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THE COST AND BENEFITS OF THE APOLLO PROGRAMME

A report for the Global Apollo Programme

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CONTENTS

EXECUTIVE SUMMARY

The Global Apollo Programme proposes to deliver a step change in research, development and demonstration (RD&D) into renewable energy.

It aims to reduce the cost of the technologies that can help produce clean energy cheaply. Governments who join the Programme would devote at least 0.02% of GDP to public expenditure on renewables RD&D over a 10-year period from 2016. This requirement for public funding comes at a time of many competing demands on government budgets. Therefore it is important to understand the extent to which the benefits of the Programme will outweigh its costs.

Our research finds that the Global Apollo Programme could deliver significant reductions in the costs of renewable energy.

Our analysis suggests that the increased RD&D spending under the Apollo programme has the potential, under plausible but relatively optimistic assumptions, to help reduce the costs of electricity generated by solar PV[1] to below the costs of electricity from coal by 2025. This would entail a fall in the costs of solar PV of 75% from today's levels.

Even under more conservative assumptions, we find significant reductions in the cost of solar PV. We develop three additional scenarios where solar costs fall between 37-57% under the Programme, compared to today's levels.

Major global benefits would be delivered by the Programme, under all scenarios.

Even in the absence of any additional climate change policy, the Programme has the potential to have a transformational impact on the energy sector. In the scenario where the costs of solar PV fall below the costs of coal, solar PV could provide 26% of global electricity generation by 2040, saving 10% of total global emissions.

The positive impact in a world where global governments sign up to a 2^{O}C climate target is likely to be extremely significant. Modelling by the Grantham Institute at Imperial College London finds that the Programme could reduce the cost of meeting a 2^{O}C climate target by $0.7-4.0 trillion out to 2040[2].

These estimates could represent a minimum. The benefits of the Programme are likely to be even greater than these estimates suggest, as we have not estimated the wider benefits of innovation, such as impacts on productivity and spillovers to other sectors. We have also not attempted to value the wider benefits associated with an increase in renewables. For example, we have not valued the health benefits related to an improvement in air quality, and the social and economic benefits that may come with connecting more off-grid properties.

Because of the market failures associated with innovation and climate change, this RD&D is not likely to happen without government intervention.

Although the potential benefits of increasing RD&D spending on renewables could be large, private spending is low. This is because market failures relating to innovation in low carbon energy are limiting this investment. Coordinated action between international governments has the potential to most effectively overcome these market failures.

While there is uncertainty over the scale of cost reduction, given the potential size of the benefits, there is a strong economic case for implementing the Global Apollo Programme.

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[1] This takes into account grid and storage investments required to integrate solar into the electricity system.

[2] 2013 prices.

1 INTRODUCTION

The Global Apollo Programme proposes to deliver a focused 10-year programme of research, development and demonstration (RD&D) into renewable energy technologies beginning in 2016. It aims to deliver the technologies that can help produce clean energy at a price which competes with the incumbent fossil fuel alternatives.

Frontier Economics and the Grantham Institute at Imperial College London have been commissioned by the Global Apollo Programme to quantify the potential benefits that could be delivered from this programme.

1.1 Why increase spending on RD&D now?

At the UNFCCC[3] conference in Cancun in 2010, governments formally recognised the need to take urgent action to tackle climate change. They agreed this action should be aimed at holding the increase in global average temperature below 2°C, relative to pre-industrial levels. Governments are meeting again in Paris in December 2015, to sign a deal to tackle climate change.

There is a real prospect of gaining agreement. However, the national pledges to cut emissions submitted in advance of the Paris talks to date will not move the world onto a 2 °C path.[4]

What can be done to help bridge this gap? The Global Apollo Programme has put one option on the table: **a proposal for governments to increase spending on RD&D on renewable energy to an average of 0.02% of GDP from 2016-2025** (Box 1).

Box 1: The Global Apollo Programme

The Global Apollo Programme[5] is a proposal aimed at mobilising and coordinating additional public RD&D spending on renewables (especially **solar PV**) and on the technologies required to integrate renewables into the electricity system (primarily **electricity storage** and **smart grids**).

All governments who join the Programme would pledge to spend an annual average of 0.02% of GDP on the programme from 2016-2025. The money would be spent according to each country's discretion.

The Programme would generate year by year a clear roadmap of the scientific breakthroughs required at each stage to maintain the pace of cost reduction. There would be a Commission consisting of one representative of each member country and, under it, a Roadmap Committee of some 20 senior technologists and business representatives who would construct and revise the roadmap year by year.

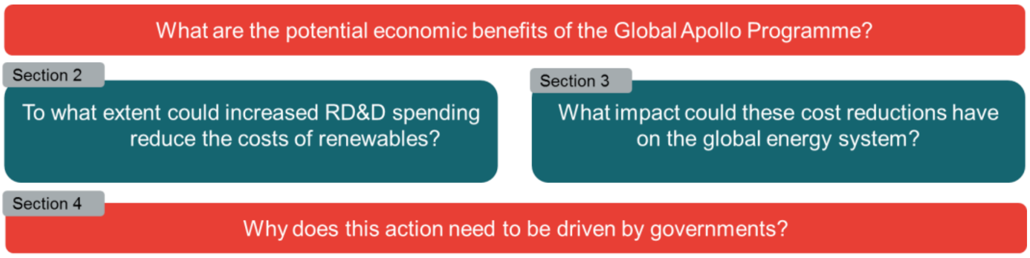
1.2 What does this report cover?

We have assessed the potential economic benefits of the Global Apollo Programme in three stages.

[3] The United Nations Framework Convention on Climate Change is a treaty negotiated at Rio de Janeiro in 1992. It sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change.

[4] UN (2015), *Synthesis report on the aggregate effect of INDCs*, http://unfccc.int/focus/indc_portal/items/9240.php

[5] http://www.globalapolloprogram.org/



- **To what extent could increased RD&D spending reduce the costs of renewables?** In Section 2, we develop four technology cost reduction scenarios, based on evidence from previous RD&D programmes.
- **What impact could these technology cost reductions have on the global energy system?** In Section 3, we consider the impact that these cost reductions could have on solar PV uptake and on the costs of meeting climate targets.
  - We first estimate the carbon savings and solar deployment that could be delivered, even if no other climate policy were applied, if the Programme were successful in its aims of bringing the costs of solar to below the costs of coal.
  - We then consider a world where there is a global agreement to meet a 2^{O}C climate target. We compare the estimated cost of meeting a 2^{O}C climate target, with and without the technology cost reductions that the Global Apollo Programme could drive, and assess whether the cost of the Programme is outweighed by these savings.
- **Why does this action need to be driven by governments?** Finally, in Section 4, we explain why the market failures associated with innovation and climate mitigation mean that this RD&D is unlikely to occur in the absence of government intervention.

1.2.1 How should the results of our analysis be interpreted?

There is a large degree of uncertainty associated with assessing the benefits of an RD&D programme out to 2040. This means that the quantitative outputs of this analysis should be interpreted carefully (Box 2).

Box 2: Dealing with uncertainty

The impact of increased RD&D on renewable technology cost is highly uncertain. By its very nature, the results of innovation are very hard to predict. Moreover, there is uncertainty about the extent to which spending on research (as opposed to, for example, deployment) drives this innovation.

In addition, the impact of technology cost reductions on global energy system costs is highly uncertain. Any analysis that attempts to consider global developments out to 2040 is going to be subject to a high degree of uncertainty, given it requires long-term forecasts to be made where data is patchy. Because of this uncertainty, we have aimed to take a conservative approach.

- Throughout the analysis, we have used relatively conservative assumptions, unless otherwise stated. Where available, we have based our input assumptions on reputable published sources.
- We have worked with academic specialists from the Grantham Institute at Imperial College London, to ensure our work reflects the latest mainstream thinking in this area.
- We have not attempted to value the wider benefits of innovation (such as impacts on productivity and spillovers to other sectors).
- We have also not attempted to value the wider benefits associated with an increase in renewables. For example we have not quantified the health benefits related to an improvement in air quality, and the social and economic benefits that may come with connecting more off-grid properties.

Further, to take account of the uncertainty, our analysis is scenario based.

Nevertheless, substantial uncertainty remains and the focus should be on the broad magnitudes of the estimates, rather than on specific point estimates.

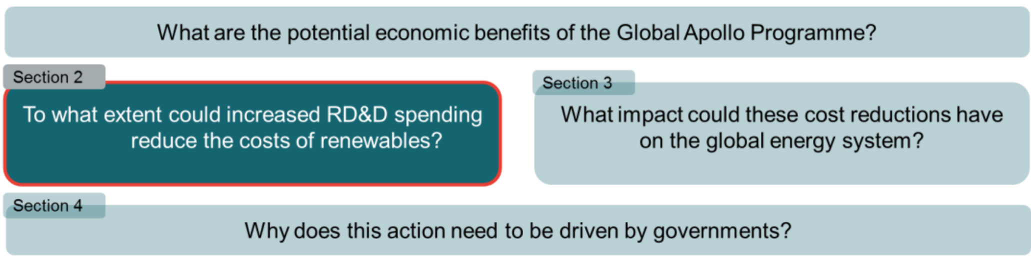
2 THE POTENTIAL IMPACT ON TECHNOLOGY COSTS

Innovation has the potential to reduce the costs of meeting climate targets. However, by its very nature, investment in innovation involves taking a leap of faith – the developments that will result from the innovation cannot be predicted with any certainty. Given this, how do we estimate the potential impact on renewable electricity costs from an increase in public spending on RD&D?

In this section, we first develop counterfactual scenarios, to represent what might be likely to happen in the absence of the Programme.

We then draw on past relationships between public RD&D spending and cost reductions to estimate the potential impact that the increase in public RD&D spending under the Programme could have on technology costs.

Based on this analysis, we produce four scenarios for the impact of the Programme on technology costs. **We find that under the Apollo Programme, the costs of solar electricity could be 37-75% lower by 2025 compared to current levels.**



2.1 Counterfactual cost scenarios

This section describes what could happen in the absence of the Programme, and forms the counterfactual for our analysis.

We first look at the costs of solar and wind. We then consider the costs of storage and grid investments required alongside these.

2.1.1 Solar PV cost counterfactual

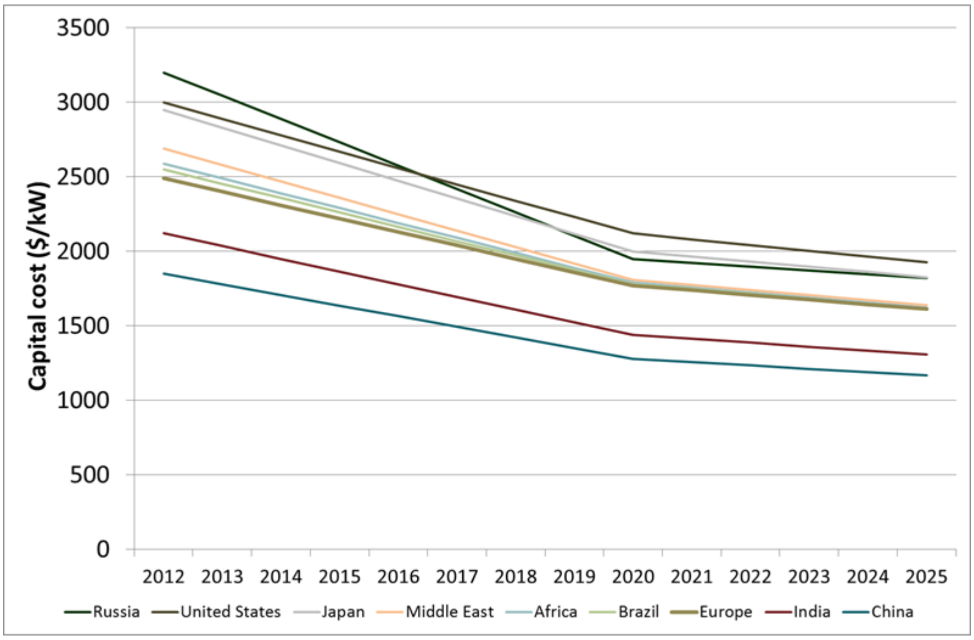
Our starting point for the analysis of solar PV costs is a set of recent long-term cost projections produced by the IEA. Figure 1 shows the “450” scenario from the 2014 World Energy Investment Outlook[6]. This scenario is consistent with a world where a 2°C target is achieved. The figure shows the capital cost of solar PV across global regions, based on the IEA’s projected generation of electricity from solar PV in each region[7]. In this scenario, costs are driven down by learning which is achieved through increased deployment. The IEA has assumed learning rates of 18% for solar PV – that is, for every doubling of capacity, capital costs fall by 18%. Overall, this scenario shows a fall of 31% between 2015 and 2025[8].

[6] IEA, WEIO 2014 – Power Generation Investment Costs, http://www.worldenergyoutlook.org/weomodel/investmentcosts/

[7] Projected generation was taken from WEIO, 2014 Annexe A.

[8] This is based on an average, weighted by the projected generation in WEO14 Annexe A.

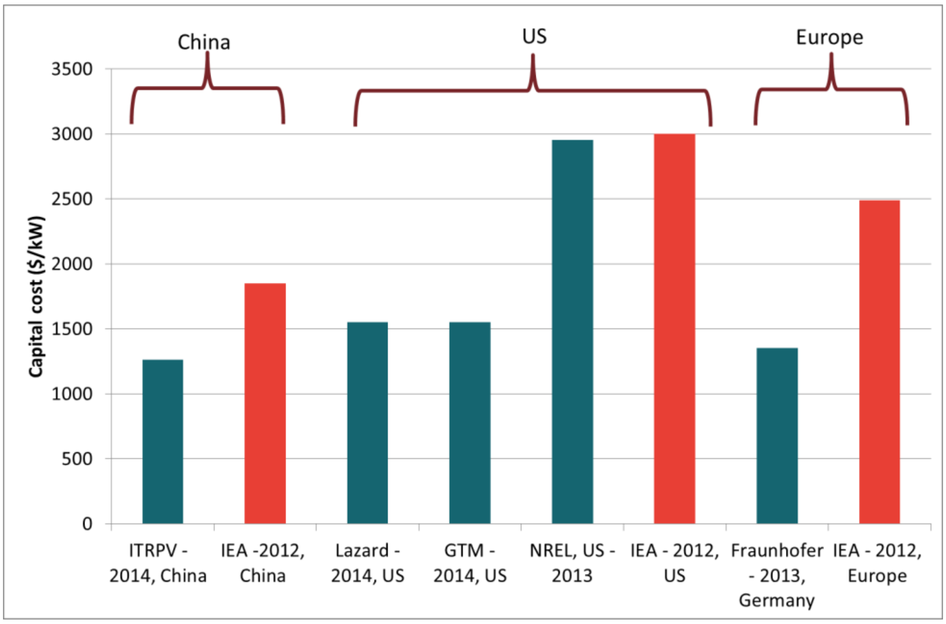
Figure 1. IEA solar PV cost projections (utility scale)



Source: IEA, WEIO 2014. Note. 2012 prices. Costs have been interpolated between the estimates published by the IEA (2012, 2020 and 2035).

Figure 2 compares estimates of capital costs in 2012 from the IEA with those in more recent years from other sources. This illustrates that, with one exception, the IEA costs are substantially higher than those from other sources. These differences are not surprising – there is huge variation in solar PV costs, even within regions.

Figure 2. IEA solar PV cost estimates compared to projections from other sources (utility scale)



Sources: ITRPV[9] IEA[10], Lazard[11], GTM[12] NREL[13] Fraunhofer [14]Note: All prices are in $2012.

9 International Technology Roadmap for Photovoltaic (2015), Roadmap 2015: http://www.itrpv.net/Reports/Downloads/2015/

There is also a large degree of uncertainty over future projections. Costs have been falling more rapidly than learning curves suggest they would do: in 2014, solar PV module costs were around 75% lower than their levels at the end of 2009[15]. Overall levelised costs have also fallen significantly; by 44-52% for utility scale solar between 2010 and 2014[16]. Under these conditions, projecting future costs is very difficult.

Other near-term projections of solar PV costs suggests that by 2017 they could be much lower than the projections from the IEA's 450 scenario, with US utility scale capital costs at around $1,200/kW, some 50% lower than IEA's estimates for this date[17].

To take the uncertainty over current and near-term projected costs into account in our analysis, we consider two counterfactuals for solar PV costs in the analysis in this report.

- **Central solar cost counterfactual.** This counterfactual is based on the IEA 450 scenario.
- **Low solar cost counterfactual**. This is based on a trajectory where costs continue to fall rapidly to 2017, in line with the GTM projections, and then follow the IEA 450 cost-reduction trajectory thereafter to 2025[18].

Figure 3 illustrates the low and central counterfactuals for three key regions.

10 IEA, WEIO 2014 – Power Generation Investment Costs http://www.worldenergyoutlook.org/weomodel/investmentcosts/

11 Lazard (2014), *Lazard's levelised costs of energy analysis – version 8*.0, https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf

12 Greentech Media (GTM), http://www.greentechmedia.com/articles/read/Its-Solar-Balance-of-System-Innovation-That-Will-Drive-Cost-Reduction

13 National Renewable Energy Laboratory (2014), *Photovoltaic System Pricing Trends*, http://www.nrel.gov/docs/fy14osti/62558.pdf

14 Fraunhofer (2013, *Levelised cost of electricity* https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity

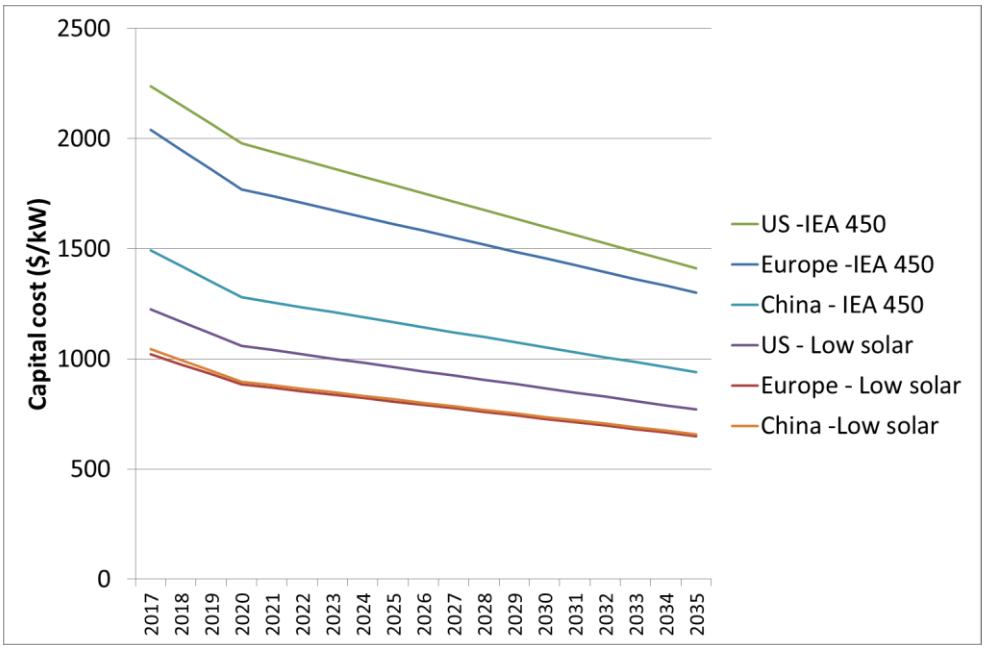
15 IRENA (2014), *Renewable power generation costs in 2014.*

16 The reason that levelised costs have fallen more slowly than module costs is that solar balance of system (BOS) costs have fallen less rapidly than the costs of modules. BOS costs consist of the costs of the structural system (structural installation, racks, site preparation and other attachments), the electrical system costs (the inverter, transformer, wiring and other installation costs) and the soft costs of system development (e.g. customer acquisition, permitting, labour costs for installation). IRENA (2014), *Renewable power generation costs in 2014.*

17 Greentech Media (GTM), http://www.greentechmedia.com/articles/read/Its-Solar-Balance-of-System-Innovation-That-Will-Drive-Cost-Reduction

18 Greentech Media (GTM), http://www.greentechmedia.com/articles/read/Its-Solar-Balance-of-System-Innovation-That-Will-Drive-Cost-Reduction

Figure 3. Solar PV cost counterfactuals (utility scale)



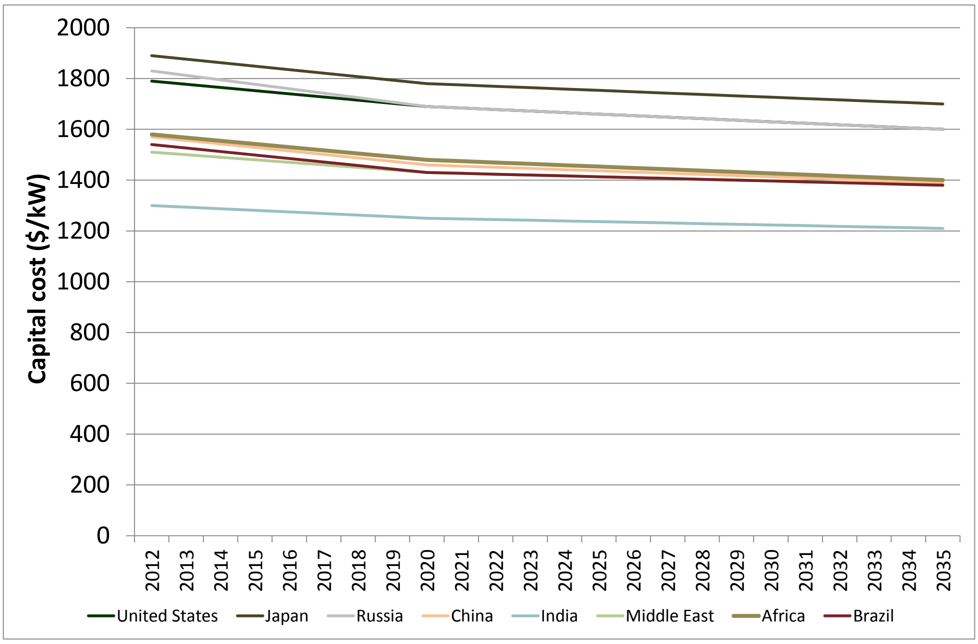
Source: IEA, WEIO 2014. Grantham Institute, Imperial College London. Note. 2012 prices. . IEA costs have been interpolated between the estimates published by the IEA (2012, 2020 and 2035).

2.1.2 Wind costs

Our counterfactual wind costs are based on the IEA's projections[19]. These are illustrated in Figure 4. In the recent past, wind costs have fallen less rapidly than solar PV costs, and there is arguably less uncertainty over their future path. We therefore only look at one counterfactual for wind.

[19] IEA, WEIO 2014 – Power Generation Investment Costs http://www.worldenergyoutlook.org/weomodel/investmentcosts/

Figure 4. Wind capital costs



Source: IEA, WEOI 2014. Note. 2012 prices. Costs have been interpolated between the estimates published by the IEA (2012, 2020 and 2035).

2.1.3 Grid and storage costs

Electricity demand needs to be matched by supply on a second by second basis. Both solar PV and wind produce power intermittently (i.e. when the wind is blowing or when there is sunlight). They are often also located in different areas to conventional generation. This means that additional investment will be required to integrate them into the electricity system. To take account of this we have included additional grid and storage costs in our analysis.

- **Storage costs.** The costs of intermittency per unit of additional renewable capacity vary significantly according to the characteristics of the particular national, regional or local system (for example, according to the spare capacity available and the penetration of other renewables)[20]. However, if intermittent renewables are accompanied by storage, these impacts are mitigated. To represent the costs of mitigating these effects, for each kW of installed solar or wind capacity, we have assumed 0.5kW storage is applied, at a cost of $500/kW in the US.[21] We apply the same proportional mark up to regions other than the US.
- **Grid costs.** In addition, based on the IEA's methodology to calculate intermittent renewables grid integration costs, we assume that each kW of solar PV and wind requires an additional $250/kW of grid integration investment[22].
- **Cost trajectory.** We assume that these storage and grid cost mark-ups fall by 0.5 percentage points per year as a result of learning by deployment. This is based on a combined learning by

[20] For example, widely varying estimates of balancing costs for different regions are provided in OECD and NEA (2012), *Nuclear Energy and Renewables*: *System Effects in Low-carbon Electricity Systems* , https://www.oecd-nea.org/ndd/pubs/2012/7056-system-effects.pdf

[21] Based on modelling for a scenario in which solar PV and wind together produce 90% of electricity generation across the US East Coast, with no loss of reliability compared to current systems See Budischak et al, 2013: http://www.sciencedirect.com/science/article/pii/S0378775313000839

[22] Based on the IEA's methodology to calculate intermittent renewables grid integration costs, available at: http://www.worldenergyoutlook.org/media/weowebsite/energymodel/Methodology_TransmissionDistribution.pdf

deployment rate of improvement for electricity grids and storage from the Low Carbon Innovation Coordination Group's Technology Innovation Needs Assessment[23].

2.2 The impact of the Programme on technology costs

The counterfactual scenarios outlined above describe what might happen in the absence of the Programme. We now turn to assessing the impact of the Programme itself on technology costs.

To do this, we draw on past relationships between RD&D spending and cost reductions.

- We begin by estimating the impact that the Global Apollo Programme could have on levels of public RD&D spending.
- We then draw evidence from the empirical literature on the past relationship between public RD&D spending and technology costs.

2.2.1 How would the Global Apollo Programme impact on current spending levels?

The Global Apollo Programme asks governments to spend 0.02% of GDP on RD&D into renewables and enabling technologies. This equates to an average of $15bn a year, each year from 2016-2025[24]. However, many governments already spend on RD&D. So would the Global Apollo Programme make a difference?

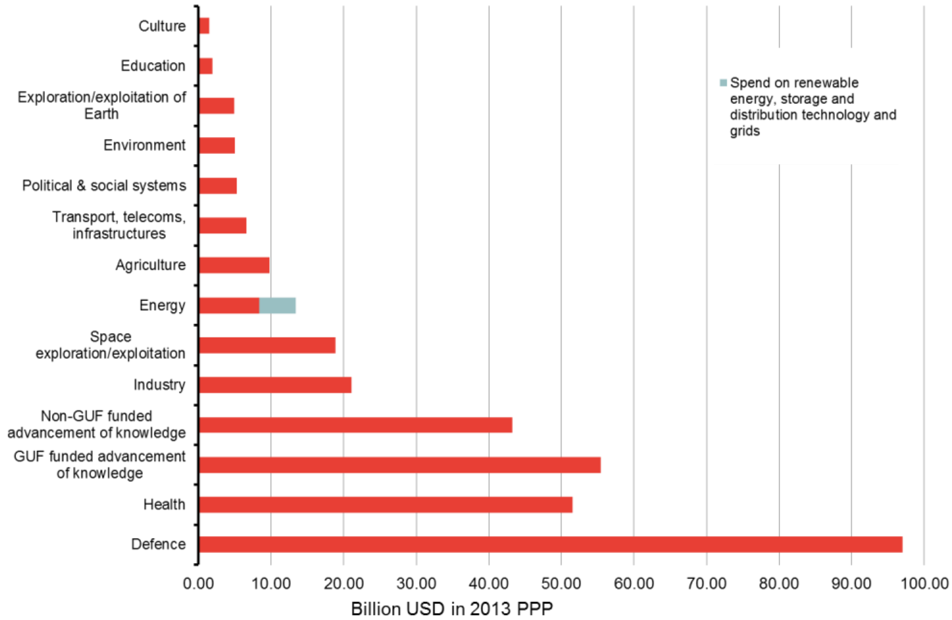
Current spending on RD&D

Figure 5 presents OECD data on current research spending, for the countries for which data is available. This shows that research spending on renewables is very low at present. Public spending on energy-related R&D in total was around 4% of global public R&D expenditure in 2011. An even smaller proportion (around 2%) was spent on renewable energy, storage and distribution technology and energy grids in 2011.

[23] Low Carbon Innovation Coordination Group (2012), *Technology Innovation Needs Assessment : Electricity Networks and Storage*

[24] This assumes countries accounting for around 70% of global GDP in 2013 sign up to the Programme (2013 prices).

Figure 5. Public spending on R&D in IEA countries, 2011



Source: OECD. Note: Data includes all IEA members, except Poland, Switzerland and Turkey. GUF refers to General University Funds Advancement of knowledge: non-oriented R&D concerning medical, agricultural, engineering, natural and social sciences and humanities

Spending on RD&D under the Global Apollo Programme

We estimate the impact of the Programme on cumulative renewable research spending as follows:

- **Cumulative public RD&D spending to 2016.** We first estimate cumulative spending on solar PV, wind, storage and smart grids from 1974-2016 using IEA data[25], with emerging country data added from Kempener et al (2010), where available.[26] Data prior to 1974 is not available.
- **Spending under the Global Apollo Programme from 2016-2025.** We then take the IMF figures for Global GDP[27], and project these forward to 2025 based on the IEA assumptions on GDP growth rates[28]. We scale this down, to take account of the fact that some countries may not join the Programme[29]. The Programme asks governments to spend 0.02% of GDP on renewables research. This equates to around $15bn a year on average from 2016-2025[30].
- **Allocation of the spending between technologies.** We have assumed that going forward, the Programme's RD&D spend is allocated across technologies in proportion to the cumulative levels up until 2013[31].

[25] This covers IEA countries only. IEA, Detailed Country RD&D Budgets. http://www.iea.org/statistics/RDDonlinedataservice/

[26] Kempener, R., Anadon, L.D. and Condor, J. (2010), "Governmental Energy Innovation Investments, Policies and Institutions in the Major Emerging Economies: Brazil, Russia, India, Mexico, China, and South Africa", Cambridge, Massachusetts: Harvard Kennedy School. Available at http://belfercenter.ksg.harvard.edu/publication/20517/.

[27] We use 2013 global GDP in real PPP terms. https://www.imf.org/external/pubs/ft/weo/2012/02/weodata/weorept.aspx?pr.x=72&pr.y=7&sy=2010&ey=2017&scsm=1&ssd=1&sort=country&ds=.&br=1&c=001&s=PPPGDP&grp=1&a=1

[28] A growth rate of 3.5% is assumed. GDP growth rate 2014-2025: Energy and Climate Change: World Energy Outlook Special Report 2015 (IEA) p. 33

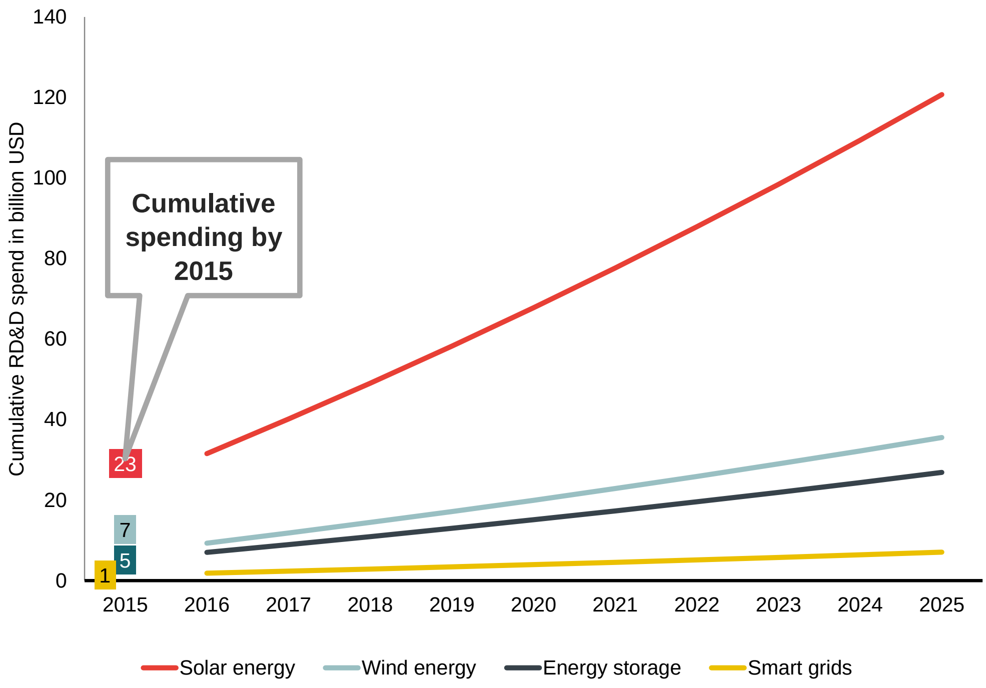
[29] We assume that countries accounting for around 70% of global GDP join the Programme.

[30] In 2013 prices.

[31] Once again, this is based on IEA data and data from Kempener et al (2010). Solar energy has received the largest RD&D spending of the renewable technologies. The average global spending on solar RD&D has been around $600

The results of these calculations are shown in Figure 6. This shows the signficant impact that the Programme would have on cumulative RD&D public spending on the two most important renewable technologies (solar PV and wind) and the key enabling technologies (storage and smart grids). Cumulative spending would increase more than five-fold from 2016-2025 under the programme.

Figure 6. Cumulative renewable RD&D spending under the Global Apollo Programme to 2025



Source: Frontier Economics

2.2.2 The past relationship between RD&D spending and renewable technology costs

The Global Apollo Programme would constitute a step change in the provision of global RD&D spending. To understand the potential benefits associated with the Programme, we need to assess how effective this spending is likely to be. How can the relationship between spending on renewables RD&D and renewable technology costs be estimated? We have reviewed empirical studies that estimate 'learning by research rates' for renewable technologies.

Literature on learning by research

'Learning by research' rates are empirical estimates of the percentage cost reduction in a technology that is observed for each doubling of cumulative RD&D, distinct from any cost reductions that occur as a result of increased deployment. They provide a quantitative measure of how much increased RD&D spending reduces the cost or price of the technology. They should be distinguished from the more commonly used learning by doing rates (Box 3).

million per year during 1974-2013, apart from a surge following the 1970s oil crisis and the stimulus packages associated with the economic downturn in the late 2000s. The spending on wind energy and energy storage has been significantly lower, averaging just $150 million per year. Smart grids have seen a large increase in RD&D since 2008 from a low base.

Box 3: Learning rates

The most commonly used learning rates estimate the effect of cumulative deployment on the cost of technology (learning by doing). Learning by doing curves are widely used in the development of scenarios for the future costs of low-carbon technologies. For example, they are employed by the IEA in the global technology cost scenarios underlying the World Energy Outlook.

Because of our focus on the impact of RD&D spending, we are using 'two-factor learning curves', which allow estimation of learning by research. These take RD&D spending as an explanatory variable of technological learning and attempt to separate the cost reductions that result from RD&D expenditures from reductions coming from deployment (Kahouli 2008)[32].

Learning rates are useful tools in energy modelling. However, their limitations have been recognised (e.g. Winksel et al 2014)[33]. These include:

- limits to the robustness of the data used in the estimations: for example, in the absence of cost data, many studies use price data;
- masking of geographical diversity: both innovation dynamics and the policy context varies across regions, nations and organisations;
- masking of different development stages: learning rates can vary significantly over time, as technologies pass through different stages of development, and there may be step changes and discontinuities; and
- inability to capture the fact that learning effects may vary considerably between different component parts of a technology system.

Nevertheless, learning rates are an established and widely adopted means of incorporating technological change into long run modelling[34]. And many of the limits mentioned above may be 'ironed out' when the rates are applied over the long term (Winksel et al 2014).

Learning by research rates have been estimated in the literature for the renewable technologies expected to make the biggest contribution to meeting the global targets: solar PV and onshore wind[35].

Figure 7 summarises the literature we have found in this area. We are focussing on the three highlighted studies. While the other studies are useful as context, there are a number of reasons why they may not be directly applicable to this study.

- Several of them base the learning rate on a mix of public and private RD&D spending. To develop technology cost scenarios, we apply the learning rate scenarios to increases in public RD&D expenditure under the Global Apollo Programme. Therefore, those studies focussing solely on public expenditure are more appropriate for our use.

[32] Kahouli-Brahmi, S., 'Technological learning in energy–environment–economy modelling: A survey' , *Energy Policy* 36 (2008) 138–162

[33] Winskel M., Markusson N., Jeffrey H, Candelise C., Dutton D., Howarth P., Jablonski S, Kalyvas C., Ward D. 'Learning pathways for energy supply technologies: Bridging between innovation studies and learning rates' in *Technological Forecasting & Social Change,* 81 (2014) 96–114

[34] Engineering approaches are an alternative, but are less suitable for long run modelling. Logistic curves which incorporate top-down S-curves into the estimation are also suitable for long run modelling. However, these are less widely estimated, and require additional data inputs. See: Mukora A., Winskel M, Jeffrey H. and Mueller M: 'Learning curves for emerging energy technologies', Proceedings of the ICE - Energy, Volume 162, Issue 4, 01 November 2009 , pages 151 –159; Pan H. and Köhler J., 'Technological change in energy systems: Learning curves, logistic curves and input–output coefficients' *Ecological Economics*, Volume 63, Issue 4, 15 September 2007, Pages 749–758.

[35] For example, solar and wind play a major role in the IEA's scenarios.

- One paper reports averages across a range of papers (some of which include a mix of public and private spending).
- Two papers are cited in other papers, but we have not been able to access the original paper.

However, we note that despite differences in the inclusion of public and private data, the studies included in Figure 7 mainly estimate learning by research rates in the range of 5%-25%.

Figure 7. Learning by research rates[36]

Study	Solar learning by research (for each doubling of cumulative RD&D spending)	Wind learning by research (for each doubling of cumulative RD&D spending)	Notes
Kobos et al (2006)	**14.3% with a range of 12.9% to 25.9%**	**18.0% with a range of 4.9% to 25.7%**	**Public data only. Includes time lags of 3 years for solar and 5 years for wind. Assumes depreciation of 2.5% for wind and 10% for solar.**
Klaassen et al (2005)		**12.6%**	**Public data only. Assumes time lag of 2 years.**
Soderholm, and Klaassen, (2007).		**13.2%**	**Public data only**
Criqui et al (2000)	9-25%	4.4%	Cited in other papers, but original paper not available
Jamasb (2007)		26.8%	Also includes private RD&D. Time lag and depreciation do not appear to have been modelled. A learning rate for solar thermal is estimated but not for solar PV or CSP.
Kahouli-Brahmi (2009)	0.69%-3.23%.	19.9%	Also includes private RD&D. Depreciation of 3% is included.
Kahouli-Brahmi (2008)	20%	11%	Numbers cited here are averages across papers, including those that use private RD&D
Klaassen, et al (2001)	10%		Cited in other papers, but original paper not available.
Kouvaritakis et al (2000).	10%	7%	Includes private R&D. Time lags and depreciation are not mentioned.

36 Kobos PH, Erickson JD, Drennen TE. 'Technological learning and renewable energy costs: implications for US renewable energy policy'. *Energy Policy* (2006) 34:1645–58; Klaassen, G., Miketa, A., Larsen, K., Sundqvist, T., 'The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom.' *Ecological Economics* (2005) 54, 227–240; Soderholm, P. and Klaasen, G, 'The Efficiency of Energy R&D Expenditures'. E*conomic Modelling of Environmental Policy and Endogenous Technological Change Workshop*. Institute for Environmental Studies (2007); Criqui, P., Klaassen, G., Schrattenholzer, L., 'The Efficiency of Energy R&D Expenditures'. *Economic Modelling of Environmental Policy and Endogenous Technological Change Workshop*. Institute for Environmental Studies, (2000); Jamasb, T 'Technical Change Theory and Learning curves: Patterns of Progress in Electricity Generation Technologies', The Energy Journal (2006) Vol. 28, No. 3; Kahouli-Brahmi, Sondes, 2009. "Testing for the presence of some features of increasing returns to adoption factors in energy system dynamics: An analysis via the learning curve approach," Ecological Economics, Elsevier, vol. 68(4), pages 1195-1212; Kahouli-Brahmi, S., 'Technological learning in energy–environment–economy modelling: A survey' , *Energy Policy* 36 (2008) 138–162; Klaassen, G., Miketa, A., Riahi, K., Schrattenholzer, L., 2001. Targeting technological progress towards sustainable development. 18th Congress of the World Energy Council. Buenos Aires, Argentina, October 21-25. Kouvaritakis, N., Soria, A., Isoard, S., 2000. Modeling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. International Journal of Global Energy Issues 14 (1-4), 104–115.

Factors to take account in the application of learning by research rates

Learning by research rates estimate the cost reduction in a technology that is observed for each doubling of cumulative RD&D. Therefore to develop technology cost assumptions associated with our learning rates, we need to apply them to the cumulative spending set out in Section 2. However, before doing this, we need to consider three further adjustments.

- **Time lags.** There is likely to be a lag between when the money is spent, and when the impact on technologies is felt. Klaasen (2005) reviews the literature on time lags and finds that a 2-3 year lag may be appropriate for individual technologies. We are assuming a 3 year lag in our work.
- **Knowledge depreciation.** Many studies assume that the stock of knowledge depreciates over time. This would mean, for example, that investments in RD&D in the 1970s would be given a lower weight than investments in the current decade when calculating the size of the knowledge stock. Where annual depreciation rates have been included and reported in the studies set out in Figure 7, these have ranged from 2.5%-10%. The higher the depreciation rate, the greater would be the impact of additional RD&D spending, since this impact is calculated relative to the current stock of knowledge. However, we have tested the impact of including a 10% depreciation rate, and the impact on our technology cost scenarios is small. In addition, data on spending before 1974 is not available, and is therefore not included in our analysis. Because of this, to be conservative, we have not included a depreciation rate in our analysis.
- **"Business as usual" RD&D spending.** We also need to account for the fact that countries will continue to spend on RD&D (though at a much lower level) in the absence of the Global Apollo Programme. We assume that in the absence of the Programme, spending would continue at the levels seen in 2012-2013. We net off this spending when analysing the impacts of the Programme.

Three learning by research scenarios

The range of estimated learning rates shown in Figure 7 is relatively wide. Because of this, we have decided to build the analysis around three distinct scenarios based on learning rates of 5%, 10% and 25% for each doubling of cumulative RD&D spending. We have deliberately picked round numbers and a wide range to avoid giving a false impression of precision and to reflect uncertainty in this area.

To be conservative, we apply these cost reductions to capital costs only (we do not apply them to operating and maintenance costs).

Though these rates have been calculated based on analysis of literature and data relating to solar and wind, in the absence of any more specific evidence, we apply them to grid and storage costs also.

2.3 Scenarios for technology costs under the Apollo Programme

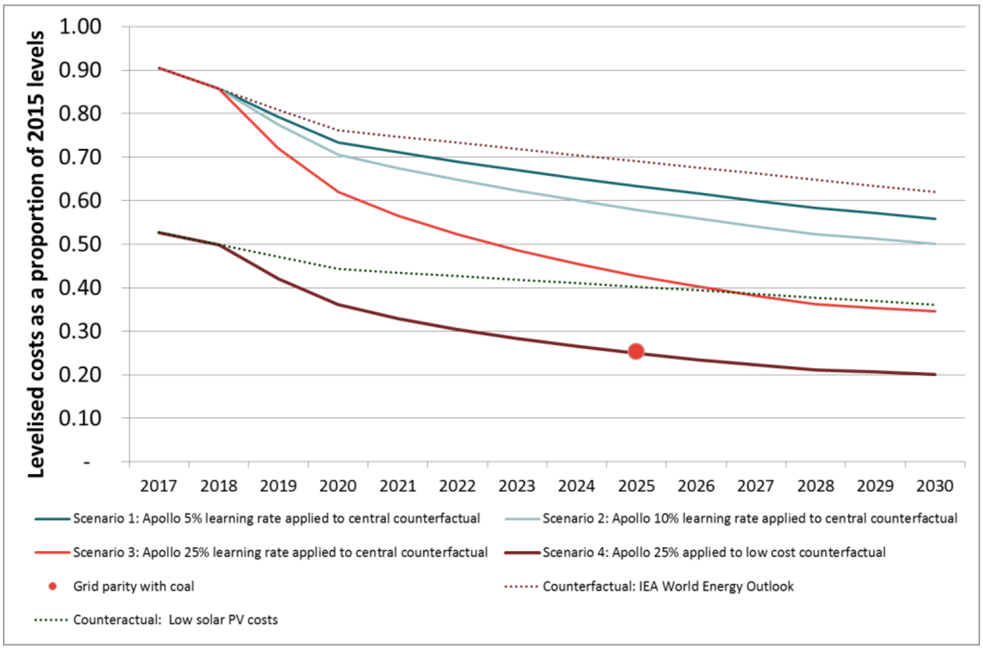
Putting these learning rates together with the two counterfactual scenarios allows us to produce four Apollo scenarios for future energy costs:

- **Scenario 1:** Apollo with 5% learning rate. This scenario applies the 5% learning rate to the central counterfactual.
- **Scenario 2:** Apollo with 10% learning rate. This scenario applies the 10% learning rate to the central counterfactual.

- **Scenario 3:** Apollo with 25% learning rate. This scenario applies the 25% learning rate to the central counterfactual.
- **Scenario 4:** Apollo with low solar costs and 25% learning rate. The first three scenarios are based on conservative assumptions. Using conservative assumptions can give us confidence that we are not overestimating the benefits associated with the Programme. However, it also risks missing the transformational impact that the Programme could have on the energy system, if the Programme were to meet its aim of bringing the costs of electricity generation from solar PV (including related grid and storage costs) to below the costs of coal-fired electricity generation. To ensure we are not missing the potential for transformational impacts, the final scenario applies the 25% learning rate to our low solar PV counterfactual (and to the central counterfactual for all other technologies). Though it is within the range of what is plausible, this scenario is more optimistic about the future costs of solar PV, and applies the highest learning rate from within our range. In this scenario, our analysis suggests that solar PV would reach parity with coal in many parts of the world, even when grid and storage costs are included, and no carbon price is applied.

Figure 8 illustrates these scenarios for solar PV (including the grid and storage costs). Levelised costs have been calculated using inputs from IEA publications[37]. A 10% discount rate has been assumed. Global averages, weighted by projected generation, are shown.

Figure 8. Solar PV electricity generation cost scenarios



Source: Frontier Economics and Grantham Institute, Imperial College London.

[37] IEA, WEIO 2014 – Power Generation Investment Costs http://www.worldenergyoutlook.org/weomodel/investmentcosts/

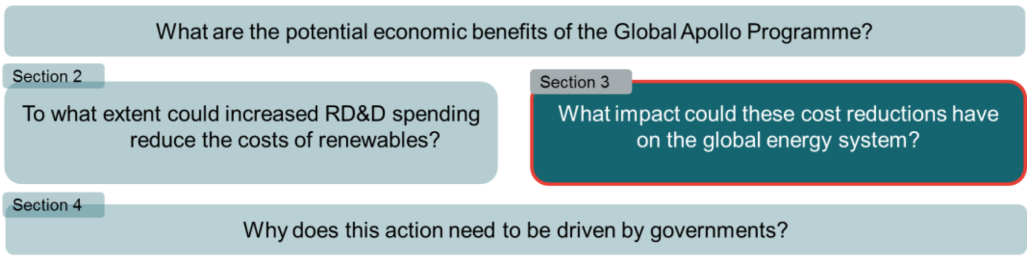
3 IMPACT ON THE GLOBAL ENERGY SYSTEM

Section 2 showed that the Global Apollo Programme could deliver significant reductions in the costs of renewables and enabling technologies (grid integration and storage). But the Programme also entails costs. We now consider whether these costs are likely to be outweighed by the impacts of the Programme.

We consider this question in two different ways.

- **Transformational impacts associated with a grid parity scenario.** We showed in Section 2 there is a plausible scenario (Scenario 4) where solar reaches grid parity with coal under the Programme. We find that the Global Apollo Programme has the potential to deliver 6Gt of annual CO_2 savings in 2040 in a world where no climate policy is applied. This equates to 10% of global CO_2 emissions in 2040.
- **Cost savings associated with a world where climate policy is applied.** Given the potential for a global climate change agreement, it is also useful to understand what impact the reductions in renewable electricity costs could have on the overall costs of meeting a 2^{o}C climate target. We compare these cost reductions to the costs required to deliver the Programme. In the context of a global climate target, our modelling finds that the RD&D spending under the Global Apollo Programme has the potential to save between of $0.7-4.0 trillion out to 2040.

This section first outlines the global energy system modelling methodology at a high level (with full details given in Annex 1). It then describes the results for each type of analysis.



3.1 Global energy system modelling

The Grantham Institute at Imperial College London has used a global energy systems model to assess the impact the Global Apollo Programme could have on the overall costs of meeting a 2^{O}C climate target[38].

This model, TIAM-Grantham, described in Box 4, simulates how climate targets can be met through a transition to a low-carbon energy system, by choosing the least cost global energy technology and fuel mix consistent with reducing CO_2 emissions to a specified level.

[38] Throughout this report, a 2^{O}C climate target refers to achieving a level of cumulative CO_2 emissions from fossil fuel combustion and industrial processes which is consistent with a 50% likelihood of limiting average global warming to below 2^{O}C above pre-industrial levels, as described in further detail in Annex 1.

Box 4:TIAM-Grantham

The TIAM-Grantham model consists of a detailed energy systems model, representing all major energy extraction, conversion, supply, distribution and consumption processes over 15 global regions. The model couples this energy system model with a climate module relating emissions to temperature change, though it can be run purely as an energy model with CO_2 emissions constraints specified exogenously, as it is used in this analysis.

TIAM-Grantham can optimise the global energy system for given climate constraints by minimising the total discounted energy system cost over a given time-horizon. This allows an assessment of the costs of meeting a climate target by estimating the costs associated with substituting low-carbon energy technologies for existing technologies while meeting current and future world energy service needs. The model uses exogenous inputs of factors such as GDP, population, household size and sectoral output shares to project future energy service demands across the agricultural, commercial, industrial, residential and transport sectors in each region. Energy system data such as technology costs, build constraints, resource supply curves and annual resource availability are also input into the model.

The TIAM-Grantham model is the Grantham Institute at Imperial College London's version of the ETSAP-TIAM model, which is developed and maintained by the IEA's Energy Technology Systems Analysis Programme (ETSAP). ETSAP-TIAM's structure and functionality appears in peer-reviewed scientific journals (see Loulou and Labriet, 2007 and Remme and Blesl, 2008)[39]. ETSAP-TIAM has been adopted and developed by several academic modelling groups worldwide, featuring in a number of peer-reviewed model inter-comparison studies of mitigation to stringent climate change goals, including the 22nd and 27th Stanford Energy Modelling Forum studies (EMF22, Clarke et al, 2009, and EMF27, Kriegler et al, 2014)[40].

TIAM-Grantham is currently being used as a central tool of analysis on the feasibility of transitioning to stringent long-term temperature goals, as part of the UK Government's AVOIDing dangerous climate change research programme (www.avoid.uk.net) to inform the UK and international evidence base towards the 2015 UNFCCC international climate summit in Paris (COP 21).

A full description of the global energy systems modelling methodology is presented in Annex 1.

3.2 Grid parity scenario

Scenario 4 (described in Section 2) presents an optimistic, but plausible scenario where electricity generation from solar PV reaches parity with coal-fired electricity generation in many global regions under the Programme. In this section we consider the impacts that this could have on the energy sector, even in the absence of other climate policies.

39 R. Loulou and M. Labriet, 'ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure', Comput. Manag. Sci., vol. 5, no. 1–2, pp. 7–40, Feb. 2007; U. REMME and M. BLESL, 'A global perspective to achieve a low-carbon society (LCS): scenario analysis with the ETSAP-TIAM model', Clim. Policy, vol. 8, no. sup1, pp. S60–S75, Jan. 2008;

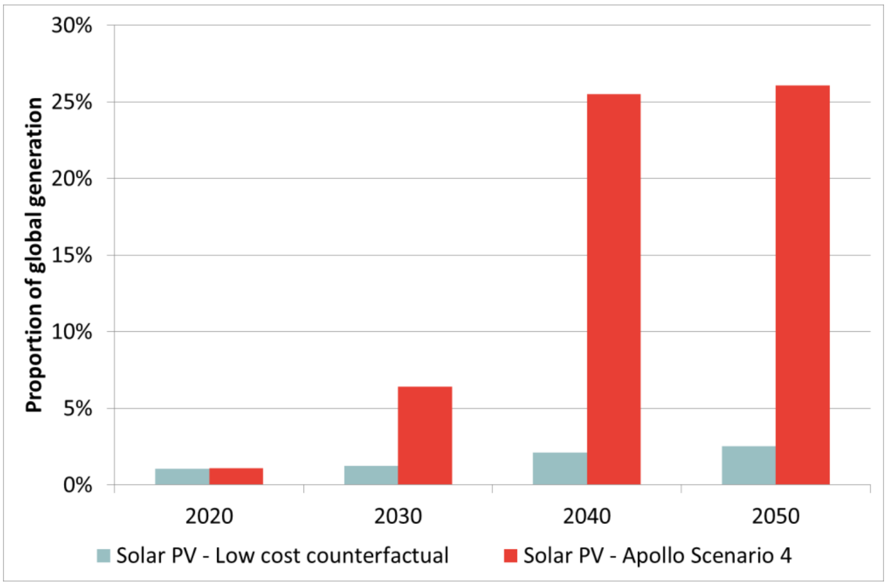
40 L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, 'International climate policy architectures: Overview of the EMF 22 International Scenarios', Energy Econ., vol. 31, Supplement 2, no. 0, pp. S64–S81, Dec. 2009; E. Kriegler, J. P. Weyant, G. J. Blanford, V. Krey, L. Clarke, J. Edmonds, A. Fawcett, G. Luderer, K. Riahi, R. Richels, S. K. Rose, M. Tavoni, and D. P. van Vuuren, 'The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies', Clim. Change, vol. 123, no. 3–4, pp. 353–367, Jan. 2014.

To assess this scenario, the Grantham Institute at Imperial College London implemented a scenario where solar PV generation (including associated grid and storage costs) achieves cost parity with coal by the mid-2020s (in line with Scenario 4, described in Section 2)[41]. In this case the model was run without a carbon constraint. In addition, no carbon price was applied in the analysis. This therefore represents a world where no climate policy is applied apart from the Global Apollo Programme. Given the commitments that have already been made to climate policy, this is not meant to be a realistic scenario. It is simply meant to illustrate the impact the Programme could have, even in the absence of any other climate policy.

Figure 9 shows global solar PV generation under this scenario, compared to the low solar PV cost counterfactual. This illustrates that the Global Apollo Programme would result in a major increase in solar PV generation under these conditions, as solar begins to substitute for fossil fuel plants over the next decades. Under this scenario, solar PV reaches 26% of global generation by 2040.

However, even though its costs are lower, solar PV does not completely dominate the global energy system under this scenario. This is partly because it has not reached grid parity with coal in all regions. It is also because generation from fossil fuel plants becomes cheaper as the demand for fossil fuels decline, and fuel costs fall.

Figure 9. Scenario 4: Solar generation (annual)

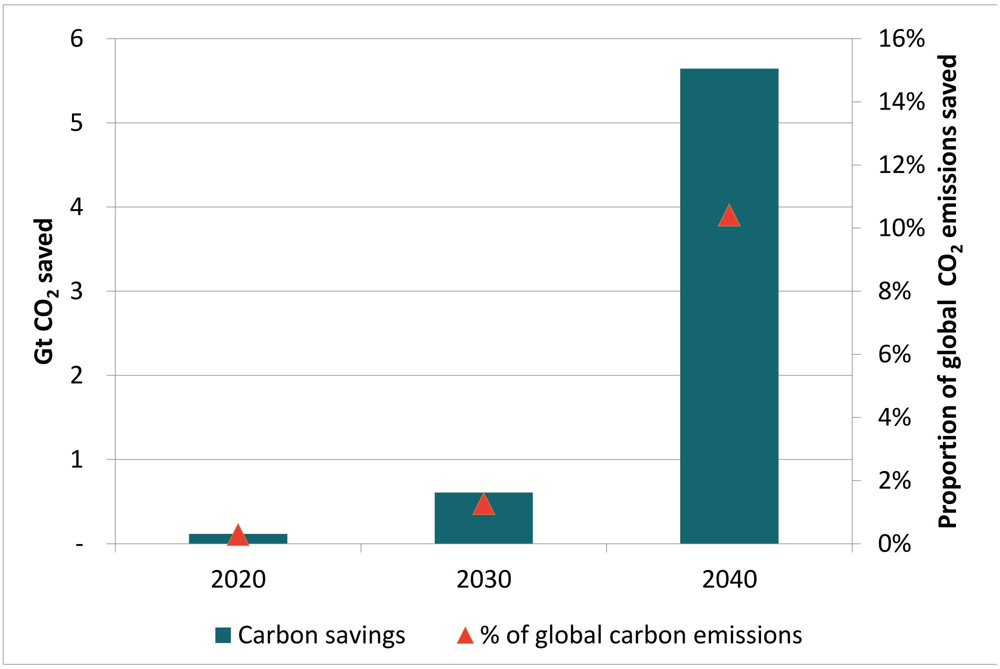


Source: Grantham Institute, Imperial College London

Figure 10 shows the CO_2 savings that would be delivered by the Programme in this scenario. This analysis shows that the Programme could save almost 6GtCO_2 annually in 2040, reducing emissions to about 10% below 2040 global CO_2 emissions in the case without the Programme.

[41] This meant varying the cost of solar PV to a different degree to that shown in Figure 8, due to differences in the endogenously produced coal price in TIAM-Grantham and the coal price used in the coal-parity analysis in Section 2. However, this doesn’t affect the key intention of the analysis, which is to show the degree to which PV could be deployed, and the associated carbon savings in a coal parity scenario.

Figure 10. Scenario 4: Annual carbon savings



Source: Grantham Institute, Imperial College London

In this scenario, the cost of electricity generation from solar PV reaches a similar level to the cost of the coal-fired generation it is displacing. Therefore cost savings are not significant.

3.3 Climate policy scenario

Given the potential for a global climate change agreement, it is also useful to understand what impact the reductions in renewable electricity costs could have on the overall costs of meeting a 2°C climate target.

The Grantham Institute at Imperial College London has therefore also undertaken modelling to assess the cost savings that could be associated with the Global Apollo Programme, in a world where climate targets are met.

TIAM-Grantham allows an assessment of the costs of meeting climate targets under each of our technology cost reduction scenarios. Comparing each scenario to our counterfactual (which includes no additional RD&D spending) gives us an estimate of the cost reductions associated with the Global Apollo Programme.

We have run an additional three scenarios, and compared them to a central counterfactual.

- This time, our counterfactual run is based on the IEA's 450 scenario, which represents a world where a 2°C target is met (central counterfactual).
- The three technology cost reduction scenarios presented in Section 2 have then been run through the model:
  - Scenario 1: 5% learning rate;
  - Scenario 2: 10% learning rate; and
  - Scenario 3: 25% learning rate.

Our results in terms of cost savings are based on a comparison of the baseline scenario to each of the technology cost reduction scenarios.

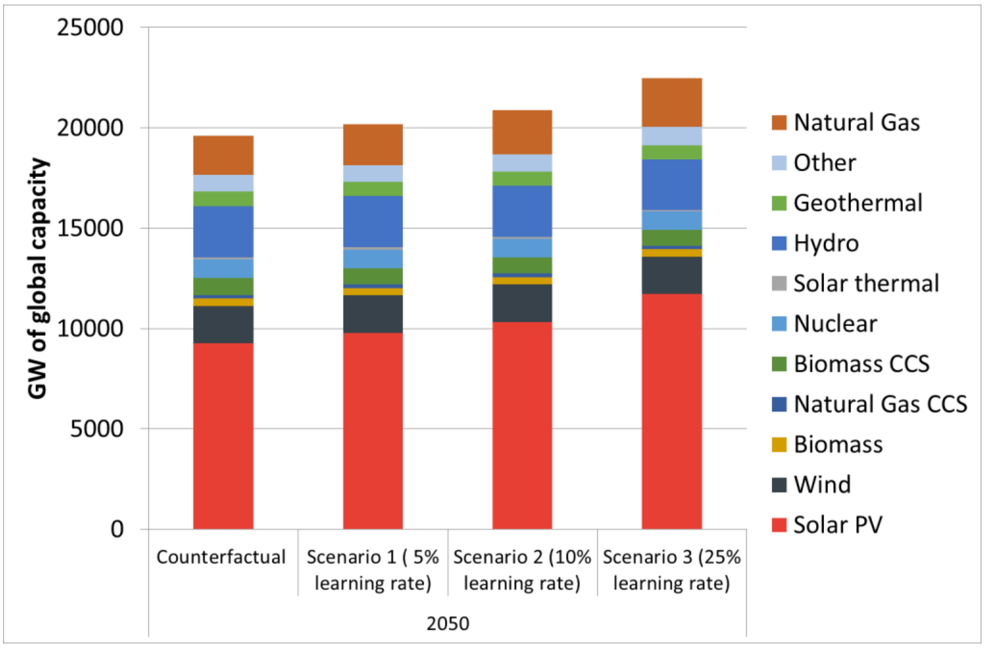
3.3.1 Results

Varying technology costs has two main impacts in the TIAM-Grantham runs.

- The technology mix used to meet global energy demand varies across scenarios.
- The overall costs of meeting global energy demand (subject to a climate target constraint) varies across scenarios.

As expected, a reduction in the costs of wind and solar PV results in an increase in their deployment across scenarios. Solar PV dominates across all scenarios by 2050. This is illustrated in Figure 11.

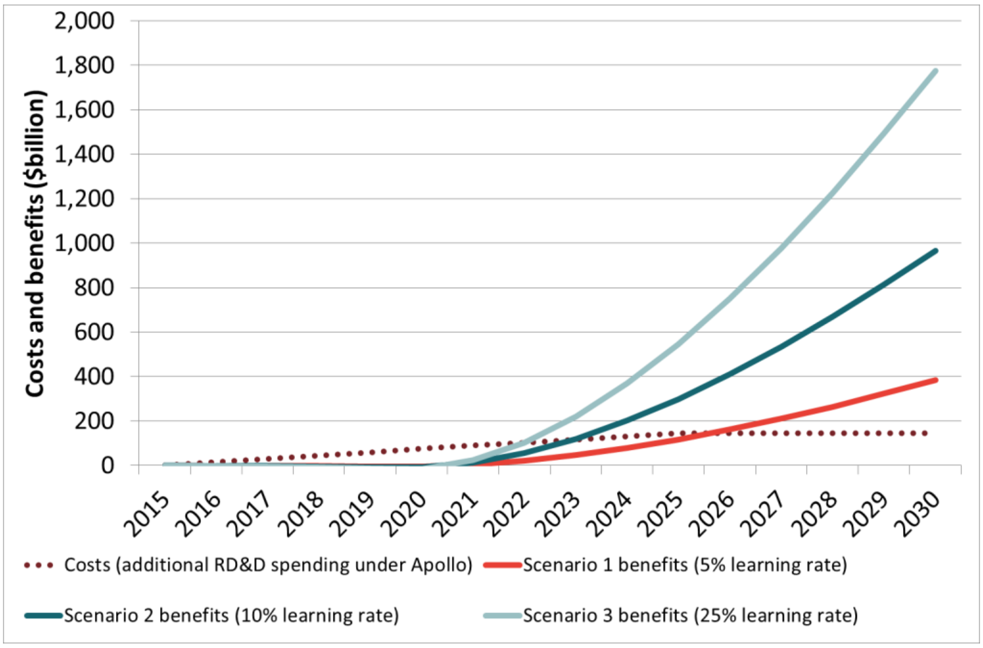
Figure 11. Technology mix by scenario in 2050



Source: Grantham Institute, Imperial College London

Figure 12 shows the cost savings associated with each of the Apollo learning rate scenarios and compares this to the additional RD&D spending under the Global Apollo Programme.

Figure 12. Cumulative discounted cost savings compared to the additional spending under the Global Apollo Programme



Source: Grantham Institute, Imperial College London. All figures are discounted at 5%.

These cost savings significantly outweigh the increased RD&D spending under the Global Apollo Programme. Taking the net present value of the cost savings net of additional Programme spending suggests that the Programme has the potential to save between of $0.7-4.0 trillion out to 2040.

These cost reductions are likely to underestimate the full benefits of increased RD&D:

- The increased learning by doing (as opposed to learning by research) that may be experienced in the Apollo scenarios, relative to the baseline, is not accounted for in this analysis. Given the significant increase in solar PV deployment (Figure 11) and the potential this could have for further cost reductions through learning by doing, this may mean that we are likely to be underestimating the potential benefits.
- We have not valued the wider benefits of innovation (such as impacts on productivity and spillovers to other sectors).
- We have also not valued the wider benefits associated with an increase in renewables. For example, we have not quantified the health benefits related to an improvement in air quality, and the social and economic benefits that may come with connecting more off-grid properties.

Box 5: The benefits of a doubling of RD&D spending

Since this analysis was carried out, Mission Innovation has been launched[42]. This is a undertaking by a coalition of 20 governments to double public spending on clean energy innovation.

We have not modelled this proposal. However, based on the analysis we have carried out, it is possible to make a broad assessment of its benefits.

We have shown that the Apollo Programme would deliver major benefits. The Apollo Programme would constitute more than a doubling in spending on RD&D on solar, wind, storage and grids.

The learning rate analysis presented in Section 2 suggests that there are diminishing marginal returns associated with spending on RD&D on renewables[43]. The logic of diminishing marginal returns means that any spending Programme investing less than the Apollo Programme would also deliver net benefits, (though these would be smaller than the benefits associated with the Programme).

Therefore, there are likely to be significant net benefits associated with the Mission Innovation proposals. Both the benefits and the costs would be smaller than those associated with the Apollo Programme.

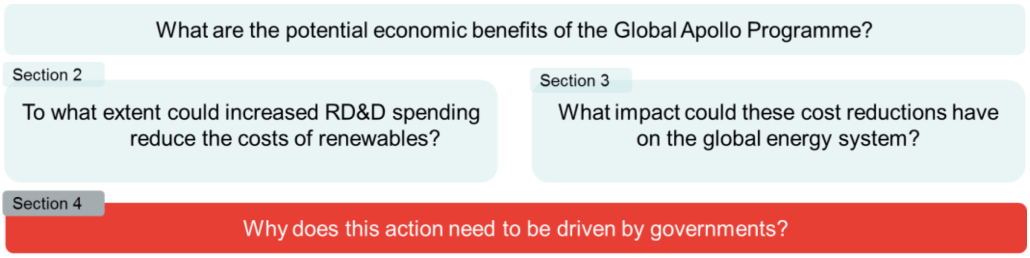
[42] http://mission-innovation.net/

[43] Learning rates apply for every doubling of the cumulative stock of RD&D. Therefore the more money that is spent on RD&D, the lower the additional returns.

4 THE NEED FOR COORDINATED GOVERNMENT INTERVENTION

We have shown that the potential benefits of increasing RD&D spending on renewables could be large. However, available data suggests that private spending on RD&D is low[44]. Given all the potential benefits, why is the private sector not investing?

In this section we describe the market failures that mean that government intervention is required to lead spending on RD&D at this time, and we look at why a coordinated approach between governments may help deliver this most efficiently.

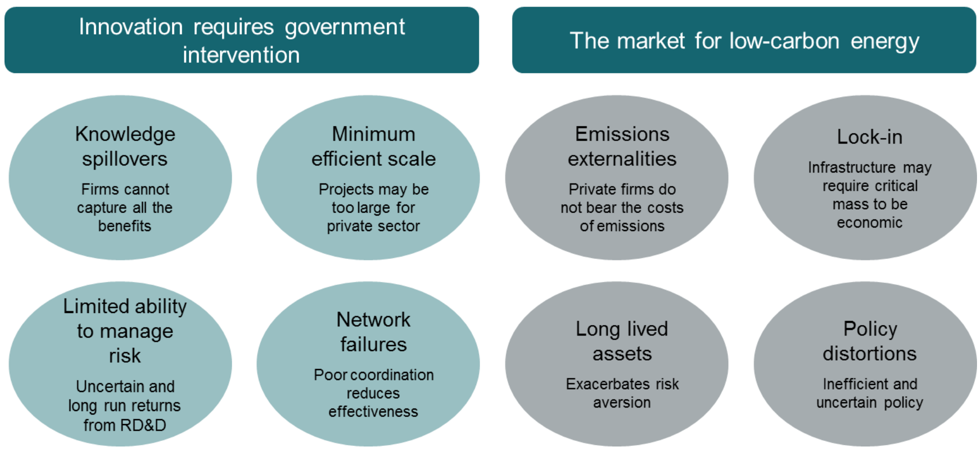


4.1 What market failures can reduce investment in renewables RD&D?

The characteristics of innovation in the renewables sector means that markets alone may not deliver the optimal amount of RD&D in renewables and associated technologies like storage and smart grids.

There are two types of market failures that will limit private investment in RD&D: those relating to innovation generally and those relating to low-carbon energy specifically (Figure 13).

Figure 13. Why is government intervention required?



Source: Frontier Economics

44 Approximately $6 billion was spent on electricity, gas and water supply in 2011 together. The amount spent on renewable technologies will only be a portion of this. This compares to the $20bn on renewable electricity alone that the Global Apollo Programme proposes to mobilise from governments. Source : OECD. Data includes all IEA members, except Switzerland, plus China, Taipei, Israel, Romania, Singapore and Slovenia

4.1.1 Market failures around innovation

Four types of market failures associated with innovation are identified in Figure 13.

- **Knowledge spillovers.** Knowledge spillovers occur when others benefit from the knowledge created by an innovator. These spillovers mean that businesses cannot appropriate the full returns from its investment. This will reduce the firm's potential rate of return on an RD&D project and will lead to underinvestment in RD&D.
- **Minimum efficient scale.** There is often a minimum efficient scale above which investments in RD&D become feasible. The private sector may not be able to take on really large projects, especially where financial market imperfections restrict credit availability.
- **Limits to firms' abilities to manage risk**. Firms can be risk averse and there is considerable uncertainty about the risks and rewards associated with the returns to RD&D. In addition, returns to RD&D investment can be slow to accrue. This long payback period means the investment will be at risk for a prolonged period. While investors have options for managing risk (such as diversifying their portfolio), these options are limited and imperfect[45].
- **Network failures**. Poor coordination between agents involved in RD&D investment may act as a barrier to innovation or make the process inefficient[46]. Inadequate knowledge networks may prevent the timely transfer of information between organisations, for example between the university conducting the research and the firm who will use it.

Without government intervention, these market failures will lead to underinvestment in RD&D.

4.1.2 Market failures around low-carbon energy

The barriers associated with investment in low-carbon energy innovation are even more acute.

- **Public goods and externalities.** The atmosphere is a global public good and greenhouse gas emissions are externalities. The growth of the low-carbon energy sector reduces carbon emissions but businesses do not directly benefit from these effects and so will undervalue RD&D in low-carbon energy. There are also further positive externalities associated with renewables, such as the health benefits associated with improvements in air quality.
- **Long asset lives**. Low-carbon energy investments are capital-intense and have long payback periods. This exacerbates the problems associated with risk management.
- Policy distortions. The long lifetime of RD&D projects in the energy sector also means that there is significant policy risk associated with policy priorities changing over time. Investors in RD&D in the low-carbon energy sector must face the risk that policy changes will limit profitability.
- **Stranded assets.** Firms have invested in fossil fuel-fired power plants and have less than optimal incentives to make them obsolete.

Without government intervention, these issues will exacerbate the problem of under-investment in low-carbon energy innovation.

[45] Arrow, K. (1962), 'Economic Welfare and the Allocation of Resources for Invention' in National Bureau of Economic Research, *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Princeton University Press, http://www.nber.org/chapters/c2144.pdf

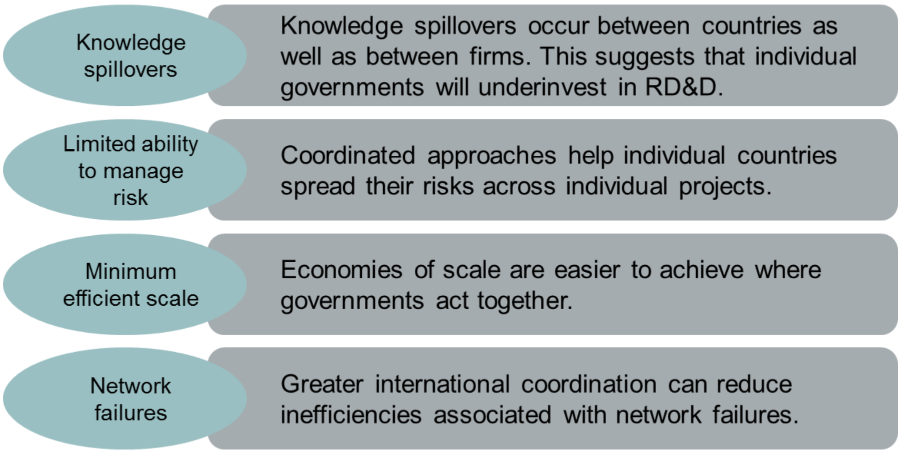
[46] BIS (2014), *The case for public support of innovation,* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/334369/BIS_14_852_The_Case_for_Public_Support_of_Innovation.pdf

4.2 Cooperation between governments

There will be underinvestment in low-carbon innovation in the absence of government intervention. However, the Global Apollo Programme is going further – it is specifically aiming to mobilise international coordination between governments. Are there additional benefits associated with this?

International coordination between governments can overcome the market failures associated with innovation more effectively than one government acting alone. This is illustrated in Figure 14. Essentially all the market failures that apply to firms can also be understood as either limiting the incentives for individual countries to invest, or reducing the effectiveness of each individual country's innovation investments.

Figure 14. Benefits to international coordination



Source: Frontier Economics

5 CONCLUSIONS

The Global Apollo Programme has the potential to deliver major global benefits.

- The Global Apollo Programme could deliver significant reductions in the costs of renewable energy. Our analysis suggests that the increased RD&D spending under the Apollo programme has the potential, under plausible, but relatively optimistic assumptions, to help reduce the costs of electricity generated by solar PV to below the costs of coal-fired electricity generation by 2025, (including grid and storage investments required to integrate solar PV into the electricity system). This would entail a fall in solar PV investment costs of 75% over today's cost levels. We also find that, even under more conservative assumptions, solar PV costs could fall between 37-57%, compared to today's levels.
- Major global benefits would be delivered by the Programme, even in the absence of any other climate policy. Even in the absence of any additional climate change policy, the Programme has the potential to have a transformational impact on the energy sector. In the scenario where the costs of solar fall below the costs of coal, solar could provide 26% of global generation by 2040, saving 10% of total global CO_2 emissions.
- The positive impact in a world where global governments sign up to a $2^{O}C$ climate target is likely to be extremely significant. Modelling by the Grantham Institute at Imperial College London, finds that the Programme could reduce the cost of meeting a $2^{O}C$ climate target by between $0.7-4.0 trillion out to 2040.
- These estimates are likely to represent a minimum. The benefits of the programme are likely to be even greater than this, as we have not estimated the wider benefits of innovation, such as impacts on productivity and spillovers to other sectors). We have also not attempted to value the wider benefits associated with an increase in renewables. For example, we have not valued the health benefits related to an improvement in air quality, and the social and economic benefits that may come with connecting more offgrid properties.
- Because of the market failures associated with innovation and climate change, this RD&D will not happen without government intervention. International coordination of this RD&D can further help overcome barriers.

While there is uncertainty over the scale of the cost reduction that could result, given the potential size of the benefits, this analysis suggests there is a strong economic case for implementing the Global Apollo Programme.

6 ANNEX 1: GLOBAL ENERGY SYSTEM MODELLING

This annex sets out the details of the modelling undertaken to estimate the impact on global mitigation costs of the Global Apollo Programme's proposal to increase investment in public research, development and demonstration (RD&D) for solar PV, wind, storage and smart grid technologies.

The modelling framework is based on the Grantham Institute at Imperial College London's TIMES Integrated Assessment Model (TIAM-Grantham).

TIAM-Grantham consists of a detailed energy systems model representing all major energy extraction, conversion, supply, distribution and consumption processes, coupled with a climate module which relates greenhouse gas emissions levels to global temperature change levels. This allows an assessment of the cost and technology implications of meeting different climate targets through substituting low-carbon energy technologies for existing, carbon-intensive technologies while meeting current and future world energy service needs.

In this assessment, TIAM-Grantham is used purely as an energy systems model, without the climate module. We have used it in in two ways.

- first, to consider the technology deployment and emissions implications of solar reaching cost parity with coal, in the absence of any other climate policy (Section 3.2); and
- second, to calculate the least-cost energy technology transition pathway that meets current and future energy service needs without exceeding a specified cumulative level of CO_2 emissions over the 21st century (Section 3.3). This level, at 1,340 $GtCO_2$ for emissions from fossil fuel combustion and industrial process emissions, has been calculated as consistent with a 50% likelihood of keeping global average temperature change in 2100 below 2^{O}C above pre-industrial levels[47]

6.1 Details of TIAM-Grantham

TIAM-Grantham is the Grantham Institute at Imperial College London's version of the ETSAP-TIAM model, which is the global, 15-region incarnation of the TIMES model generator, as developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP[48]). The model is a linear programming tool representing in rich resource and technological detail all elements of the reference energy system (RES) for each region represented, mapping energy commodity flows all the way from their extraction and refining to their distribution and end-use. TIAM has the ability to optimise the energy system for given climate constraints through either minimising the total discounted energy system cost over a given time-horizon, or through minimising total producer and consumer welfare when (optionally) accounting for elastic demand responses to energy prices. In the latter case, the model is solved as a partial equilibrium. There is no linkage to a macroeconomic model to observe full equilibrium impacts of changes in energy prices. The model uses exogenous inputs of factors such as GDP, population, household size and sectoral output shares to project future energy service demands across the agricultural, commercial, industrial, residential and transport sectors in each region. Energy system data such as technology costs,

[47] A detailed explanation of the methods used to relate cumulative CO_2 emissions to temperature is given in Gambhir A, et al (2015). 'Assessing the challenges of global long-term mitigation scenarios - AVOID 2 WPC2a,' www.avoid.uk.net

[48] ETSAP details, including further details of the TIAM model, are available at: http://www.iea-etsap.org/web/

resource supply curves and annual resource availability are also input into the model. In solving, the model allows trade in energy commodities between regions.

6.2 Methods to calculate the impact of the Global Apollo Programme

The overall process by which the impact of the Apollo programme on mitigation costs has been calculated is outlined in Figures A1 and A2, and consists of the following steps:

- First, input parameters such as energy demand growth and technology costs are specified. In Scenarios 1-3, and the central counterfactual scenario, cumulative CO_2 emissions limits are specified.
- Next, the energy system evolution over the remainder of the 21st century (starting from 2012, which is the model's calibrated base year) is simulated by TIAM-Grantham, with an objective to minimise the present cost of the energy system, while still meeting all future energy service demand. This minimisation is carried out subject to a CO_2 limit in Scenarios 1-3, whereas in Scenario 4 and the low solar cost counterfactual, no CO_2 limit is applied, in order to simulate the potential take-up of solar PV even in the absence of specific low-carbon policy support.
- Key model outputs are collated and analysed for the different scenarios (which differ in their assumptions on input costs for solar, wind and associated electricity storage and transmission and distribution network costs). For Scenarios 1-3, and the central counterfactual we are interested in the present value of the cost of the energy system and the deployment levels of the different energy technologies when there is a CO_2 limit in line with achieving the 2^{O}C goal by 2100. For Scenario 4 and the low solar cost counterfactual, we are interested in the deployment levels of solar PV in the absence of a CO_2 limit, as well as the impact of these levels of solar PV deployment on global CO_2 emissions.

Figure A1. Steps in the modelling process using the TIAM-Grantham model (Scenarios 1-3, and the central counterfactual)

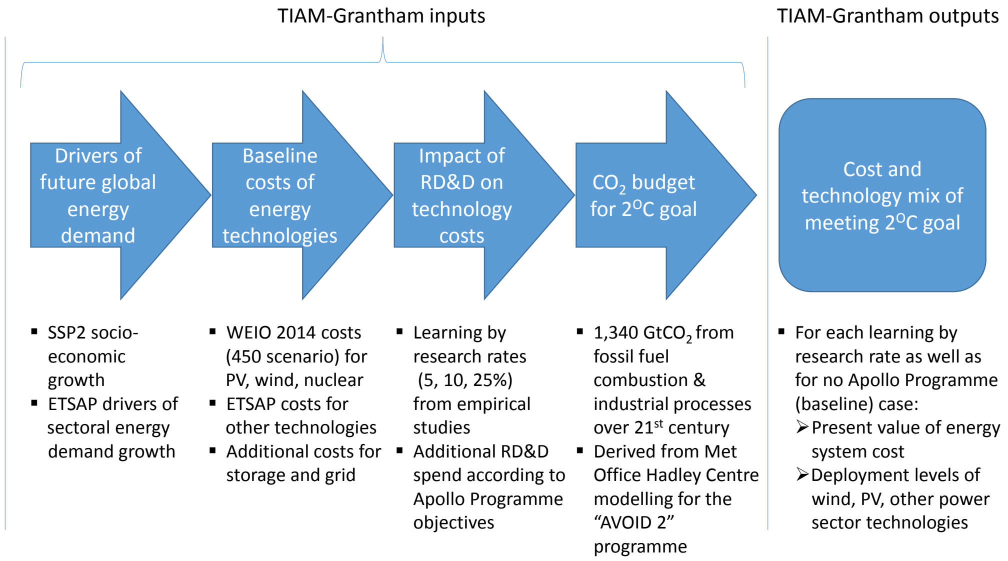
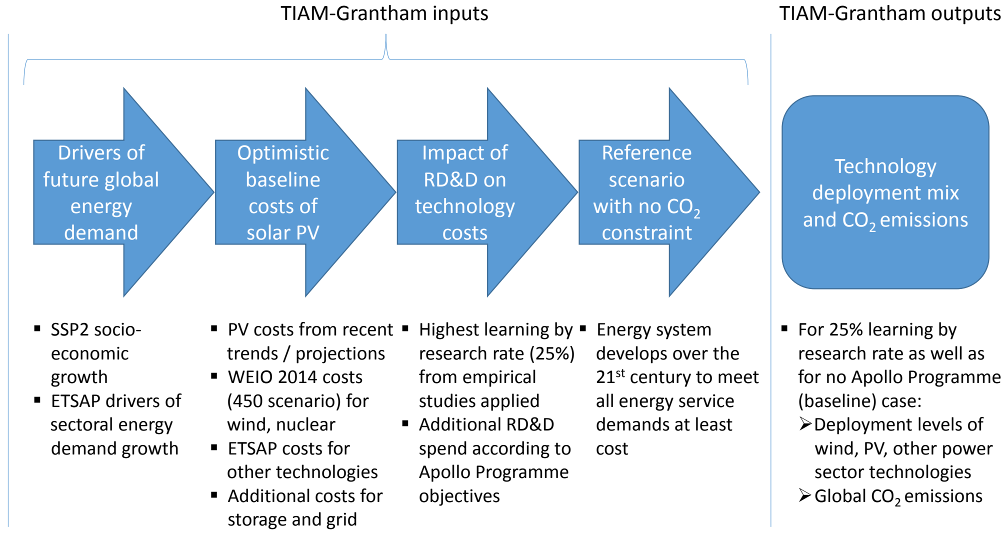


Figure A2. Steps in the modelling process using the TIAM-Grantham model (Scenario 4 and the low solar cost counterfactual)



Notes: SSP2 is one of the new shared socio economic pathways developed by the integrated assessment modelling (IAM) and impacts, adaptation and vulnerability (IAV) communities to define a limited set of standardised storylines on economic and population growth[49]. AVOID 2 is the current phase of the UK Government-funded AVOIDing dangerous climate change programme[50].

Input parameters

Input parameters of the model can be categorised in four areas (see Figures A1 and A2).

- **Drivers of Energy Demand in each region represented by the model.** Energy demand is driven by economic activity and population growth, in this study using socio-economic projections from the new Shared Socio-Economic Pathways (SSPs) initiative. Specifically, the second of the five scenarios (SSP2) has been employed, as this represents a "middle of the road" scenario which continues (broadly speaking) past trends in economic and population growth. As such, it is arguably the least normative of the SSPs. Factors relating these drivers to activity levels across the main economic sectors in each of the model's regions (such as industrial product demand, travel demand and building heating and other energy service demand) have been specified by ETSAP, the organisation which oversees the TIAM model's development and maintenance.
- **Baseline Costs of Energy Technologies.** For Scenarios 1-3, and the central counterfactual, capital costs and operation and maintenance (O&M) costs for solar PV, wind and nuclear energy are taken from the "450" scenario of the IEA's World Energy Investment Outlook (WEIO) 2014. For Scenario 4 and the low solar cost counterfactual, we take a more optimistic baseline cost trajectory for solar PV, as described in Section 2.1.1. Existing costs within the TIAM-Grantham model are used for the other technologies, since in general they match reasonably closely to the IEA data but there is a more detailed specification of technologies (e.g. several types of coal and gas plant). The WEIO 450 scenario accounts for cost reductions related to learning by deployment, and is tailored to achieve a $2^{O}C$ long-term limit to temperature increase. Two further steps have been taken in order to more fully specify wind and solar PV costs within the TIAM-Grantham model:

49 For full details of the different SSPs see: https://www2.cgd.ucar.edu/sites/default/files/iconics/Boulder-Workshop-Report.pdf and the SSP database at: https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about#

50 Full details of outputs to date at: http://www.avoid.uk.net/

- In TIAM-Grantham, decentralised and centralised electricity generation is distinguished. Compared to centralised technologies, decentralised power generation exhibits higher investment costs per unit of installed capacity. Since the WEIO published technology cost estimates do not account for this difference for wind technologies, we increase the capital costs by 15 % for decentralised wind, consistent with the literature[51].
- Given that wind and solar are intermittent technologies, an adequate capacity of electricity storage is important to balance electricity demand and supply, and additional grid integration costs are also required. There are as yet significant uncertainties around the energy storage requirement to adequately support intermittent renewable electricity generation – this depends on a number of factors including other technologies in the electricity system, the particular degree of complementarity between solar and wind resources, the size of the region over which the electricity system is based and the degree of demand side management. For this study, an overarching figure of 0.5 kW of electricity storage for each kW of intermittent (wind and/or solar PV) electricity generation is implemented, at a cost of $500/kW in the US, based on modelling for a scenario in which solar PV and wind together produce 90% of electricity generation across the US East Coast, with no loss of reliability compared to current systems[52]. In addition, each kW of solar PV and wind requires an additional $250/kW of grid integration investment[53]. Other regions' solar PV and wind investment costs are marked up as a result of additional storage and grid investment costs by the same percentage as in the US. These storage and grid cost mark-ups are reduced at a linear rate of 0.5% per year as a result of learning by deployment[54].

- **Cost Reductions due to RD&D being in the centre of the Apollo programme's goals.** For Scenarios 1-3, for each doubling of RD&D investment, different learning by research rates (5 %, 10 % and 25 %) are considered. A scenario without cost reductions due to RD&D investment (central counterfactual) serves as a reference. We assume that the effect of RD&D spending on cost reduction is delayed by three years in line with the literature[55]. This delay accounts for the time that is needed to implement and market an incremental innovation rather than a completely new technology. For Scenario 4 and the low solar cost counterfactual, we compare the impacts of technology costs with and without the Apollo programme, taking only the highest learning by research rate of 25% that has been found in the literature. As discussed in Section 2.1.1, this combination of optimistic solar PV baseline costs and the 25% learning by research rate allows solar PV to reach coal parity by 2025.
- **Carbon Budgets.** CO_2 limits are applied in Scenarios 1-3. A 2^{O}C goal (which means a median temperature increase of 2^{O}C above pre-industrial levels by 2100) requires a maximum global emissions level of 1,340 $GtCO_2$ from fossil fuel combustion and industrial processes over the 21st century. This carbon budget was calculated by the Met Office Hadley Centre for simulations for the AVOID 2 project[56]. A further assumption is imposed such that global

51 IRENA (2012), *Renewable Energy Technologies: Cost Analysis Series: Wind Power* https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-WIND_POWER.pdf; DECC (2013), *DECC Electricity Generation Costs* (https://www.gov.uk/government/collections/energy-generation-cost-projections

52 See Budischak et al, 2013: http://www.sciencedirect.com/science/article/pii/S0378775313000839

53 Based on the IEA's methodology to calculate intermittent renewables grid integration costs, available at: http://www.worldenergyoutlook.org/media/weowebsite/energymodel/Methodology_TransmissionDistribution.pdf

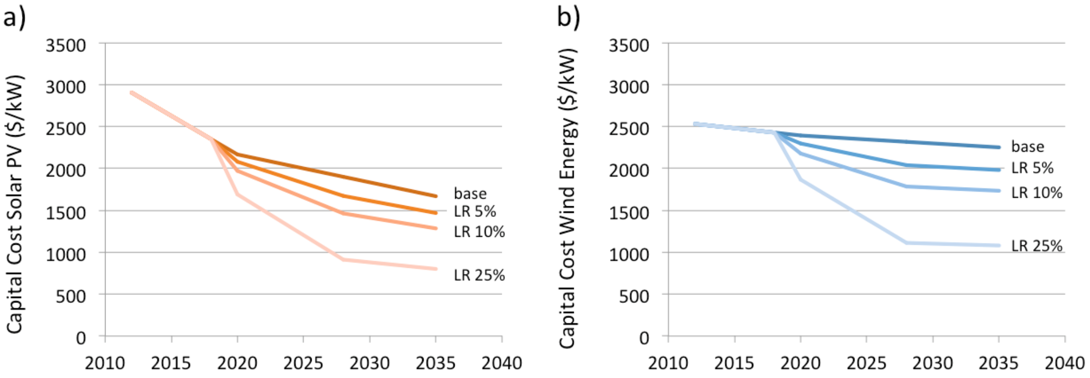
54 This is based on a combined learning-by-deployment rate of improvement for electricity networks and storage, from the LCICG Technology Innovation Needs Assessment (TINA), available at: http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/electricity_networks_storage/

55 Kobos et al. (2006), http://www.sciencedirect.com/science/article/pii/S0301421504004100; Klaassen et al. (2005), http://www.sciencedirect.com/science/article/pii/S0921800905000340; Söderholm and Klaassen (2007), http://link.springer.com/article/10.1007/s10640-006-9025-z

56 Gambhir A, et al (2015). 'Assessing the challenges of global long-term mitigation scenarios - AVOID 2 WPC2a,' www.avoid.uk.net

coordinated mitigation action towards meeting this CO_2 budget begins in 2020, before which each region's emissions develop in accordance with their unilateral Cancun 2020 pledges.

Figure A3. Capital costs for solar and wind for learning by research rates 5 %, 10 % and 25 % due to RD&D in Scenarios 1-3



Notes: The baseline scenario refers to the counterfactual (the case where the RD&D spending remains at the current level). Capital costs account for storage and grid costs.

TIAM-Grantham Output

Having defined all input parameters, the TIAM-Grantham model simulates the least-cost development of the global energy system commensurate with meeting future energy service demands in all regions and economic sectors.

For the Global Apollo Programme, Scenarios 1-3, and the central counterfactual are considered which satisfy the global CO_2 constraint to 2100:

- **Central counterfactual:** no learning by research over and above that assumed in the baseline technology costs;
- **Scenario 1:** a 5% reduction against baseline costs for each doubling of cumulative public RD&D;
- **Scenario 2:** a 10% reduction against baseline costs for each doubling of cumulative public RD&D; and
- **Scenario 3:** a 25% reduction against baseline costs for each doubling of cumulative public RD&D.

In addition, Scenario 4 and the low solar cost counterfactual are run without a CO_2 constraint:

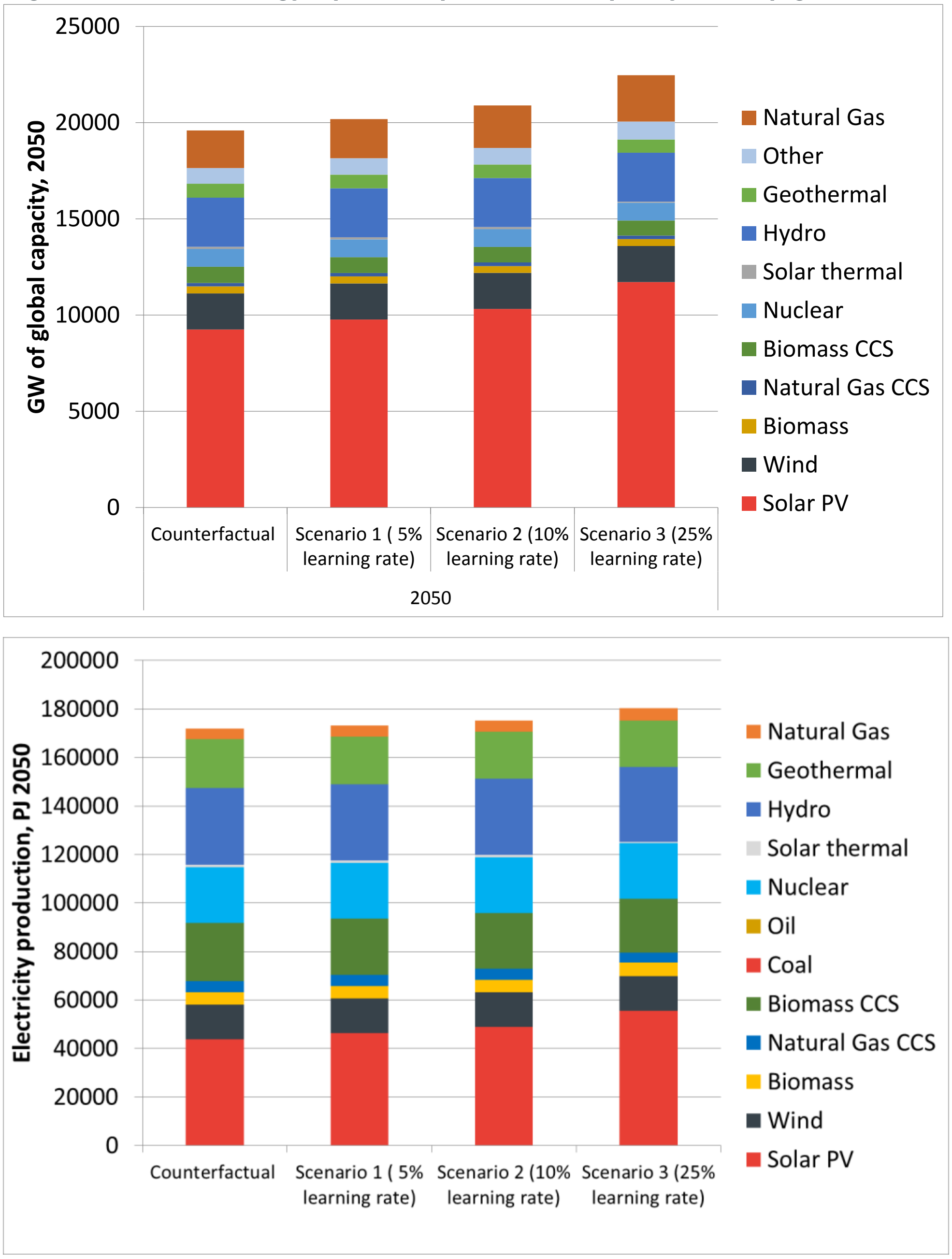
- **Low solar cost counterfactual:** with baseline costs as in Scenarios 1-3 except for solar PV, whose baseline cost trajectory falls more aggressively; and
- **Scenario 4**: a 25% reduction against these baseline costs for each doubling of cumulative public RD&D.

For Scenarios 1-3 and the central counterfactual, the model's outputs include the capacity of each major electricity generation technology deployed, electricity generation from each technology, and overall energy system costs. For Scenario 4 and the low solar cost counterfactual, key outputs are the capacity and generation of each electricity technology, as well as global CO_2 emissions. The model reports outputs in 10 year time steps (starting from a base year of 2012, then 2020, 2030 and so on to 2100). Outputs are linearly interpolated between these time points.

6.3 Results

Figure A4 shows the installed capacities and generated electricity for each major electricity generation technology. Higher learning by research rates reduce the capital costs for solar and wind resulting in more installed solar capacity by 2050. In 2050, solar PV provides the largest share of electricity in all cases. Wind, biomass with carbon capture and storage (CCS) and geothermal energy grow moderately until 2050[57]. Electricity from coal vanishes completely.

Figure A4. Technology specific a) installed capacity and b) generated electricity (2050)



Cumulative Discounted Energy System Costs are calculated (from 2015 until 2100 in $2005) using a discount rate of 5 % per year. The additional cumulative discounted energy system cost for the 2^{O}C scenario with baseline costs, when compared to the reference case with no mitigation, is $79 trillion over the 21st century. This corresponds to about 2.5% of cumulative discounted global GDP over the period 2015-2100. For learning by research rates of 5%, 10% and 25% the additional 2015-2100 cumulative energy system cost decreases by 3.3%, 6.5% and 17.2% compared to the 2^{O}C scenario with baseline costs.

[57] Note that by 2100 the capacity of solar and wind energy is about equal at around 30,000 GW

Extra RD&D Spending vs. Mitigation Cost Savings

Figure A5 relates the extra spending for RD&D to the cost savings achieved through decreased capital costs for solar and wind energy. Extra RD&D investment and mitigation cost savings are accumulated and discounted with a 5% discount rate. Cost savings are defined as the difference between the scenario without increased RD&D spending and the scenarios with learning by research rates of 5%, 10% and 25%. For learning by research rates of 5%, the investment in RD&D breaks even in 2026. Higher learning rates decrease the mitigation cost further. For a learning rate of 25% the break-even point is in 2022.

Figure A5. Cumulative discounted RD&D spend and mitigation cost saving due to reduced energy system costs related to lower capital costs for wind and solar for learning rates of 5 %, 10 % and 25 % ($2013)