Carbon Tracker Initiative

Grantham Institute
Climate Change and the Environment
An institute of Imperial College London

Expect the Unexpected

The Disruptive Power of Low-carbon Technology

February 2017

Acknowledgements

About Carbon Tracker

The Carbon Tracker Initiative is a team of financial specialists making climate risk visible in today's capital markets. Our research to date on unburnable carbon and stranded assets has started a new debate on how to align the financial system with the energy transition to a low-carbon future.

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Modelling was led by Dr. Tamaryn Napp, Research Associate, and Ajay Gambhir, Senior Research Fellow, with support from Dr. Florian Steiner, Research Associate, and Dr. Adam Hawkes, Head of Energy Modelling, all of the Grantham Institute at Imperial College London. Thanks to the European Climate Foundation (ECF) and ClimateWorks Foundation for their support.

Thanks to Ajay Gambhir, Dr. Tamaryn Napp, Alyssa Gilbert, Mark Fulton (Energy Transition Advisors), Matt Gray and Andrew Grant (Carbon Tracker) for reviewing.
Designed and typeset by Margherita Gagliardi, Carbon Tracker.

This report has an accompanying online interactive so readers can fully delve into the scenario outputs. This can be found at carbontracker.org/expect-the-unexpected-dashboard

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Executive Summary

The time for energy transformations is now

Achieving climate stability will require deep and widespread changes in the global energy sector. Fossil fuel industry projections, however, continue to show a future energy system with few changes to that of today. This is in spite of examples of disruption in the energy sector at the hands of the low-carbon transition. This scenario analysis was produced in partnership between Carbon Tracker and the Grantham Institute at Imperial College London and explores the extent to which ongoing cost reductions could see solar photovoltaics (PV) and electric vehicles (EVs) impact future demand for coal, oil and gas. The findings of this study should motivate energy companies and their investors to retire the use of business as usual (BAU) scenarios and further integrate the consideration of downside demand scenarios.

Updating model assumptions is critical

This study demonstrates the importance of using the latest available data and market trends for technology costs and climate policy in energy modelling. Applying up-to-date solar PV and EV cost projections, along with climate policy effort in line with the Nationally Determined Contributions (NDCs), should now be the starting point for any scenario analysis. This is not a radical disruptive scenario in terms of its inputs, but a reflection of the current state of play. The key findings in this scenario are presented below.

Low-carbon technologies

- Solar PV (with associated energy storage costs included) could supply 23% of global power generation in 2040 and 29% by 2050, entirely phasing out coal and leaving natural gas with just a 1% market share. ExxonMobil sees all renewables supplying just 11% of global power generation by 2040.

- EVs account for approximately 35% of the road transport market by 2035 – BP put this figure at just 6% in its 2017 energy outlook. By 2050, EVs account for over two-thirds of the road transport market. This growth trajectory sees EVs displace approximately two million barrels of oil per day (mbd) in 2025 and 25mbd in 2050. To put these figures in context, the recent 2014-15 oil price collapse was the result of a two mbd (2%) shift in the supply-demand balance.

Fossil fuel demand

- Although this study focuses on the decarbonisation of the global power and road transport sectors, which today account for only 51% of global CO_2 emissions and fossil fuel demand approximately, this scenario sees:
  - Coal demand peaking in 2020;
  - Oil demand peaking in 2020; and
  - Gas demand growth curtailed.

Global warming

Global average temperature rise is limited to between 2.4°C (50% probability) and 2.7°C (66% probability) by 2100 in this scenario – far below the BAU trajectory towards 4°C and beyond used by fossil fuel companies. If climate policy exceeds the pathway prescribed by NDCs, and overall energy demand is lower, cost reductions in solar PV and EVs can help limit global warming to between 2.1°C (50% probability) and 2.3°C (66% probability). Efforts must be made to align with this more carbon-constrained trajectory.

The '10% threshold'

In the past Carbon Tracker has shown that a 10% shift in market share can be crippling for incumbents, such as in the value destruction experienced by EU utilities and the near collapse of the US coal sector. Scenarios produced in this study indicate that 10% shifts in market share from incumbents to solar PV or EVs could occur within a single decade. This contrasts with many BAU scenarios which do not see these technologies gaining a 10% market share, even over several decades. Breaking through these kinds of thresholds is significant because they signal the peak in demand for coal or oil; changing the fundamental market dynamic for these fossil fuels.

No more business as usual

By definition, BAU scenarios involve no additional climate policy mitigation action beyond the present level, or acceleration in the extent to which low-carbon technologies impact energy markets. Given the energy transition is clearly already underway, and there is no way that BAU can meet the climate targets that many countries, states and companies have committed to, it is our contention that it is time to retire the conventional approach to use BAU as a starting point in scenario analyses. The current state of the low-carbon transition means it is highly risky to justify any business strategy by using a BAU scenario as a reference case. By changing the starting point, it shifts the focus on to how to achieve the Paris COP climate targets, i.e. a 2°C reference scenario, rather than the gap between BAU and what is already happening.

Ensuring transparency of assumptions

As noted by the draft guidance from the Financial Stability Board (FSB) Taskforce on Climate-related Financial Disclosures (TCFD), it is important to know the assumptions underlying any energy modelling analysis. This is particularly true for the costs of energy supply technologies given the binary nature of how integrated assessment models (IAMs) tend to select the lowest cost options in their projections of the future energy mix. Equally important are disclosures of efficiency variables, capacity factors and any exogenous constraints applied by the modellers. This analysis demonstrates how it is possible to provide this transparency in accordance with TCFD recommendations (see Appendix) and why it is important to do so.

Decarbonisation of industry and buildings is vital

This study focuses on the potential impacts from growth of solar PV and EVs. It does not address specific measures for other carbon-intensive sectors such as heavy industry, buildings or other transport sectors (rail, maritime and aviation). This analysis shows, however, that decarbonisation of power and road transport alone may not be enough to achieve international climate targets; so all sectors will need to contribute to future emissions mitigation.

Recommendations

Policy Makers

Policymakers are constantly preparing for the future energy needs of their populations. Ensuring that the fundamentals of factors such as demand and technology costs are up-to-date in the models being used to assess policy options is essential to accurately identify the most efficient solutions for the future.

Energy Companies

Companies must move beyond BAU strategies and articulate how they are adjusting to the low-carbon transition and publicly quantify the risks. They should also communicate where they see opportunities in the low-carbon transition and how they could drive the potential growth of technologies such as solar PV and EVs.

Energy/Climate Modellers

The scientific community has recognised the strengths and limitations of integrated assessment models to date. It now needs to develop the next generation of energy/climate models which can better reflect the dynamics of the complex interacting factors involved in our energy and climate systems.

Investors

Shareholders must require more information on the processes used by energy companies to manage transition risk. Many companies already conduct some form of lower demand/price scenario analysis; investors must require full disclosure of these scenarios and use them to better align their investments with a carbon-constrained future.

Financial Regulators

There is an essential role for scenario analysis in understanding transition risk. Financial regulators should issue guidance on the scenarios that should be used by companies, This should include a 2°C scenario to deliver consistent, comparable risk metrics for investors.

Image via Wikimedia Commons

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1 Introduction

This report was produced in partnership between Carbon Tracker and the Grantham Institute at Imperial College London. This study analyses the potential for continued cost reductions in solar photovoltaics (PV) and electric vehicle (EV) technologies to displace demand for currently dominant fossil fuels and mitigate CO_2 emissions. In doing so, the report reviews the validity of continuing to base corporate strategies on 'business as usual' scenarios.

Value destruction from low-carbon transformations should be avoided

Achieving climate stability will require deep and widespread changes in the global energy system - the largest single source of CO_2 emissions and focus of this report. Such changes are afoot. Solar PV module costs have fallen 99% since 1976[i] with record global installations being made for the second consecutive year in 2016.[ii] Similar downward cost trends exist in other renewable energy technologies. Few predicted these energy transformations, in what proved to be a costly oversight for many. For example, the EU's five largest utilities lost over €100bn in value from 2008 to 2013 largely because of a failure to predict the penetration of low-carbon technologies resulting from this cost deflation (see Carbon Tracker's *EU Utility Death Spiral*[iii]). Companies have since recognised that they are entering the low-carbon market 10 years too late.

Challenging demand assumptions

In spite of recent examples of low-carbon shifts, current energy industry scenarios still suffer from 'straight-line syndrome' – an approach where fossil fuel demand continues to grow at an unerring pace. This inevitably leads to outputs that present harmonious, incremental shifts in energy, while eliminating the possibility of foreseeing step-changes. This approach runs the risk of energy industry participants overlooking influential changes in supply side inputs, such as technology cost reductions, and demand side fundamentals, such as efficiency gains. Recent shifts in energy markets have also shown that the loss of 10% market share for a technology can be enough to have a significant financial impact, rather than entire sectoral overhauls. (see Carbon Tracker's *US Coal Crash*.)[iv] Moreover, in the case of value destruction for EU utilities or the US coal mining sector, these inflection points occurred well within 10 years, not the long, foreseeable time frames often purported by the fossil fuel industry.

Focusing on solar PV and EVs

This report models the impact on fossil fuel demand from applying the latest available data and market projections for future cost reductions in solar PV and EVs. Global climate policy effort and energy demand are also varied across this study's scenarios to explore their role in impacting on future fossil fuel demand. Consequently, this study reveals the level of CO_2 emissions and climate change mitigation that can result from credible, up-to-date modelling assumptions in just a few sectors of the energy system. In doing so, this analysis also highlights the scope for even greater decarbonisation of the global energy system if technological innovation in sectors and industries outside the scope of this study results in cutting emissions.

> *Current energy industry scenarios still suffer from 'straight-line syndrome' - an approach where fossil fuel demand continues to grow at an unerring pace".*

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Methodology

How the model works

The scenario outputs of this report have been generated by Imperial College London using the Grantham Institute's TIMES Integrated Assessment Model (TIAM-Grantham) following input and assistance from Carbon Tracker. TIAM-Grantham is a multi-region, least-cost optimising model. The model minimises the total present value cost of the global energy system (using a 5% discount rate) to meet future energy service demands. Details of the macro-level demand assumptions and supply-side technology cost assumptions in each scenario are fully described in the Technical Report accompanying this study.[1]

Forecasting approach

One key element of this study is that it explores future energy system evolution pathways without any predetermined temperature outcome. This constitutes a 'forecast', whereby the impact on temperature is assessed post-hoc in light of the policy strength and technology cost assumptions applied to meet the required energy demand level. Models such as TIAM-Grantham are more commonly used in a 'backcast' sense, to explore the least-cost energy system evolution pathways towards meeting prescribed climate targets. But such scenarios are numerous and do not form the focus here. Rather, this study is focused on exploring the fossil fuel and climate implications of the changing economics of key low-carbon technologies.

Economic calculations and technology constraints

TIAM-Grantham uses extraction costs for supplying fossil fuels and does not factor in taxation or subsidy regimes for energy resources or generation activities. This means it doesn't fully replicate real-world economic decisions which account for such factors. Going forward, the removal of subsidies or tax breaks is desirable to create a level playing field and to promote the most efficient energy choices in the future. Subsidies are often used to stimulate the uptake of new technologies and are then removed as costs come down with deployment of greater volume. However, a number of established energy sources, (eg nuclear, oil and gas extraction), continue to receive subsidies or special tax treatments, or public financial support for clean-up/decommissioning liabilities, often over the course of several decades.

Because TIAM-Grantham operates on a least-cost basis, it is possible that the cheapest technology in any sector can be deployed without limit until it dominates that sector; a pattern which in the near-term at least is unlikely to be realistic. As such, technology growth constraints are frequently employed in such models, in order that technology penetration pathways are not unrealistically rapid. In addition, it is important that energy storage technologies and/or other electricity system balancing measures are included where the penetration of intermittent renewable electricity generation technologies becomes significant. Further information on these assumptions made in this study are available in the relevant sections of this publication and the accompanying Technical Report.

Scenario structure

The scenarios in this study have been constructed by varying three main factors, as well as updating and recalibrating the TIAM-Grantham model from a 2005 start year, to a 2012 baseline:

A. Technology

This study is not an exercise in applying wildly optimistic cost reduction trends, but rather an exploration of how plausible advances in solar PV and EVs could impact on future fossil fuel demand, as well as efforts to reach international climate targets. These two technologies are the focus of this report because their respective costs: i) have reduced significantly over recent years, demonstrating potential for disrupting the incumbent fossil fuel suppliers; and ii) are expected to fall further in the future, potentially making a significant contribution to decarbonising the global energy system. To explore the potential impact of future penetration of solar PV and EVs on fossil fuel demand, this study compares:

- Scenarios produced with '**original**' cost assumptions from the TIAM-Grantham model (these cost estimates were made in 2012 for solar PV and 2014 for EVs); against
- Scenarios produced with **'lower cost'** assumptions developed from the latest available data and current low-cost market projections.

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[1] http://www.carbontracker.org/wp-content/uploads/2017/02/CTI_TechnicalReport_FINAL.pdf

B. *Climate policy*

As well as focusing on these technological solutions, each scenario in this study features variations of climate policy effort. This study models four levels of international climate policy effort, as represented through a range of carbon prices applied from 2020 onwards, each growing at 5% discount rate per annum (in real terms). This policy effort is not intended to represent only existing carbon pricing mechanisms such as emissions trading schemes and carbon taxes, but aims to reflect any policy that could serve to constrain CO_2 emissions.

C. *Energy demand*

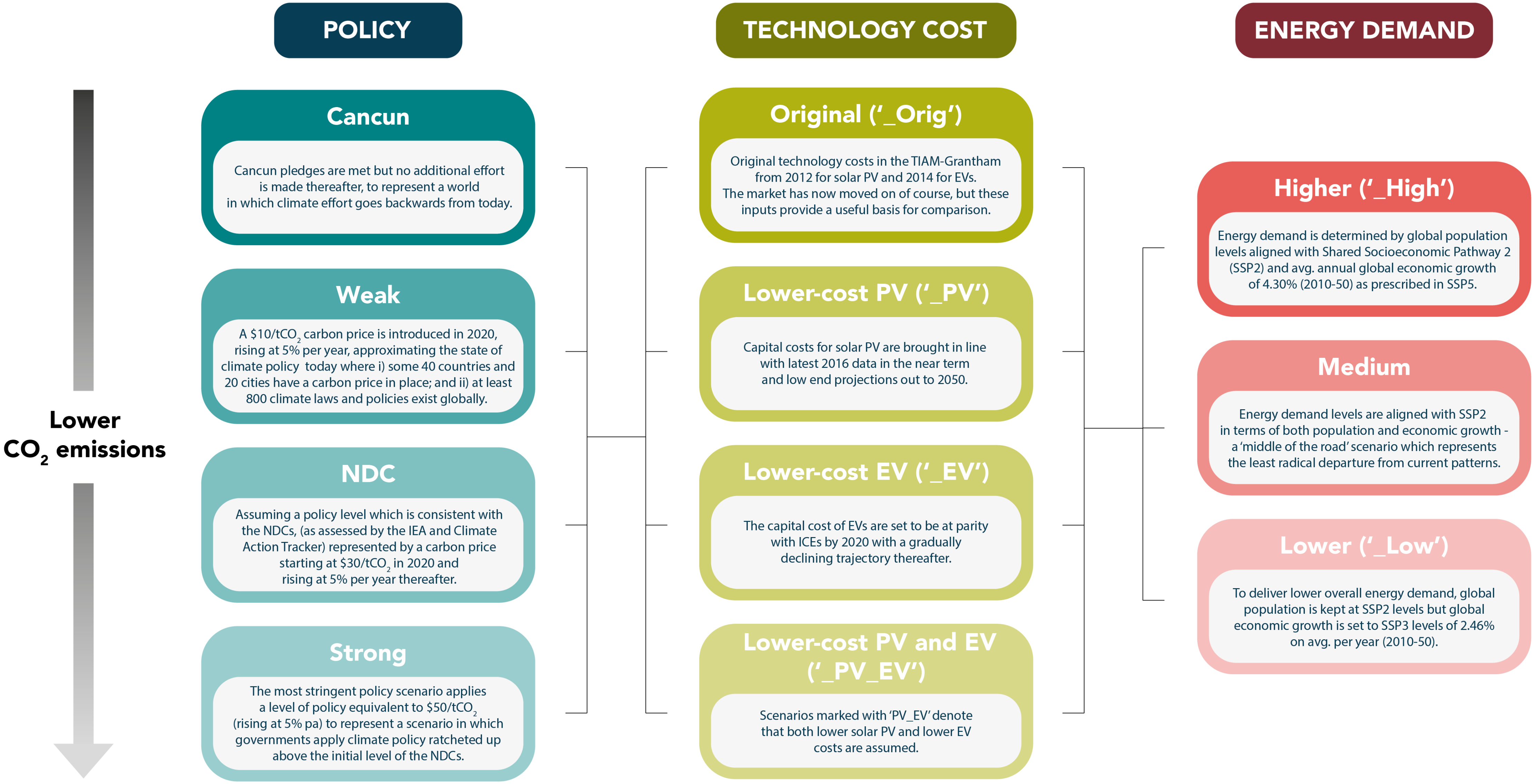
Energy demand levels in the scenarios are centred on the socio-economic projections made in the Shared Socioeconomic Pathway 2 (SSP2)[v] scenario with: i) population levels of peaking in 2070 at 9.4 billion before falling to 9.0 billion in 2100; and ii) average annual economic growth of 3.13% from 2010 to 2050.

Together, these assumptions set our baseline '**medium**' level of energy demand. Higher and lower levels are achieved by varying global economic growth levels to 4.30% and 2.46% respectively over the same time period (levels derived from the highest and lowest GDP growth rates of the full set of SSPs), while keeping global population levels the same as SSP2.

Factor combinations

Figure 1 summarises the structure of all the scenarios conducted for this study, along with the prefix used to denote the policy, technology or energy demand assumption made. These are in brackets in Figure 1. To illustrate, the scenario that assumes: i) policy effort consistent with the NDCs; and ii) lower solar PV cost assumptions, is referred to as 'NDC_PV'. The scenario with: i) an NDC level of climate policy; ii) lower solar PV and EV costs; and iii) lower energy demand assumptions, is referred to as 'NDC_PV_EV_Low', and so on.

Figure 1: The structure of scenario assumptions



POLICY

Cancun

Cancun pledges are met but no additional effort is made thereafter, to represent a world in which climate effort goes backwards from today.

Weak

A $\$10/tCO_2$ carbon price is introduced in 2020, rising at 5% per year, approximating the state of climate policy today where i) some 40 countries and 20 cities have a carbon price in place; and ii) at least 800 climate laws and policies exist globally.

NDC

Assuming a policy level which is consistent with the NDCs, (as assessed by the IEA and Climate Action Tracker) represented by a carbon price starting at $\$30/tCO_2$ in 2020 and rising at 5% per year thereafter.

Strong

The most stringent policy scenario applies a level of policy equivalent to $\$50/tCO_2$ (rising at 5% pa) to represent a scenario in which governments apply climate policy ratcheted up above the initial level of the NDCs.

TECHNOLOGY COST

Original ('_Orig')

Original technology costs in the TIAM-Grantham from 2012 for solar PV and 2014 for EVs. The market has now moved on of course, but these inputs provide a useful basis for comparison.

Lower-cost PV ('_PV')

Capital costs for solar PV are brought in line with latest 2016 data in the near term and low end projections out to 2050.

Lower-cost EV ('_EV')

The capital cost of EVs are set to be at parity with ICEs by 2020 with a gradually declining trajectory thereafter.

Lower-cost PV and EV ('_PV_EV')

Scenarios marked with 'PV_EV' denote that both lower solar PV and lower EV costs are assumed.

ENERGY DEMAND

Higher ('_High')

Energy demand is determined by global population levels aligned with Shared Socioeconomic Pathway 2 (SSP2) and avg. annual global economic growth of 4.30% (2010-50) as prescribed in SSP5.

Medium

Energy demand levels are aligned with SSP2 in terms of both population and economic growth - a 'middle of the road' scenario which represents the least radical departure from current patterns.

Lower ('_Low')

To deliver lower overall energy demand, global population is kept at SSP2 levels but global economic growth is set to SSP3 levels of 2.46% on avg. per year (2010-50).

No baseline, no business as usual, but a new starting point

'Business as usual' is generally defined as a:

> *baseline case, which assumes that future development trends follow those of the past and no changes in policies will take place.*
> IPCC (2013).[vi]

A typical approach to climate and energy modelling would use such a BAU scenario to make comparisons with lower-carbon scenarios. Traditionally, therefore, the 'Cancun_Orig' scenario would be used as the baseline in this study because it assumes: i) no further climate policy effort beyond the Cancun pledges made back in 2010; ii) no acceleration in technological advances beyond those original costs projections made in TIAM-Grantham a number of years ago; and iii) medium energy demand levels.

This kind of BAU approach carries the risk of extrapolating the past into the future. This is no longer a sensible approach when considering the energy/climate nexus. First, it does not reflect the energy transition that is already underway, which is seeing governments and companies act, and rapid changes in low-carbon technology. Second, it ignores the fundamental imperatives of climate science - the energy system will have to transition to low-carbon solutions if the world is to deliver on its stated and agreed objectives to prevent dangerous levels of climate change.

This study demonstrates that the scope for significant penetration of low-carbon technologies in the future is vast. Consequently, the concept of BAU is becoming increasingly redundant and a very high-risk corporate strategy. As such, this approach is not used in this study, meaning scenarios with climate policy consistent with the Cancun pledges are not included in the report (but can be explored through the online tool accompanying this report if desired[2]). Instead, the findings of this study are framed around scenario 'NDC_PV_EV'. While the outcomes in this scenario are not guaranteed, this pathway is a credible reflection of the low-carbon transition as indicated by current technology trends and policy commitments, and should be used as the new starting point for any scenario analysis.

At present, the energy industry tends to focus on outdated BAU scenarios. In the past, Carbon Tracker has reviewed where these BAU scenarios have been used to justify corporate strategies in the face of structural change. For example, see *No Rhyme or Reason* reviewing the use of EIA scenarios by the US coal mining sector[vii]. Using a scenario such as 'NDC_PV_EV' should limit the potential for the energy industry to misread future demand in the power and road transport sectors specifically, and would constitute effective risk management in the face of these sectoral low-carbon transformations.

The 'NDC_PV_EV' scenario does not achieve a 2°C outcome (either at 50% or 66% probability thresholds), so does not reflect even the minimum objective of the UNFCCC Paris COP21 agreement, let alone the full range of its ambition to limit global anthropogenic warming to well below 2°C and pursuing efforts towards 1.5°C. However, if energy companies use a scenario like 'NDC_PV_EV' as a starting point, there would be less of a gap to bridge to approach these more ambitious climate targets, and the fossil fuel demand downsides they comprise, compared to baseline scenarios that are on track for 4°C and over.

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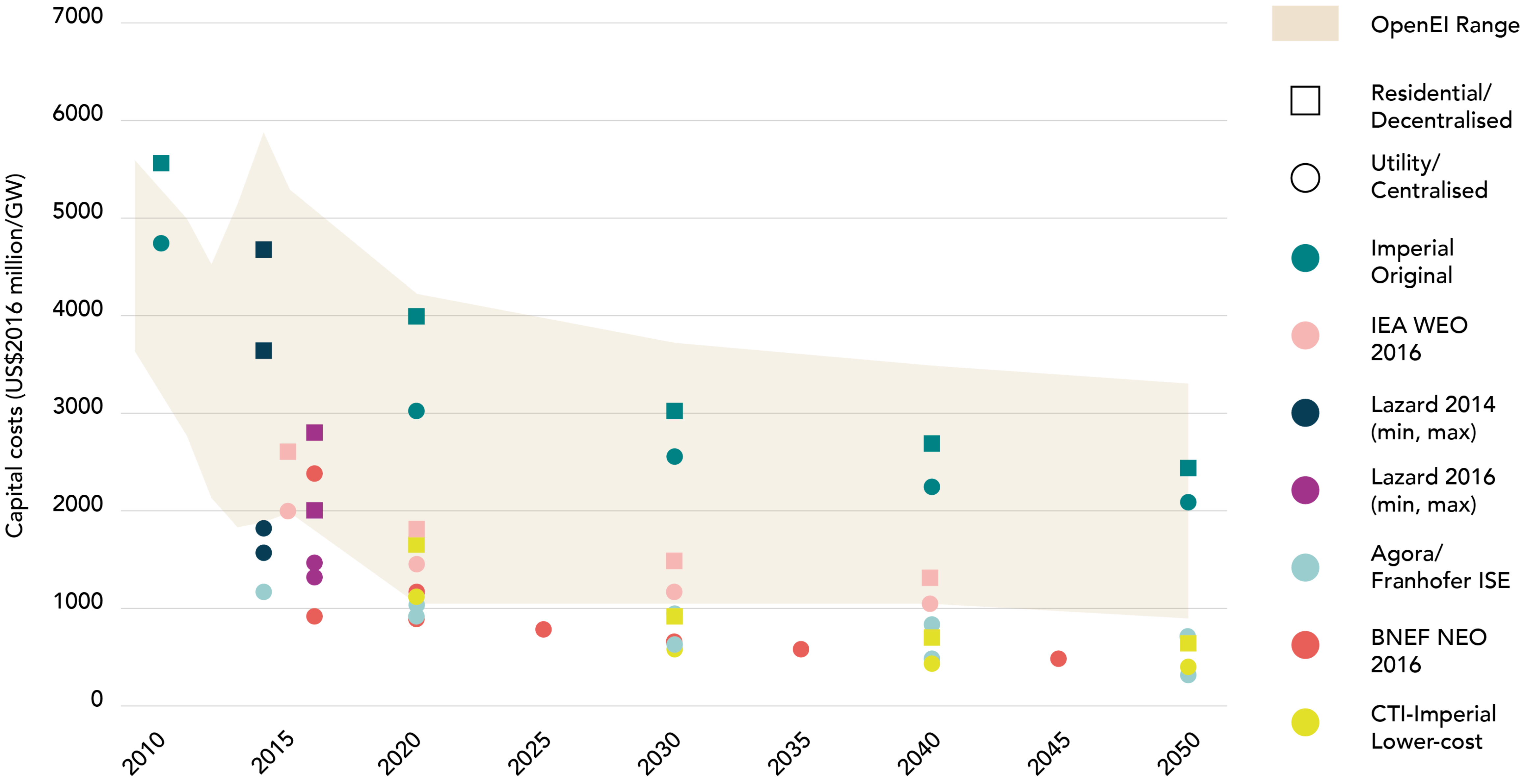
[2] *Available at: www.carbontracker.org/expect-the-unexpected-dashboard*

3

How far can solar PV penetrate global power markets?

Image via Wikimedia Commons

Figure 2: Original and lower solar PV capital cost assumptions compared against wider literature[3]



Source: OpenEI data includes Lazard 2009-13, IPCC 2014, EIA AEO 2012, 2013 & 2015, IIASA 2014, US DOE 2011 & 2012, IEA PV 2010 & 2012, US EPA 2013. Additional sources include Agora/Franhofer ISE 2015, IEA WEO 2016, BNEF NEO 2016, Lazard 2014 and 2016 and CTI-Imperial 2016.

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[3] *Conversion of Agora Energiewende data from €2014/kW to US$2014/kW uses exchange rate of US$1.22 to €1. Conversions to US$2016 used rates from the US Department of Labor, available at: http://www.bls.gov/data/inflation_calculator.htm.*

Recent advances

The cost of solar PV modules has fallen 99% since 1976 according to Bloomberg New Energy Finance (BNEF).[viii] Over the last seven years alone, solar PV costs have come down 85% according to the latest research from Lazard.[ix] This cost deflation is the primary driver for an increase in solar PV installations globally. In regions that have seen higher than average growth, penetration of solar PV has resulted in disproportionately large disruptions as a result of a lack of preparedness. For example, in the EU, major utilities dismissed the potential of solar PV. RWE said in 2005 that there is ‘little hope that [solar photovoltaic] systems linked to the power grid will ever manage to generate electric power in a truly cost-efficient manner’.[x] These companies have since recognised that they missed the boat and are now coming late to renewables, but the damage has been done. Between 2008 and 2013, renewable power generation, of which solar PV was a big part, grew by 8% in total. The five major European utilities were very much misaligned with this shift, costing them €100 billion in value over the period.[xi] This demonstrates exactly why the extent to which solar PV costs fall further in the future, and subsequent penetration, is critical to those in the global energy sector.

Updating current solar PV costs

One of the challenges of producing scenarios centred on solar PV is that the model inputs must remain consistent with such a quickly evolving market. This study’s scenarios demonstrate this point aptly. For example, the ‘original’ solar PV costs were set in TIAM-Grantham in 2012. In the four years since, these cost projections have been made to look somewhat outdated. Figure 2 shows that utility scale capital costs for solar PV were originally estimated in TIAM-Grantham to be roughly $3721m/GW in 2016 (**green**). Latest Lazard research estimates this figure is approximately $1375m/GW (**purple**).[xii] This is even less than the low-end of estimates made by studies captured in the OpenEI database (**pastel**) that range from 2009 to 2013 publications. Solar PV cost reductions have largely been achieved in module costs, but increasingly non-module costs, such as cabling, inverters and installation, are now contributing to total system cost reductions. The speed of change in solar PV emphasises the importance of regularly updating starting cost levels.

Updating projected solar PV cost reductions

In light of the faster than expected cost reductions in solar PV to date, a set of ‘lower-cost’ scenarios (**gold**) were run in this study. These scenarios see consistent cost deflation result in residential solar PV costing $643m/GW and utility-scale solar PV price at $390m/GW in 2050. This is in line with current solar PV cost points and in accordance with projections from BNEF’s 2016 New Energy Outlook[xiii] (**red**) and Agora Energiewende/Franhofer ISE[xiv] (**blue**) thereafter refer to Figure 2. While these assumptions are at the low-end of the current range of projections, it is worth remembering the degree to which expectations have been exceeded in the solar PV sector in recent years. In fact, if recent analyses on the next generation of solar PV materials are correct, our lower-cost assumptions may prove to be conservative. For example, printable PV could achieve very low module production costs, which when combined with lowest Agora Energiewende/Franhofer ISE estimates for balance of system costs, see total system costs for utility scale solar of less than $250m/GW by 2050. This is more than 35% less than our lower-cost assumption for the same year. This demonstrates how there could still be further room for greater shifts in the energy sector than we are modelling here.

> *If recent analyses on the next generation of solar PV materials are correct, our lower-cost assumptions may prove to be conservative”.*

What impact does solar PV have on the power mix in our scenarios?

Figure 3: Lower costs shifts the balance towards solar PV from fossil fuel alternatives

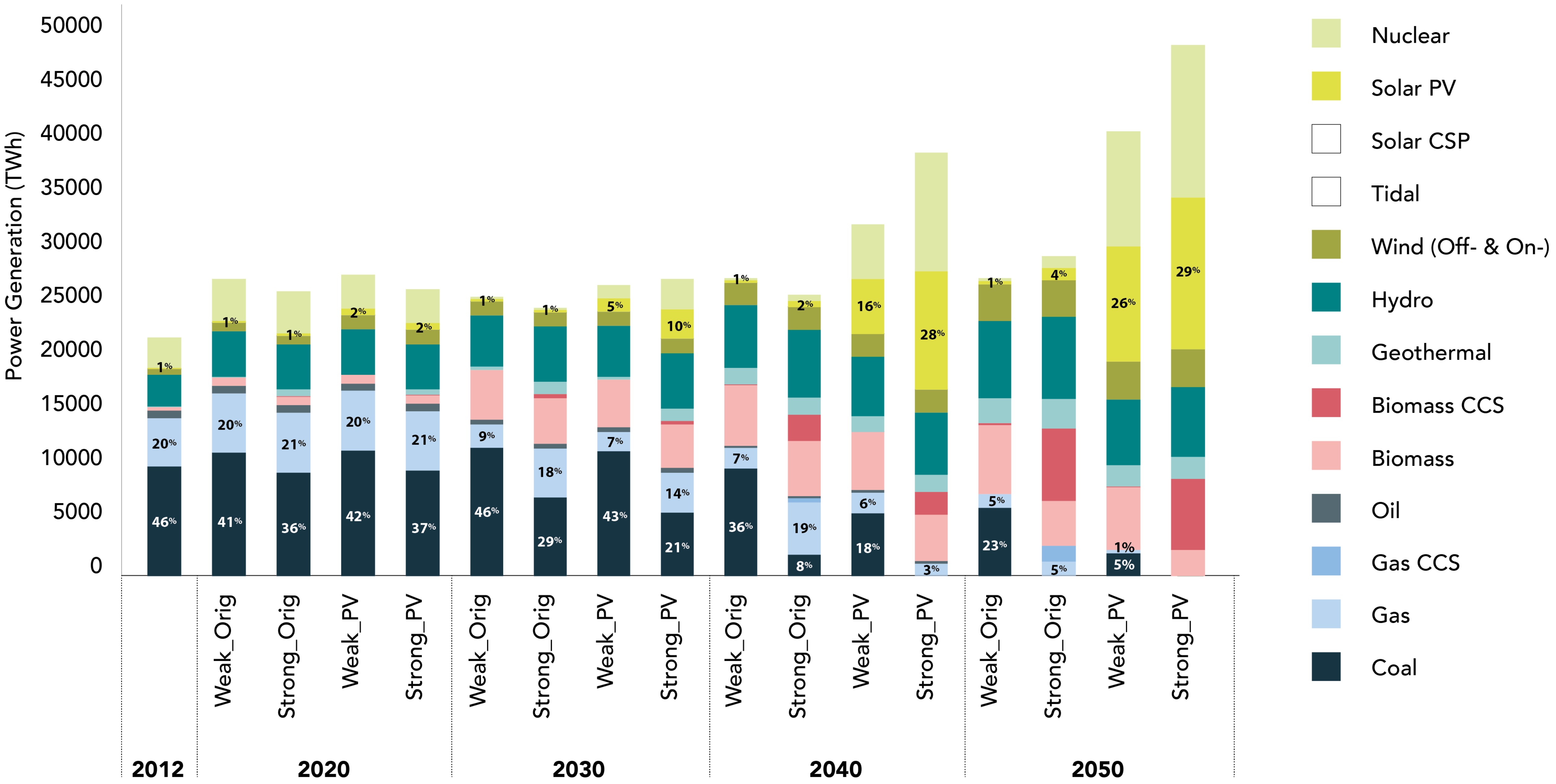


Figure 3 compares the global power mix out to 2050 in scenarios in which original and lower-cost solar PV assumptions are paired with climate policy that either exceeds current NDCs, ie 'Strong' policy effort, or under-delivers on the NDCs, ie 'Weak' policy. The scenarios with NDC level climate policy feature in between these two pathways in terms of the balance between fossil fuels and renewable energies.

Even with now outdated solar PV costs, climate policy kills coal

The results show that 'Strong' climate policy sees demand for coal-fired power generation constrained significantly, regardless of assumed solar PV costs – see scenario 'Strong_Orig'. Under these conditions, coal loses 10% of global market share by 2020 on 2012 levels, ie the same sized market swing that caused €100bn of value destruction to EU utilities from 2008-2013[xv], and the near collapse of the US coal industry.[xvi] By 2040, coal has just 8% of the power market before being entirely phased out in 2050.

This dramatic shift does not result in any material uplift in demand for solar PV power however, when assuming original solar PV costs. By 2040, solar PV makes up just 2% of the global power mix in scenario 'Strong_Orig' because natural gas, geothermal and hydropower take up the displaced coal-fired power generation. By 2050, biomass with Carbon Capture and Storage (CCS) has also gained market share due to the carbon price being used as a proxy for climate policy, thereby reducing gas demand to just 5% of the power mix, down from 19% just 10 years earlier. In these scenarios solar PV only grows to 4% market share by 2050. We have already seen a rate of cost reductions to date in solar PV that render this outcome to be very unlikely.

Updating solar PV costs results in strong growth

Updating solar PV costs with the latest available data and cost reduction projections, as described in the methodology, results in a huge gain in market share for solar PV at the expense of fossil fuel alternatives. Figure 3 shows that by 2030, solar PV accounts for 10% of global power generation when lower costs are coupled with 'Strong' climate policy effort scenario 'Strong_PV'. By 2050, this share has grown to 29%, which is almost consistent across 'Weak' and NDC consistent policy levels as well. To put this in perspective, ExxonMobil sees all renewables supplying just 11% of global power generation by 2040[xvii]. Meanwhile, coal is phased out of the power mix by 2040 – 10 years earlier than with original solar PV cost assumptions – and natural gas follows soon afterwards.

Wind power is a growth market

In addition to potential growth in solar PV, wind power also grows significantly across all scenarios to 2050, up to around 12% of the power market. The absolute level of power generated by wind does not vary considerably between scenarios because its growth has been artificially capped in the modelling – full details in the Technical Report.[xviii] This is because wind power, particularly onshore wind, is already cost-competitive with other power sources today in many regions of the world. Therefore, given the binary nature of least-cost optimising models, wind capacity will always be added as the least-cost option in the most viable geographies and the power mix would become very 'windy' without being limited. This could be an interesting modelling exercise, but given our focus on solar PV and its potential growth from further cost reductions, such a flooding of the power mix by wind would mask our area of interest.

Conservative estimates

It is worth noting that the TIAM-Grantham model does not factor in subsidy assumptions or preferential policies for renewable power sources explicitly; to an extent subsidies are factored in to the modelling by the carbon price used as a proxy for general climate policy effort. While subsidies for solar PV are already being phased out in a number of regions as costs fall, this omission in the modelling means in reality more solar PV and wind power capacity would likely be installed than shown in these scenarios, particularly in the short-term.

How do other energy industry projections of solar PV compare?

Figure 4: Installed solar PV capacity projections

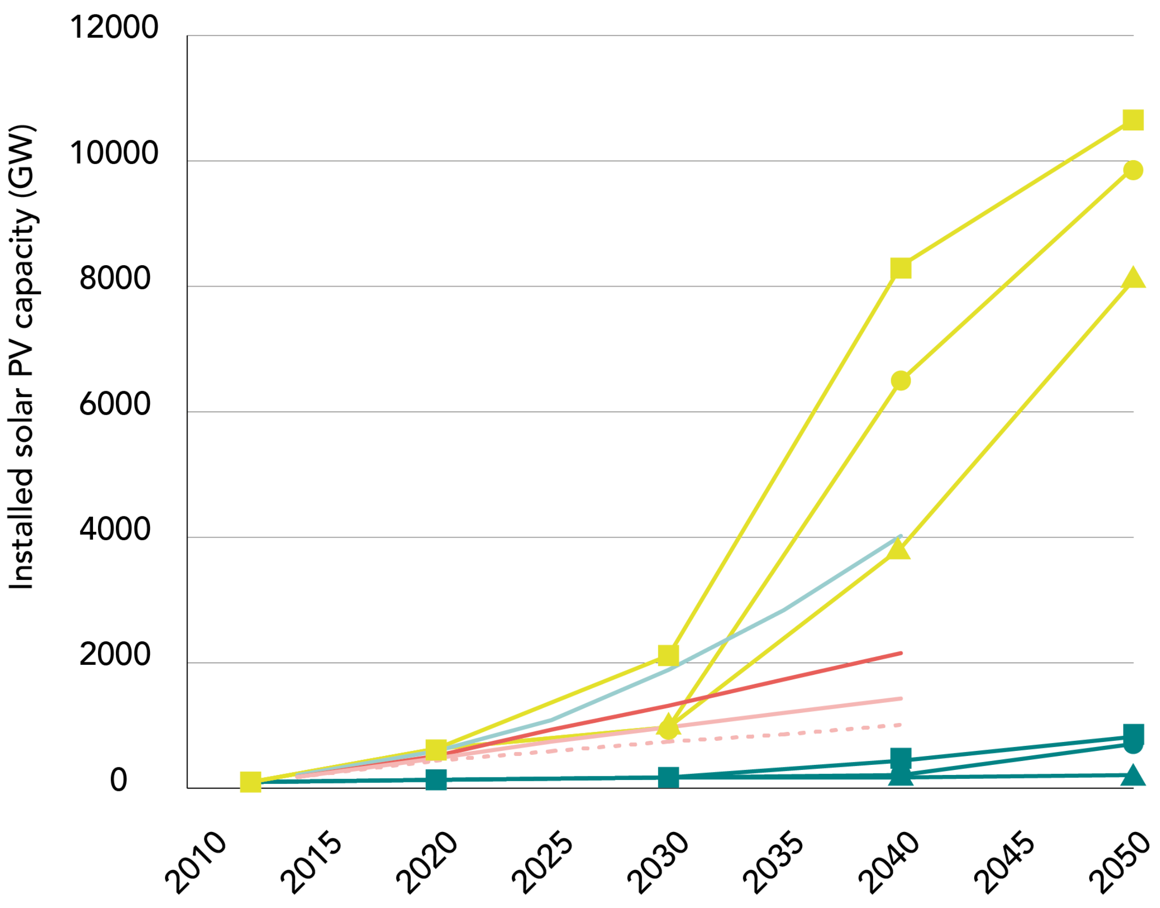
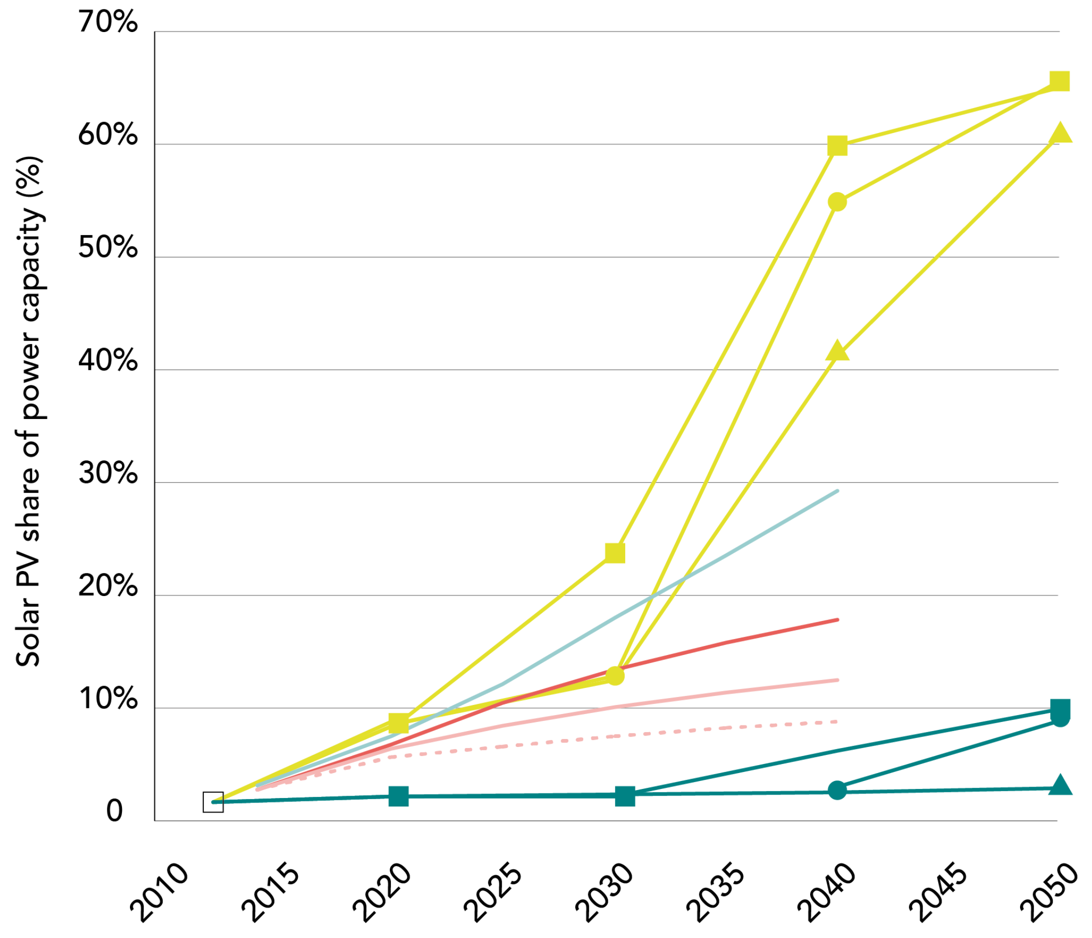


Figure 5: Projections for solar PV share of power market



Sources: IEA World Energy Outlook 2016,
BNEF New Energy Outlook 2016, and CTI-Imperial analysis 2016.[xix]

Earlier in Figure 3 we showed scenario pathways for solar PV in terms of power generation. Figures 4 and 5 explore what this solar PV generation means in terms of the installed capacity supplying this power and how this study's scenarios compare to projections from other institutions.

Outdated BAU scenarios pose risky bet

The capacity charts above reveal a number of trends. They confirm the degree to which the solar market has moved on from the original solar PV costs in TIAM-Grantham set in 2012, ie installed solar PV capacity in these original cost scenarios (**green**) are very conservative compared to the latest scenarios from the IEA and Bloomberg New Energy Finance. This shows why if fossil fuel incumbents use pathways which extrapolate BAU or use outdated assumptions, they conclude the share of solar PV generation will not exceed single digit percentages. Figures 4 and 5 also show that installed solar PV capacity could go substantially higher in the longer term than other scenarios suggest, if solar PV costs fall in line with low-end market projections (**gold**). By 2040 solar PV accounts for between 40% and 60% of global power capacity and by 2050, the solar PV share of capacity is over 60% in all lower PV scenarios, which reflects the continuing roll-out of solar PV in this decade beyond the time period of many existing scenarios.

Potential for fossil fuel asset stranding

To grow to 60% of global power capacity by 2050 will require a huge build-out of solar PV, much of which occurs between 2030 and 2040. Scenario 'NDC_PV' sees solar PV capacity grow by over 5000GW in this 10 year period, for example. Such a rapid deployment of solar PV reflects a shift that could arise when solar PV becomes materially cheaper than alternative power options, and utility and consumer preferences change accordingly. In such a scenario of significant change, the mass stranding of downstream fossil fuel assets is highly likely. After all, it took just an 8% increase in market share for renewables for EU utilities to lose €100bn in value from 2008-2013 and a 10% loss of power market share for the US coal industry to almost collapse entirely.

Transparent reporting of capacity factors is important

The missing link between installed capacity and power generation shown in Figures 3-5 is the 'capacity factor' assumed for solar PV in each scenario, ie the actual power output expressed as a percentage of the maximum output possible for that capacity if operating continuously over a period of time. This means a scenario could project vast amounts of solar PV capacity being installed over time, but with little power generated from it as a result of a low capacity factor assumption. Our scenarios assume a 15%-20% capacity factor for solar PV over the projection period. This is consistent with capacity factors assumed in the IEA's 2016 World Energy Outlook that used a range of capacity factors between 2015-40 of 11%-24% for large-scale solar and 9%-20% for buildings, depending on the region.[xx] It is our contention that modellers must publish the capacity factor assumed to allow the bridge between capacity and generation to be made by those using the information.

What storage is included to adapt the grid to widespread penetration of intermittent power?

Solar power is intermittent in its supply. This poses a challenge in scenarios like ours where solar PV could supply up to 30% of global power generation. Consequently, our scenarios integrate energy storage capacity to mitigate any intermittency. We assume 0.25GW of storage to support each GW of solar PV and wind generation capacity when penetration of renewables exceeds 20% market share. This cost is added to the total system costs for renewables in the model once a high level of penetration is achieved. There are a range of views on the likely level of storage needed to complement solar PV generation, depending on other back-up generation options and demand-side management advances, but our scenarios are realistic and achievable within this context.

What could lower-cost solar PV mean for fossil fuel demand in the power sector?

Figure 6: Comparing projections for coal's share of power generation

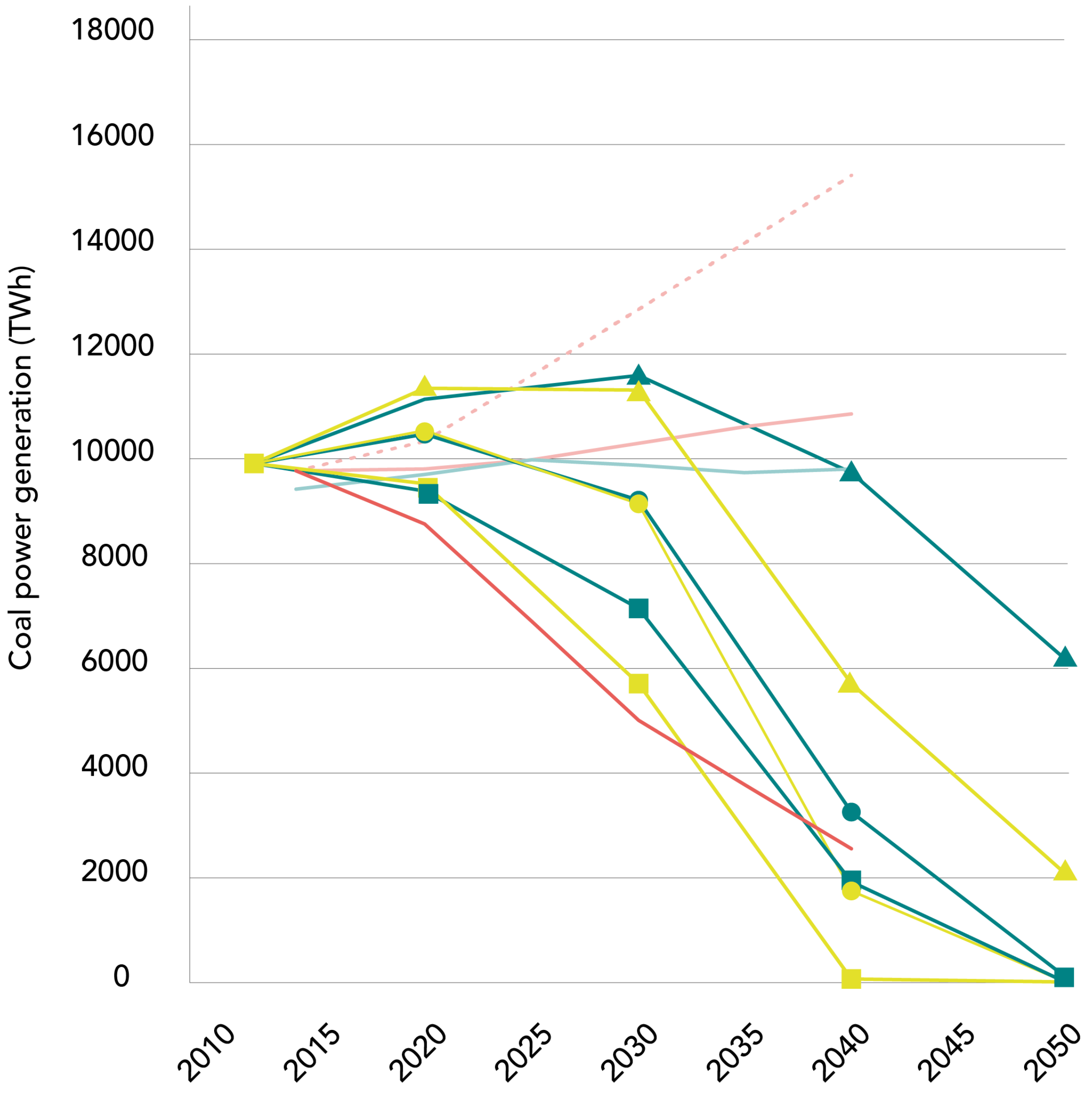
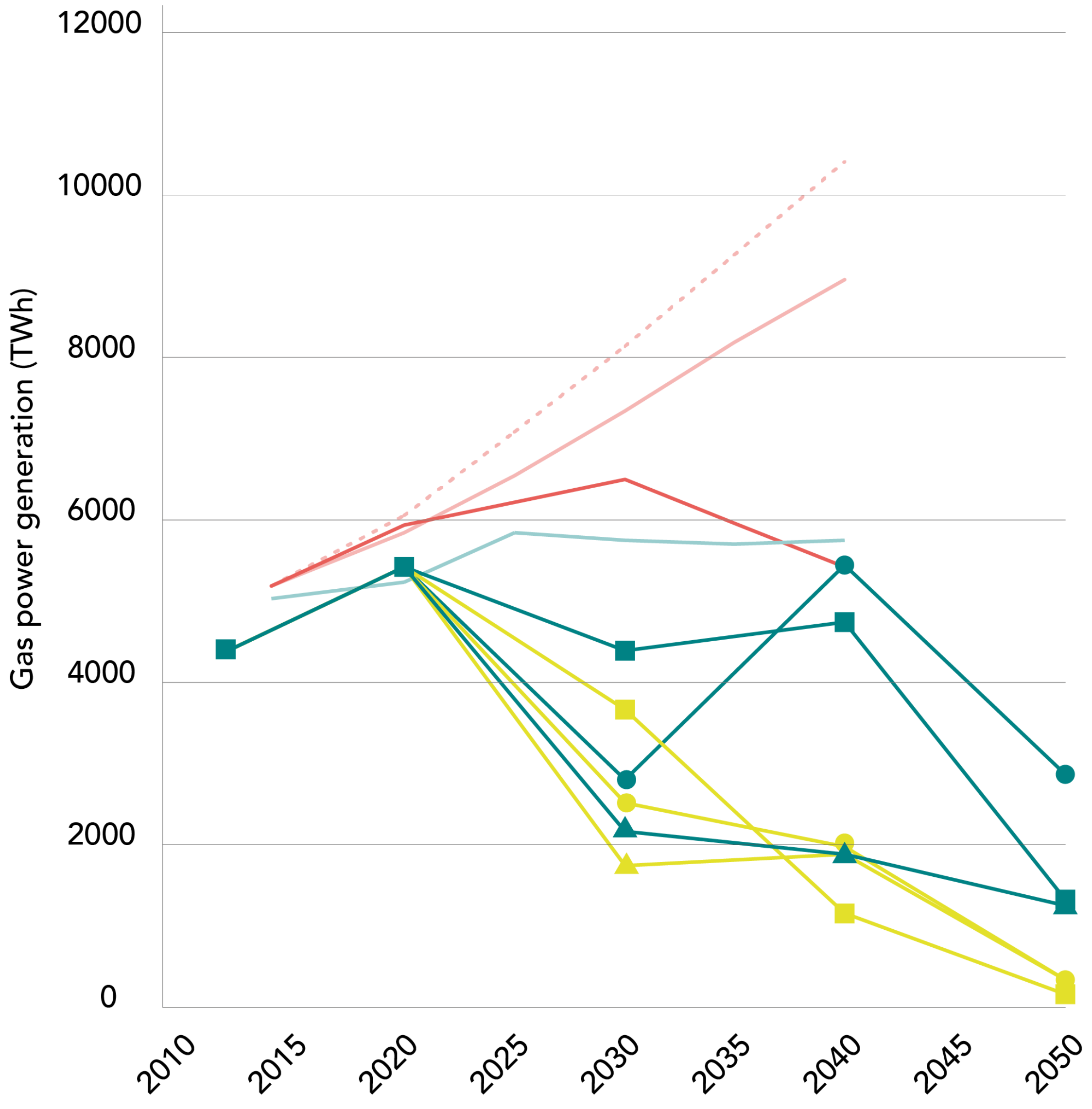


Figure 7: Comparing projections for gas's share of power generation



- ■ Strong_PV
- ● NDC_PV
- ▲ Weak_PV
- ■ Strong_Orig
- ● NDC_Orig
- ▲ Weak_Orig
- — BNEF 2016
- — IEA 450 2016
- — IEA NPS 2016
- ···· IEA CPS 2016

Sources: IEA World Energy Outlook 2016, BNEF New Energy Outlook 2016, and CTI-Imperial analysis 2016.[xxi]

Figures 6 and 7 take a deep-dive on the impact of solar PV costs, combined with an assumed level of climate policy, on fossil fuel demand in our scenarios and compares the results against other energy industry projections.

Coal in decline

Figure 6 shows that coal-fired power generation is heavily exposed to climate policy effort. Under original solar PV cost assumptions (**green**), the NDCs are likely to result in coal-fired power generation peaking in the 2020s. If governments exceed this level of policy effort in the very near-term, this peak occurs prior to 2020 – see 'Strong_Orig'. Lower solar PV costs (**gold**) accelerate the decline of coal, rather than drive it. For example, in scenarios assuming NDC consistent climate policy effort, coal's decline post-2030 is drastic – see 'NDC_PV', while in scenario 'Strong_PV' this significant switch away from coal occurs from 2020 onwards, in a trajectory largely consistent with the IEA's 450 scenario.

Natural gas uncertainty

The black and white nature of least-cost optimising models means they can flip-flop between favoured technologies depending on the cost-competitiveness landscape in that decade. This happens with natural gas-fired power generation in our scenarios – refer to Figure 7. After a small increase in demand to 2020, all our scenarios see natural gas-fired generation declining to 2030. In scenarios with original solar PV costs, this is due to the widespread take-up of biomass as a power source; in lower cost scenarios, solar PV picks up some demand. By 2040, scenario 'NDC_Orig' has stringent enough climate policy for coal demand to collapse, but not to overly penalise natural gas – hence a temporary spike in generation as previously idled plants are brought back online. In scenarios with lower solar PV costs, natural gas-fired power generation continues to decline through to 2050 as it is out-competed. Figure 7 is significant because it demonstrates exactly how bullish industry projections could be for power generation from natural gas. Even considering the drastic demand fluctuations in some original cost scenarios, our set of pathways see natural gas-fired power generation below even BNEF and the IEA's 450 scenario.

The volatility seen in gas generation here could be interpreted to reflect how marginal natural gas options are. This is already the situation in some markets such as Europe where the uncertainty over future carbon, commodity and power prices makes it almost impossible for commercial operators to decide to invest in new gas generation. The signals being sent from some governments regarding the phase out of coal create some opportunities for gas as a transition fuel but as the model shows this may only be a temporary respite, as gas is outcompeted by alternatives soon after, resulting in cripplingly low utilisation rates and asset stranding. Although no carbon budget is in place in these scenarios, this would constitute a further problem for those considering gas as a transition option – if ever-tightening emissions constraints are to be met, then new gas plants would have a very limited lifetime.

The need for scenario analysis

The modelling undertaken shows a clear warning that peak power generation by coal, and even gas, could occur around 2020. This demonstrates why it is important for fossil fuel suppliers to test their business plans for resilience against a range of scenarios, which consider how far and how fast coal or gas demand could fall in the power sector over the next decade.

> *Our set of pathways see natural gas-fired power generation below even BNEF and the IEA's 450 scenario".*

4

What share of road transport could EVs command?

Image via Wikimedia Commons

Over recent years, EVs have gained noteworthy market share in a number of regions. 2015 saw EVs grow beyond one million globally, up from hundreds just 10 years earlier. In the Netherlands, EVs command 10% market share, while in Norway it is up to 23%.[xxii] This is largely the result of government incentives, consumer preferences and falling costs to date. The capital cost of the battery is the main component affecting overall purchase price of EVs. Estimates vary, but according to 2016 research by the US Department of Energy, battery costs have fallen from $1000/kWh in 2008 to $268/kWh in 2015; a 73% reduction in seven years.[xxiii]

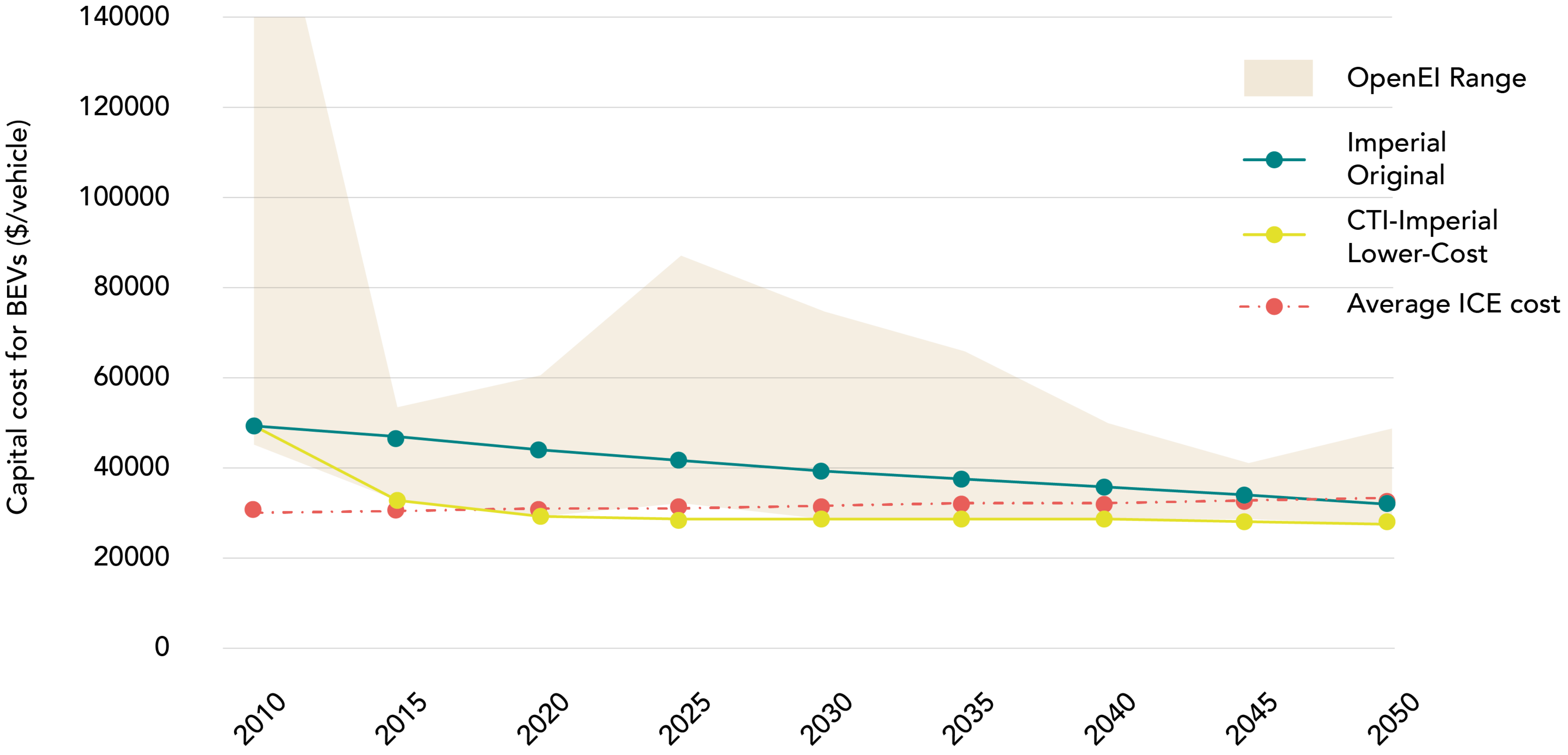
Updating EV cost reduction projections

To analyse the potential growth of EVs, this study compares scenarios applying 'original' costs set in TIAM-Grantham in 2014, and 'lower' cost assumptions, based on latest available data and current market trends. Figure 8 displays these two different cost projections for battery electric vehicles (BEVs) in the context of wider literature in the form of the OpenEI database.

Figure 8: Original and lower capital cost assumptions in this study for battery electric vehicles (BEVs) compared against average costs for Internal Combustion Engine (ICE) vehicles

The chart shows that the original TIAM-Grantham assumption (**green**) was for BEV capital costs to fall steadily to 2050. This is consistent with studies captured by the OpenEI database. Our lower-cost scenario (**gold**), however, takes into account more recent developments and cost reductions in the EV market, such as General Motors claiming that its battery costs have fallen to US$145/kWh since October 2015.[xxiv] In response, EV capital costs were reduced in 2015 compared to original assumptions – refer to Figure 8. Furthermore, it is assumed in the lower-cost scenarios that through maintained R&D and strong investment, the capital cost of BEVs, plug-in hybrids (PHEVs) and hydrogen fuel cell vehicles (FCVs) will reach cost parity with ICEs by 2020. This new EV capital cost level is in line with the low-end of the range supplied by the OpenEI database from 2020 onwards.

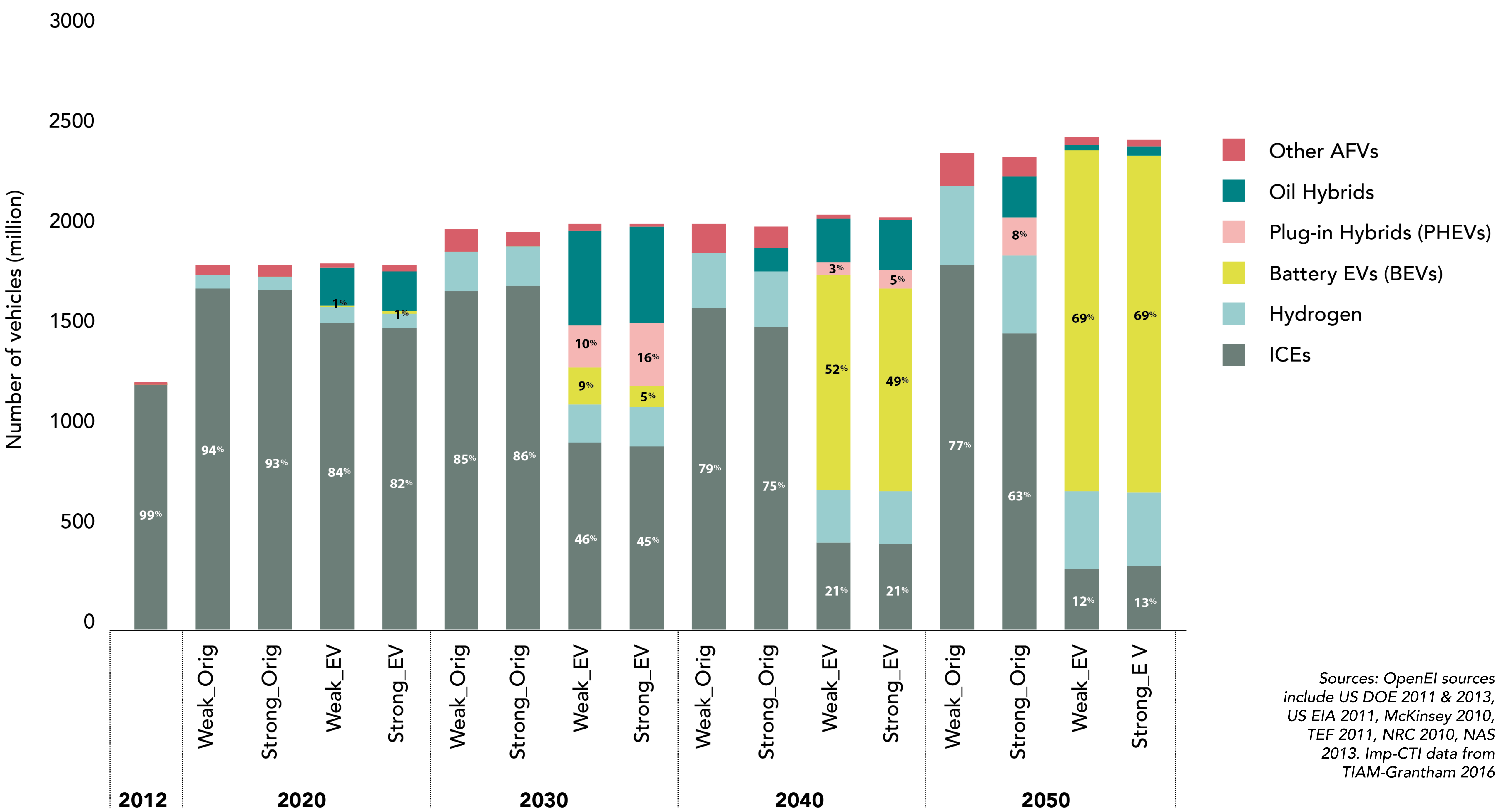
This cost projection is credible given that most studies believe EVs will be cost-competitive with ICEs when battery costs are between $150-300kWh[xxv] and Tesla already claims that batteries will cost as little as US$100/kWh by 2020. Furthermore, Volkswagen asserts that its ID vehicle will be launched in 2020 *'at a price on a par with a comparably powerful and well-equipped Golf'*, and the next batch of EVs available in 2020 will have double or triple the range of the current ones, offering 200-300 miles per charge.[xxvi] There is a growing disparity between the direction being set by the automobile industry and the BAU scenarios being followed by the oil and gas sector. This presents an interesting dilemma for investors with a portfolio covering both sectors as to which eventuality they think will come to pass.



Sources: OpenEI sources include US DOE 2011 & 2013, US EIA 2011, McKinsey 2010, TEF 2011, NRC 2010, NAS 2013. Imp-CTI data from TIAM-Grantham 2016

When could EVs scale-up globally?

***Figure 9: The share of road transport met by different vehicle technologies under original and lower EV costs, and varying climate policy effort*[4]**



Sources: OpenEI sources include US DOE 2011 & 2013, US EIA 2011, McKinsey 2010, TEF 2011, NRC 2010, NAS 2013. Imp-CTI data from TIAM-Grantham 2016

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[4] The scenarios conducted with NDC-consistent levels of climate policy feature in between the 'Weak' and 'Strong' climate policy pathways in terms of the balance between EVs and ICEs. 'Oil hybrid' is defined in the model as an ICE with an electric battery, making it 30% more fuel efficient than conventional ICEs, but it does not have the capacity to plug-in.

EV penetration reliant on cost-competitiveness[5]

Figure 9 shows that penetration of BEVs plus PHEVs is virtually the same whether 'Weak', NDC or 'Strong' climate policy effort is assumed. This represents the fact that in our modelling, EVs are cheaper from 2020 onwards and are selected by the least-cost optimising TIAM-Grantham from then onwards. Any cost penalty incurred by ICEs only increases the cost discrepancy to EVs. This modelling approach explores the potential penetration of EVs when they are the cheapest option available to economically rational consumers. It assumes, therefore, that perceived challenges, such as range anxiety, are overcome and the infrastructure required for high EV penetration is installed. The future demand and use of EVs are not yet known, but if these obstacles are overcome, then there seems potential for a faster switch to EVs from ICEs than thought by many commentators.

EVs are material by 2030

Under original TIAM-Grantham cost assumptions set in 2014, EVs are too expensive to threaten ICEs before 2050. Today, in 2017, we have already seen that cost reductions in EVs have progressed at such a rate that this is not realistic. Nevertheless, under these original cost assumptions, ICEs lose market share to 2030 to hydrogen fuels, principally in the heavy truck and passenger vehicle sub-sectors.

In scenarios applying our lower-cost assumptions, in which EVs achieve cost parity with conventional internal combustion engine vehicles (ICEs) by 2020, EVs take a 19-21% share of the road transport market over the subsequent ten years. To put this in perspective, BP's 2017 energy outlook sees EVs only commanding a 6% (100 million vehicles) share of the market five years later than this in 2035.[xxvii] Along with the emergence of hydrogen fuel and more efficient ICEs with an on-board battery ('oil hybrids'), lower-cost EVs contribute to ICEs losing market share to 45%/46% by 2030. This is less than half the market share of ICEs in 2012 – a drastic turnaround in less than 20 years.

ICEs and EVs trade places by 2050

BEVs are the preferred alternative to ICEs post-2030 in our lower-cost EV scenarios. ICEs and PHEVs lose demand and market share as a result. The split between the types of EV (BEV and PHEV in our classification) varies slightly across the climate policy levels, but overall, EVs occupy over half the road transport market in 2040 and ICEs just a fifth. By 2050, BEVs have saturated the passenger vehicle fleet, which accounts for 69% of the road transport market. ICEs now account for just 12%/13% of vehicles, almost exclusively due to demand in medium-duty vehicles and commercial trucks. These scenarios demonstrate that EVs can trade places with ICEs and go from being a niche player to monopolising the market in just a few decades.

Wrong number

Technological solutions are notoriously hard to predict. Many have missed the mark in the past – for example, McKinsey and Company's 1980 projection of 900,000 mobile phone subscribers by 2000; the number was in fact 109 million. One certainty with scenarios analysis is that most of the scenarios will turn out to be wrong – hence focusing on just BAU is a high risk strategy. That is why it is important to develop a range of scenarios that look to keep ahead of the curve rather than continue playing catch-up.

Mobility revolution

The modelling here does not factor in changes in mobility behaviours, especially where technologies combine to offer alternative transport solutions. If global cities continue to expand and become more densely populated, mobility solutions such as car pooling and autonomous vehicles could boom. This would lead to increased deployment of EVs as the economics of mobility improve under this more intense use of vehicles. Furthermore, air pollution concerns are a factor that favours EVs for new mobility services such as car sharing. Much will depend on key growth regions such as China, which is currently backing EVs strongly and could catalyse global EV growth if it becomes the production centre of the world, much like it did for solar PV.

> *There seems potential for a faster switch to EVs from ICEs than thought by many commentators".*

> *EVs occupy over half the road transport market in 2040 and ICEs just a fifth. By 2050, BEVs have saturated the passenger vehicle fleet".*

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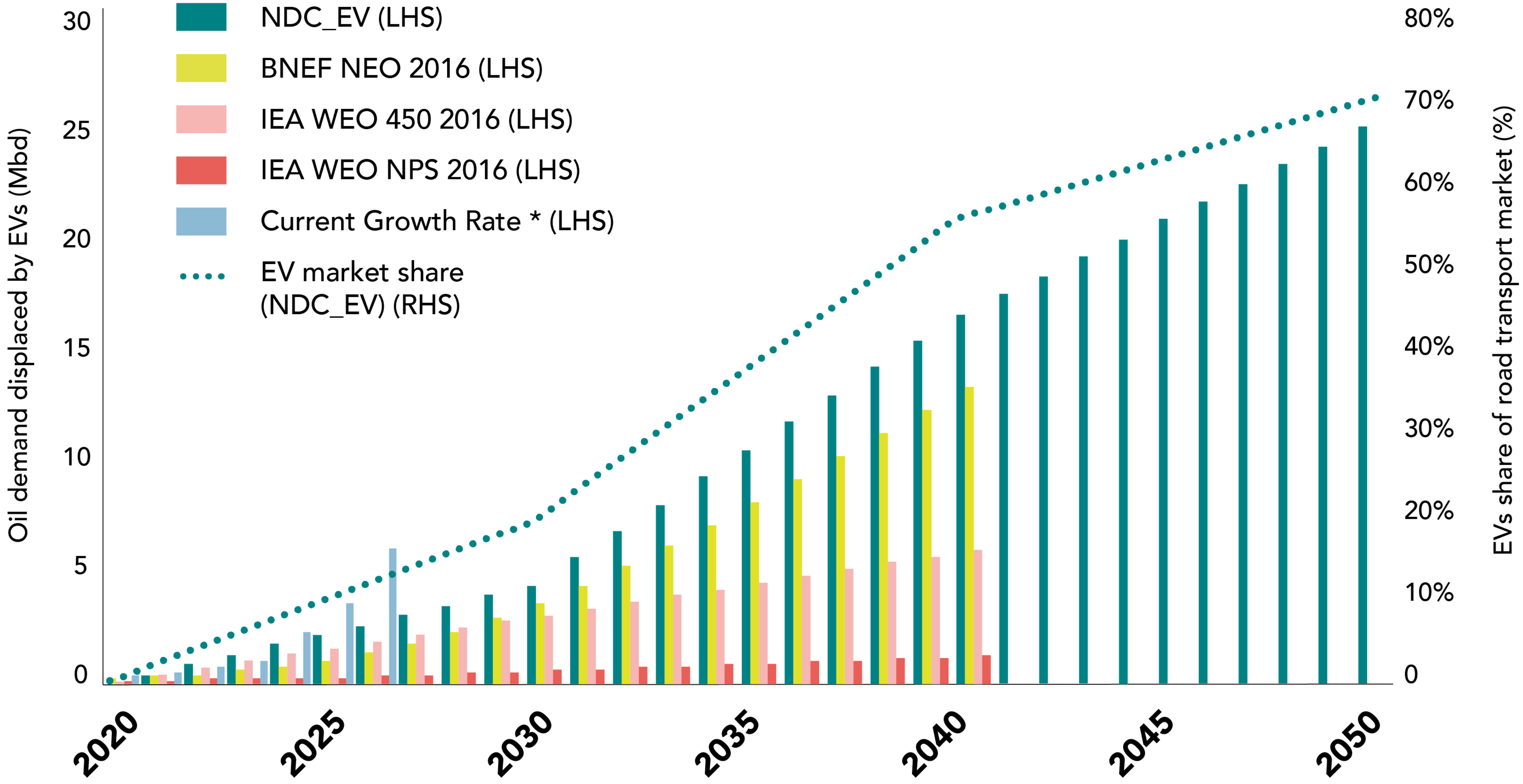
[5] *When the term 'EVs' is used in this study it refers to both plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) cumulatively.*

What could lower-cost EVs mean for oil demand?

Figure 10: Comparing levels of oil demand displaced by EVs across institutional projections[6]



Sources: IEA World Energy Outlook 2016, BNEF New Energy Outlook 2016, and CTI-Imperial analysis 2016.[xxviii]

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[6] ** 'Current Growth Rate' is derived from BNEF and assumes EV sales increase by 60% year on year. Data can be found at: https://www.bloomberg.com/features/2016-ev-oil-crisis/. IEA projections shown in Figure 10 assume linear interpolation between given data points in the 2016 WEO.*

Oil industry behind the curve?

Figure 10 shows that scenario 'NDC_EV', ie the scenario assuming an NDC consistent level of climate policy action combined with lower EV costs, sees 16.4 million barrels of oil per day (mbd) being displaced annually by 2040 due to EV penetration in the road transport sector. By 2050 this figure is 24.6mbd in 'NDC_EV'. This level of oil displacement due to EVs is a little above that from BNEF's 2016 New Energy Outlook (NEO). Both are significantly above the IEA's 2016 New Policies Scenario (NPS) and even the IEA's 2°C (450) scenario that shows EVs could displace six mbd of oil demand by 2040. The fossil fuel industry is equally conservative about the potential for EVs to displace demand for oil; BP's 2017 energy outlook sees 1.2mbd being displaced by switching to EVs by 2035[xxix] and this is after a significance increase from the 2016 outlook that put this figure at 0.7mbd.[xxx]

To put these figures in context, the recent 2014-15 oil price collapse was as a result of a 2% shift in the supply-demand balance, roughly two mbd.[xxxi] The IEA's NPS does not see two mbd of oil being displaced by EVs before 2040. BNEF sees this displacement threshold being surpassed by 2028, while 'NDC_EV' sees two mbd of oil displaced as soon as 2025. Figure 10 also shows the extent to which oil demand would be reduced if EVs maintain current growth rates year on year. This projection shows both how striking recent growth in EVs has been and that scenario 'NDC_EV' is plausible even if the rate of deployment drops off a bit from current levels.

An obvious question is how long the EV market can sustain its current 60% year-on-year growth rate. It is always difficult to tell exactly what stage of growth a technology is at and the strength of the forces driving it, but looking back at the adoption of colour TV, and then High Definition TV, provides a couple of examples of where a 'better' product that provides a similar service has quickly monopolised a market.

What do these calculations assume?

There are a number of variables that determine the level of oil demand displaced by EVs. Of course, the number of EVs on the road is a key determinant - our 'NDC_EV' scenario sees 1.1 billion EVs in the global vehicle fleet by 2040, compared to 150 million in the IEA NPS. Equally significant is the assumption of how much these EVs are used. This is a big unknown. One might assume that new vehicles are used more, or perhaps that EVs are used more in cities than rural areas where air quality concerns are higher. Equally significant is the assumed lifetime for each vehicle type – this study assumes a 12.5 year lifetime for passenger vehicles. All together this determines the level of total EV demand, which is divided by the assumed efficiency of the equivalent ICE vehicle type it is replacing, to give the oil demand displaced.

Getting on the same page

With there being so many moving parts when referring to EVs and their potential impact on future oil demand, it is important all assumptions are disclosed to allow comparisons such as in Figure 10 to be conducted as accurately as possible. Currently, this is not the case. Different energy institutions, and the oil and gas companies, often cite different variables, eg projections of the number of EVs; percentage growth rates of EVs; or the percentage of new car sales being EVs. Often, simply by omitting reference points such as the starting number of EVs or total fleet sizes at relevant dates, it is very hard to compare the different projections and scenarios. With EVs attracting ever greater attention as cost parity to ICEs nears, modellers must fully disclose assumptions in a consistent manner to inform interested parties – see the Appendix.

EVs are climate change mitigators

A typical concern is that growth of EVs might not constitute a path to CO_2 emissions mitigation if the power to drive them is from fossil fuels. Our calculations indicate that for EVs to result in fewer emissions than ICEs today, the power supply charging them must emit less than 720gCO_2 per kWh, factoring in any subsequent uplift in power demand.[7] Countries such as Norway, Canada and Brazil, with large amounts of hydropower, or France, with significant nuclear power, are already below 200gCO_2/kWh, whilst China is probably at a marginal point, but is set to decarbonise its power mix through its 13th Five Year Plan.

It is also likely that countries aiming to decarbonise are typically tackling both the power and transport sectors. Going forward the synergy between EVs as storage options and renewable power could further drive the simultaneous roll out of the two. By 2020 the emissions mitigation threshold will increase to 800gCO_2/kWh due to increasing EV efficiency. By 2050, it will be 960gCO_2/kWh, all the while the global power sector is expected to continue decarbonising. As such, scenarios like 'NDC_EV' that see over a billion EVs on the road by 2050, mitigate 3.3GtCO_2 annually by this date compared to an all ICE fleet.

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[7] *This is largely consistent with the view of the IEA that put this threshold at 700gCO_2/kWh. See page 14, EV Outlook 2016 - https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf*

5

What impact can solar PV and EVs have on global demand for coal, oil and gas?

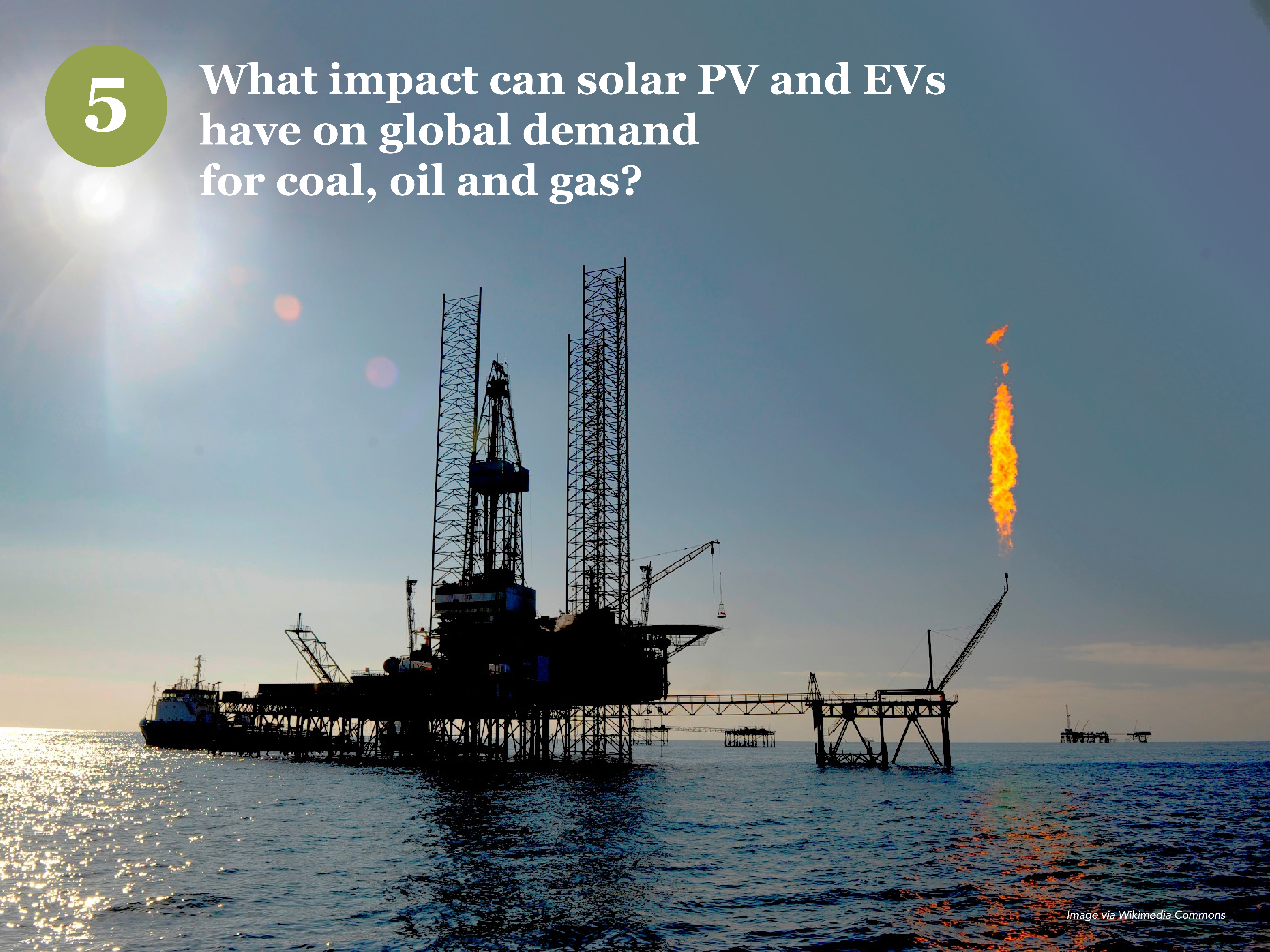
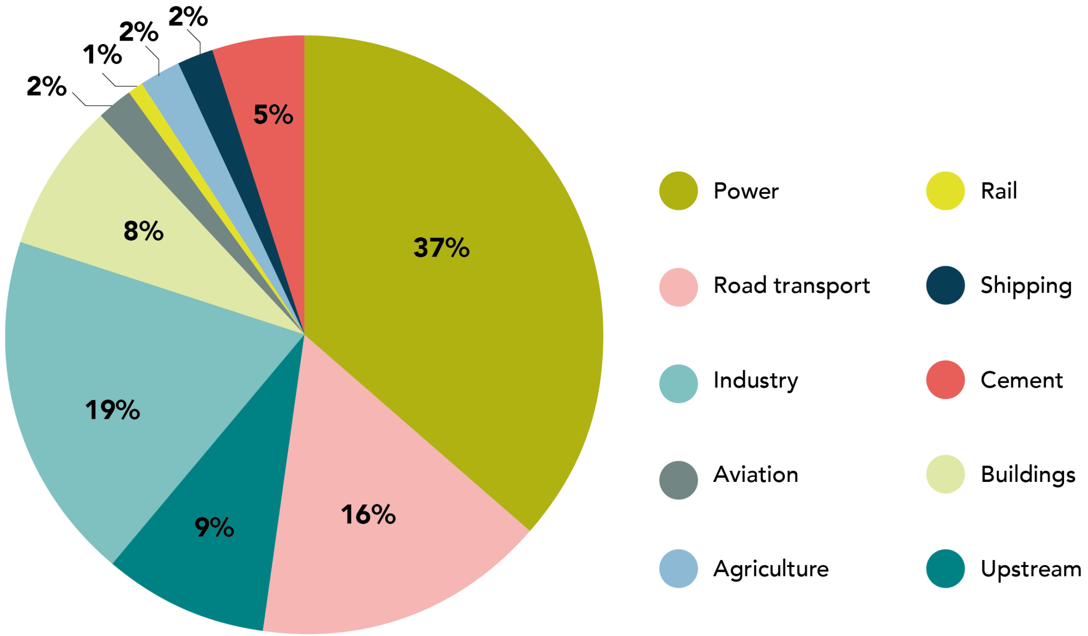


Image via Wikimedia Commons

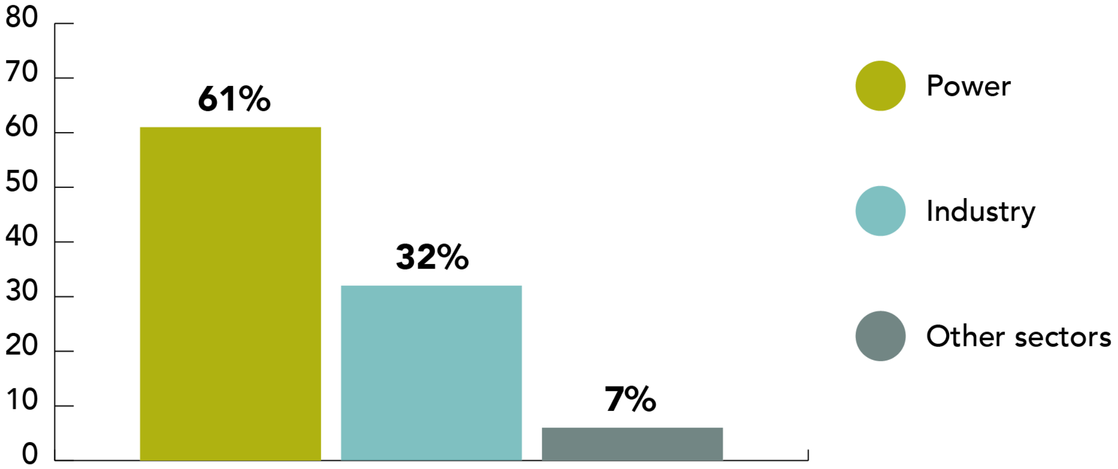
So far this report has explored the potential impact of lower-cost solar PV and EVs on the power and road transport sectors specifically. This section looks at how these cost assumptions, and subsequent penetration, translate into changes in total primary energy demand for coal, oil and gas. In doing so, it's important to remember that our lower-cost scenarios focus on technologies in just the power and road transport sectors, which account for around 61% of coal consumption, 51% of oil consumption and 46% of gas consumption today – refer Figures 12-14 – or, alternatively, 51% of global CO_2 emissions – refer Figure 11. If similar technology innovation and cost reduction phenomena occurred across the whole energy system, then it follows that downwards pressure on primary fossil fuel demand and emissions could be significantly greater than in this study's scenarios. This is a key area for further research.

Figure 11: The power and road transport sectors account for 51% of CO_2 emissions in 2012



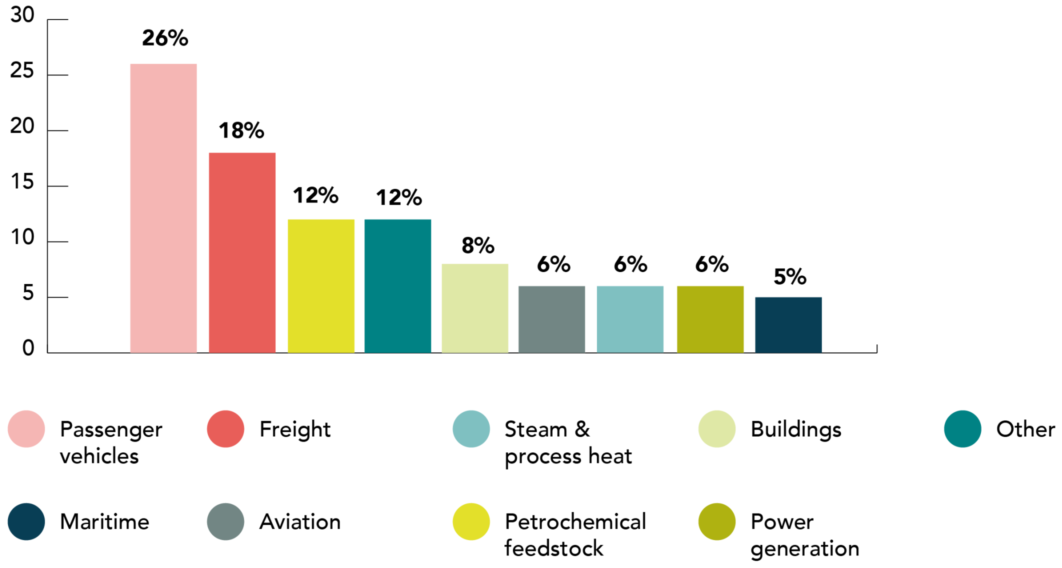
Source: TIAM-Grantham

Figure 12: Global coal consumption by sector (2014)



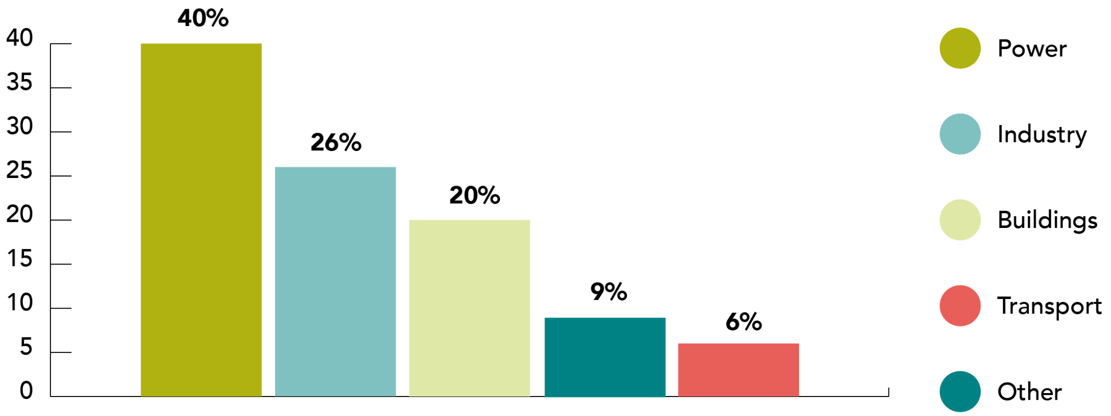
Source: IEA WEO 2016

Figure 13: Global oil consumption by sub-sector (2015)



Source: IEA WEO 2016

Figure 14: Global gas consumption by sector (2014)



Source: IEA WEO 2016

When could peak coal, oil and gas demand occur?

Figure 15 shows primary energy demand for total fossil fuels and coal, oil and gas separately. At this stage, we also draw on climate policy and energy demand sensitivities that impact across all sectors in TIAM-Grantham, not just power and road transport, resulting in upside and downside fossil fuel demand against our 'NDC_PV_EV' scenario. Underlying these charts are some complex interactions between sectors, as declines in demand for a fuel in the road transport or power sector can sometimes lead to an uplift in other sectors. These rebounds highlight why it is important to use full energy system models for scenario analysis and the need for coordinated, system-wide decarbonisation efforts if we are to hit climate goals, rather than target sectors in isolation.

Decarbonisation of part of the energy system still has big impacts

Figure 15a shows total fossil fuel demand in scenarios ranging from the most fossil fuel intensive in our set, 'NDC_PV_EV_High', to the least fossil fuel intensive, 'Strong_PV_EV_Low'. The chart shows exactly how significant the 2015 Paris Agreement could be – climate policy effort consistent with the NDCs sees total fossil fuel demand peaking in 2030 even with original technology cost assumptions ('NDC_Orig'). Applying lower-cost solar PV and EV assumptions instead results in an 11% reduction in fossil fuel demand against this scenario by 2050 ('NDC_PV_EV'). Reduced energy demand serves to accentuate the decline after the 2030 peak even more. Any policy effort beyond the NDCs – 'Strong_PV_EV_Low' for example – could result in global fossil fuel demand peaking in 2020 and subsequent CO_2 emissions taking a much lower trajectory.

In fact, even when assuming higher energy demand levels, driven through higher global economic growth assumptions ('NDC_PV_EV_High'), it appears that overall fossil fuel demand would still plateau from 2030 onwards. It is worth noting, however, that recent OECD economic growth forecasts[xxxii] suggest the world economy is on a growth path to 2050 which is somewhere between the levels assumed in our medium and lower energy demand scenarios, a far cry from the level in the higher demand scenario.

BAU assumptions not playing out

These fossil fuel demand charts reinforce the message that BAU, ie scenarios which translate into an extrapolation of continued growth for all fossil fuels, are not reflective of the current state of play in terms of climate policy direction and low-carbon technological advances. This means that to justify BAU scenarios there would need to be backward movement in either sphere. As long as major regions of the world continue to drive forward investment in low-carbon technologies, subsequent cost reductions are likely to be felt around the world, with basic economics driving higher penetration.

The recent announcement by China of at least $360bn of investment into renewable energy sends a signal that they see an opportunity in the low-carbon transition and that others should follow.[xxxiii]

Coal demand peaks in 2020

The demise of coal demand forms a big part of the trends in total fossil fuel demand described above. In all scenarios assuming NDC levels of climate policy or more, global coal demand peaks in 2020. With lower solar PV and EV costs, coal demand in 2050 is 50% lower than 2012 levels, marking a sector in major decline – see 'NDC_PV_EV'. Trends in today's coal market, however, suggest that more bullish low-carbon scenarios might more accurately reflect future coal demand. Coal demand stalled in 2015 and is projected to do so until 2021 by the IEA.[xxxiv] This is directly in accordance with scenario 'Strong_PV_EV_Low' – refer Figure 15b – a scenario in which short-term coal demand falls far more quickly than prescribed in any of our NDC consistent scenarios.

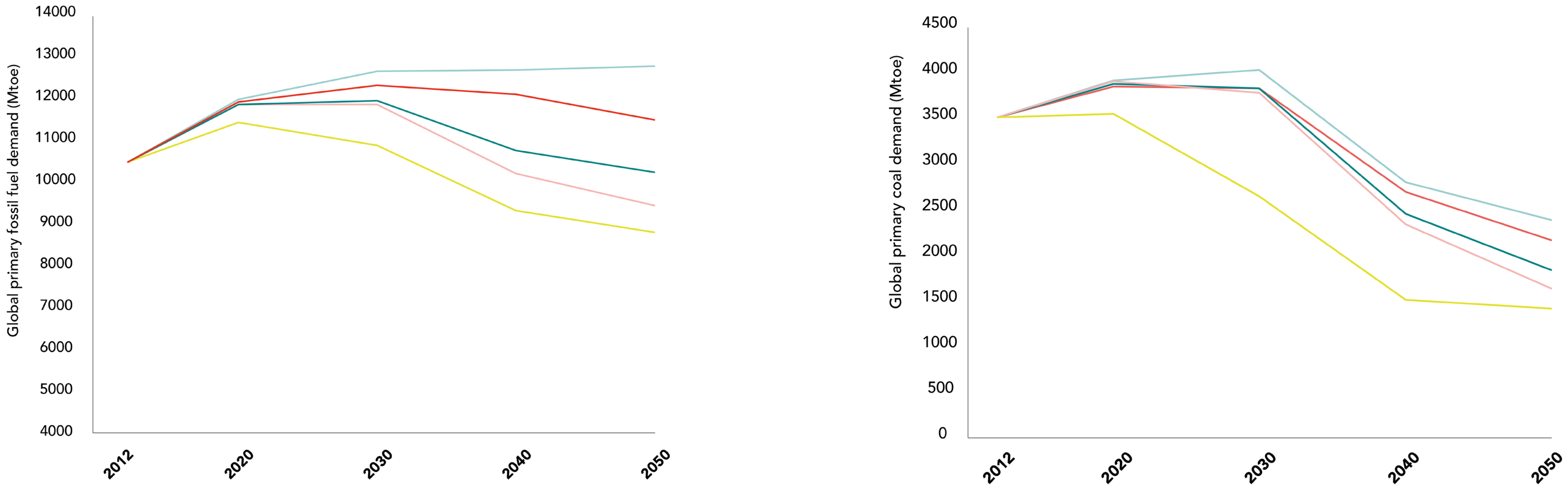
Oil demand peaks in 2020

The impact of widespread EV penetration on global oil demand shown in Figure 15c is profound. Under original EV cost assumptions and NDC levels of climate policy, global oil demand peaks in 2030 after relatively strong growth from 2012 – see 'NDC_Orig'. With our lower EV cost assumptions instead, oil demand peaks in 2020 and plateaus for 10 years at a level 10% lower than under original cost assumptions – see 'NDC_PV_EV'. From 2030-2050, oil demand falls steadily in all scenarios, even those under high energy demand assumptions. Figure 15c confirms the potential impact on global oil demand from EVs, which, to date, continue to see faster cost reductions than most expected.[xxxv] This shows why the debate has recently shifted to peak oil demand, rather than peak oil supply.

Gas demand grows to varying degrees

Integrated assessment models such as TIAM-Grantham tend to position natural gas as a transition fuel when no CO_2 emissions constraints are put in place, like in our scenarios. This means the decline of coal is, to a degree, substituted with natural gas, such as in scenario 'NDC_Orig' – refer to Figure 15d. When lower solar PV costs are applied, gas demand growth is lower – refer scenario 'NDC_PV_EV'. In such a scenario, however, lower power sector usage of gas can also reduce the cost of using it in industry or heating buildings, which may rise to compensate overall gas demand somewhat. Lower energy demand reduces natural gas demand growth across all sectors, but it is only in our most bullish 'Strong_PV_EV_Low' scenario that we see natural gas demand peak in 2030 and fall thereafter. These findings reiterate the need for holistic climate policy and low-carbon technological progress that challenges the full spectrum of fossil fuel consuming sectors and not just the low hanging fruit. In essence, the degree to which natural gas demand grows or not to 2050 could be one of the key factors that determine whether we achieve the 2°C target.

Figure 15: Global energy demand for

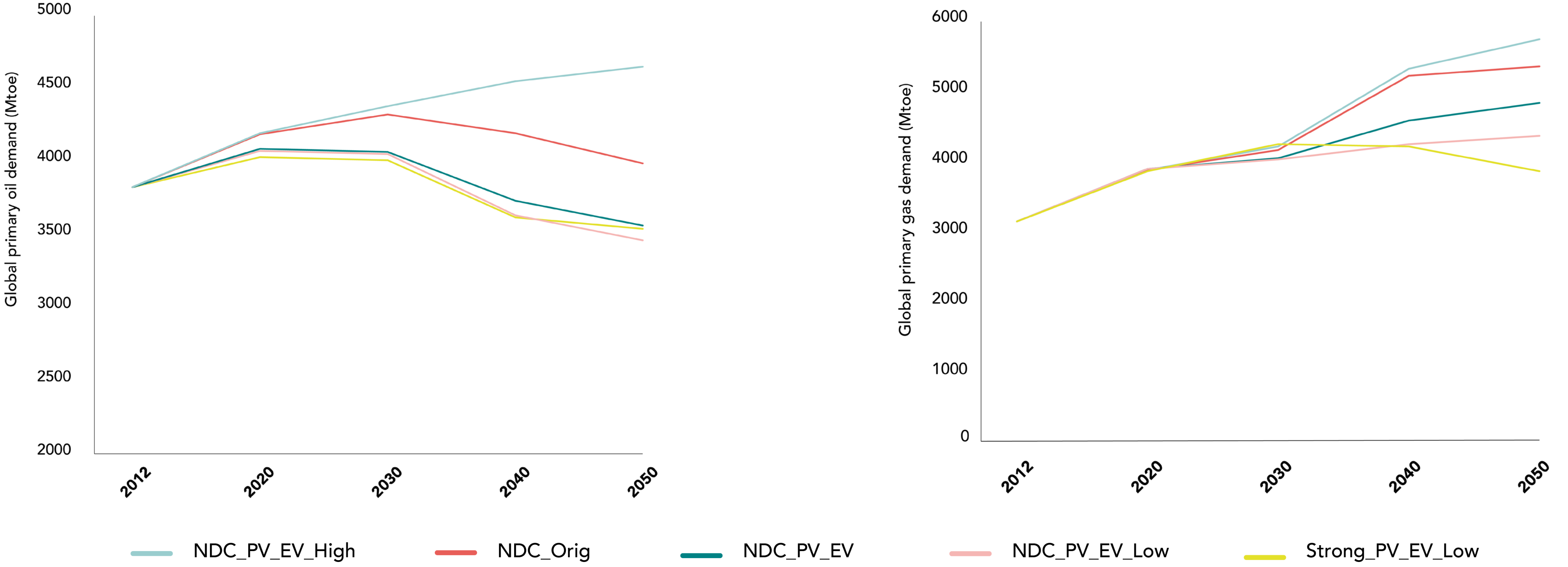


a) total fossil fuels

b) coal

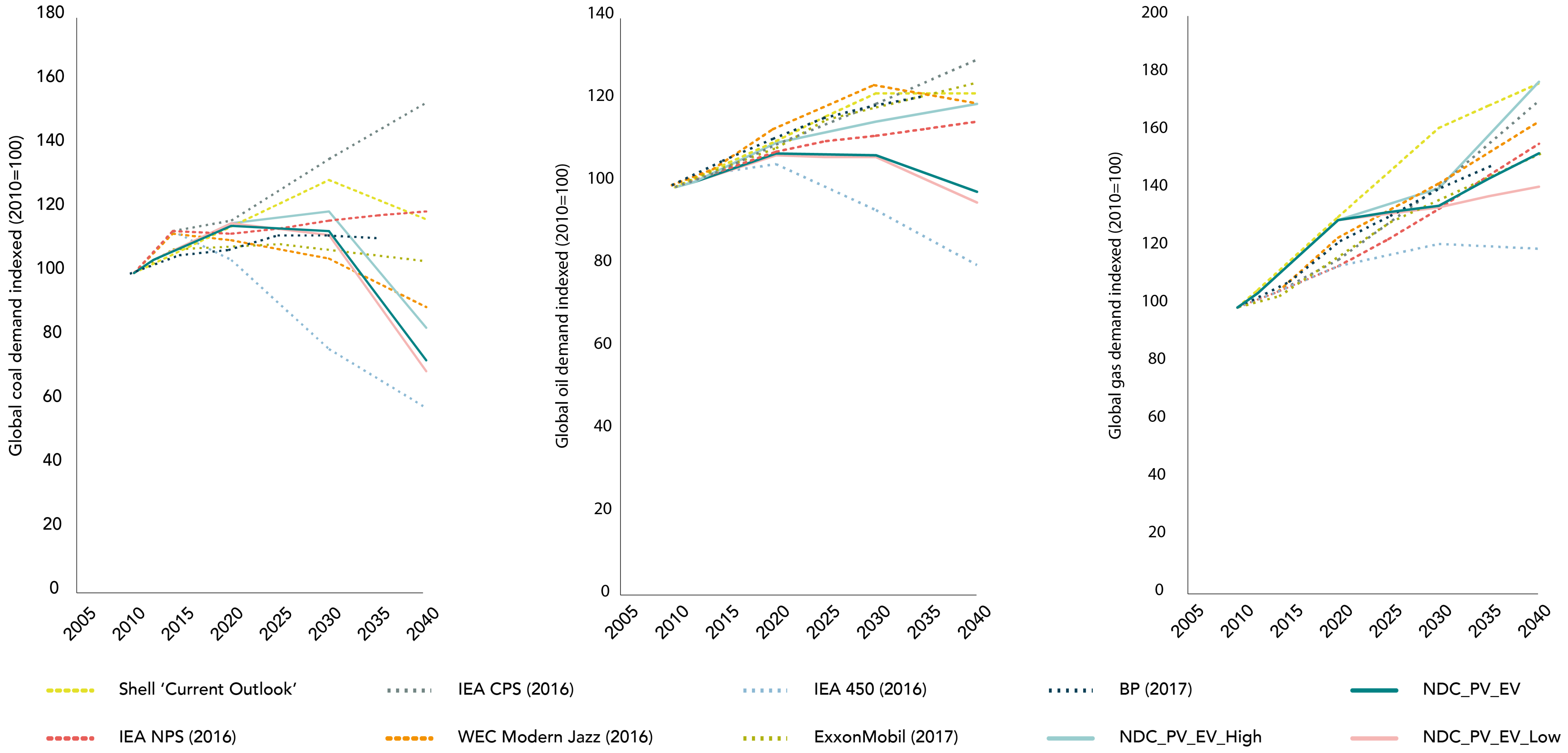
c) oil

d) gas



What does the energy industry say about coal,oil and gas demand?

Figure 16: Energy industry projections for a) coal; b) oil; and c) gas demand diverge from our scenarios when the power and road transport sectors are decarbonised[8]



Source: Royal Dutch Shell 2014, IEA World Energy Outlook 2016, ExxonMobil Energy Outlook 2017, BP Energy Outlook 2017, CTI-Imperial analysis 2016.[xxxvi]

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[8] *Shell's 'Current Outlook' refers to the projection presented by Shell in an investor note on the carbon bubble and stranded assets, available at: https://s02.static-shell.com/content/dam/shell-new/local/corporate/corporate/downloads/pdf/investor/presentations/2014/sri-web-response-climate-change-may14.pdf. This scenario was described by Shell as 'our current outlook for global energy demand until 2050'.*

Figure 16 compares coal, oil and gas demand in our 'NDC_PV_EV' scenario against projections from the energy and oil and gas industry. On the whole, industry projects stronger fossil fuel demand than this scenario, even though it only focuses on low-carbon technologies in the road transport and power sectors, which account for over half of total fossil fuel demand. Figure 16 shows the need for the energy industry to reevaluate its scenarios and give greater weight to lower future coal, oil and gas demand.

Significant downside potential for coal demand

Industry projections show little consensus on when peak coal demand may occur globally – refer to Figure 16a. The IEA's NPS does not see peak coal occurring before 2040, while Shell and BP put peak coal demand occurring around 2030 after strong growth and ExxonMobil is five years earlier around 2025. Scenario 'NDC_PV_EV' projects peak coal demand to occur in 2020, before deep cuts from 2030-2040. Higher or lower energy demand sensitivities result in relatively little change around this scenario, which we argue is now the minimum that should be expected in terms of future policy and technology pathways. Current trends suggest future coal demand could in fact plateau over the next five years; a pathway shown in Figure 15b to be consistent with scenario 'Strong_PV_EV_Low'. As such, the downside potential on fossil fuel industry projections is even greater than that suggested by Figure 16a.

At odds over oil demand

Figure 16b shows our scenarios diverge noticeably from those of the oil and gas industry post-2020, ie when EVs become cost-competitive with ICEs. No oil and gas company sees peak oil demand occurring within current forecast periods to 2040. Lower EV costs result in oil demand peaking around 2020 in the 'NDC_PV_EV' scenario, well on the way to achieving the 450 scenario if decarbonisation progress is made in other oil consuming sectors. This divergence is the direct result of the oil and gas industry's pessimism on the potential growth of EVs. For example, BP projects 100 million EVs on the road by 2035[xxxvii], compared to say the *IEA 450* which puts that figure at 450 million.[xxxviii] Of course this leads BP to conclude that reduced oil demand from EVs will not be 'game-changing'.[xxxix] ExxonMobil takes a similar stance in its 2017 Outlook stating that PHEVs and BEVs will account for 'less than 10% of new car sales in 2040'.[xl] Oil and gas industry expectations of oil demand exceed even our higher energy demand scenario, which assumes 4.3% average annual GDP growth to 2050, an assumption that looks exceptionally bullish in light of the latest forecast from the OECD that foresees long-term, annual economic growth of 2.9%.[xli] This is lower than the 3.1% average annual GDP growth assumed in our medium energy demand scenarios, suggesting even our new starting point, scenario 'NDC_PV_EV', could be on the upside in terms of oil demand (and coal and gas demand for that matter).

Lower energy demand crucial to curbing gas demand

As shown in Figure 15d earlier, gas demand is very much the marginal energy source in integrated assessment models. As such, gas demand growth in the 'NDC_PV_EV' scenario is strong to 2020 before falling broadly in line with the IEA's NPS. Lower energy demand curtails post-2030 growth somewhat. Figure 16d shows that the oil and gas industry is largely consistent with our higher demand, 'NDC_PV_EV_High' scenario, which as explained above, is based on aggressive economic growth assumptions.

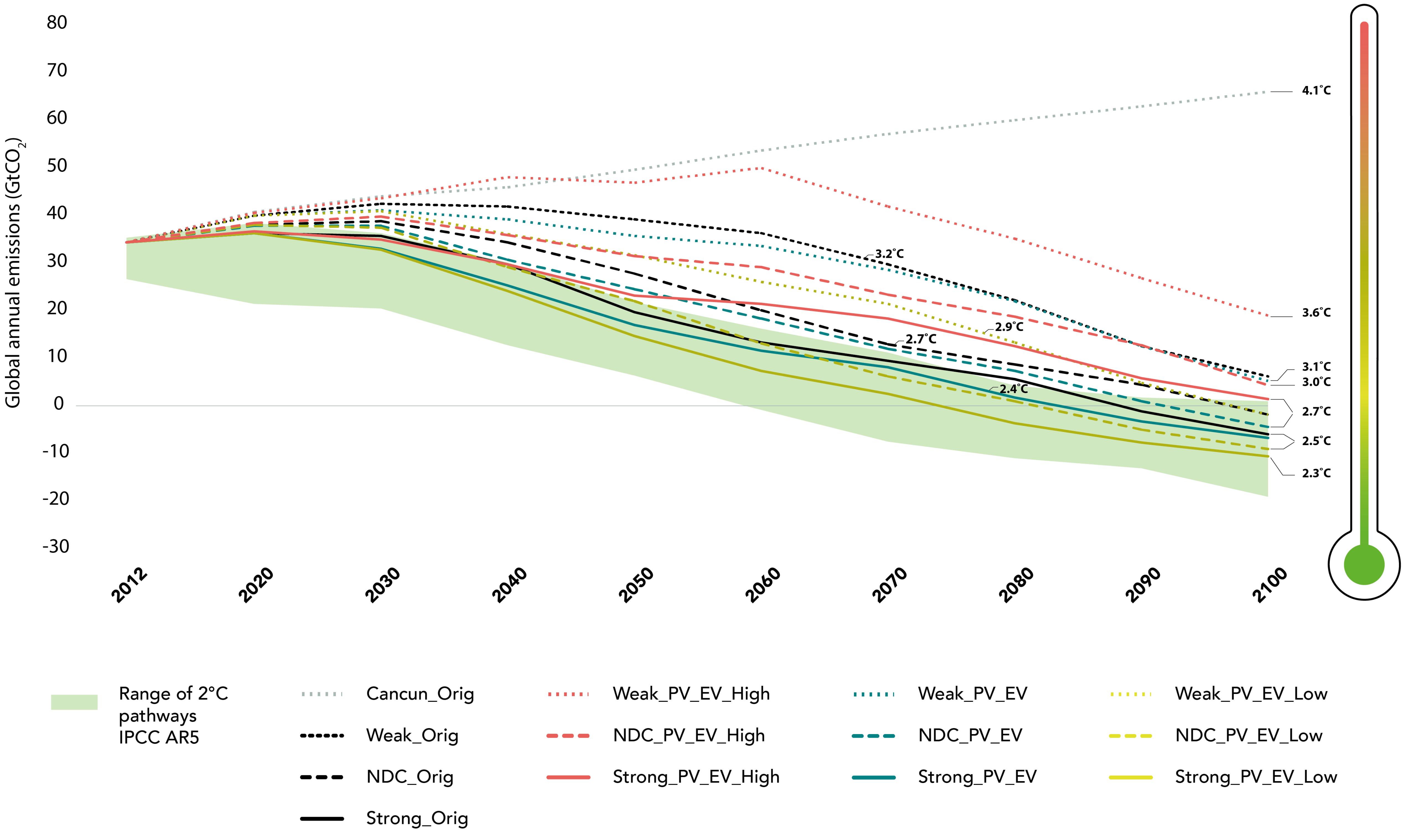
> *Current trends suggest future coal demand could plateau over the next five years...suggesting the downside potential on fossil fuel industry projections is greater than in Figure 16a".*

6

What contribution can accelerated solar PV and EV penetration make to achieving a 2°C target?

Image via Wikimedia Commons

Figure 17: Annual CO_2 emissions in each scenario featured in this report and implied average temperature increases assuming 66% probability[9],[10]



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[9] The range of 2°C pathways is sourced from the IPCC AR5 database covering emissions from fossil fuel combustion and industrial processes only. The range comprises high and low emissions' levels for each decade from the integrated assessment models in the database. Four of the 52 2°C scenarios were excluded as outliers, so the range covers the 4%-96% percentiles.

[10] The classification of CO_2 emissions for scenarios produced in this study includes those from fossil fuel combustion and industrial processes only.

Table 1: Temperature outcomes across our scenarios in terms of 50% probability and 66% probability

Temperature Increase, 2012-2100 (°C)			**Temperature Increase, 2012-2100 (°C)**			**Temperature Increase, 2012-2100 (°C)**		
Scenario	*50% probability*	*66% probability*	*Scenario*	*50% probability*	*66% probability*	*Scenario*	*50% probability*	*66% probability*
Weak_Orig	*2.87*	*3.18*	*NDC_Orig*	*2.47*	*2.74**	*Strong_Orig*	*2.29*	*2.54*
Weak_PV_EV	*2.81*	*3.11*	*NDC_PV_EV*	*2.39*	*2.65*	*Strong_PV_EV*	*2.20*	*2.44*
Weak_PV_EV_Low	*2.61*	*2.89*	*NDC_PV_EV_Low*	*2.25*	*2.49*	*Strong_PV_EV_Low*	*2.08*	*2.30*
Weak_PV_EV_High	*3.23*	*3.57*	*NDC_PV_EV_High*	*2.70*	*2.99*	*Strong_PV_EV_High*	*2.47*	*2.74*

** This is consistent with estimates from the IEA and Climate Action Tracker - http://climateactiontracker.org/news/224/indcs-lower-projected-warming-to-2.7c-significant-progress-but-still-above-2c-.html; although of course there is variation in estimates - http://www.wri.org/blog/2015/11/insider-why-are-indc-studies-reaching-different-temperature-estimates*

Figure 17 shows annual CO_2 emissions for each of the scenarios in this study, along with average temperature increase values as calculated by the UK Met Office, to look at the potential contribution that penetration of solar PV and EVs can make towards achieving climate targets. In Figure 17, the temperature readings assume a 66% probability of achieving that outcome to be consistent with the approach of the Intergovernmental Panel on Climate Change (IPCC). Table 1 also shows the temperature outcomes for selected scenarios if a 50% probability is assumed, as per the IEA. The results show that:

- The direction of travel is firmly that global CO_2 emissions will decline in the short- to medium-term. Aside from one high energy demand scenario (that assumes very strong global economic growth) and an obsolete 'BAU' scenario ('Cancun_Orig'), all scenarios see peak CO_2 emissions occur in 2030 or earlier.
- In scenario 'NDC_PV_EV', in which lower solar PV and EV costs are achieved alongside global climate related policies set to achieve the sum total of countries' NDCs by 2030 and make moderate policy progress thereafter, global average temperatures increase by between 2.39°C (50% probability) and 2.65°C (66% probability) to 2100.
- Delivering the outcome in the 'NDC_PV_EV' scenario is contingent on governments delivering on their NDCs and continued effort thereafter, as well as continued R&D and capital flowing towards solar PV and EV to deliver on the optimism of current cost deflation trajectories. The 'Weak' policy effort and high energy demand sensitivities in Figure 17 reflect scenarios in which technology and policy progress under-delivers on the levels assumed in 'NDC_PV_EV', and higher CO_2 emissions result.
- However, global CO_2 emissions could very well be lower than 'NDC_PV_EV'. If nations exceed the policy effort outlined in NDCs, as well as lower solar PV and EVs costs, average global temperature increase lowers to between 2.20°C and 2.44°C to 2100 – see 'Strong_PV_EV'. A further 0.1°C is saved if global energy demand is lower than the central growth scenario.
- The scenarios we believe are the most realistic and informative are significantly lower than the 3.72°C/4.12°C (50%/66%) temperature increase in the most CO_2 intense scenario, 'Cancun_Orig', which would typically reflect the BAU case in a study like this. We have included this scenario in Figure 17 to show how much it differs from a starting point that reflects the current direction of travel like 'NDC_PV_EV'.

Whilst at first it may appear small change to be dealing in terms of 0.1 degree Celsius changes in outcome, in fact each tenth of a degree could be very significant in terms of the level of resulting climate impacts. The natural tendency is to think in terms of whole degrees, but once BAU is dismissed, the range of possible temperature outcomes resulting from significant changes in assumptions shrinks considerably, making it incredibly valuable to understand where each of these gains can come from.

2°C: a range of possibilities

Instead of referring to just one possible 2°C pathway, Figure 17 includes the emissions trajectories for a range of 2°C scenarios from the IPCC AR5 database (shaded green). This approach demonstrates that the 2°C target can be achieved through a vast array of pathways, each keeping to the finite 2°C carbon budget - approximately 1000$GtCO_2$ from fossil fuel combustion and industry from 2011-2100, assuming a 66% probability.[xliix] In essence, scenarios that achieve deeper CO_2 emissions cuts pre-2050 are not required to achieve as much mitigation post-2050, relative to other 2°C possibilities. And vice versa.

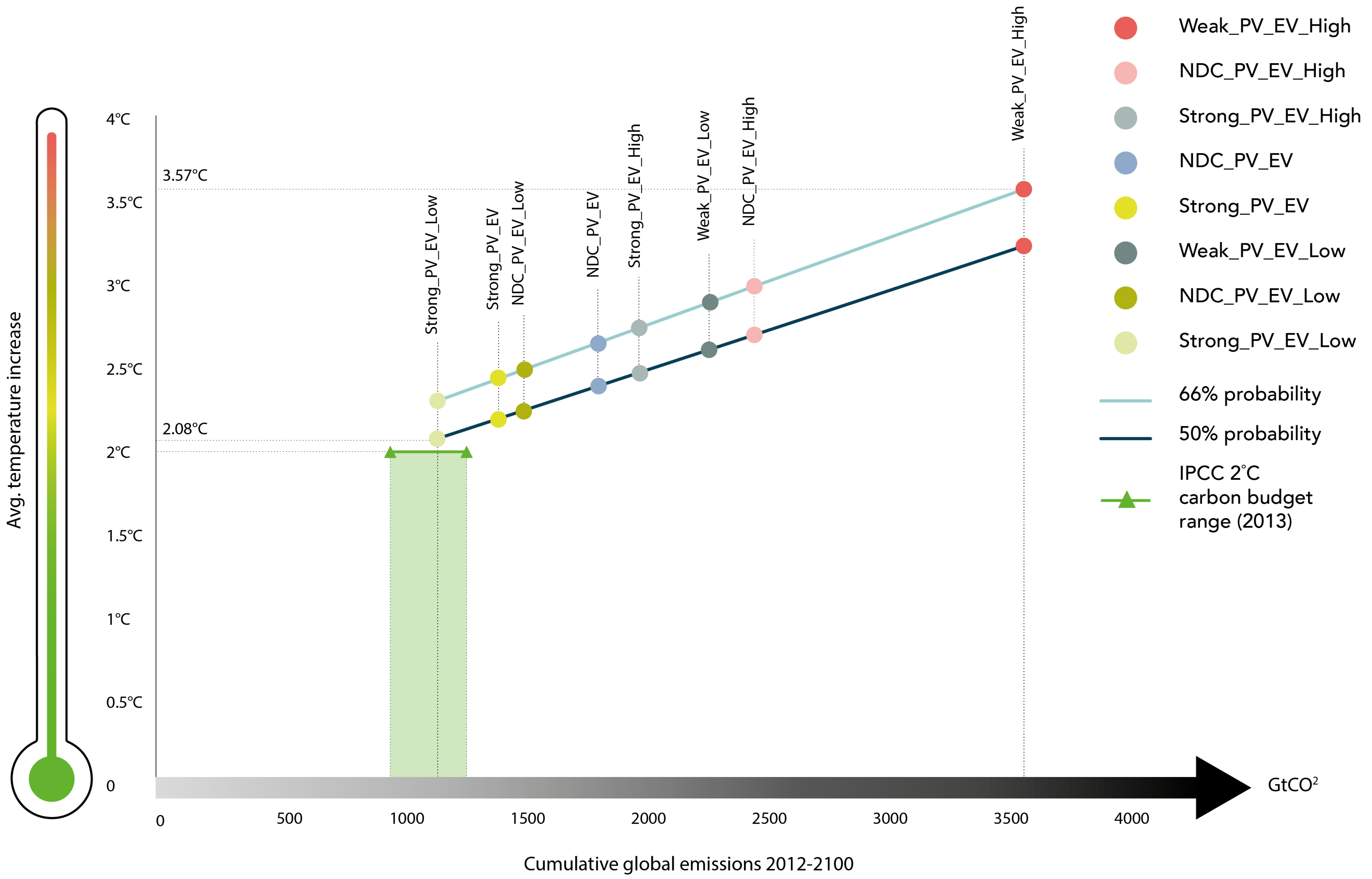
With this in mind, Figure 17 is encouraging that so many of this study's scenarios achieve annual emissions consistent with 2°C for many decades. On the whole, however, these scenarios assume either stronger climate policy effort than the NDCs or lower overall energy demand. Even then, these scenarios tend to struggle in the short-term to 2030/2040, hence the fact that no scenario achieves 2°C or lower according to the UK Met Office – see Table 1.

Carbon budgets

Future CO_2 emissions can be framed in terms of a 'carbon budget', ie the cumulative emissions over time to keep within a certain temperature outcome. When dealing in terms of carbon budgets, the assumed likelihood for delivering a temperature outcome is crucial. The IPCC AR5 report in 2013 found the carbon budget to keep to 2°C was between 1000GtCO_2 (66% probability) and 1300GtCO_2 (50% probability) from 2011-2100.[xliii] The IEA utilises carbon budgets with a 50% probability.

Figure 18 presents the core set of scenarios in this study in terms of cumulative emissions and compares them against the IPCC's range of 2°C carbon budgets, edited to 968-1268GtCO_2 to be consistent with our scenarios that start from 2012, rather than 2011. The UK Met Office calculates that our lowest-carbon scenario 'Strong_PV_EV_Low' delivers between 2.08°C and 2.30°C (50% and 66% probability), although cumulative emissions are 1155GtCO_2, ie well within the 2°C range published by the IPCC. This discrepancy reflects the importance of different climatic modelling assumptions, such as climate sensitivity, non-CO_2 forcings etc. Therefore, depending on climatic and probability assumptions, 'Strong_PV_EV_Low' could be seen as giving a reasonable chance of a 2°C outcome.

Figure 18: Cumulative CO_2 emissions across our scenarios, 2012-2100, result in different temperature outcomes depending on likelihood



Which other sectors must decarbonise to hit 2°C?

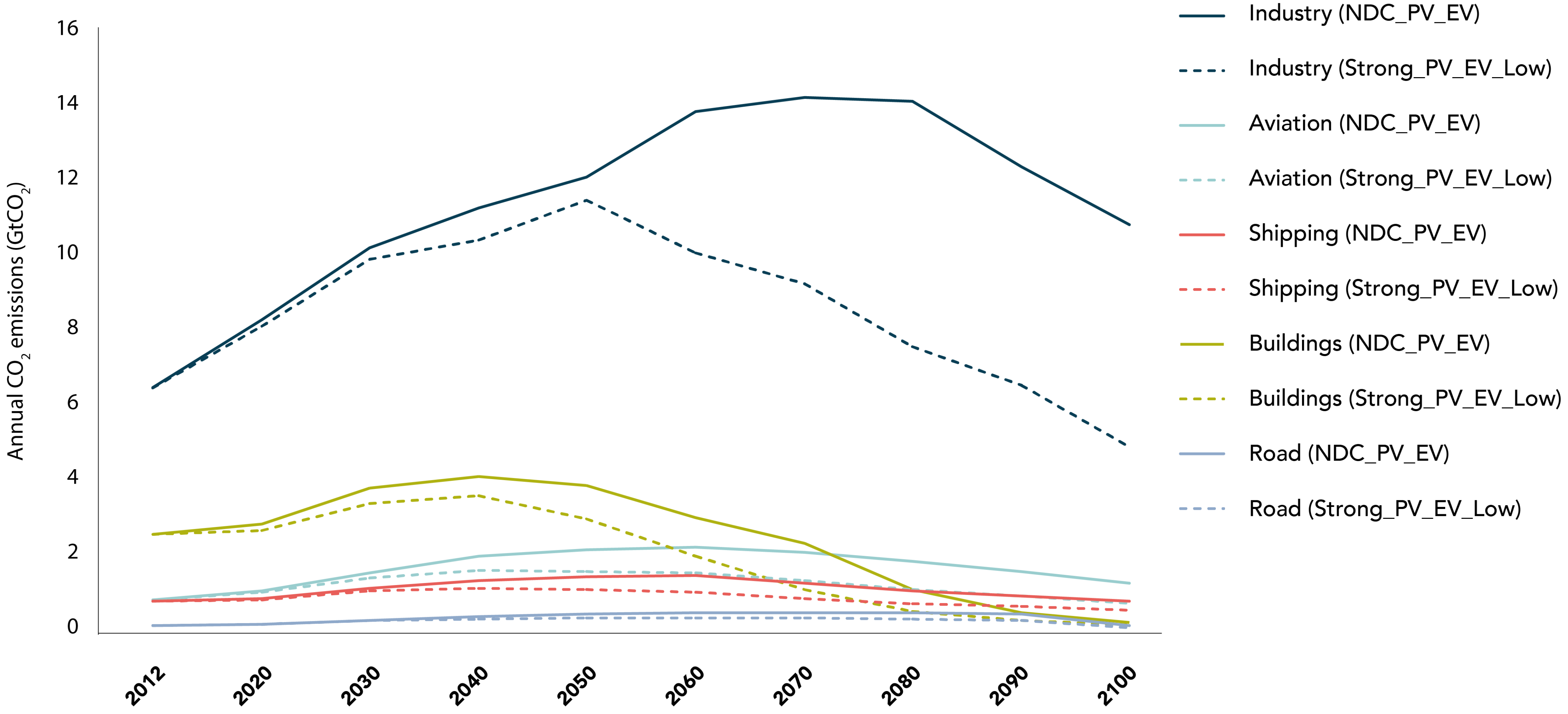
Figure 19 shows CO_2 emissions to 2100 in those sectors other than power and road transport. It shows that industry (which includes cement, iron and steel, chemicals and other energy-intensive sectors), in particular, will be a big contributor of CO_2 emissions going forward. In scenario 'NDC_PV_EV', industrial CO_2 emissions grow strongly until 2080, when they peak. Applying stronger climate policy and lower energy demand ('Strong_PV_EV_Low'), which affect all sectors in TIAM-Grantham, not just road transport and power, goes some way to mitigating this emissions' growth by bringing this peak forward to 2050, but still only after strong growth up to this point.

Evidently, industry will need to play a much bigger role in cutting emissions than solely relying on indirect gains from the decarbonisation of the power sector, if the 2°C target and below is to be achieved.

Major industrial sectors such as steel and cement will need to seek technological solutions, such as CCS, advanced production processes (eg smelt reduction in steel) and the uptake of alternative lower-carbon materials. Longer-term it will also be important to eliminate the residual emissions streams.

The scale of emissions from sectors such as industry and buildings are traditionally related to the levels of economic growth and urbanisation. Globally, there is some decoupling of this relationship as major emerging economies such as China start to shift away from heavy industry and have lower-carbon options to select from in new urban developments. Aviation and shipping are smaller contributors of CO_2 emissions, but still have the potential to cut emissions with the right measures in place. These areas are not the primary focus of this study, but Figure 19 demonstrates how important it is for more work to be done on these sectors which tend to receive less analysis or are perceived to have less potential to cut emissions.

Figure 19: Decarbonisation in industry will be key to hitting the 2°C target



Other energy transition technologies

Carbon capture and storage is outcompeted in the power sector, but could have a role in heavy industry

CCS has the potential to be used in a number of industries if it can be proven to be cost-competitive and viable at scale. A modelling exercise like this brings home the fact that if there are cheaper alternatives available, then CCS will not feature. The future application of CCS, therefore, may become industry specific.

Across our scenarios, this analysis shows very little uplift in fossil fuel demand due to CCS deployment in the power sector. No CCS is deployed with coal or gas in any scenario assuming climate policy effort less than the NDCs because the carbon price is too low for CCS to become cost-competitive. This is in spite of a declining capital cost trajectory for CCS from 2020 to 2050. Once the carbon price becomes high enough for CCS to become viable in some situations, gas with CCS is favoured over coal with CCS, which is not deployed in the power sector in any scenario. Even so, CCS with gas only makes up 5% of total power generation by 2050 in its most prevalent scenario ('Strong_Orig').

The role for CCS is even smaller in scenarios with lower solar PV costs, which is preferred in the model. As a result there is almost no difference in fossil fuel demand between scenarios that have CCS options available and those that block CCS (to explore this difference). Results that see such a small role for CCS are very different to IEA outputs – for example, the IEA requires that 70% of remaining coal-based power comes from plants equipped with CCS by 2040 to meet the 2°C (450) trajectory.[xliv] In our scenarios, by the time emissions are so heavily penalised that coal or gas with CCS has become cost-competitive, so has bioenergy with CCS (BECCS), which gets selected in preference and displays quite strong growth from 2040 onwards – see discussion below on net negative emissions technologies.

CCS may yet prove significant in the power sector, but clearly it is risky betting future business models and projections of high fossil fuel demand on its viability. In non-power sectors such as heavy industry, however, CCS is likely to have a much more important role because there are currently few viable low-carbon alternatives for achieving deep decarbonisation. Furthermore, if CO_2 can be utilised in other industrial processes, this added value will serve to improve the viability of CCS.

Net negative emissions technologies

Integrated assessment models often see net negative emissions technologies becoming cost-competitive in scenarios that apply 'Strong' levels of climate policy proxied through a carbon price. As discussed above, our scenarios see a role for BECCS (the only net negative technology currently available in TIAM-Grantham), which leapfrogs conventional CCS under high carbon prices. However, even in these 'Strong' climate policy scenarios, BECCS only commands just over a 10% share of power generation from 2050 onwards. Whether the capture and sequestration of CO_2 emissions from BECCS is possible cost-effectively and on the scale envisaged remains uncertain. What is for sure is that net negative emissions technologies exist today, such as afforestation, reforestation, direct air capture of CO_2 to be used as a fuel in production processes, as well as BECCS at relatively small pilot scales[xlv], and the latest climate science research shows that in current models these solutions are likely to be essential later in the century if global warming is to be kept at or close to 2°C.[xlvi] Research effort and capital needs to be invested to ensure these technologies become viable at scale, as well as cost-competitive, by the latter half of this century.

> *CCS may yet prove significant in the power sector, but clearly it is risky betting future business models and projections of high fossil fuel demand on its viability".*

Further development of energy models

Integrated assessment models are not new and there is a wealth of material critiquing their strengths and weaknesses; it is not the intention to address this topic in any detail here. We would note that IAMs are not known for their ability to model rapid disruption of sectors, and the energy and climate modelling community continues to work on improving IAMs and developing the next generation of models.[11] Some academics have called for the third wave of climate models, considering options such as dynamic stochastic general equilibrium (DSGE) models and agent-based models (ABM) to overcome the challenges faced by existing tools in modelling something as complex as climate change. The importance being placed on the results of today's energy system models means it is critical that are as good as they can be.

We hope that this report enables those seeking to conduct scenario analysis to understand the mechanics of the models better, and apply our findings accordingly. We would echo the views of Lord Stern who wrote in Nature last year:

> *Calling on scientists, engineers and economists to help policymakers by better modelling the immense risks to future generations, and the potential for action".*
>
> Lord Stern (2016) [xlvii]

The Appendix and Technical Paper accompanying this report gives more in-depth details of the modelling work featured in this study.[xlviii] As discussed, it is increasingly important that key assumptions underlying projections in energy models are made widely available, so that analysts and decision makers can better understand the basis of scenarios.

> *The energy and climate modelling community continues to work on improving IAMs and developing the next generation of models".*

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[11] For example, see Doyne Farmer, J., Hepburn, C., Mealy, P. and Teytelboym, A. (2015) A third wave in the economics of climate change. Environ Resource Econ, 62, 329-357. Available at: http://www.inet.ox.ac.uk/files/publications/Farmer%20Hepburn%20et%20al%20(2015).pdf

7 Conclusions

No more business as usual

By definition, BAU scenarios involve no additional climate policy mitigation action beyond the present level nor do they assume acceleration in the extent to which low-carbon technologies could impact energy markets. Given the energy transition is clearly already underway, and there is no way that BAU can meet the climate targets that many countries, states and companies have committed to, we think it is time to retire the conventional approach to use BAU as a starting point in scenario analyses. The current momentum of the low-carbon transition means it is now highly risky to justify any business strategy by using a BAU scenario as a reference case.

Updating model assumptions is critical

This study demonstrates the importance of using the latest available data and market trends for low-carbon technology costs and climate policy in energy modelling. Applying up-to-date solar PV and EV cost projections, along with climate policy effort in line with the NDCs, should now be the starting point for any scenario analysis. This is not a radical disruptive scenario in terms of its inputs, but a reflection of the current state of play. This then enables more focus on how to achieve a 2°C reference scenario.

The '10% threshold'

In the past, Carbon Tracker has shown that a 10% shift in market share can be crippling for incumbents, such as in the value destruction experienced by EU utilities and the near collapse of the US coal sector. Scenarios produced in this study indicate that 10% shifts in market share from incumbents to solar PV or EVs could occur within a single decade. This contrasts with many BAU scenarios which do not see these technologies gaining a 10% market share, even over several decades. Breaking through these kinds of thresholds is significant because they signal the peak in demand for coal or oil, changing the fundamental market dynamic for these fossil fuels.

More technology and policy to come

Along with the ever-growing threat of unchecked climate change, recent innovation and cost advances have built momentum behind low-carbon technologies in terms of capital investment, R&D and public backing. This could result in a global explosion of low-carbon technology deployment in the coming decades. This would not only increase our chances of approaching the 2°C target, but would also likely have a greater downward impact on fossil fuel demand than shown in this study's lowest emissions scenarios. Policy in all its various forms will continue to ratchet up as well, whether driven by concerns over climate change, energy independence or public health.

Ensuring transparency of assumptions

It is important to know the assumptions underlying any scenario analysis, as noted by the draft guidance from the FSB Taskforce on Climate-related Financial Disclosures. This is particularly true for the assumed costs of energy supply technologies given the binary nature with which IAMs tend to select the lowest cost options in their projections of the future energy mix. Equally important are disclosures of efficiency variables, capacity factors and any exogenous constraints applied by the modellers. This analysis demonstrates how it is possible to provide this transparency in accordance with TCFD recommendations (see Appendix) and why it is important to do so.

Decarbonisation of heavy industry and buildings is vital

This study focuses on the potential impacts from growth of solar PV and EVs. It does not address specific measures for other carbon-intensive sectors such as heavy industry, buildings or other transport sectors (rail, maritime and aviation). This analysis shows, however, that decarbonisation of power and road transport alone may not be enough to achieve international climate targets and so all sectors will need to contribute to future emissions mitigation.

8 Recommendations

Energy companies

There is little value for energy companies to focus on a BAU strategy when clearly changes are already underway that render this approach increasingly obsolete. Energy company management must articulate how it is adjusting to the low-carbon transition and publicly quantify the risks. Companies should also communicate where they see opportunities in the low-carbon transition and how they could drive the potential growth of technologies such as solar PV and EVs as shown in this report.

Investors

Currently, energy company management is not adequately communicating how they are responding to potential lower demand/lower-carbon futures. Shareholders must require more information on the processes being used by energy companies to manage low-carbon transition risk. Companies are most likely conducting some form of lower demand/lower-carbon scenario analysis: investors must require comprehensive disclosures of these scenarios, and the assumptions underpinning them, and use this information to better align their investment decisions with a carbon-constrained future.

Financial regulators

As indicated in the special report of the FSB Taskforce's on Climate-related Financial Disclosure's draft guidance[xlix], there is an essential role for scenario analysis in understanding low-carbon transition risk. Financial regulators should issue guidance on the scenarios that should be used by companies, including a 2°C reference scenario, and the modelling assumptions that should be disclosed, to provide consistent, comparable transition risk metrics for investors.

Energy/climate modellers

The scientific community has recognised the strengths and limitations of integrated assessment models to date. It now needs to develop the next generation of energy/climate models which can better reflect the dynamics of the complex interacting factors involved in our energy and climate systems. This would serve to benefit all stakeholders utilising scenarios.

Energy policymakers

Policymakers are constantly preparing for the future energy needs of their populations. Ensuring that the fundamentals of factors such as demand and technology costs are up to date in the models being used to assess policy options is essential to accurately identify the most efficient solutions for the future.

Appendix

The draft guidance from the FSB Taskforce on Climate-related Financial Disclosures (TCFD) included in its technical supplement, a guide for key parameters/assumptions to disclose when conducting scenario analysis.[i] The aim of this guidance is for businesses to be able to evaluate their performance and for investors and other stakeholders to analyse organisations' disclosures around scenario analysis. Carbon Tracker strongly advocates that institutions conducting scenario analysis follow this guidance and do so below for this study.

Discount rate: The TIAM-Grantham is a multi-region, least-cost optimising model. The model minimises the total present value cost of the global energy system, using a 5% discount rate, to meet future energy service demands.

Carbon price: This study assumes four different carbon price levels across its scenarios as a proxy for global climate policy effort. First, \$0/tCO_2 to represent no additional climate policy effort beyond the Cancun pledges made back in 2010. Second, \$10/tCO_2 entitled 'Weak' levels of climate policy to reflect the extent of climate policies globally today. Third, \$30/tCO_2 in scenarios entitled 'NDC' because academic studies broadly agree that this level of carbon price reflects a pathway expected to be in line with the NDCs established at COP21. Finally, this study models \$50/tCO_2 in scenarios modelling 'Strong' levels of climate policy effort in which international governments exceed on the level of climate policy established in the NDCs. In all cases, carbon prices are assumed to rise at 5% per year, in common with other IAM scenarios which reflects that policy stringency increases (in real terms) with economic growth.

Energy demand and mix: The tables below show selected outputs from our scenarios on fossil fuel and renewable energy uptake, as well as cumulative CO_2 emissions over time.

Table A.1: Power generation (TWh) from fossil fuel and renewable sources in the highest and lowest carbon scenarios from Figure 3

	Weak_Orig				***Strong_PV***			
	Coal	*Gas*	*Wind (Off- & Onshore)*	*Solar PV*	*Coal*	*Gas*	*Wind (Off- & Onshore)*	*Solar PV*
2012	*9859*	*4368*	*474*	*127*	*9859*	*4368*	*474*	*127*
2020	*11076*	*5387*	*747*	*194*	*9461*	*5387*	*1271*	*599*
2030	*11534*	*2139*	*1232*	*213*	*5675*	*3648*	*1260*	*2695*
2040	*9678*	*1852*	*2027*	*213*	*66*	*1136*	*2084*	*10680*
2050	*6129*	*1228*	*3310*	*261*	*0*	*144*	*3411*	*13674*
Avg. Annual % CAGR (2012-2050)	*-1.2%*	*-3.3%*	*5.3%*	*1.9%*	*-100.0%*	*-8.6%*	*5.3%*	*13.1%*

Table A.2: Installed solar PV capacity in selected scenarios from Figure 4

	Installed solar PV (GW)				Solar PV share of global installed power capacity (%)			
	Weak_Orig	Strong_Orig	Weak_PV	Strong_PV	Weak_Orig	Strong_Orig	Weak_PV	Strong_PV
2012	96.6	96.6	96.6	96.6	2%	2%	2%	2%
2020	147.3	146.3	481.0	481.0	2%	2%	7%	7%
2030	161.9	160.9	932.2	2050.6	2%	2%	13%	24%
2040	161.9	418.1	3743.4	8128.0	3%	6%	41%	60%
2050	198.8	809.2	7892.4	10406.4	3%	10%	60%	65%

Table A.3: Number of vehicles (million) in the highest and lowest carbon scenarios from Figure 9

	Scenario	ICEs	Battery EVs (BEVs)	Plug-in Hybrids (PHEVs)
2012		1232	0.004	0
2020	Weak_Orig	1713	0	0
	Strong_EV	1510	12	0
2030	Weak_Orig	1697	0	0
	Strong_EV	921	106	323
2040	Weak_Orig	1614	0	0
	Strong_EV	432	1018	96
2050	Weak_Orig	1832	0	0
	Strong_EV	314	1693	0
Avg. Annual % CAGR (2012-2050)	Weak_Orig	1.0%		
	Strong_EV	-3.5%	41.1%	

Table A.4: Global primary energy demand for coal, oil and gas in selected scenarios from Figure 15

	Coal			Oil			Gas		
	NDC_Orig	NDC_PV_EV	Strong_PV_EV_Dem	NDC_Orig	NDC_PV_EV	Strong_PV_EV_Dem	NDC_Orig	NDC_PV_EV	Strong_PV_EV_Dem
2012	3501.7	3501.7	3501.7	3815.3	3815.3	3815.3	3089.4	3089.4	3089.4
2020	3833.2	3860.5	3538.6	4175.8	4076.0	4017.7	3815.0	3830.6	3795.4
2030	3820.3	3812.5	2640.2	4310.4	4058.3	3997.2	4103.1	3987.7	4181.3
2040	2683.7	2447.2	1506.0	4181.0	3723.5	3607.7	5162.3	4513.5	4159.6
2050	2159.6	1833.5	1408.0	3973.9	3553.5	3528.0	5281.6	4774.3	3799.8

Table A.5: Cumulative CO_2 emissions in selected scenarios from Figure 18

	Budget (2012-2100 incl.)(GtCO2)	**Temperature rise (°C)**	
Scenario		**50%**	**66%**
Weak_PV_EV_High	3569	3.23	3.57
NDC_Orig	1985	2.47	2.74
Strong_Orig	1599	2.29	2.54
NDC_PV_EV_High	2460	2.70	2.99
NDC_PV	1848	2.41	2.67
Strong_PV	1438	2.21	2.45
Strong_PV_EV_High	1978	2.47	2.74
NDC_PV_EV	1818	2.39	2.65
Strong_PV_EV	1407	2.20	2.44
Weak_PV_EV_Low	2278	2.61	2.89
NDC_PV_EV_Low	1516	2.25	2.49
Strong_PV_EV_Low	1155	2.08	2.30

Costs of key commodities and products: The following tables show the capital cost and operation and maintenance (O&M) costs assumed in the power and road transport sectors in the original and lower cost scenarios in this study.

Power sources

Table A.6: Capital cost assumptions (in M$2016/GW) for power generation technologies in the original and lower cost scenarios

Technology	Baseline					Lower Costs				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
Biomass	3098-6179	2924-5744	2611-5222	2611-5222	2611-5222					
Coal	3081-3385	2820-3342	2820-3342	2820-3342	2820-3342					
Gas	522-5715	522-2959	522-2089	522-2089	522-2089					
Geothermal	2383-17136	2287-13916	2235-10696	2172-7476	2089-4900					
Oil	1253-2089	1253-2089	1253-2089	1253-2089	1253-2089					
Hydro	1161-4252	1148-4176	1134-4101	1121-4026	1110-3963					
Nuclear	3706-4200	3706-4200	3706-4200	3706-4200	3706-4200					
Solar PV	4760-5569	3029-3991	2548-3018	2256-2695	2081-2444	5350-7936	1120-1661	610-915	430-700	390-643
Solar thermal	5145-5145	4762-4762	4073-4073	3551-3551	3121-3121					
Wind onshore	1890	1780	1687	1640	1640					
Wind offshore	5390	4090	3343	2970	2970					
BECCS		5483-5483	4700-4700	4386-4386	4386-4386					
Coal CCS		4177-4177	3655-3969	3446-3760	3446-3760					
Gas CCS		1400-1567	1330-2611	1330-2611	1330-2611					

Table A.7: O&M cost assumptions (in M$2016/GW) for power generation technologies in both original and lower cost scenarios

Technology	Fixed Operation & Maintenance Costs				
	2010	2020	2030	2040	2050
Biomass	50-82	50-78	50-74	50-74	50-74
Coal	52-66	49-60	46-60	46-60	46-60
Gas	38-202	38-52	38-52	38-52	38-52
Geothermal	34-245	33-199	32-153	31-107	30-70
Oil	4-38	4-38	4-38	4-38	4-38
Hydro	17-64	17-62	16-58	15-55	15-53
Nuclear	60-85	60-85	60-85	60-85	60-85
Solar PV	22-23	12-14	11-11	10-11	10-11
Solar thermal	0	0	0	0	0
Wind onshore	0	0	0	0	0
Wind offshore	0	97-97	90-90	82-82	82-82
BECCS	0-96	0-96	0-96	72-96	72-96
Coal CCS	0-40	0-40	34-64	32-64	32-64
Gas CCS	50-82	50-78	50-74	50-74	50-74

Road Transport

Table A.8: Comparison of vehicle capital cost ($ per vehicle) assumptions used in TIAM-Grantham for the original and lower cost scenarios

Technology		**Original Costs**						**Lower Costs**				
		2006	**2010**	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
Car	ICE	36440	36834	37874	38970	40122	41331					
	BEV	68229	64926	57365	50690	44788	39574	64926	36257	33882	31971	30074
	PHEV	41485	41232	40628	40024	39433	38843	41232	37874	37874	37874	37874
	Alcohols	34936	35372	36468	37593	38759	39968					
	LPG/gas	47908	48189	48891	49622	50367	51140					
	Hydrogen	56115	54007	49074	44591	40530	36820	54007	37874	37874	37874	37874
LDVs	ICE	36440	36834	37874	38970	40122	41331					
	BEV	68229	64926	57365	50690	44788	39574	64926	36257	33882	31971	30074
	PHEV	41485	41232	40628	40024	39433	38843	41232	36257	37874	37874	37874
	Alcohols	34416	34838	35920	37044	38197	39377					
	LPG/gas	47908	48189	48891	49622	50367	51140					
	Hydrogen	56115	54007	49074	44591	40530	36820	54007	49074	37874	37874	37874
Medium truck	ICE	27701	27701	28031	28692	28692	28692					
	Alcohols	27412	27412	27185	27701	27701	27701					
	LPG/gas	29683	29683	29435	29992	29992	29992					
	ICE	90892	90892	92442	94798	94798	94798					
	Alcohols	91760	91760	93372	95728	95728	95728					
	LPG/gas	95852	95852	97526	100006	100006	100006					
Heavy truck	ICE	214512	214512	218232	223728	223728	223728					
	Alcohols	211320	211320	214992	220416	220416	220416					
	LPG/gas	226296	226296	230232	236040	236040	236040					
	Hydrogen	1055496	1055496	298920	278184	257448	236712	1055496	298920	278184	257448	236712
Bus	ICE	224776	224776	231062	233076	237104	241010					
	BEV	710459	710459	329840	309243	288645	268016	710459	231062	209305	197678	185930
	PHEV	607500	607500	396913	340216	302651	265087	607500	231062	231062	231062	231062
	Alcohols	224776	224776	231062	233076	237104	241010					
	LPG/gas	240705	240705	247449	249585	253888	258068					
	Hydrogen	1350274	1350274	566579	394869	326850	258801	1350274	566579	231062	231062	231062

Table A.9: O&M cost assumptions (in M$2016/billion vehicle-km/annum) for road transport technologies in both original and lower cost scenarios

Technology		**O&M costs**				
		2010	**2020**	**2030**	**2040**	**2050**
Car	ICE	52	52	54	55	57
	BEV	97	92	82	72	64
	PHEV	59	59	58	57	56
	Alcohols	50	50	52	54	55
	LPG/gas	68	69	70	71	72
	Hydrogen	120	115	105	95	87
LDVs	ICE	52	52	54	55	57
	BEV	97	92	82	72	64
	PHEV	59	59	58	57	56
	Alcohols	49	50	51	53	54
	LPG/gas	68	69	70	71	72
	Hydrogen	120	115	105	95	87
Light truck	ICE	27	27	27	28	28
	Alcohols	27	27	26	27	27
	LPG/gas	29	29	29	29	29
Medium truck	ICE	29	29	30	31	31
	Alcohols	30	30	30	31	31
	LPG/gas	31	31	31	32	32
Heavy truck	ICE	179	179	182	186	186
	Alcohols	176	176	179	184	184
	LPG/gas	189	189	192	197	197
	Hydrogen	1319	1319	374	348	322
Bus	ICE	147	147	151	153	155
	BEV	466	466	216	203	189
	PHEV	398	398	260	223	198
	Alcohols	147	147	151	153	155
	LPG/gas	158	158	162	164	166
	Hydrogen	1327	1327	557	388	321

Energy storage

When high penetration of renewable power sources occurs, ie combined penetration in excess of 20%, energy storage capacity is assumed for each unit of installed solar PV and wind capacity. It is assumed that 0.25GW of electricity storage is required to support each gigawatt (GW) of solar PV and wind generation capacity. This is derived from specific, more detailed electricity system modelling.[li] Grid-scale storage costs are included at an assumed current cost of $1/W ($424/kWh) for a 20-year lifetime lithium titanate central battery storage system.[lii] Costs are assumed to fall by 75% by 2040 to about $0.25/W for a 20-year life system, in line with costs of just over $100/kWh for a 20-year lifetime system. These costs are modelled as an additional storage cost per installed GW of solar and wind capacity of $0.06/W.

Macro-economic variables: The level set for macro-economic factors is crucial in determining the absolute level of energy service demand to be met by supply technologies in TIAM-Grantham. This study tests three levels of energy demand. The central, 'medium' level of energy demand is set by assumptions from Shared-Socioeconomic Pathway 2 (SSP2).[liii] This equates to an average annual economic growth of 3.13% from 2010 to 2050. The 'lower' energy demand scenario reduces economic growth to 2.46% over the same time period, while 'higher' overall energy demand is modelled by increasing economic growth to 4.30%.

Demographic variables: Population growth levels remain constant across all scenarios in this study, growing to a peak in 2070 at 9.4bn before falling to 9bn in 2100. This is again in accordance with SSP2.

Efficiency:

Capacity factors

Table A.10: Capacity factor assumptions for power generation technologies in both original and lower-cost scenarios

Technology	Value
Biomass	0.5-0.9
Coal	0.7-0.7
Gas	0.7-0.9
Geothermal	0.2-0.9
Oil	0.2-0.9
Hydro	0.38-0.5
Nuclear	0.85-0.88
Solar PV	0.15-0.2
Solar thermal	0.2-0.2
Wind	0.2-0.4
BECCS	0.9-0.9
Coal CCS	0.9-0.9
Gas CCS	0.9-0.9

Vehicle lifetimes

Table A.11: Vehicle lifetimes (years) for road transport technologies in both original and lower-cost scenarios

Vehicle Category	Lifetime
Cars	12.5
LDVs (i.e. vans, minivans etc.)	12.5
Commercial Trucks	15
Medium Trucks	15
Heavy Truck	15
Buses	15
Two/three-wheelers	10

Geographical tailoring of transition impacts: The inputs to the TIAM-Grantham are split by 16 different regions. The capital cost and O&M assumptions disclosed above are either averages or ranges across these regions.

Climate sensitivity assumptions: The calculations of CO_2 emissions into average temperature increase in this study's scenarios were conducted by the UK Met Office.

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February 2017