, 2017).

Key to reaching the transformation point for mobile phones was the perceived advantage of the new technology, relative ease of access and scalability compared to the incumbent land-line technology (which never penetrated many parts of the world due to high infrastructure costs).

The key characteristics of an "S-curve" of new technology dispersion and adoption (middle panel) are the *rate of increase (speed)* and the *maximum achievable level (scale)*. Even after the transformation point, some effort (e.g. policy support or financial incentives) may be needed to speed up take off and completion phases and to avoid sliding back to the old system.

Another important characteristic of the S-curve transformation is that the rate of change accelerates. The system changes slowly in the beginning, but speeds up over time. "The future can be very different than the past." (Grubb, 2018)

To achieve the aim of full decarbonisation (bottom panel) a concerted and far-sighted effort will be needed to initiate the transformation (as has happened in the past for the power sector) and to then keep the transformation going at the necessary speed. One driving force will be the considerable advantages associated with the transformation to a zero-carbon society, such as co-benefits in cost, comfort and convenience that are already starting to appear.

POTENTIAL TRANSFORMATION POINTS

There are several sectoral or sub-sectoral developments in the energy system where "transformation points" appear to have already occurred or are expected to occur in the near future (Table 1) depending on the particular circumstances of the sector. While they may be more likely in some areas, because certain technological developments can diffuse relatively easily to the global market (e.g. distributed renewable energy technologies and battery storage), it may be more difficult in other sectors, where backsliding into the previous 'system state' is possible (e.g. switching back to conventional fuels in industry). But even in the power sector, the influence of incumbents (e.g. the fossil fuel industry) can slow down or even halt the fast transformation that would be expected based on the processes described here.

Table 1. Potential transformation points in the energy system

Potential transformation point	Potential reason(s) for transformation point	Global reduction potential[1]	Status[2]
Parity for renewable electricity generation with storage	The generation costs of (certain types of) renewable energy plus storage reach parity with either new or existing fossil fuel sources.	High	Take off
Electrification of passenger vehicles	Electric vehicles reach up-front cost parity with conventional cars or find large-scale niches, e.g. in cities.	Medium	Development
Electrification of freight vehicles	Hydrogen or electric trucks reach cost parity with regular trucks.	Medium	Initiation
Zero energy buildings	Cost of building a new net-zero energy home is equal to or insignificantly higher than inefficient homes	Medium	Initiation
High intensity heat	Technological development (e.g. H_2) advances to supply competitive, zero carbon, high intensity heat for industrial processes	Medium	Initiation
Electric bicycles	E-bikes become standard for certain distances that were previously covered by car, e.g. through attractive city bike sharing schemes.	Low	Take off
Direct air capture	Direct capture of CO_2 from the atmosphere with storage becomes cheaper than alternative mitigation options in difficult sectors (e.g. aviation, industry)	Medium	Initiation

POWER SECTOR – A BREAKTHROUGH IN ELECTRICITY STORAGE TECHNOLOGY

What is the status of the transformation?

In the power sector, the **first major hurdle has been overcome**: the levelised cost of electricity for newly-installed utility-scale onshore wind and solar PV is now competitive with fossil fuel power generation in many regions (IRENA, 2018b). Over twice as much renewable capacity as net fossil fuel generating capacity was commissioned in 2017 (Frankfurt School-UNEP Centre/BNEF, 2018). Another critical transformation point has been reached in specific markets in Europe, the US, and Australia (Ivanova, 2018; Jones, 2018): Building new wind and solar is now cheaper than operating *existing* coal-fired power plants.

On a global level, Paris Agreement compatible pathways require faster decarbonisation in the power sector than other sectors, with CO_2 emissions nearing zero by the 2040s (IPCC, 2018). Zero emissions for the power sector implies a fully renewable electricity mix, unless other low/zero/negative carbon alternatives are used (IPCC, 2018).

Therefore, the next hurdle is to deal with the increasing shares of renewables in electricity generation, particularly variable renewable energy sources like wind and solar. Electricity systems that are dominated by variable renewables function very differently from fossil-fuel powered systems. This applies to the technical operation of the electricity grid, the electricity market and the roles of different actors (IRENA, IEA and REN21, 2018).

Given that variable renewables are dependent on the environment—wind turbines produce electricity when the wind is blowing, solar panels produce electricity when the sun is shining—their production does not always match demand. If the supply from renewables is too high, and it cannot be absorbed elsewhere, it is curtailed, meaning the energy is wasted. If the supply is too low, it needs to be compensated for by other sources.

This match needs to occur over the course of a day (flexibility), as well as over the course of a year (seasonality). Therefore, one of the remaining challenges in full power sector decarbonisation is how to maintain this balance over different time scales. Possible solutions include shifting demand to times when generation is high, expanding grids to cover larger regions, and installing diverse sources of renewable energy.

Energy storage is an up and coming solution that is becoming a game-changer for renewables. Studies that simulate very high renewable shares in the grid (80–100%) also include storage capacity to varying degrees (Blanco and Faaij, 2018). Some argue that storage capacity is essential for the operation of a fossil fuel free grid (McKenna, Barton and Thomson, 2017).

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[1] Based on the current share of emissions of the targeted technology

[2] Initial indication, full determination of timing of a transformation point is probably only possible in hindsight.

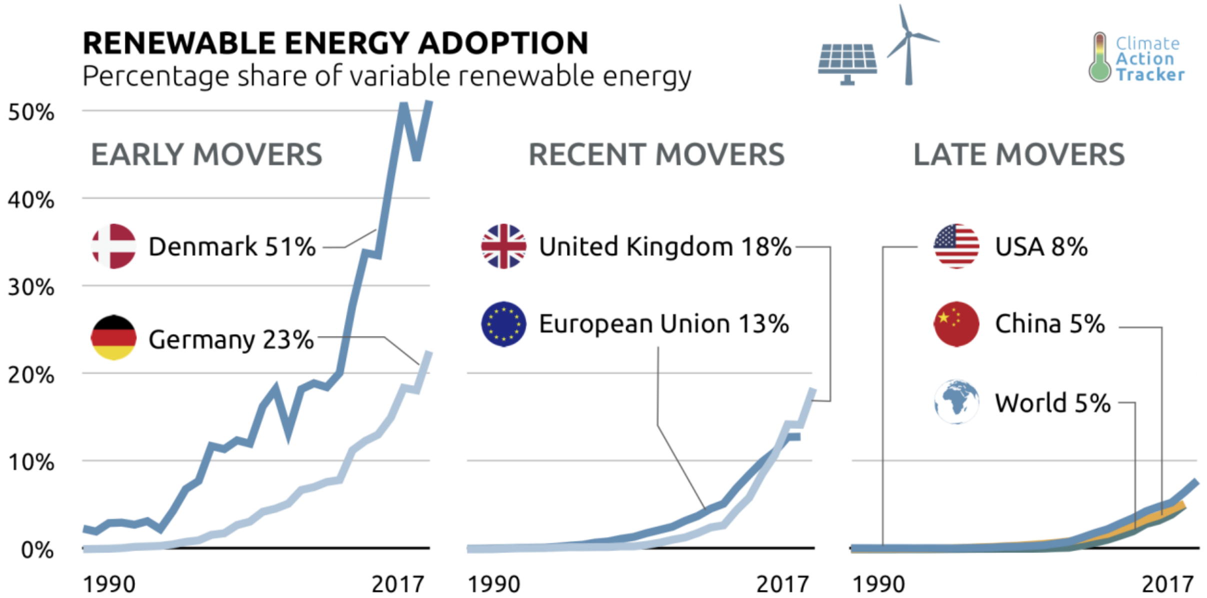

Figure 3: Uptake of variable renewables in electricity generation shows S-Curve characteristics. Early movers like Denmark and Germany crossed a transformation point earlier than recent movers like the United Kingdom.

Storage has multiple benefits in a high renewables system: it can not only shift supply to match demand, but may also provide ancillary services that have traditionally been supplied by fossil fuel plants, such as providing necessary frequency regulation to maintain grid stability, as seen with batteries in South Australia and parts of the United States (Geuss, 2018; U.S. Energy Information Administration, 2018b). Storage, when combined with renewables, can also reduce electricity costs by decreasing network investment, generation investment, curtailment, and fuel costs (Blanco and Faaij, 2018).

Reaching a transformation point in electricity storage capacity deployment could help those grids with already relatively high shares of renewable generation push those shares even higher. This will be necessary to achieve the deep decarbonisation needed for Paris Agreement compatibility and can include both utility-scale and consumer scale storage.

Scenarios estimate that in electricity systems with 100% shares of renewables, storage needs could be up to 6% of total annual electricity demand, depending on system characteristics and the extent to which other flexibility options (e.g. grid extension) are used (Blanco and Faaij, 2018). In 2017, there was an estimated 4.67 TWh of storage capacity available globally, mostly pumped-hydro (IRENA, 2017), making up around 0.02% of electricity demand (IEA, 2018c). 1.5°C compatible scenarios envision significant increases in electricity demand in 2050 as part of efforts to decarbonise other sectors like transportation and industry (IPCC, 2018), meaning that additional storage capacity will likely be needed.

Why are we potentially close to a transformation point?

Systems will need storage: as shares of renewables in electricity systems increase, the systems will need to adapt to new operating conditions. This will require flexibility, likely including both short-term and seasonal storage. Renewables and storage are coupled: breakthroughs in storage technology could help electricity systems integrate higher shares of renewables, but demand for higher shares of renewables will also drive breakthroughs in storage technology.

Technology is available: there are multiple technologies that store energy. These include mechanical systems like pumped-hydro and flywheels, thermal systems that store heat to be later turned into electricity, chemical systems like hydrogen and synthetic gas systems, batteries, and super-capacitors (World Energy Council, 2016).

Battery technologies are making headlines, with Tesla installing a 100 MW lithium-ion battery at the Hornsdale Wind Farm in South Australia in 2017, the largest lithium-ion battery in the world, with additional systems in the pipeline supported by government grants (Deign, 2018). Most of these storage technologies store electricity for hours or days. Inter-seasonal storage—storing energy over several months—is another challenge to overcome. Power to X (e.g. gas, hydrogen, heat) may be an option, with hydrogen showing particular promise as a way to integrate high shares of variable renewables into the electricity system (IRENA, 2018a).

Prices are dropping: costs for lithium-ion batteries plummeted from around $1000/kWh in 2010 to $209/kWh in 2017 and are projected to continue to decline—albeit at lower rates (Gupta, 2018). Recent bids for solar plus storage projects have come in at record low prices, raising generation costs by as little as 20% in the western United States in a recent solicitation (Colthorpe, 2018), and short-duration batteries are now the cheapest source of new fast-response and peaking capacity in all major economies except the US (Parkinson, 2018). Costs for many other storage technologies such as compressed air, flow batteries, and power-to-gas are projected to fall in the future (World Energy Council, 2016).

Regional policy supports storage: in some regions, policy initiatives require or incentivise added storage capacity. California, for example, has mandated that 1.3 GW of energy storage must be procured by 2020, and has provided financial incentives for customer-sited energy storage (U.S. Energy Information Administration, 2018b).

Consumers demand storage: residential consumers and companies are increasingly installing "behind-the-meter" storage systems (batteries) to store energy onsite for later use, for example from rooftop solar panels. Behind-the-meter deployments accounted for 55% of storage deployments in the United States in the last quarter of 2017 (GTM Research, 2018). The technology is being commoditised, exemplified by IKEA's offering of home solar panels with battery storage. This gradually places technology choice with the customer, rather than the utility.

Electric vehicles will provide (some of) it: the electrification of transportation will increase power load significantly. Electric vehicle and vehicle grid integration (VGI) technologies could be an opportunity to actively manage and spread the load across locations and time and therefore prevent or decrease infrastructure upgrade and grid balancing costs (Navigant Research, 2017).

The Nissan Leaf electric vehicle was approved for participation in the German power grid in October, 2018 (Bosworth, 2018). Various projects on VGI technologies are underway for individually owned or fleet vehicles (mostly in the US and the EU, including in the UK, Spain and Denmark) and have already proven their potential for grid balancing services development (Navigant Research, 2017).

How do we reach a transformation point in energy storage?

To make reaching a transformation point in energy storage (not limited to battery technology) more likely, the following steps could be taken:

- **Market rules and financial incentives for storage:** governments set rules to allow electricity storage services to participate in capacity, energy and ancillary services markets, following front-runner examples like California (Lazard, 2018; U.S. Energy Information Administration, 2018b). This includes governments providing upfront or performance-based financial incentives make storage investments viable. Wholesale and utility programme rules are set to create favourable revenue opportunities for storage, for example by rewarding storage's ability to quickly respond to changes in demand and to help manage peak loads (Lazard, 2018).

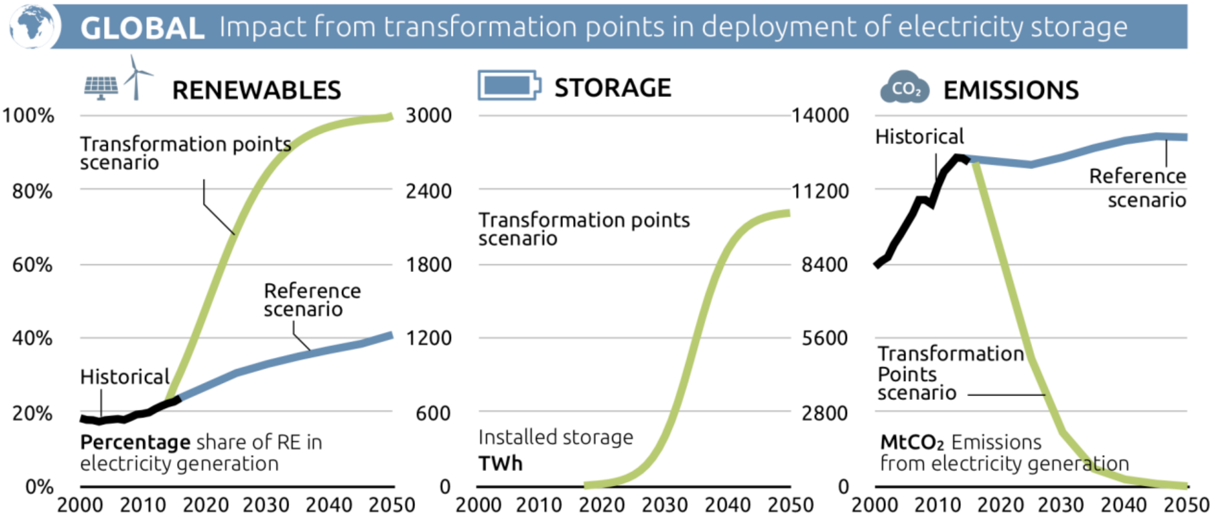

Figure 4: In the "Transformation Points" scenario, renewables shares globally increase in an S-Curve shape to reach 100% in 2050, saving ~13 $GtCO_2e$/yr in 2050 compared to the IEA's Reference Technology Scenario. Storage requirements in a 100% renewables scenario could be up to 475 times higher than today in 2050, depending on how other flexibility options are used.

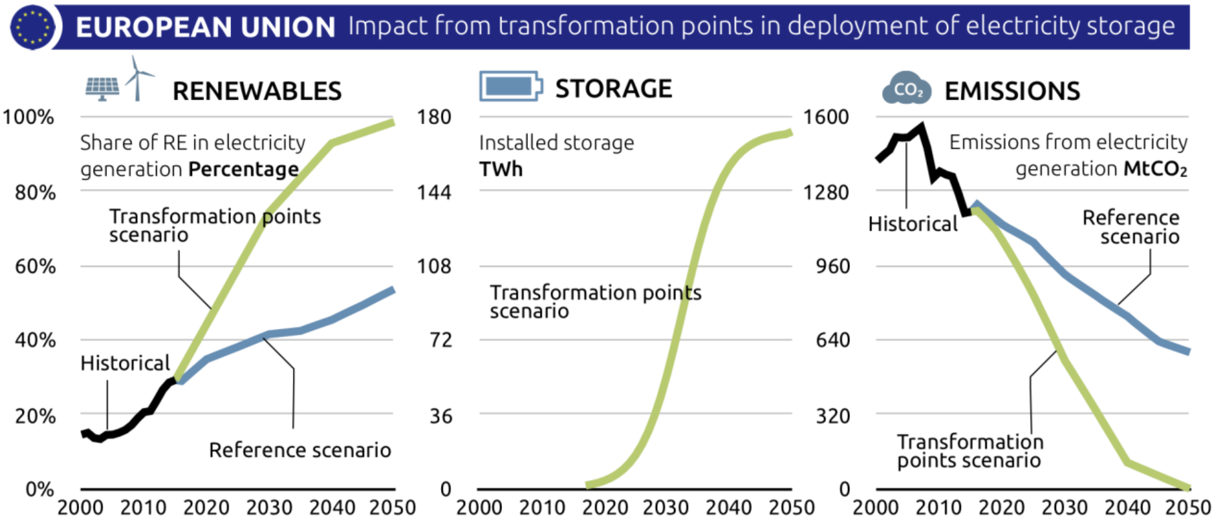

Figure 5: In the EU "Transformation Points" scenario, wind and solar shares increase in an S-Curve shape and combine with hydro and biomass to reach 100% in 2050. Emissions would be 590 MtCO2e/ye lower in 2050 compared to the Climate Action Tracker's Current Developments (CDS) Scenario. Storage requirements in a 100% renewables scenario could be up to 110 times higher than today in 2050.

- **Targets:** governments guide development by setting explicit targets or goals for energy storage, as in California and New York (U.S. Energy Information Administration, 2018a), and having electric utilities incorporate storage into long term planning mechanisms (U.S. Energy Information Administration, 2018b).
- **R&D on inter-seasonal storage:** a group of governments take the lead and invest in R&D for energy storage technologies, including—but not limited to—batteries, and particularly focussed on technology options for inter-seasonal storage, such as hydrogen. The Australian government, for example, is providing partial funding for a large-scale trial project to produce hydrogen from wind and solar (Paul, 2018).
- **Large scale demonstration:** governments and industry cooperate to initiate large scale demonstration projects of systems with very high shares of renewables plus storage (e.g. following the model of the battery storage project in Southern Australia).

What would the GHG emissions be if the transformation point is reached?

If a transformation point in energy storage technology, combined with effective policies and favourable market conditions, helps renewables reach a 100% share in electricity generation by 2050, what could it mean for emissions globally? And how much storage is needed to achieve such high shares? We additionally look at future storage needs in the European Union, as some member states and neighbours are frontrunners in variable renewable integration.

Energy storage technology at reduced costs is only one ingredient to increasing shares of renewables quickly enough to fully decarbonise the electricity sector by the 2040s in line with a 1.5°C Paris Agreement compatible pathway[3]. Ambitious policy frameworks, appropriate development of transmission grids, new regulatory and market approaches, will also be necessary (Climate Action Tracker and ClimateWorks Foundation, 2017).

Here, we consider what it means for emissions once renewables shares take off globally from today's levels in the kind of S-curve that would reach 100% in 2050. This would move electricity production from existing fossil fuel power plants out of the market.

Globally, emissions under a 100% renewables scenario would lead to 13 $GtCO_2e$/yr of emissions savings in 2050 compared to the IEA's Reference Technology Scenario (IEA, 2017a), **a similar magnitude to China's total emissions today.**

In the EU, a 98% renewables scenario would lead to emissions reductions of 590 $MtCO_2e$/yr in 2050 compared to the Climate Action Tracker's Current Developments Scenario (Climate Action Tracker, 2018).

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[3] Power sector decarbonisation by the early 2040s is a necessary but insufficient element to staying within the 1.5°C limit. This benchmark must be complemented by rapid near-term emissions reductions, as continuing fossil fuel use for too long could put the 1.5°C limit out of reach unless negative emissions technology is deployed at scale later on.

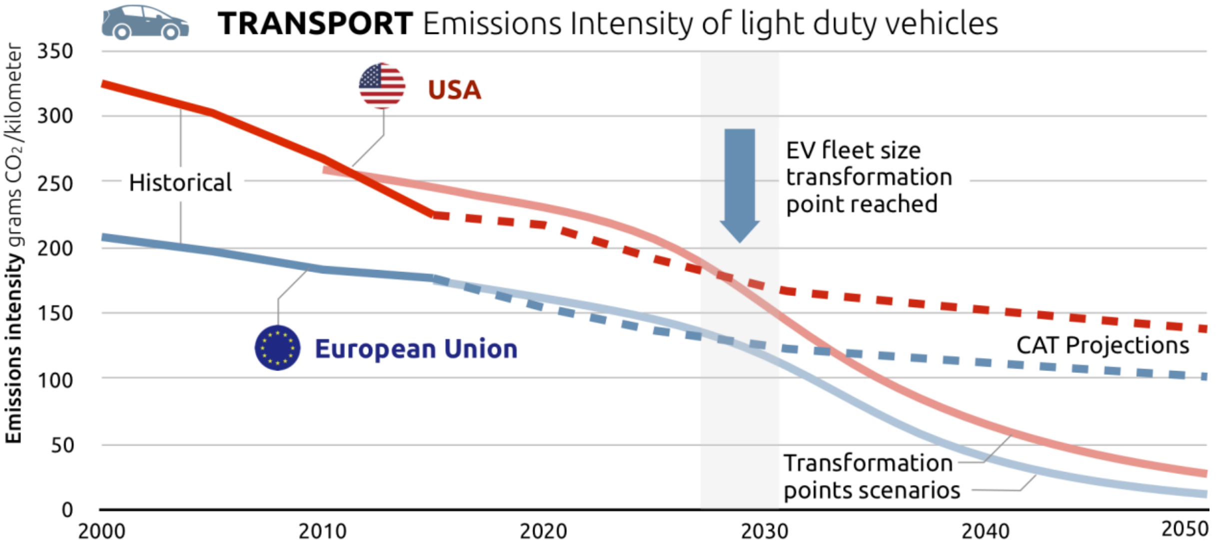

Figure 6: Emissions intensity for personal vehicles. Projections if a transformation point is reached using the model introduced in the text. Historical data and projections from the Climate Action Tracker data portal.

We also illustrate what the necessary installations of storage could be, assuming that 6% of electricity demand is covered by storage (Blanco and Faaij, 2018) and based on demand scenarios from the IEA's B2DS scenario for the world and the European Union (IEA, 2017a).[4]

Global storage capacity may need to be as much as 475 times higher than today's levels by 2050, although it could be significantly lower if other flexibility measures like grid extension and demand management are used. **Storage in the EU may need to increase to as much as 110 times its current level.**

TRANSPORT SECTOR – FAST DIFFUSION OF PASSENGER ELECTRIC VEHICLES

What is the status of the transformation?

For the world to meet the Paris Agreement's 1.5°C warming limit, the road transport sector needs to reach zero emissions by 2050, especially in advanced economies. This means that by 2035, most cars sold globally need to be zero-emission vehicles (Climate Action Tracker, 2016b), requiring a step-change rather than continued incremental improvements in the existing dominant technology.

Overall, Internal Combustion Engine Vehicles (ICEVs) have been improving in efficiency. One indicator of efficiency, the emissions intensity (measured in gCO_2/km), is shown in Figure 6. The efficiency trend is expected to continue, with decreases of 1–2%/year being typical. However, even at this rate, and given overall increases in fleet size, improvements in ICEVs will not be enough to meet deep decarbonisation targets (Climate Action Tracker, 2016a).

It is clear that to get to a 1.5°C consistent pathway, the world needs to make a paradigm shift to zero emissions vehicles. The most promising technology for this is electric vehicles (EVs).

The first hurdle in the EV sector was the initial launch of the technology: the transportation sector has significant inertia, both in consumer habits and in the implicit and explicit policies in place that support internal combustion engine vehicles (ICEVs), in part driven by the influence of the incumbent industry resisting the transformation. Electric vehicles had been confined to a niche market. Elon Musk helped change the dynamics with the launch of the Tesla series, designing cars that would appeal to a range of consumer tastes. This was supported by a federal government loan of USD 465 million, and provision for federal tax rebates which aided price competitiveness (Harpaz, 2013).

The key spark in this growing shift in technology came from a single early actor from outside the existing industry, able to leverage an idea because of well-designed policy support and create much broader interest that is now spreading around the world and throughout the automobile industry. This policy support was not a targeted subsidy to Tesla, but an overall driver for innovation in the field.

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[4] In a review of modelled simulations of electricity and energy systems with up to 100% renewables, Blanco and Faaij (2018) found that storage resources of between 0.0 and 14% of the total electricity demand are required, depending on other system characteristics and flexibility options. 90% of the studies required storage of 6% of annual demand or less. The scenario presented here is therefore a high storage scenario, and storage needs could be less if other flexibility options are used.

Today, sales of electric vehicles are rising globally, with over one million cars sold in 2017 (IEA, 2018a) and preliminary numbers for 2018 showing further growth: the Netherlands saw a threefold in numbers increase compared to 2017 and the US is said to be up 81% from 2017 (Beckman, 2019; Pyper, 2019). In Norway, most recent data show that EVs have surpassed 50% of new vehicle sales, up from about 5% just five years ago (Norsk elbilforening., 2018). EV sales in California, the most advanced market in the US, have also grown steadily, to 6%, with a trend similar to that in Norway toward all-electric vehicles as opposed to plug-in hybrid vehicles (Pyper, 2018). Likewise, the share of EV sales in China has doubled in just the past year, to reach about one million vehicles in 2018, a share of 2.4% of new vehicles sales (Kane, 2018). Although the shares of EV are still relatively small, the growth rates in each of these examples is impressive.

Shares of electric vehicles will still need to increase rapidly in a Paris Agreement compatible scenario and they must be powered by zero carbon electricity, requiring a simultaneous decarbonisation of the power sector.

To make EVs mainstream, four main hurdles remain:

The higher up-front cost of electric vehicles to consumers. As battery technology improves with increasing market size and production experience, purchase costs are decreasing toward the range of higher-end ICE vehicles (Soulopoulos, 2017). EVs are already a factor of two to three cheaper to *operate* and should have fewer mechanical problems than ICE vehicles. Once the up-front cost of EVs achieves parity with ICEVs, there will be an even stronger incentive for consumers to make the switch (McMahon, 2018).

"Range anxiety"—the fear of being "stranded" on the road with an empty battery. This hurdle will continue to decrease as charging infrastructure expands, and battery sizes increase. The vast majority of automobile trips are already within the range of current EVs (Needell *et al.*, 2016).

Inertia in the existing stock of ICEVs. Half of all LDVs are older than 15 years; achieving a transformation to 100% emissions-free vehicles by mid-century will require incentives to retire vehicles earlier than their "natural lifetimes", or be retrofitted. The earlier we act now to reduce the stock the more manageable it will be.

Lack of policy support for EVs —partly driven by influence of incumbent industries resisting regulation such as ambitious standards that would push ICEVs out of the market much faster. The comparison of the markets in countries/regulatory environments with policy signals/regulation/standards (e.g. Norway, EU) and others without (Australia) shows how important government policy signals are.

Why are we potentially close to a transformation point in the transport sector?

We see signs of an approaching transformation point in various related areas:

Policy is pushing for a switch: policies support EVs in many parts of the world through a broad fleet of measures. Regulatory policies, such as CO_2 standards, send clear signals for automakers to make long-term investments and push the deployment of low emissions models into the market. Today, nearly 80% of new light duty vehicles are already subject to some kind of emissions or fuel economy standard. The example of the few markets without any standards, such as Australia where the development is far behind, shows how important strong policy signals are to push the necessary transformation.

Policy also sets consumer incentives in favour of EVs; for example, countries such as Norway, the Netherlands or Germany provide purchase grants of various amounts paired with partial or full exemption of ownership taxes.

A nascent sign of an approaching transformation point is that several countries and regions directly require the deployment of EVs or have announced some level of ban on ICEVs in the next decade or two for environmental motivations that go beyond climate change to include co-benefits of reduced air pollution in urban areas (Burch and Gilchrist, 2018). California's Zero-Emission Vehicle regulation, for example, requires automakers to sell electric cars and trucks in California and nine other states (California Air Resources Board, 2018). China's New Energy Vehicle quota system will require a rising share of new vehicles shares (Sia and Yu, 2017).

These strong policy signals have driven automakers to buy into an electric future, enabled the reduction of costs, and provided positive signals for infrastructure development.

Automakers are now buying in to EVs: initial attempts by California to jump-start the EV market in the 1990s with mandates for zero-emission vehicles, and by General Motors with the introduction of the EV1 were a start, but ultimately failed due to insufficient infrastructure or commitment from automakers (Edwards, 2006). In contrast, we see today that most car manufacturers have full electric models and many will have a portfolio of vehicles by 2022. This is driven by government policies such as standards in California and in the EU.

The initial move by Tesla Motors to introduce high-end, aesthetically pleasing models served as a spark for others to develop EV technology. Manufacturers are trying different strategies, from designing all-new models with novel materials to making slower transformations by extended existing hybrid models (Toyota, Honda) to plug-in capability, and to accommodating perceived needs for much larger SUVs that are fully electric (BMW, 2018).

Global automakers are planning an unprecedented investment of over US$ 300 billion to develop and procure batteries and EVs over the next five to 10 years (Reuters, 2019).

Up-front costs are dropping: partly due to greater buy-in from manufacturers, the up-front cost barrier of EVs is expected to quickly disappear as the market increases, as was the case with solar panels, for example. Achieving cost-parity is likely to happen within a few years (Hodges, 2018), also buoyed by other policies, as was the case with solar photovoltaics. For example, the Netherlands instituted an exemption from registration fees, the City of London exempted EVs from congestion charges, China initially provided subsidies to manufacturers, and the state of California created tax rebates to encourage adoption of EVs (Kane, 2016; Lambert, 2018; Perkowski, 2018).

Many of these policies change over time, providing examples of the need for flexible design of tools in a fast-changing landscape. But the cost question is also relative: many mid to high-end ICEVs cost more than EVs today. As costs decrease and the presence of EVs spreads, the speed of uptake will increase, moving up the S-curve.

Critical infrastructure is emerging: another important sign for a potential transformation point is the increase in supporting infrastructure necessary for a transformation. In the case of EVs this means charging stations in public spaces: numbers are growing rapidly, in parking garages, at workplaces, and on city street corners and are easily tracked by consumers through apps such as Chargepoint and Plugshare.

While the dynamics of lowered purchase and operating costs can provide their own incentives, infrastructure building will require continued policy intervention on the part of municipalities and institutions as well as national governments If clear policy direction is not present in a given location, lack of infrastructure, and thus a perception of inconvenience for consumers, can impact both the speed of uptake and the maximum penetration of EVs.

What is needed now to reach the transformation point in the transport sector?

There are several reasons to be optimistic about a potential transformation point in EV adoption, but reaching this point will require significant, and sustained policy support. A mix of policies is needed, in light of historical evidence that market demand has not preceded technology development (Choi, 2018). In this section, we evaluate policies that can help drive a sustained push towards EV adoption.

- **Changing time horizons of consumers:** the first significant challenge to the adoption of electric vehicles lies in the fact that many consumers believe EVs will be as common as non EVs only a decade from now (Cox Automotive, 2017). This ensures that EVs are still viewed as a “radical technological departure” from conventional vehicles, which is a significant barrier to rapid adoption of EVs by consumers (Sovacool and Hirsh, 2009). To this end, a strong government commitment to phase out fossil-fuel based vehicles in the transportation system can create the right conditions for EV adoption, and enable the success of further policy interventions suggested in this section. We see positive signs on this front, with several national and sub-national governments committing to phase-out fossil fuel vehicles (The Climate Group, 2018), though none have passed binding laws yet.
- **Coordinated information campaigns**: consumers are often unable to distinguish EVs from other types of vehicles (Plug-in hybrid vehicles, for instance), and display low levels of awareness regarding available EV options (Jin and Slowik, 2017). Automakers now offer a wide range of electric vehicles that not only have improved ranges, but also have a diverse range of end-uses (from small cars to minivans). Information campaigns coordinated between the government and automakers can help to bridge this “identification gap” to help consumers who want to “go electric”.
- **Well-designed financial incentives:** the provision of financial incentives, and presence of charging infrastructure are two significant factors that drive EV adoption (Sierzchula *et al.*, 2014). Electric vehicles are similar to renewable energy technologies, in that they have high upfront costs, but the cost of operation is lower than conventional alternatives. However, the high upfront cost

often disproportionately skews the decision of consumers to opt for conventional vehicles. Offering tax credits can play a large role in guiding early adopters towards EVs. However, these need to be carefully designed to avoid unintended consequences such as unwanted distributional effects (Alicandri, 2018). Given the positive signs we see in cost reductions, a well-defined phase-out period for these subsidies is just as important as the decision to introduce them.

- **Multi-level governance coordination to provide charging infrastructure:** financial incentives are usually established by national governments, while the responsibility for charging infrastructure provision is often delegated to municipalities/ cities (Sierzchula *et al.*, 2014). Given the important role charging infrastructure plays in facilitating the achievement of a transformation point, strong governance coordination (possibly driven by a comprehensive EV strategy at the national level) is necessary.

  In many regions of the U.S. and some European countries, charging infrastructure expansion is keeping pace with EV sales. One example for a fast technology diffusion pathway is the potential of electric lampposts on city streets to be turned into charging points for a mass charging network (ubitricity, 2018). More generally, cities can streamline processes for installing charging infrastructure, incorporate comprehensive planning to ensure maximum convenience, use their own fleets as examples of EV technology and charging infrastructure, and educate citizens about the many benefits of e-mobility.

Why is reaching a near-term transformation point in transport critical to reduce GHG emissions in line with the Paris Agreement?

Decarbonisation of transportation goes hand-in-hand with that of the grid: electric vehicles are only as GHG emissions-free as the electricity used to power them. However, even today electric vehicles result in lower emissions than ICEVs in nearly all regions (Nealer, Reichmuth and Anair, 2015), with emission reductions accelerating as the electricity grid decarbonises further. As we show in Fig. 7 fast growth rates for electric vehicle sales translate into a significant penetration of EVs into the total vehicle fleet (Fig. 7A and 7D).

This adoption of EVs will slash CO_2 emissions. Even assuming that the overall vehicle fleet grows, the low-carbon electricity system,

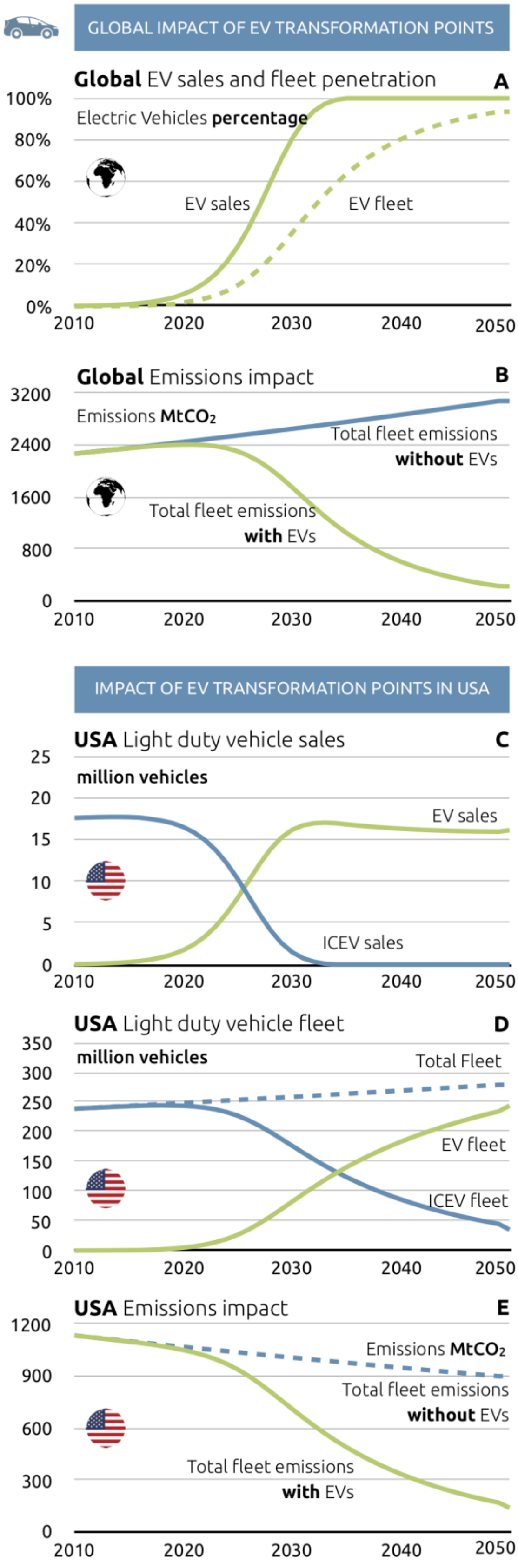

Figure 7: Transformation points for personal transportation. A) Model scenario of global change in EV sales and fleet penetration (percentages). B) Reduction in CO_2 emissions for the high-penetration EV scenario compared to a no-EV alternative. C) For the USA, a model of the transformation away from ICEVs to EVs, as well as D) the increase in EV fleet size as well as E) the accompanying reduction in emissions compared to a non-EV future scenario. See Methodology section for details

decreasing to nearly zero-emissions by 2050, leads to a 90% decrease in emissions from LDVs, in line with scenarios that are 1.5°C compatible (Fig. 7B and 7E). A recent report by BNEF indicates a plateau of 50–60% EVs in total LDV sales by 2040 based on *current* developments (Soulopoulos, 2017). To be compatible with the Paris Agreement's 1.5°C long-term temperature goal we assume that sales instead approach the mark of 100% EVs by the 2030s, with stock turnover then leading to total fleet penetration of nearly 100% by about mid-century.

Future ICEVs will be more efficient (here we assume 1–1.5% per year) but that incremental change does not lead to the deep reductions necessary for compatibility with the Paris Agreement. Only a shift in the whole system, to zero-emission vehicles with a very-low carbon grid can accomplish this goal.

We use EVs as the most advanced technology to decarbonise the light-duty vehicle transportation sector, but other technologies such as hydrogen vehicles might also play a role. The transformation must be to carbon-free passenger transport, and EVs will likely be a major component of the transformation. As mentioned in the section on storage Vs are not only dependent on the decarbonised grid, but can also play a role in helping to provide grid stabilisation services. The key for any technologies, including hydrogen, is a decarbonised grid being part of the coupled solution, whether to charge vehicles directly or to produce hydrogen.

INDUSTRY – A COMBINATION OF NEW AND EXISTING SOLUTIONS IS NEEDED TO IDENTIFY POTENTIAL TRANSFORMATION POINTS

What is the status of the transformation?

Energy-intensive industrial sectors have made some progress in moving towards best practices and improving process energy efficiency, often driven by economic co-benefits (IEA, 2017c).

In some subsectors, decarbonisation progress has been faster than in others—such as the pulp and paper industry based on the opportunity to use readily available biomass as main fuel. Progress also differs between regions with, for example, industrial energy management systems being more advanced in Europe and North America (IEA, 2017c). However, in a 1.5°C scenario, industrial emissions need to be reduced at a much higher scale and speed in order to reach near zero (65–90% reduction from 2010 levels) by 2050 (IPCC, 2018) and to decrease thereafter, even while industrial production is expected to grow significantly. In this sense, transformation points for this sector have not yet been reached—but are in sight for some subsectors.

Further energy and process efficiency improvements are needed but are by themselves insufficient. **The next hurdle is therefore to identify the combination of new and existing solutions to meet the *scale* and *speed* required** for the decarbonisation of the sector.

The complementary decarbonisation solutions listed Table 2 are concrete examples of what some industrial sectors may need to transition to low carbon production. They are technically proven at various scales, but lack large-scale deployment, underlining the need for further policy support, targeted research and development and large investments. These solutions will also need to be complemented by circular economy development and broader industry wide initiatives to deliver the required level of change in all sectors.

Reaching a transformation point in deployment of these technologies will also require overcoming key barriers and specific challenges of large-scale industrial installations. There are many sub-sector specific *technical* challenges, mostly because heavy industry emissions are often intrinsically linked to a specific production process.

There are also *economic* and *financial* challenges. Many zero-carbon technologies are still at an early stage and cannot compete with established technologies in terms of production costs. This is partly due to the low levels of policy coverage for a zero-carbon transformation of the industry sector so far (compared to, e.g. the substantial policies for decarbonising the power sector). One hurdle for unilateral policy action are concerns around competitiveness and carbon leakage.

Finally, there are *organisational* challenges. Developing some of these technologies will require partnerships between different actors (e.g. entanglement of the cement industry with its entire value chain, including for access to waste or clinkerless cement), creation of new legal entities or business models or definition of different risk management approaches.

Table 2 Examples for decarbonisation solutions in industry

Decarbonisation solution	Examples	Status
Zero carbon fuels and feedstocks	• Biogas and waste for cement • • Biocoke for steel • Green hydrogen for ammonia production	• Widely applied in e.g. Poland (alternative fuel share above 60%) • CanmetEnergy Pilot-scale coke oven in Canada[5] • Pilot plant set to open in 2019 in Western Australia[6]
Innovative processes	• Hydrogen direct reduction for steel production • Clinkerless cement	• HYBRIT pilot plant in Luleå, Sweden[7] • R&D stage
Electrification of energy demand	• Green hydrogen production • Steel production through Electric Arc Furnaces • Power to Heat in the chemical industry	• Various projects under development • Share of 26% in global steel production, 67% in the US[8] • R&D stage
Carbon capture and storage (CCS)	• Capturing of off-gases from steel or cement production	• Demonstration project to produce advanced bioethanol from blast furnace steel waste gas in Ghent, Belgium[9] • Commercial direct reduced iron-making process plant with CCS in Mussafah, UAE[10] • Demonstration project including a full CCS value chain in Brevik, Norway[11]

The cement sector is one of the most important in terms of industrial emissions and a good example of a sector with some promising initial developments and where a vision for decarbonisation has already been defined by different actors (Favier *et al.*, 2018; IEA, 2018b; World Cement, 2018). Figure 8 highlights the emissions intensity improvement cement production has achieved in various countries.

Why are we potentially close to a transformation point?

Technology is (or will be) available in most sectors: the industry sector is complex and very diverse. New and existing technologies are needed, and examples are shown in the table above: low or zero-carbon fuels and feedstocks, innovative processes, electrification and for some processes, CCS.

These solutions are technically proven at various scales. In Poland's cement industry, alternative fuels (largely based on waste) already have a more than 60% share of the fuel mix (World Bank, 2017). The Kujawy cement plant in central Poland, for example, is even reaching 80% of energy substitution and is targeting even higher levels in the coming years (World Cement, 2018).

Innovative solutions such as electrification of cement making are still in the pilot phase but could reduce emissions per tonne of cement by 40% by 2030 (Vattenfall, 2018).

Fossil-free steelmaking based on hydrogen direct reduction is also less advanced. For example, the HYBRIT steel plant in Luleå, Sweden, is only expected to be commercially viable in 2035 (LKAB SSAB Vattenfall, 2018).

The simpler approach of fuel substitution by hydrogen could also displace more than 25% of fossil fuel used for iron reduction in blast furnaces by 2040 if transformational technologies are successfully developed and demonstrated (Committee on Climate Change, 2018).

The IEA highlighted a range of options for use of renewable energy in various high energy intensity sectors (IEA, 2017b). In geographies with very high solar and wind resources, such as Australia, economic viability of energy intensive processes based on renewable energy and electrification (direct or indirect through hydrogen) could come much faster and potentially represents an early mover competitive advantage (Beyond Zero Emissions, 2018).

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[5] See https://www.nrcan.gc.ca/energy/efficiency/industry/processes/energy-systems/5611

[6] See https://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

[7] HYBRIT = Hydrogen Breakthrough Ironmaking Technology. See http://www.hybritdevelopment.com/

[8] See https://www.worldsteel.org/en/dam/jcr:3e275c73-6f11-4e7f-a5d823d9bc5c508f/Steel%2520Statistical%2520Yearbook%25202017_updated%2520version090518.pdf

[9] http://www.steelanol.eu/en/news/arcelormittal-and-lanzatech-break-ground-on-150million-project-to-revolutionise-blast-furnace-carbon-emissions-capture

[10] https://www.globalccsinstitute.com/projects/abu-dhabi-ccs-project-phase-1-being-emirates-steel-industries-esi-ccs-project

[11] See https://www.norcem.no/en/carbon_capture

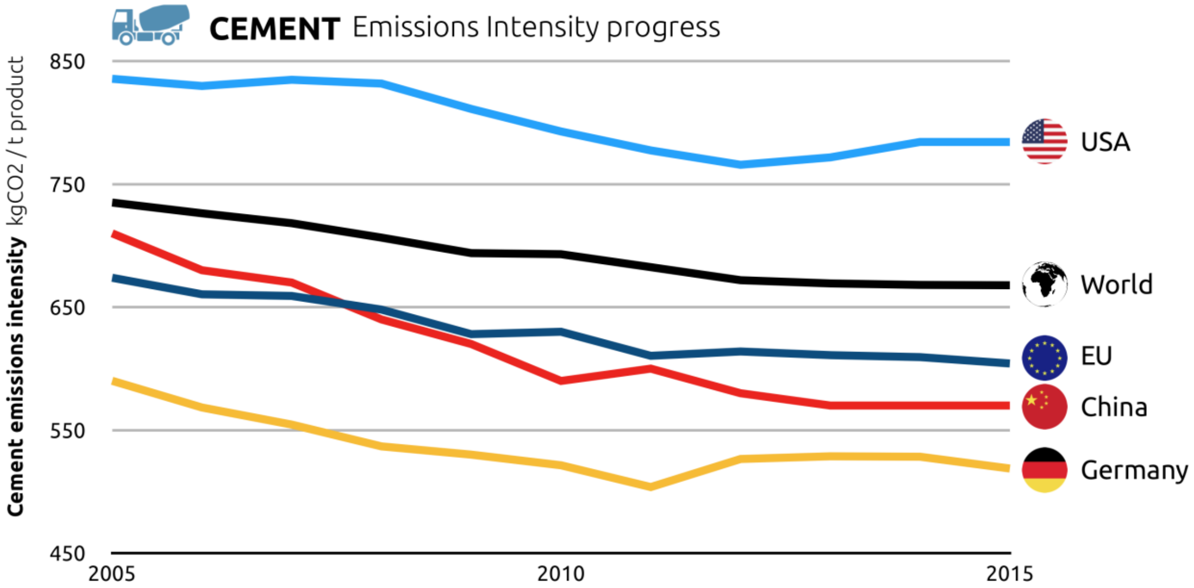

Figure 8: Cement emissions intensity for various countries. Historical data and projections from the Climate Action Tracker data portal.

The examples presented above show that transformation points in the industry sector can be reached in combination with the shift to renewables in power production, and can happen much faster with enough policy signals and targeted international initiatives (IEA, 2017b).

Large scale deployment in sight for some technologies and geographies: in most industrial subsectors, transformation points towards these solutions are still far off, due to the economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations described above (IPCC, 2018).

However, there are promising initial developments in the cement sector, where some existing solutions such as low-carbon fuel switch are being deployed and could take-off more rapidly to decrease energy-related emissions. Across Europe and beyond, there is a large potential for further uptake, as there are no major technical limitations to increasing the share of alternative fuels to as high as 95% (Ecofys, 2016).

Similarly, Electric Arc Furnace (EAF) steelmaking, which uses electricity to manufacture steel from predominantly scrap metal feedstock, is a well-established, less carbon-intensive production route that could become even cleaner as a result of the low-carbon transition of the power sector. By 2050, EAF production could account for around half of steel production in major steelmaking countries, but is ultimately limited by scrap availability and quality (Climate Action Tracker, 2017b).

A combination of innovative solutions can go to zero or even negative emissions: to fully decarbonise the cement sector, fuel switching needs to be combined with other measures such as clinker substitution since process emissions typically account for more than half of cement-related emissions. These emissions can only be abated by a change in feedstock but alternatives for limestone are not yet available at scale (McKinsey, 2018).

The full decarbonisation of cement production therefore also relies on innovative solutions such as carbon capture and storage (CCS), with demonstration plants now appearing in the cement sector. Such early developments require substantial investments by industry and governments, and have not yet demonstrated long-term economic viability. At the Norcem cement factory in Brevik, Norway, a full CCS value chain including capture, transport and storage could be in operation by 2022 if the Norwegian government, which is funding engineering and design studies, were to invest in the demonstration plant (BusinessGreen, 2018). Capturing emissions from the cement industry could eventually even generate negative emissions when biofuels are used.

What is needed now to reach the transformation point?

To speed-up decarbonisation of industrial production, the following steps should be taken:

- **Clear policy signals:** for example through the adoption of economy-wide long-term strategies (LTS) as mandated by the Paris Agreement, with clear objectives for all sectors, including industry.

- **Large scale demonstration:** most of the solutions highlighted above are still in early R&D stage. Partnerships between governments and companies would enable further developments of pilot projects to demonstrate the technical feasibility of decarbonisation solutions such as electrified cement production.
- **Financial incentives to invest in technology deployment, including (additional) carbon pricing:** a group of regional, national or local governments with critical mass should incentivise the deployment of low-carbon solutions in the industry. For example, for the use of waste fuels in cement production, the costs for upgrading industrial plants could be covered by gate fees for waste disposal and treatment (Ecofys, 2016).

  Innovative policies such as subsidies per tonne of emission reductions for industrial technologies that have the potential to decarbonise the sector at-scale could help steer these developments further: such scheme would subsidise technologies pre-commercialisation by covering the gap between the cost of the emissions-saving technology and the market price of the avoided emissions. The Dutch government is planning to implement such a scheme on a competitive basis by 2020 in order to stimulate promising climate-friendly technologies (Sociaal-Economische Raad, 2018). Carbon taxes and emissions trading systems can also facilitate low-carbon innovation, as they can provide long-term certainty in countries with significant industrial production. Policy instruments such as these are particularly important for the industry sector, as they provide broad incentives across a sector that is otherwise extremely diverse in terms of technologies and opportunities to reduce emissions.

- **New coalitions of industrial actors:** new partnerships between key industrial sectors and their broader value chain are needed to overcome the organisational barriers. For example, different actors in the construction value chain can work together to develop circular economy principles and achieve overall higher level of decarbonisation. Fertiliser producers could partner with the food industry on emission reduction strategies. Other coalitions could involve the steel and chemistry developing hydrogen-based solutions or industrial actors building a CCS grid with utilities and government support.
- **Sector-specific issues must be overcome:** Each sector will have specific challenges to be considered, depending on the regional context. In the cement sector, for example, cost-competitive access to high quality waste and sustainably sourced biomass will be required to enable a high share of alternative fuel. Local waste collection and separation networks need to be developed to ensure the access to high quality waste. The quality of waste is crucial to guarantee stable operations of clinker furnaces and proper quality of cement production (WBCSD, 2016).

A constant policy push will be needed in the coming decades, as most decarbonisation solutions in the industry are not irreversible, making backsliding possible.

What would the GHG emissions be if the industry sector reaches a transformation point?

As highlighted above, transformation points towards the required solutions to decarbonise the industry sector require immediate concerted effort. What would be the potential GHG emissions reduction if (1) the use of low-carbon fuels for cement production was taking-off today, combined with (2) the transformation to a fully decarbonised power sector by 2050 and (3) medium term development in innovative solution to reduce process emissions? What could it mean for the sector emissions globally and more specifically in China?

Direct energy-related and indirect (electricity-related) emissions today represent ~40% of the cement sector's total emissions (both globally and for China)[12], the remaining 60% are process emissions. If low-carbon fuel and electrification were widely adopted by the industry[13], this large share of energy and electricity-related emissions could potentially be reduced by 92% by 2050 at global level. To ensure substantial emissions savings, the amount of fossil fuel-based products such as plastics should be reduced in the waste fuel mix by recycling these waste components as much as possible. Similarly, biomass fuels should be sustainably sourced.

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[12] Assumptions for current trend are based on projections of cement production growth rate (van Ruijven et al. 2016) and (ClimateWorks Foundation, 2016). Projections for energy efficiency and energy mix are based on ETP (IEA, 2016). Refer to annex on methodology for the Industry for details on modelling approach.

[13] Assumptions for transformation point scenarios: low-carbon fuel mix of 50% in 2030 and 80% in 2050 + increased electricity intensity (up to 2% growth per year in 2050) + 100% decarbonised power in 2050 (Climate Action Tracker, 2017a)

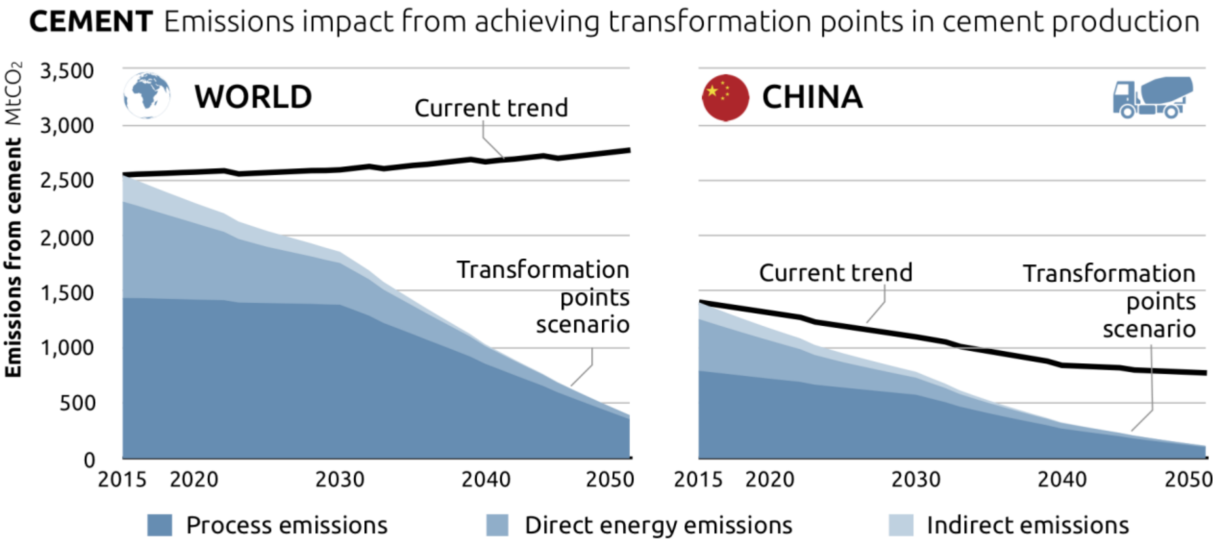

Figure 9: Results from different scenarios (current trend, low carbon fuel and electricity measures, and process emissions measures) in the cement sector globally and in China

Process emissions in cement production come mainly from the chemical breakdown of limestone, which has very few practical alternatives due to its abundance and widespread distribution in the earth's crust (Favier *et al.*, 2018). Reaching emission reductions in line with the Paris Agreement's 1.5°C long-term temperature goal will require the use of emerging and innovative technologies such as carbon capture, storage and utilisation and the use of alternative binding materials for cements (IEA, 2018b). As shown in Figure 9, a large reduction in the clinker to cement ratio [14] together with a wide deployment of CCS as from 2030[15] could reduce emissions close to a level compatible with the Paris Agreement (-83% globally and -92% in China in 2050 compared to current levels).

Although large scale deployment of certain solutions such as fuel-switching in the cement industry is in sight, zero-carbon transformation points remain challenging in some other industries. In these subsectors breakthroughs are needed that facilitate the rapid deployment of cost-competitive decarbonisation solutions. Therefore, significant research, development and large-scale deployment investments for new technologies and collaboration across companies and sectors will be required to reach (further) transformation points in the industry sector as early as possible. To achieve this, funding should be targeted both at technologies with high breakthrough potential and technologies with high risk but deep decarbonisation potential. Stringent carbon pricing policies in all countries with significant industrial production could ease competitiveness and carbon leakage concerns and facilitate low-carbon innovation. In addition, customer and public procurement preferences need to value zero-carbon industrial products (IEA, 2017b).

Ultimately, a combination of solutions and new coalitions of industrial actors will be required to fully decarbonise the sector due to the diverse set of challenges in curbing industry emissions.

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[14] Used assumption = Clinker / cement ratio of 60% in 2030 and 50% in 2050 (Favier et al., 2018)

[15] Used assumption = CCS deployment of 2% of the plants in 2030 up to 80% of the plants in 2050 with capture rate of 90% (Favier *et al.*, 2018; IEA, 2018b)

ANNEX: SUPPLEMENTARY MATERIALS

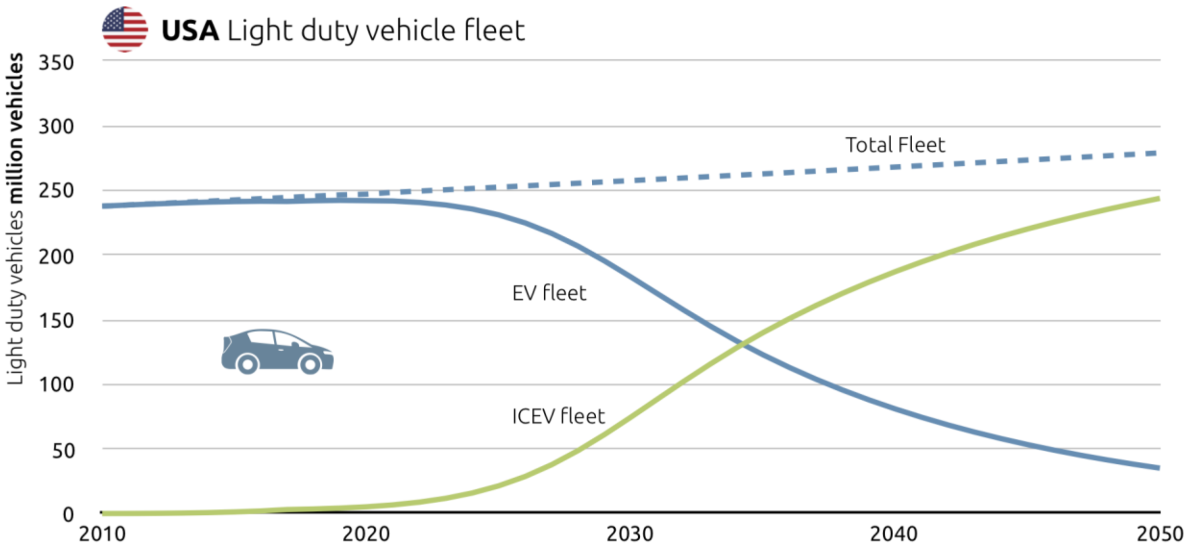
ELECTRICITY SECTOR

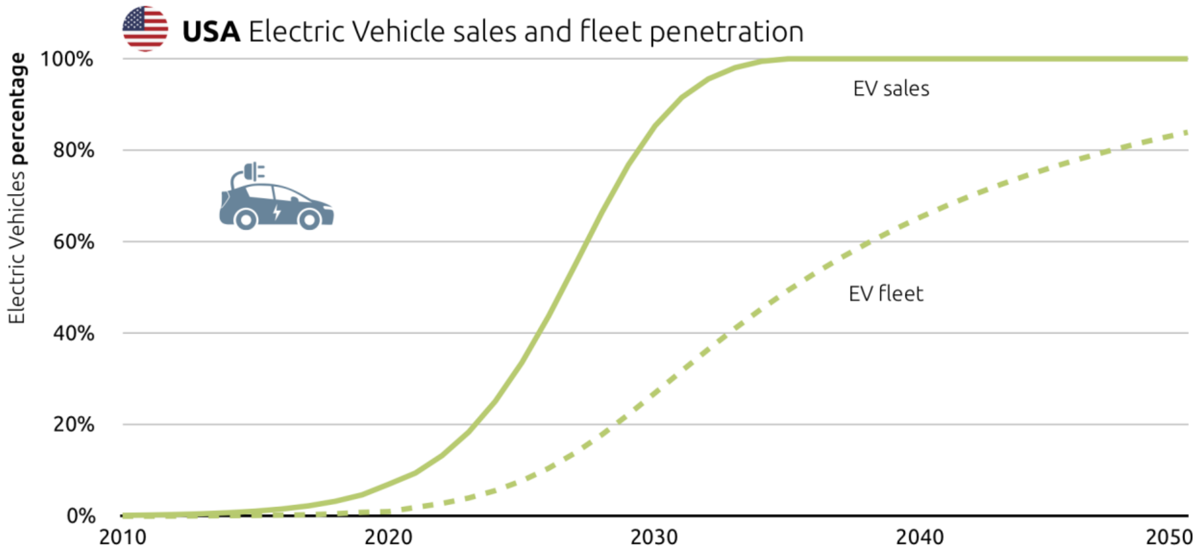
Global: In the global transformation points scenario, total renewables increase from their 2016 level at 24% of electricity generation, following an S-curve shape as illustrated in figure 4, to reach 100% of electricity generation in 2050. Other fuel shares are modified from the IEA Energy Technology Perspectives B2DS. Coal and oil are phased out by 2030. No CCS is assumed in this scenario. To calculate emissions based on this scenario, we use electricity demand from the IEA Energy Technology Perspectives B2DS scenario and emissions factors based on historic trends from the IEA CO_2 Database. We calculate a maximum needed storage scenario based on the assumption that 6% of electricity demand will need to be covered by storage in 100% renewables systems, based on a review study of energy and electricity systems models that investigate systems with high penetrations of renewables (Blanco and Faaij, 2018). That study showed that for systems with 100% renewables, storage needs range from 0 – 14% of annual electricity demand, depending on other system factors. 90% of studies include storage needs of 6% of annual electricity demand or less, which is why we take this as an upper bound. The studies that have higher values have unique characteristics that require particularly high storage needs, see (Blanco and Faaij, 2018) for details.

European Union: The transformation points scenario presented here is identical to the upper ambition bound of the 1.5°C Paris Agreement Compatible scenario developed by the Climate Action Tracker for its Scaling Up analysis for the European Union (Climate Action Tracker, 2018). In this scenario, renewables reach 98% of electricity generation in 2050. Nuclear makes up the remaining 5%. Electricity demand is based on sectoral demand analysis using the PROSPECTS EU tool, also developed by the Climate Action Tracker (Climate Action Tracker, 2018). We calculate emissions using emissions factors based on historical data from the IEA CO_2 Database combined with trends from the IEA World Energy Outlook for the European Union. For a complete description of the Climate Action Tracker's Current Development Scenario and 1.5°C Paris Agreement Compatible scenario for the European Union please see (Climate Action Tracker, 2018).

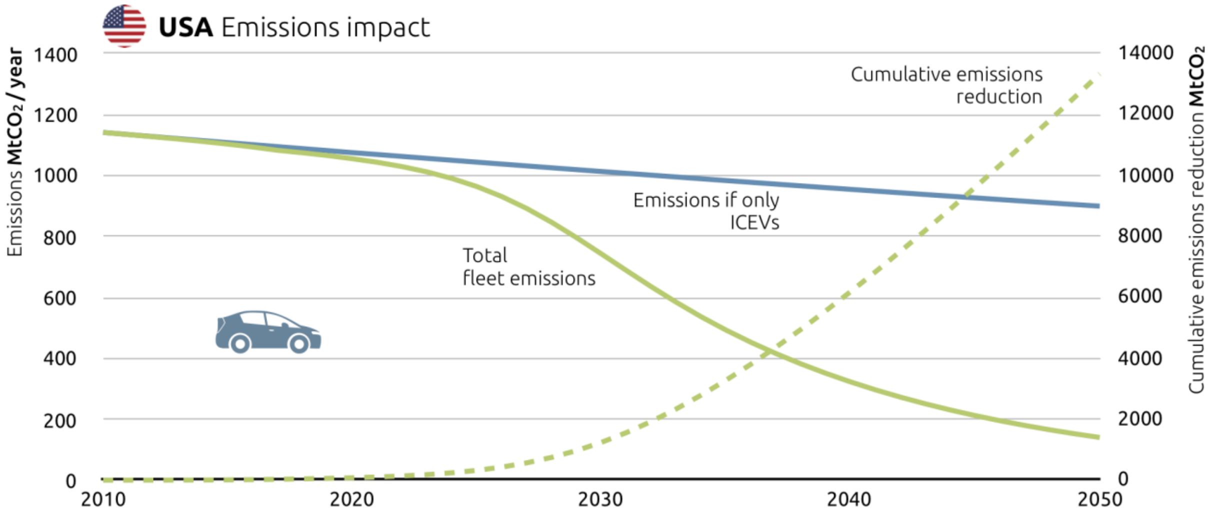
TRANSPORT SECTOR

In what follows we describe the methodology used to for the model results shown in the main text, based on data for the US. World and EU scenarios are constructed similarly. We assume that the total fleet will grow slowly (blue curve, left-hand axis; 1.0% for the US,), and that cars have an average lifetime of about 9 years, such that 8% of the existing vehicles on the road are retired each year, as are 5% of EVs. This is equivalent to policies that would actively encourage the replacement of ICEVs since historical experience shows a somewhat longer lifetime for vehicles. Sales of all vehicles have to make up the net growth and replace the retirements. Starting with the given growth rate of EV sales (yellow, right-hand axis, 35%/year for the U.S.), maintaining the fleet determines the sales of non-EVs. (gray curve, right-hand axis). At this growth rate, EV sales soon overtake the sales of ICEVs and the fleet of ICEVs is swapped out over time (sum of green curve and red curve, left-hand axis).





As a starting point, ICEVs are extremely inefficient even in the best of cases, but especially for the vast majority of LDVs on the road, which result in 240g of CO_2 emissions for each kilometre travelled. Doubling the efficiency of vehicles would cut emissions in half; here we assume improvement at 3%/year to match historical data as shown in Fig. 2. For electric vehicles, which travel three to four times as far on a given amount of input energy (electricity vs. liquid fuel), there is also a gain in terms of greenhouse gas emissions as the grid itself is made cleaner with increasing shares of renewable and other carbon-free energy. This coupling of electricity decarbonisation and electric vehicle technology is the key difference in emissions reductions through incremental improvements (i.e. in ICEVs) and a true change of state of the system to decarbonised transport.



Here we assume a grid with typical current emissions intensity of 400g/kWh, decreasing by 8% per year. This rate of decrease corresponds to calls {cite} to cut emissions by half each decade. For the given parameters, the combination of the growing fleet, the continued fleet of ICEVs on the road and the carbon intensity of the grid delays the reductions of emissions for some time, but then the advantages kick in very strongly. Of course, in a region with a lower carbon intensity now, or by reducing the carbon intensity of the grid even more quickly, the effects of electrification of personal vehicles will be even stronger.

A summary of the assumptions made in the model, as they apply to the figures in this Memo, are shown in the Tables below.

Variable	World	USA	Unit
EV initial growth	45%	45%	per year
initial EV fleet	1.24	0.4	Million (2015)
initial EV sales	0.85	0.2	Million (2015)
ICEV retirement rate	10%	7%	of fleet per year
EV retirement rate	5%	5%	of EV fleet per year
fleet growth	1.8%	1.0%	per year
initial fleet	870	230	Million vehicles
Distance travelled	10000	18500	km per auto per year
EV efficiency	7	7	km per kWh for EVs
ICEV emissions intensity	250	250	gCO2/km for ICEVs
Electricity emissions intensity	400	400	gCO2/kWh initial carbon intensity of grid
Electricity emissions intensity improvement rate	8.0%	5.0%	per year decrease in carbon intensity
ICEV emissions intensity improvement rate	1.0%	2.0%	per year decrease in ICEV carbon intensity

INDUSTRY SECTOR

The calculations in this analysis were performed using a prototype of the PROSPECTS model, under development by the Climate Action Tracker team[16]. The prototype used for this study contained simplified modules for the power and cement sector, interlinked such that electricity-related emissions could be allocated to the end-use sectors in industry. Logic charts for the calculations in these sectoral modules are shown in Figure 10 and Figure 11. As indicated in the legend, some of these metrics are necessary as input data to run the calculations.

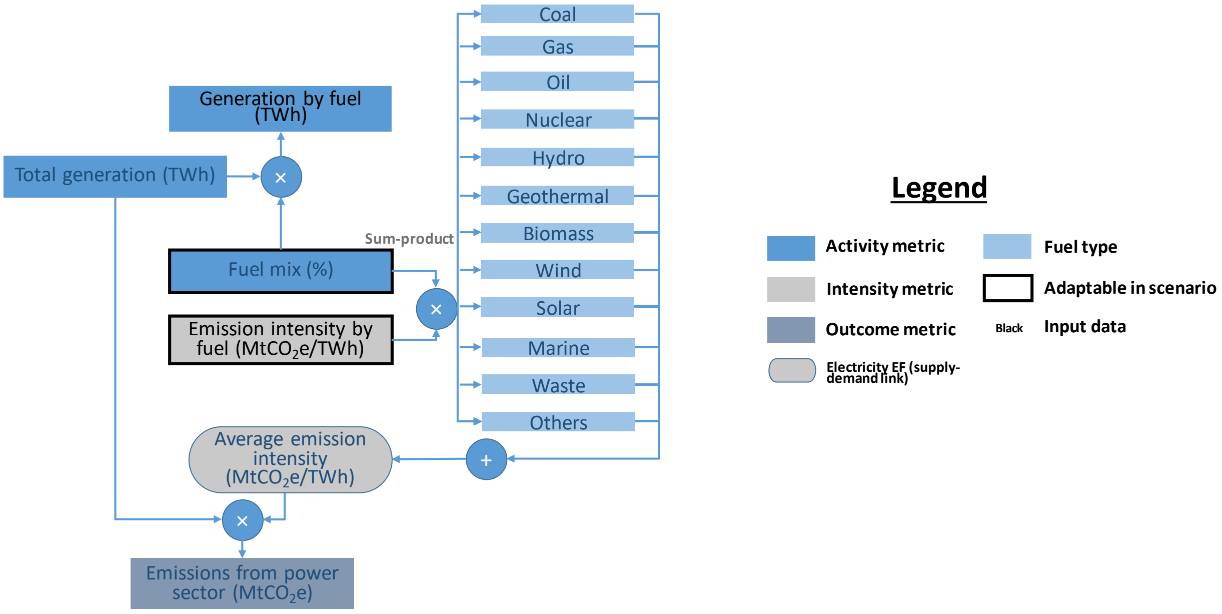


Figure 10: Flowchart showing the logic of the power sector in the present analysis. EF = Emission factor.

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[16] PROSPECTS stands for Policy-Related Overall and Sectoral Projections of Emission Curves and Time Series. The aim of the model is to estimate historical emissions time series across all economic sectors, coupling energy supply and demand, and allow for user-defined scenarios of activity/intensity indicators for emissions projections.

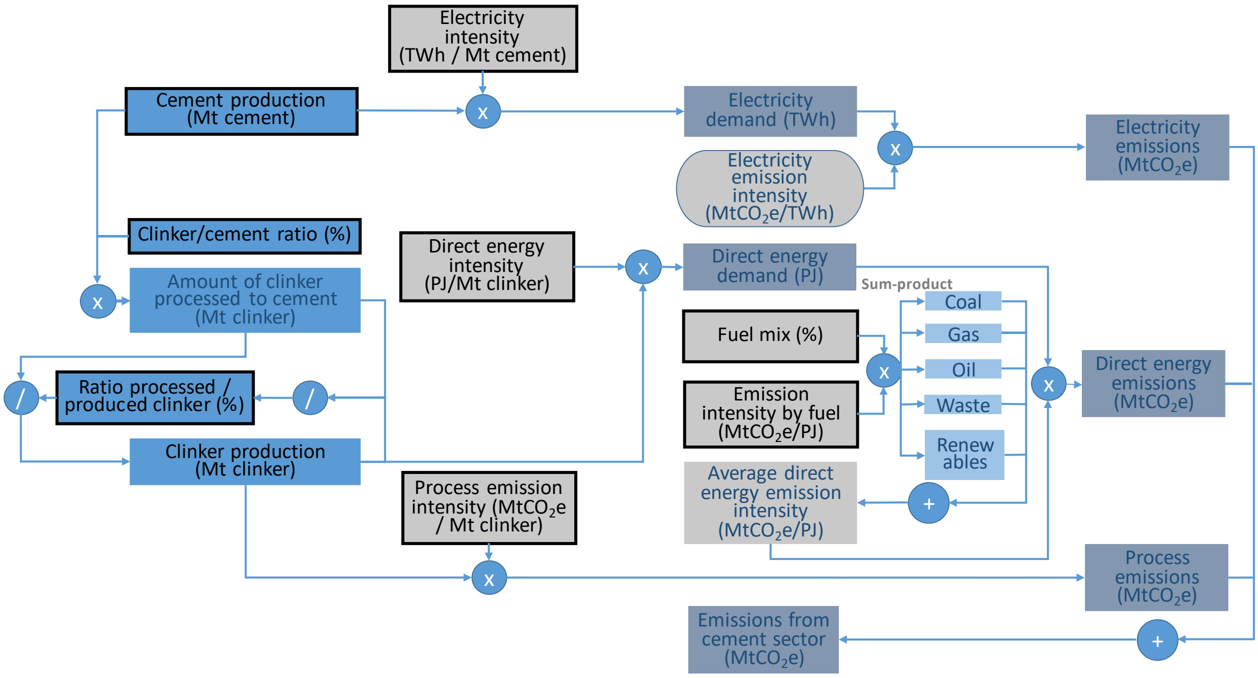

Figure 11: Flowchart showing the logic of the cement sector in the present analysis.

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