A Climate Risk Report

Climate Solutions 2: Low-Carbon Re-Industrialisation

A report to WWF International based on the Climate Risk Industry Sector Technology Allocation (CRISTAL) Model

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Climate Risk Pty Ltd provides specialist professional services to business and government on risk, opportunity and adaptation to climate change.

www.climaterisk.net

Climate Risk

WWF

Climate Risk Pty Limited (Australia)
Sydney: + 61 2 8243 5767
Brisbane: + 61 7 3040 1621
www.climaterisk.net

Climate Risk Europe Limited
London: + 44 752 506 8331

This report was prepared by:

Dr. Karl Mallon
karl@climaterisk.com.au

Dr. Mark Hughes
mark@climaterisk.com.au

Sean Kidney
sean@climaterisk.net

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This report was commissioned by:

WWF-Australia
Level 13, 235 Jones Street
Ultimo NSW 2007
Australia
Tel: + 61 2 9281 5515
Fax: + 61 2 9281 1060

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For WWF International correspondence:

Dr. Stephan Singer
Director, Global Energy Policy Program
WWF International
c/o WWF European Policy Office
168 Avenue de Tervueren
Brussels 1150
Belgium
Tel: + 32 2 743 8817
ssinger@wwfepo.org

Climate Risk Team

Dr. Karl Mallon

Dr. Karl Mallon is director of Science and Systems at Climate Risk Pty Ltd. He is a First Class Honours graduate in Physics and holds a Doctorate in Mechanical Engineering from the University of Melbourne. Karl has worked in climate change and energy since 1991, and is the editor and co-author of "Renewable Energy Policy and Politics: A Handbook for Decision Making", published by Earthscan (London). He has worked as a technology and energy policy analyst for various international government and non-government organisations since 1997. As an invited expert consultant, he participated in the World Bank Extractive Industries Review. Karl specialises in both climate change mitigation and adaptation, working closely with global insurers on managing emerging commercial hazards.

Dr. Mark Hughes

Dr. Mark Hughes heads the Industry and Modelling Section of Climate Risk Pty Ltd. Mark holds a doctorate in Materials Science from the University of Cambridge and a First Class Honours degree in Materials Engineering. He has been awarded research fellowships with Darwin College (University of Cambridge), the Chevening Technology Enterprise Program (London Business School and Imperial College), the Oppenheimer Trust and the Commonwealth Trust. Since 1999, he has been based in the field of energy storage and the environment, and is author of a range of peer-reviewed publications in internationally distributed journals. Mark has also worked on commercialisation and fundraising for new technologies in the energy sector.

Sean Kidney

Sean is the London-based Europe manager for Climate Risk as well as the strategy and social marketing consultant to the EU's new European Web Site on Integration. Sean has 25 years experience as a social change strategist. He has been an advisor to governments, non-government organisations and pension funds, particularly in the areas of organisational development, marketing and communications and political lobbying. Sean has worked extensively with the Australian pension fund sector on marketing and communications, winning a dozen Combined Major Superannuation Fund awards. His current focus is on climate change and the intersection between the interests of long-term capital and the progress of economic and social evolution.

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Foreword

We are poised at a decisive moment in our planet's history. In a few weeks, the Copenhagen climate change talks will seek to set the foundation stone for the world's response to man-made climate change.

The progress of climate change has not paused while our leaders have debated the issues over the past decades. The clock has continued to tick, inexorably counting down to the moment when, even if we do act, it may be too late to avoid runaway climate change.

Climate Solutions 2 models this point of no return. It shows that the constraints of our industries, working in a market economy, leave us with just five years before the speed of transition required puts a viable solution beyond our reach. No matter how strong our desire for a transformation to a low-carbon world may be, the ability to make this transformation is restricted by available resources, manpower and technologies. That is why we only have until 2014 to set the wheels in motion. Beyond this, a "war-footing" may be the only option remaining, with no guarantee of success.

If we started today, the transformation required to move to a low-carbon world would need to be greater than any other industrial transformation witnessed in our history, but research shows that it can be achieved. This report not only indicates the size of the challenge, it shows us how it can be met and how we can proceed to a clean energy future. It also highlights the extraordinary opportunities for those investors and countries that move early.

Historically, economic revolutions have always created opportunities for those with the vision to move early and have left behind those countries and industries that came to the revolution late. The 19th century industrial revolution improved the condition of the poor, made roads and railways commonplace and profoundly shifted world power. More recently, the IT revolution transformed the way the world does business and communicates.

The climate change revolution must be a transformation on an even larger scale.

The analysis in this report indicates that, to achieve a low-carbon world the growth of low-carbon industries will have to be substantial year-on-year, worldwide and persist for at least 40 years to reach full delivery. Such growth will produce new jobs on a scale rarely seen and many opportunities for savvy investors to get in at the ground floor on industries that could be taken up around the world.

Even now, the broader benefits of a low-carbon world are clearly apparent. For the first time in our history there is potential for every country in the world to have secure energy and the modelling shows that, in the long run, the energy we consume will be cheaper as well as cleaner.

However, for this new and prosperous world to materialise itself, our leaders must act for the good of all. The Copenhagen climate change conference is a pivotal moment where the future of the entire world is held in the hands of a few.

This report shows that we need our leaders to come together constructively, to act with unity and towering ambition but, most important of all, to act now.

James P Leape
Director General, WWF International

Preface by WWF

The time for action is now. *Climate Solutions 2* shows that if we do not start moving towards a low-carbon world in the next five years then runaway climate change may be inevitable. This report cuts straight through the equivocating that surrounds the debate on climate change. It offers a powerful warning about the results of inaction, while pointing the way to extraordinary industrial growth and cost reductions if we respond quickly to the climate crisis.

According to *Climate Solutions 2*, if we do not have critical low-carbon industries under accelerated development by 2014, then we could miss the greenhouse gas targets needed to avoid runaway climate change. Even if we were to immediately respond to this warning and start growing our low-carbon energy, industrial and agricultural industries today, they would still have to grow by 24% every year. If we dare to wait until 2014, the rate of change necessary increases to about 30% every year, pushing the limits of viable long-term industrial growth.

Historically, sustained long-term growth rates of greater than 20% a year are rare – even in times of crisis such as during wars – because the speed of industrial change remains largely inflexible and has always been limited by available resources, labour, skills, capital and equipment. Fortunately, *Climate Solutions 2* shows that this rapid change is still possible if we put in place the policies and resources required. Substantial savings and prosperity are also associated with creating the new low-carbon economy.

This report refutes the myth that a rapid change to a low-carbon society will cripple international treasuries. It shows that the economies of scale created by accelerating into a low-carbon world will deliver vast savings compared to the business-as-usual approach.

However, this transformation requires more than a carbon price, which, by itself, will not drive the change that is needed. It also requires investment in "all" low-emissions industries now – large and small – even if we have to wait two or three decades before these industries become independently competitive. Governments need to create incentives so these industries are low risk and attractive for private sector investors. Investors are eagerly awaiting regulatory certainty so they can become involved in this modern industrial revolution.

The warnings both in this report and throughout the world around us are loud, clear and urgent. The world's weather patterns are changing, bringing drought and floods on an unprecedented scale. At the same time, our oceans grow more acidic. It is increasingly clear that climate change is already affecting us all. But equally – as *Climate Solutions 2* shows – should we have the courage and foresight to commence building our low-carbon economies now, we can avoid runaway climate change and positively transform our world for ourselves and the generations to follow.

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Executive Summary

Re-Industrialising to a Low-Carbon Economy

This report models the ability of low-carbon industries to grow and transform within a market economy. It finds that runaway climate change is almost inevitable without specific action to implement low-carbon re-industrialisation over the next five years. The point of no return is estimated to be 2014.

Climate Solutions 2 recognises that every industry has constraints on its ability to grow caused by limitations of resources, technology, capital and the size and skills of its workforce.

These limits are measurable and make it possible to calculate, with considerable sophistication, the speed required to re-industrialise the energy and non-energy sectors to create a low-carbon economy in time to prevent runaway climate change.

Climate Solutions 2 accesses historical data and uses a variety of models to reach its conclusions. Two scenarios have been considered in this report:

- Emissions cuts of 63% relative to 1990 levels; and
- Emissions cuts of 80% relative to 1990 levels.

Under both scenarios, every key low-carbon resource and industry must be under their maximum rate of development by 2014. For the 63% reduction scenario, each of these resources and industries must grow at between 22% and 26% every year until they reach a scale that provides reasonable certainty of achieving the necessary global emissions levels by the mid-century.

In the second scenario, there is a significantly better chance of avoiding warming of 2°C if emissions levels are 80% below 1990 levels by 2050. However, to achieve this outcome requires the re-industrialisation process to commence immediately with growth rates of between 24% and 29% every year until deployment scale has been achieved. In addition, emissions abatements from the forestry and energy efficiency sectors must be at the upper end of what is technically possible.

The good news is that the resulting economies of scale from these low-carbon revolutions will create major long-term savings and returns when compared to the business-as-usual trajectory, especially in the energy sectors.

Where We Are Now

Higher Atmospheric Greenhouse Gas Levels than Expected

The current level of carbon dioxide in the atmosphere is 386 ppm (parts per million) while the total greenhouse gases are estimated to be 463 ppm (Tans 2009). This is precariously close to the approximate 475 ppm upper limit (for greenhouse gases) that current literature predicts makes it possible to return to a stable 400 ppm (Meinshausen 2006). Beyond this level, runaway climate change grows increasingly likely. At present, the rate of increase in atmospheric carbon dioxide has not yet begun to slow and, in fact, may be accelerating.

The Development of Low-Carbon Industry is Too Slow

This report clearly identifies that the key constraint to meeting emissions levels needed to prevent dangerous climate change is the speed at which the economy can make the transformation to low-carbon resources, industries and practices. Today, only three out of 20 industries are moving sufficiently fast enough.

There are Less Than Five Years to get Low-Carbon Re-Industrialisation Underway

To avoid major economic disruption, the report's modelling indicates that world governments have a window that will close between now and 2014. In that time they must establish fully operational, low-carbon industrial architecture. This must drive a low-carbon re-industrialisation that will be faster than any previous economic and industry transformation.

Carbon Trading Schemes, Alone, are Not a Sufficient Solution

By itself, an emissions trading scheme will not promote the growth of important but initially higher-cost technologies. A comprehensive plan for low-carbon industrial development is an integral part of the solution. If this window is missed then economically disruptive "command-and-control" style government intervention will be necessary to focus industrial production on the climate change challenge.

How to Achieve a Low-Carbon Economy

The Industries that will Lead the Way

Clean energy generation, energy efficiency, low-carbon agriculture and sustainable forestry must lead the transformation to a low-carbon economy. It is important to note that solutions that extract and store carbon from the atmosphere and biosphere, such as biomass energy production with carbon capture and storage (CCS), have not been used as part of the suite of resources in this report but are likely to be required at some stage if constraints on fuels can be resolved.

Rapid Expansion of Clean Industries

This report's modelling shows that to get key industries to a sufficient scale of deployment, from 2010 they will need to grow by 22% every year in the minus 63% scenario and by 24% every year in the minus 80% scenario to achieve the necessary cuts on 1990 levels. The scale of this re-industrialisation cannot be underestimated. Every year of delay will increase the level of growth required and increase costs.

Should re-industrialisation be delayed until 2014, low-carbon industries would need to sustain an annual growth rate of about 29% to have a greater than 50% chance of avoiding 2°C of global warming. This upper rate appears to be the limit of plausible sustained industrial growth, so further delays will tip the probability in favour of runaway climate change and its consequences.

Stable Investment Environments

Low-carbon re-industrialisation will require each government to create a secure, long-term investment environment to allow for major increases in the scale of production and installation of low-carbon technologies. This includes technologies and resources that will take two or more decades to reach commercial viability.

Investing in a Low-Carbon Economy — Costs and Returns

Long-Term Investment

Transforming to a low-carbon economy will require substantial investment in resources and infrastructure. Many of these investments will eventually become commercially viable in their own right.

The investment required to cover the additional cost of renewable energy relative to fossil fuel energy is about US$6.7 trillion in the minus 63% scenario and US$7.0 trillion in the minus 80% scenario. If the ongoing costs of CCS out to 2050 are also included, these costs would be increased by as much as US$10 trillion.

The modelling indicates that annual expenditure will peak at around US$375 billion a year in the minus 63% scenario and US$400 billion a year for the minus 80% scenario by 2025 and then start to decline. With sufficient up-front capital, energy efficiency measures will be cost-effective immediately or over a very short time period. Forest and CCS initiatives will require ongoing funding.

Since global agreements on emissions and carbon pricing are not yet in place, this report takes the conservative stance of applying no carbon pricing for the minus 63% or minus 80% scenarios.

Tipping Point into Profit

Within the period from 2013 to 2049, the average production cost of each renewable energy technology around the world is forecast to become cheaper than energy produced from their fossil fuel competition. In countries with high energy prices, this renewable energy cross-over will occur soonest.

Returns on Investment

Government, industry and institutional investors can expect to see the benefits of their investment in transforming the energy sector from 2013. This is the point when the first of the renewable energy technologies starts to outperform the current fossil fuel, business-as-usual model.

The scale of renewable energy savings from 2013 to 2050 is expected to be in excess of US$41 trillion for the minus 63% scenario and US$47 trillion for the minus 80% scenario.

Implications for Government, Industry and Investment

This report indicates that to avert runaway climate change, an international agreement on greenhouse emissions must be augmented by a program to rapidly develop a broad suite of low-carbon industries. This program must develop all low-carbon energy sectors concurrently – even those not initially profitable – and on an unprecedented scale. This means that:

- The private sector must be prepared for a massive scale-up of the low-carbon sector and not stand in the way of this transformation. It must deliver cost reductions through economies of scale.
- The investment community must commit tens of trillions of dollars, but can be rewarded with secure substantial long-term returns.
- Governments must create a stable long-term investment environment that fosters a secure market for all low-carbon industries and their investors.

Explanation of Major Findings

The Implications of an Upper Limit to Industrial Growth

A central axiom of the modelling in this report is that there are real-world limits to the rates at which companies and their industries can grow. In the energy sector, growth rates of less than 5% are typical. In the new, renewable energy sector, only a few industries have been able to sustain growth rates above 20% for long periods.

The real-world constraints to industrial growth include access to skilled people, access to resources, access to plant and machinery for manufacturing, installation and operation, and access to capital for both manufacturing and projects. Rapid growth can be just as hazardous for a company and industry as inadequate growth. Therefore, it is important when modelling the growth of low-carbon industries to establish a plausible upper limit of growth for companies and industries participating in a very rapid low-carbon re-industrialisation.

This upper limit reflects the point at which companies are likely to either fail due to excessive growth or turn away opportunities in order to maintain stability.

In this report, 30% annual average growth is considered to be the upper limit of sustained industry growth in a free market. Beyond this limit, the delivery of consistent growth is not plausible.

Under a "command and control" scenario – typically only observed during times of war – it may be possible to achieve annual growth rates slightly beyond 30% by forcing the reallocation of resources. However, since most renewable energy industries rely on specialised skills, equipment and materials, any benefits obtained by such forced resource reallocation are likely to be limited.

The 30% upper limit to industry growth used in this report reveals a very limited window of opportunity and, therefore, very little margin for policy error. Initially, delays in establishing low-carbon industries can be compensated by increases in the growth rate. However, at some stage these delays will no longer be able to be recovered by growth rate increases (when they reach their upper limit) and this will inevitably lead to delays in delivering

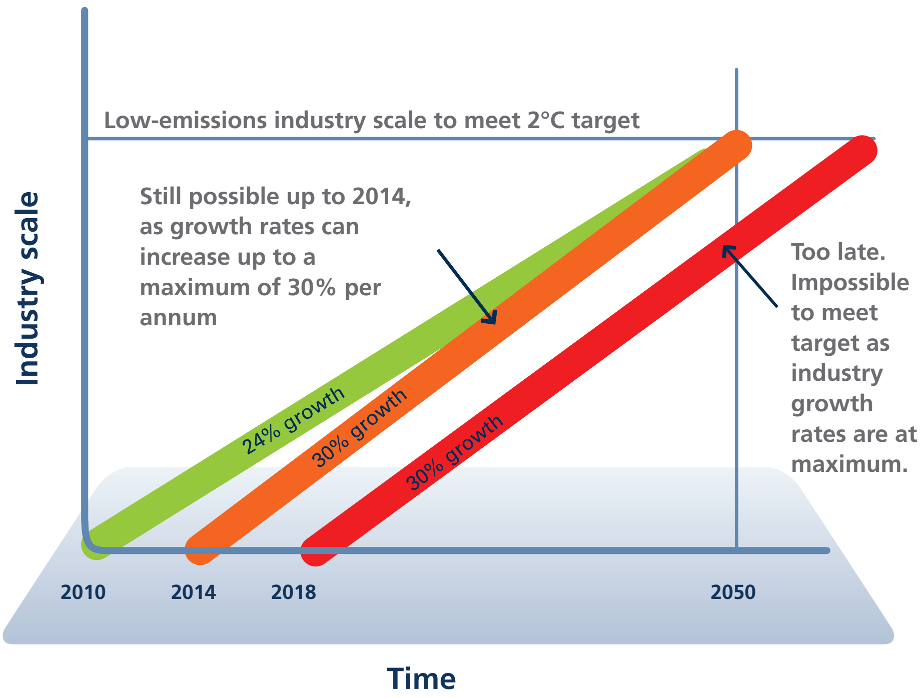


Figure 1: Missing the target. This schematic diagram illustrates that initial delays can be made up by increased growth rates. However, when the upper limits to growth are reached, further delays result in a shortfall in deployment in later years.

the low-carbon outcomes (see Figure 1). The consequence of such delays will be a failure to meet the cumulative and annual emissions reduction objectives needed to prevent runaway climate change.

The modelling indicates that it is still possible to achieve emissions levels that are 80% below 1990 levels by 2050. Reaching these levels creates a high probability of avoiding global warming of 2°C. To achieve an 80% reduction by 2050 requires immediate low-carbon industrial development growth rates of 24% every year until large-scale deployment has been achieved. At the same time, countries must maximise all plausible emissions abatement opportunities in the forestry sector and boost the adoption of energy efficiency measures.

This report finds that if re-industrialisation across all low-carbon sectors – including clean energy, forestry and agriculture – does not get underway until after 2014, then the probability of exceeding 2°C of warming and the risks of runaway climate change occurring will exceed 50%.

For all emissions abatement scenarios examined in this report, it is assumed that there are no major changes in population growth, GDP growth or fundamental lifestyle choices. If such activities were curtailed over the long-term, the low-carbon industry growth rate requirements reported here may be eased somewhat.

The Inadequacy of Trading/Carbon Price Alone

Should the development of low-carbon industries be unduly delayed, the constraints on industrial growth will create a situation where industrial production cannot respond to price signals from the market. That is, despite an increasing price for carbon, the industries most able to provide abatement at those prices will not be sufficiently developed or able to grow fast enough to meet the demand. They will be constrained by shortages of skills, materials and production output.

One foreseeable cause of delay is the exclusive use of price-based mechanisms like emissions trading. These mechanisms support the development of least-cost industries first, essentially fostering a sequential industrial development process.

This report compares a sequential development scenario with a concurrent development scenario. The comparison reveals that for the sequential approach, emissions levels in 2050 are more than double those in the concurrent case when using the same industry growth rates (see Figure 2).

Even if price-based mechanisms like emissions trading were accompanied by policies that ensured the sequential development of low-carbon industries, there would still be a need for investment in the early stages of development. Figure 3 shows that even for high carbon prices there is still a cost shortfall for low-carbon energy generation relative to that of fossil fuels that would need to be met by investment of some kind.

Investment and Returns

Changes in energy prices, driven by economies of scale, will be an intrinsic component of low-carbon re-industrialisation. For example, currently renewable energy technologies generally cost more than fossil fuel-based energy and are, therefore, priced out of the market. However, once renewable energy technologies are driven to larger scales, this situation reverses.

Since the fuels for renewable technologies (i.e. biomass, wind, sun, etc.) are obtained at zero or low cost, the core cost stems from building plants to extract that energy. Empirical evidence provides a reliable guide to the decline of future costs.

By contrast, fossil fuel costs are likely

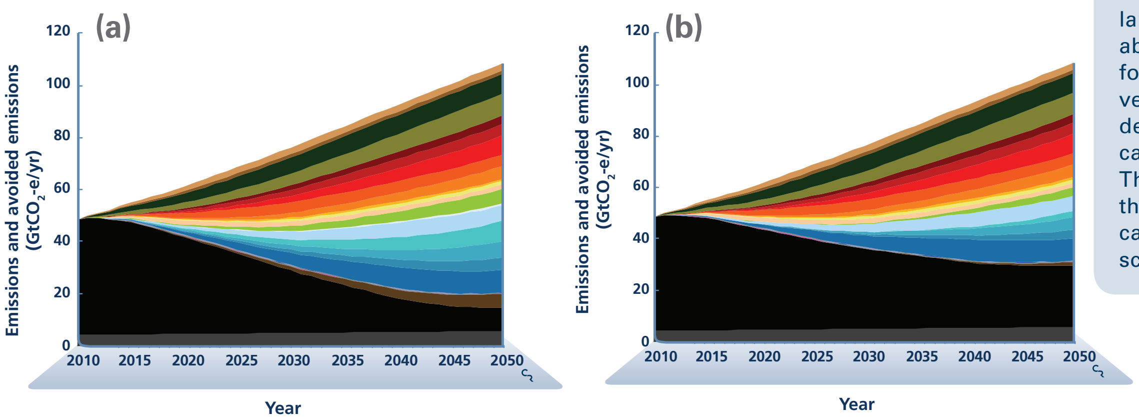


Figure 2: There is a large difference in the abatement outcomes for (a) concurrent versus (b) sequential development of low-carbon industries. This figure illustrates the difference in the case of the minus 63% scenario.

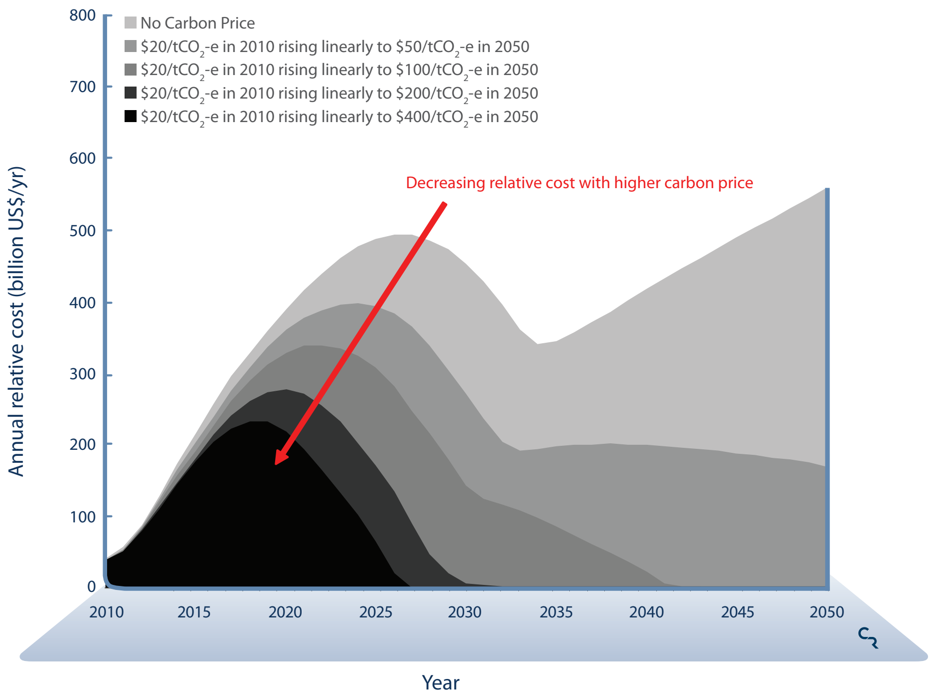


Figure 3: The impact of various carbon prices on the annual cost of low-emissions energy generation industries relative to fossil fuels in the minus 63% scenario. This annual relative cost approximates the amount of investment required for all low-carbon energy generation industries (including CCS). This figure shows that even high carbon prices do not overcome the interim cost-shortfall of low-carbon energy generation.

to increase in price due to rising fuel extraction costs and the cost of managing greenhouse gas pollution. *Climate Solutions 2* assumes that fossil fuel prices will increase by 2% every year but does not include a cost of carbon.

In this report, the point at which the first renewable energy industries, such as wind and small hydro power, start to create net savings is 2013 (assuming no retardation of learning rates). By 2049, all major renewable resources will be able to provide energy at, or below, those costs projected in the business-as-usual scenario. The final resources projected to cross the viability line are wave and ocean energy generation.

In many countries with higher energy prices, the savings will start being realised much earlier.

This presents a long-term investment picture in which short-term price support to achieve economies of scale is repaid with long-term returns from the cost savings (see Figure 4). This type of investment and return profile is most appropriate for institutional and pension fund investments. It may also lend itself to the use of "climate bonds" – structured by governments, investors and industry specifically to support this process.

Conclusions

The current trajectory of global greenhouse gas emissions is on course to trigger tipping elements that are forecast to unlock runaway climate change.

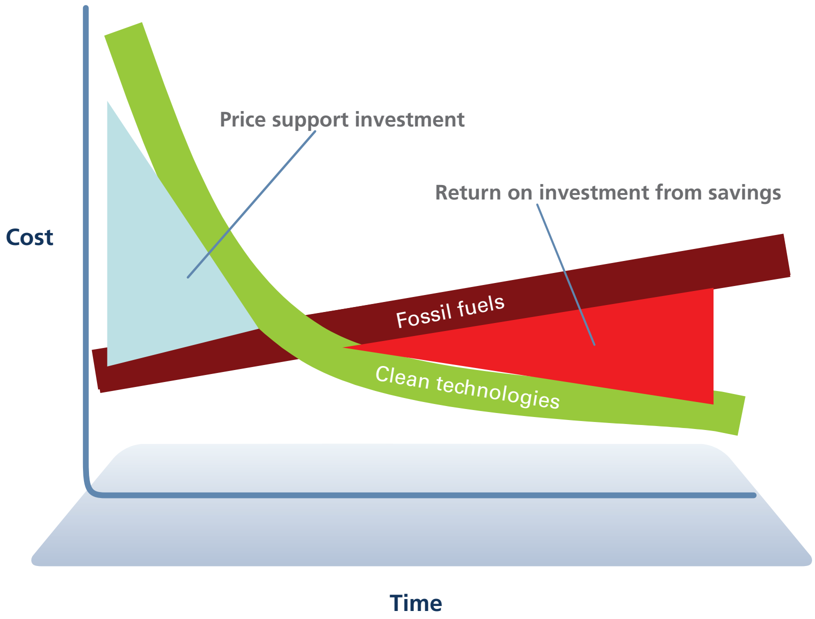


Figure 4: Short-term price support for renewable energy technologies to achieve economies of scale will result in long term cost savings.

However, a small but rapidly closing window of opportunity remains to prevent this eventuality. This window is defined by the time needed to develop and deploy low-carbon industries at a scale that will prevent a 2°C rise in global temperatures. In order to proceed through this window of opportunity, the process of low-carbon re-industrialisation must be at full speed no later than 2014.

Beyond 2014, this report finds that there is a "point of no return", where market-based mechanisms cannot be expected to meet the abatement requirement. At this point, the probability of runaway climate change is considerably greater than the probability of keeping the global average temperature from rising more than 2°C.

This finding has important policy implications and opportunities.

- Policy implications: 24 critical low-carbon resources and industries will be needed to meet the required emissions target. This implies that schemes such as carbon pricing and trading – which foster development of one technology after another, with least-cost technologies being activated first – are not sufficient by themselves. Instead, international policy is required to simultaneously drive the worldwide ramping up of the full suite of low-carbon industries and practices identified in this report.

- Opportunities: The good news is that the resources, technologies and industries required for the transformation are all available; the rates of growth are plausible and the trillions of dollars of investment required are within the capacity of the institutional investment sector.

Climate Solutions 2: Low-Carbon Re-Industrialisation

1 Objectives

The objectives of the modelling undertaken in this report are five-fold:

I. Determine whether it is possible to avoid runaway climate change.

II. Establish the time window available to commence the re-industrialisation of low-carbon industries required to avoid runaway climate change.

III. Determine the critical industrial constraints that must be overcome to provide the necessary emissions levels that will avoid runaway climate change.

IV. Compare the costs of low-carbon re-industrialisation versus the costs of business-as-usual development.

V. Identify the implications of the findings for governments, industry and the private sector.

Placement of the Scenarios in terms of Avoiding 2°C of Warming

The minus 63% scenario (Scenario A) has a global 2050 emissions level of 14.7 $GtCO_2$-e per annum (equivalent to 1.6 tCO_2-e per person per annum) and cumulative emissions between 2000 and 2049 of 1664 $GtCO_2$-e.

For the minus 80% scenario (Scenario B), the 2050 emissions requirements are 7.9 $GtCO_2$-e per annum (equivalent to 0.9 tCO_2-e per person per annum) and cumulative emissions between 2000 and 2049 are constrained to 1432 $GtCO_2$-e.

In order to put these figures within the context of the latest estimates of the emissions levels required to avoid 2°C of warming, Table 1 sets out the scenarios modelled by Meinshausen's team (Meinshausen *et al.* 2009). The scenarios used in this study are placed within the table, with the associated exceedance probabilities calculated by interpolation and extrapolation (and marked with an asterisk). The results are also shown graphically in Figure 5 and Figure 6.

Table 1: Probabilities for avoiding 2°C of warming for a range of annual emissions in 2050, and cumulative emissions over the first half of the century. The two scenarios used in this study have been added into the table by interpolation and extrapolation (and are marked with asterisks).

Global Emissions in 2050	Per Capita Emissions	2°C Exceedance Probability Low	2°C Exceedance Probability Default	2°C Exceedance Probability High
7.9 (Scenario B)	0.9	4*	13*	29*
10	1.1	6	16	32
14.7 (Scenario A)	1.6	10*	24*	40*
18	2.0	12	29	45
20	2.2	15	32	49
36	3.9	39	64	82
	Cumulative Emissions 2000–2049 (CO_2-e)	2°C Exceedance Probability Low	2°C Exceedance Probability Default	2°C Exceedance Probability High
	1356	8	20	37
Scenario B	1432	9*	23*	40*
	1500	10	26	43
Scenario A	1664	15*	32*	50*
	1678	15	33	51
	2000	29	50	70

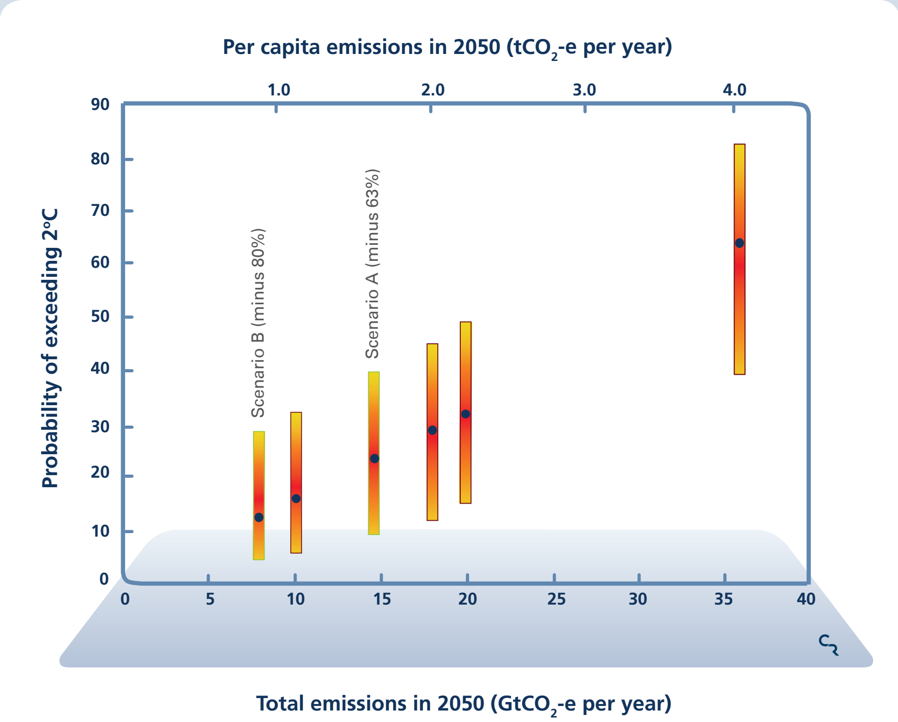


Figure 5: Exceedance probability range for various 2050 annual emissions levels (Meinshausen *et al.* 2009); the minus 63% and minus 80% scenarios used in this project are included by interpolation and extrapolation. Note that the x-axis is provided in both global annual emissions and per capita emissions assuming a population of 9.2 billion in 2050.

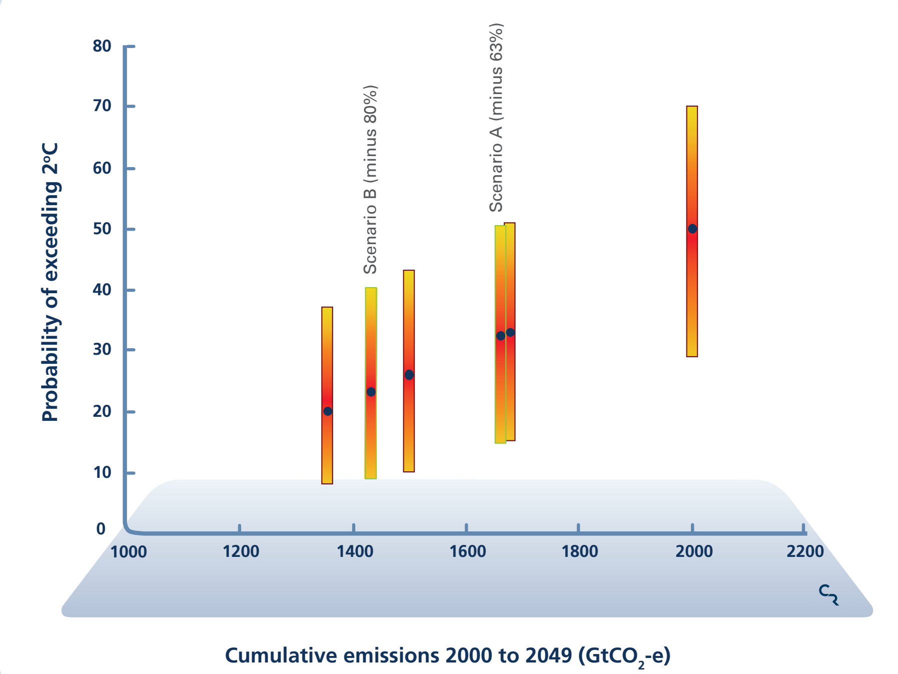


Figure 6: Exceedance probability range for various cumulative emissions levels in the half century to 2050 (Meinshausen *et al.* 2009); the two scenarios used in this project are included by interpolation.

2 Method

2.1 Step 1: Establish Threshold of Runaway Climate Change

An emerging scientific consensus finds that negative feedbacks in the climate systems will, at some level of warming, be surpassed by positive feedbacks. By accelerating climate change, these positive feedbacks would cause the current climate to flip to a different climate regime. This step of the report seeks to establish the level of warming beyond which a major change in the climate regime is likely to occur. Once established, this information can be used to explore how runaway climate change and its consequences – which are likely to be beyond the adaptive capacity of society, economies and the environment – may be avoided.

2.2 Step 2: Establish Gross Carbon Budget and Required 2050 Emissions Levels

This step aims to establish, based on current scientific opinion, the carbon budget consistent with avoiding warming levels that could lead to runaway climate change (as per step 1). This step includes identifying future emissions levels that are consistent with this gross carbon and greenhouse gas emissions budget.

2.3 Step 3: Establish the "Reducible Carbon Budget" (After Irreducible Emissions)

Some activities that contribute to the global economy have associated emissions that cannot be reduced beyond a certain limit without decreasing the activity or changing lifestyle (e.g. dietary habits cause methane emissions from livestock digestive processes). Once these "irreducible emissions" are identified and quantified, they are pre-allocated from the gross carbon budget. This yields a remaining "reducible carbon budget" for allocation across all sectors of the economy. The CRISTAL model is capable of distributing the reducible carbon budget in any proportion between various sectors. Where possible, the modelling methodology assumes that all current activities in the global economy are maintained through to 2050, consistent with future consumption estimates.

2.4 Step 4: Establish the Baseline of Energy and Non-Energy Demand

This step establishes future demand and emissions baselines. Future emissions levels will be significantly determined by energy and non-energy demand as they evolve with population, economic activity (GDP), wealth and consumption. This step uses these elements to establish demand baselines. These baselines can be adjusted to take into account the effects of climate change that may, for example, impinge on agricultural production and levels of prosperity.

2.5 Step 5: Establish Data for Relevant Industries, Growth and Resources

This step establishes which low-emissions industries and resources are available to meet baseline demand (see step 4) within the reducible carbon budget (see step 3). This step also establishes the plausible growth rates of such industries. In this report, low-emissions industries are assumed to include zero-emissions renewable energy industries with the addition of CCS-equipped fossil fuel energy generation.

The expansion of low-emissions industries will be based on the global resource base of low-carbon energy sources (e.g. renewable energy forms including bioenergy, wind and sun), the availability of suitable technology to harness these resources and the speed with which the associated industries can be expanded.

The relevant industries have specific performance and resource characteristics. These characteristics indicate both their potential contribution and the viable rates at which they may be developed. In some cases, where relevant, the performance of other comparable industries is considered as well. The various industry characteristics and fundamental parameters described herein aim to reflect the range of research, forecasts and expert opinion available from published sources.

2.6 Step 6: Input Probability Distributions in the Monte Carlo Simulator

This step allows differences in opinion and ranges of data to be included in the model. This differing opinion regarding all data used in the modelling is reflected as probability distributions of the inputs. Generally, triangular distributions are used. The development parameters of a given industry, based on the range of possible inputs established above, are run repeatedly in a Monte Carlo simulation. This builds a picture of the range and probability of outcomes that intrinsically reflect the range and probability of the inputs.

2.7 Step 7: Energy, Non-Energy and Emissions Scenario Results

Results are presented in terms of industry development and deployment, energy sector make-up, non-energy sector make-up and net emissions projections. A key result parameter focuses on the industrial growth rates needed to achieve the required emissions levels in 2050. The results are also expressed in terms of a "point of no return": the year when the balance of probabilities indicates industry deployment may no longer allow for 2050 emissions levels that would avoid runaway climate change.

2.8 Step 8: Costs, Investments and Returns

This step calculates the required annual and cumulative investment costs for low-carbon re-industrialisation. This calculation is based on the difference between business-as-usual costs for key commodities, such as electricity and fuels, and the cost of the low-carbon replacement. The total cost difference for a given resource is the product of the difference in cost for each unit multiplied by the volume of production in a given year. This cost difference is expressed as a price support requirement (e.g. as if it were met with a feed-in tariff or equivalent). It is also expressed as an investment cost on an annual and cumulative basis. Industries that have no costs above business-as-usual are not considered, i.e. savings are not calculated for energy efficiency. However, for those technologies that require price support, the returns/savings created by achieving economies of scale and competitive prices are presented.

2.9 Step 9: Extension to Minus 80%

This step expands on the minus 63% scenario developed in the previous steps by considering the options for adjusting the commencement of low-carbon re-industrialisation, the size of certain emissions abatement sectors and the growth rates needed to achieve lower emissions. The minus 80% scenario tested is for global emissions in 2050 of approximately 7.9 $GtCO_2$-e/yr.

2.10 Step 10: Limits of Delay

This step tests the time frame, or "window of opportunity", to initiate low-carbon re-industrialisation in time to avoid 2°C of warming. The step computes the latest year in which full-scale re-industrialisation can be initiated and still meet the 2050 emissions target for each scenario.

3 Introduction to the Climate Risk Industry Sector Technology Allocation (CRISTAL) Model

3.1 Introduction

This project uses a computational model called the Climate Risk Industry Sector Technology Allocation (CRISTAL) model. This model emulates real-world industrial growth. It identifies the resources, technologies and services available to reduce greenhouse emissions (adopting the Princeton/ Socolow abatement "wedges" framework; Pacala & Socolow 2004). The model then uses Monte Carlo methods to combine this information in order to calculate the industrial growth rates required to achieve the necessary emissions reductions, while satisfying the projected demand for energy and other services.

Monte Carlo methods are a class of algorithms that rely on repeated random sampling to compute their results. They are often used when simulating physical systems. They allow multiple data sets and ranges of expert opinion to be used (for example, when analysing the national abatement potential of wind or another low-emissions industry).

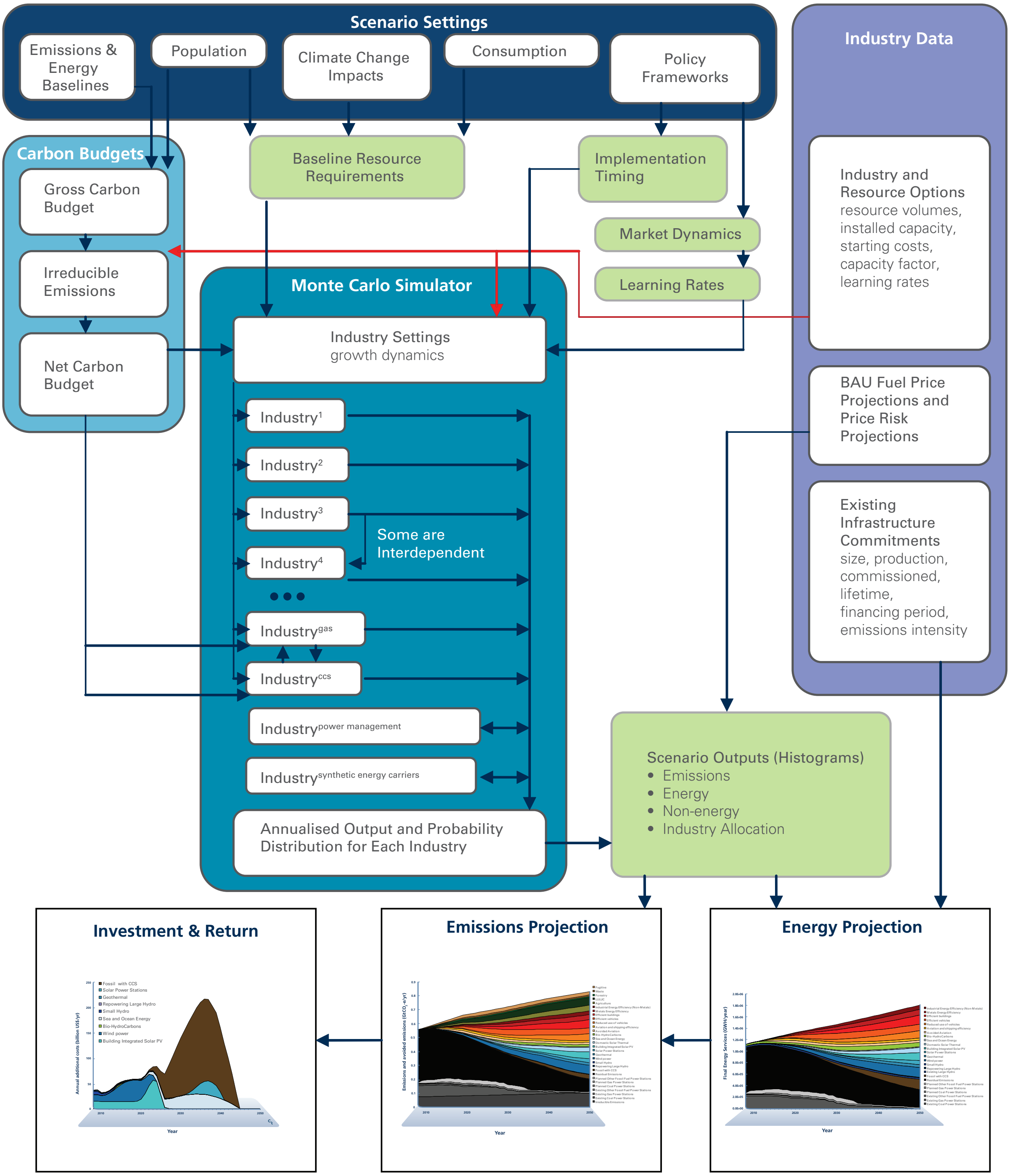
The outputs of the scenarios from this CRISTAL model focus on industrial growth rates. This focus reflects the potential of these growth rates to critically constrain delivery of future emissions levels, by fundamentally restricting the industry response rate to economic and government policy measures. By assessing the capabilities and rate of change for each industry, the model provides a picture of its output and constraints, assembling these outputs across industries.

What emerges is an overall picture of global future emissions levels, energy production and low-emissions energy investment requirements.

The CRISTAL model is primarily an "industrial model" rather than an "economic model"; price and cost have not been used to limit or guide the uptake of technologies. The model works from the point of view of the emissions outcome being fixed as an input, with the consequences for industrial development being an output. By forcing industries to deliver the required emissions outcomes (i.e. the inputs) the plausibility of output growth rates and other real-world constraints can be considered. For simplicity, a single set of industrial growth rates has been applied across all low-carbon energy generation industries in this project.

The basic structure and interdependencies of the CRISTAL model are shown in Figure 7.

Figure 7: Schematic diagram showing the basic structure of the CRISTAL model.



3.2 Key Inputs

In addition to data on the size, growth, abatement potential and cost of various emissions abatement technologies and strategies, the model also integrates important scenario input variables. These variables, which define the conditions under which these solutions develop, are described below.

3.2.1 Emissions and Energy Baselines

While a variety of global emissions and final energy baselines have been examined, those most commonly used in this project are based on the Special Report on Emissions Scenarios (SRES) outcomes produced by the Intergovernmental Panel on Climate Change (IPCC), which examines a variety of international development scenarios.

3.2.2 Population

The population input setting allows the model to consider the effects of population dynamics. In general, the UN World Population Prospects (2006) forecasts are used. In this project, the current world population is taken to be about 6.7 billion today, rising to 9.2 billion in 2050.

3.2.3 Climate Change Impacts

Ironically, most modelling for climate change mitigation activity neglects the effects of climate change impacts and adaptation. For example, there is already strong evidence that climate related natural catastrophes (such as severe hurricanes) are having a discernible impact on insured losses (Chemarin & Bourgeon 2007, Ceres 2005). Projections for increased losses and the costs required to adapt physical infrastructure to cope with this will, therefore, have a material effect on global GDP. This dynamic has been included in the analysis via a climate impact coefficient, to adjust GDP such that it reflects the burden of costs associated with climate change impacts and adaptation. In this project, a 3% climate impact retardation of GDP by 2050 is used across all scenarios presented (Stern 2006).

3.2.4 Consumption

The IPCC baselines contain implicit assumptions that link increased wealth with increased physical consumption of energy and other commodities. However, it is plausible that additional wealth in some world regions may be realised through activities not necessarily directly coupled with consumption. For example, increased wealth could be expressed as increased leisure time, voluntary work or community activity with less added consumption. A decoupling factor is included in the model to reflect a fraction of wealth that may not result in increased commodity consumption. However, for this particular report, the decoupling factor is not used, i.e. it is assumed that consumption increases directly in proportion to economic growth.

3.2.5 Policy Frameworks

The CRISTAL model is able to accommodate any international policy frameworks (such as those currently being negotiated for a post-2012 climate treaty) that may impact on future emissions, energy usage and the cost of emissions abatement technologies. In this project, no policies currently being negotiated are assumed to change the SRES baselines.

3.3 Key Features of the Model

3.3.1 All Major Emissions Sectors

The CRISTAL model includes all major emissions sectors, including stationary energy, industrial processes, transport, land use and land use change, forestry, waste, fugitive emissions, agricultural emissions and bunker fuels. This allows a side-by-side comparison of the scale of different abatement options and low-carbon activities, although no preference or order of implementation is implied.

3.3.2 Resource and Technology Costs

Only emissions abatement technologies that are commercially available, or likely to be so in the near term, have been included. The CRISTAL model is able to look at price shortfalls between included technologies and business-as-usual, as well as the impact of carbon prices.

The costs and potential savings of low-emissions energy generation technologies are expressed relative to their fossil fuel competition. Since there is considerable uncertainty surrounding the future costs of fossil fuel energy, this report conservatively assumes that the cost of energy generated using fossil fuels increases at a linear rate of 2% each year out to 2050. The rate of cost decrease for each low-emissions energy generation technology is assumed to continue along its historic learning rate trajectory.

The scenarios examined in this report do not include any carbon price impacts. However, the potential benefits and limitations of a carbon pricing scheme are briefly discussed in each case. In this report, by utilising the current costs and rational learning rates (cost reductions as a function of scale) for each abatement technology, the CRISTAL model can give an indication of the commodity cost profile for each low-emissions industry. Using this information, it is possible to determine any relative cost shortfall that must be accounted for. In this way, the CRISTAL model provides a forecast of the amount of investment (and its timing) that would be required to achieve the desired emissions reductions associated with each low-emissions technology.

3.3.3 Extending the Pacala-Socolow "Wedges" Concept

Considerable modelling has been undertaken in the fields of both climate change and energy. Many models are constructed in ways that let scenarios evolve based on key costs, such as the price of oil or the cost of carbon. A "wedges" model, developed by Pacala and Socolow (2004), is widely regarded as an elegant approach to considering and presenting the means of achieving future greenhouse gas emissions levels. Such a model provides an excellent starting point for this analysis. It divides the task of emissions stabilisation over 50 years into a set of seven wedges (delivered by emissions-avoiding technologies). Each wedge grows from a very small contribution today to a point where it is avoiding the emission of 1 gigatonne of carbon per year by 2054 (see Figure 8). Pacala and Socolow point out that many more of these wedges are technically available than are required for the task of stabilising global emissions at today's levels by 2050.

The CRISTAL model presented here builds on the Pacala-Socolow wedges model. However, it has been adapted to provide insight into measures that go beyond the stabilisation of emissions in 2050, to those that achieve reductions in global emissions consistent with various international targets. In order to do this, the CRISTAL model:

- Extends the penetration of abatement industry deployment to achieve abatements consistent with plausible future carbon budgets.

- Simulates real-world industrial growth behaviour by assuming: that the growth of any technology will follow a typical sigmoid (S-shaped) trajectory; that constraints impose a maximum on the rate of sustainable growth; and that the ultimate scale depends on estimated resources and other specific constraints.

- Draws on diverse expert opinions on the potential size and scale of emissions abatement resources and uses these as inputs.

- Employs a probabilistic approach, using the Monte Carlo computational methods so that the results can be considered as probabilities of achieving certain outcomes or risks of failure.

- Seeks to minimise the replacement of any stock or system before the end of its physical or economic life.

- Includes energy and emissions contingencies that allow for the possibility that some solutions may encounter significant barriers to development and therefore fail to meet the projections set out in the model.

3.3.4 Top-Down and Bottom-Up

The CRISTAL model is structured to combine top-down and bottom-up aspects of emissions abatement analysis. Thus, it approaches calculations of future emissions cuts from both the perspective of the global requirement for energy and abatement opportunities (top-down) and the perspective of developing options to meet these needs (bottom-up). This permits the model to capture the best of both approaches in its calculations.

The starting point for the top-down aspect of the model is the SRES baselines for energy and emissions through to 2050 (IPCC 2000, Van Vuuren 2008). However, top-down approaches can introduce perversities, such as inflated baselines, which create the illusion of greater emissions reductions than are possible.

The bottom-up aspect of the model builds a set of abatement industries to meet the projected energy services demand, sector by sector. This requires

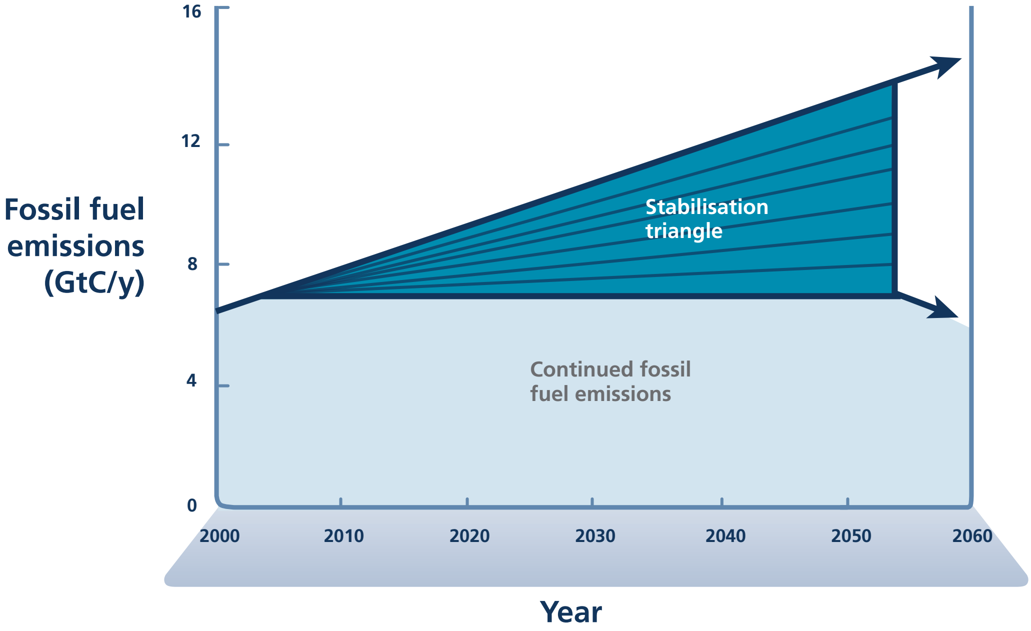


Figure 8: The Pacala and Socolow "idealised" version of future emissions where allowed emissions are fixed at 7 GtC/year: "The stabilisation triangle is divided into seven wedges, each of which reaches 1 GtC/year in 2054. With linear growth, the total avoided emissions per wedge is 25 GtC and the total area of the stabilisation triangle is 75 GtC. The arrow at the bottom right of the stabilisation triangle points downward to emphasise that fossil fuel emissions decline substantially below 7 GtC/year after 2054 to achieve stabilisation at 500 ppm." (Pacala and Socolow 2004).

some assumptions about the level and type of consumption – for example, what proportion of energy is used for transport, homes and industry, and so forth. This information is used to ensure that the emissions abatement wedges are internally consistent and avoids the "double counting" of overlapping abatement opportunities. The model accomplishes this by considering, within each sector, the total energy services needed for that sector and then the role of abatement opportunities. Thus the model maintains the best possible internally consistent evolution of energy and emissions.

3.3.5 Using Ranges of Data

Proponents of any one solution tend to be optimistic regarding the extent of its contribution and the time frame by which its benefits may be achieved, while others may be more disparaging. Rather than make value judgements, this project uses ranges of data that reflect the diversity of opinion. All such ranges of data are entered into the model as a "triangular" probability distribution defined by the lowest, highest and best estimate for any given variable (Figure 9). The project therefore seeks to include a broad range of independent sources for any given variable.

3.3.6 Modelling Industry Deployment Behaviour

Whereas Pacala and Socolow simplify the avoided emissions to a wedge shape with linear growth, in actuality any market innovation follows a standard sigmoid or S-curve, similar to that shown in Figure 10.

Such a profile is underpinned by an industry that starts from a small base, at which point it provides negligible abatement (though there may be considerable investment and growth occurring in this phase). Over time, the industry starts to make an increasingly significant contribution (the "ramp-up" phase). This growth will approach a plateau of steady development as the industry matures (the period of near-linear growth). As the unexploited resources diminish or other constraints impinge, the industry's growth gradually diminishes (the "ramp-down"). In some cases, there may be a final stage of industry contraction.

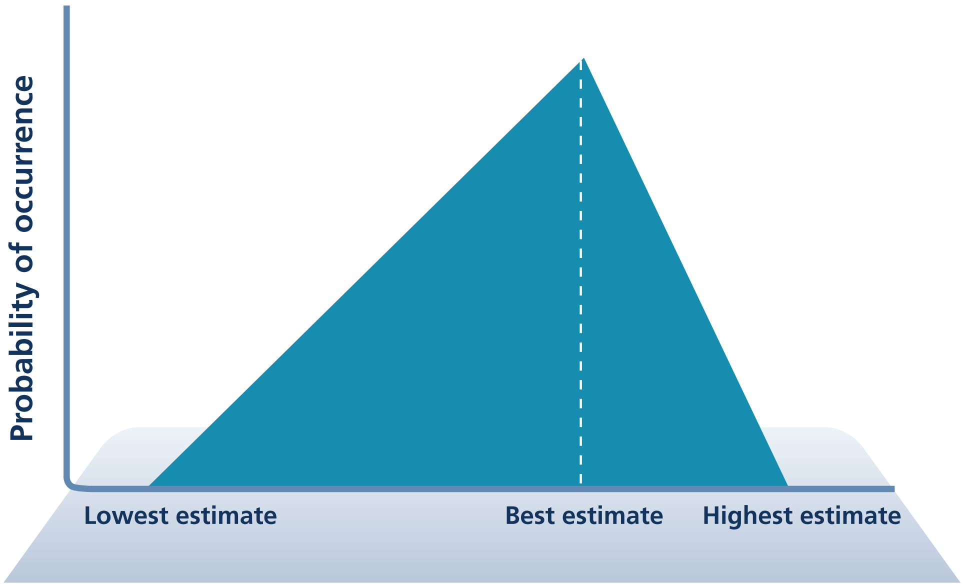


Figure 9: Instead of picking a single number for important parameters, input data are entered into the model as ranges of values. The probability distribution used is triangular and defined completely by the lowest, best and highest estimates (from published literature).

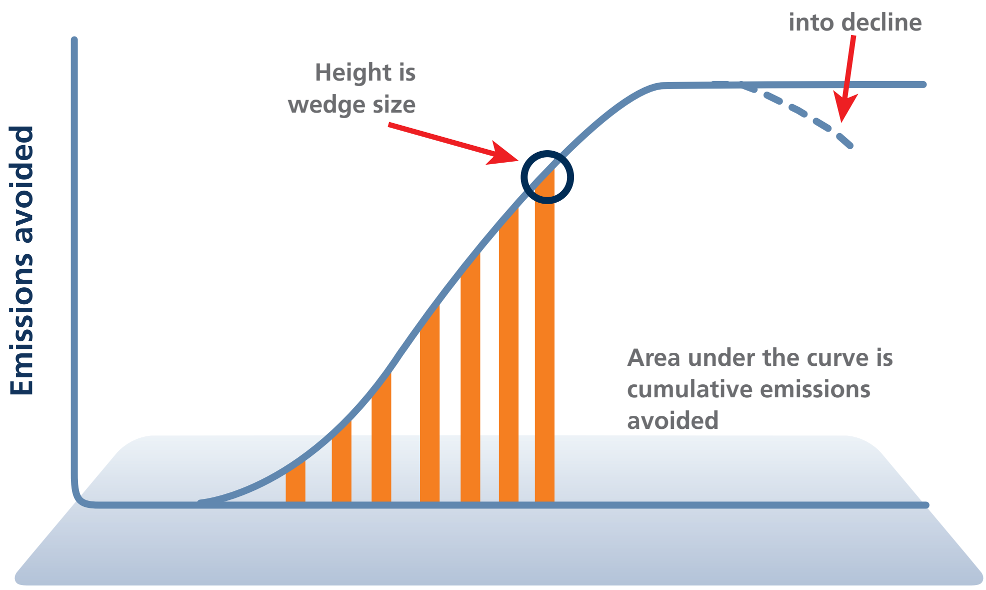


Figure 10: Emissions abated as a new industry grows.

3.3.7 A Trapezoid Approximation of Growth

The S-curve shown in Figure 10 indicates the cumulative effect of an installation or industry that grows quickly at the start, reaches a steady state and ultimately contracts. The actual growth phases might best be described by a bell-shaped curve. However, in the CRISTAL model, growth is approximated as a trapezoid, as shown in Figure 11. Within the CRISTAL model, each emissions reduction solution is described in units most appropriate to the technology or resource; for example, the number of megawatts of turbines installed, or million tonnes of oil-equivalent avoided through increased vehicle efficiency.

Any climate solution trapezoid can be fully defined by the set of variables that are designated as c, b, p, s and m in Figure 11. However, these variables are not put directly into the model because in many cases the relevant data are not known. For example, it is hard to estimate the year in which the growth of industrial energy-efficiency implementation will level-off (b in Figure 11). Instead, more easily estimated parameters are used, such as the turnover rate of industrial equipment, available resources, current installed capacity, standard or forced growth rates for each of the phases of development, or the year in which commercial roll-out commences.

Combining these various "known quantities" in simultaneous equations (which will be different for different low-carbon industries) allows variables c, b, p, s, and m to be calculated, and the shape of the trapezoid and the S-curve of cumulative annual contribution from each abatement industry to be estimated.

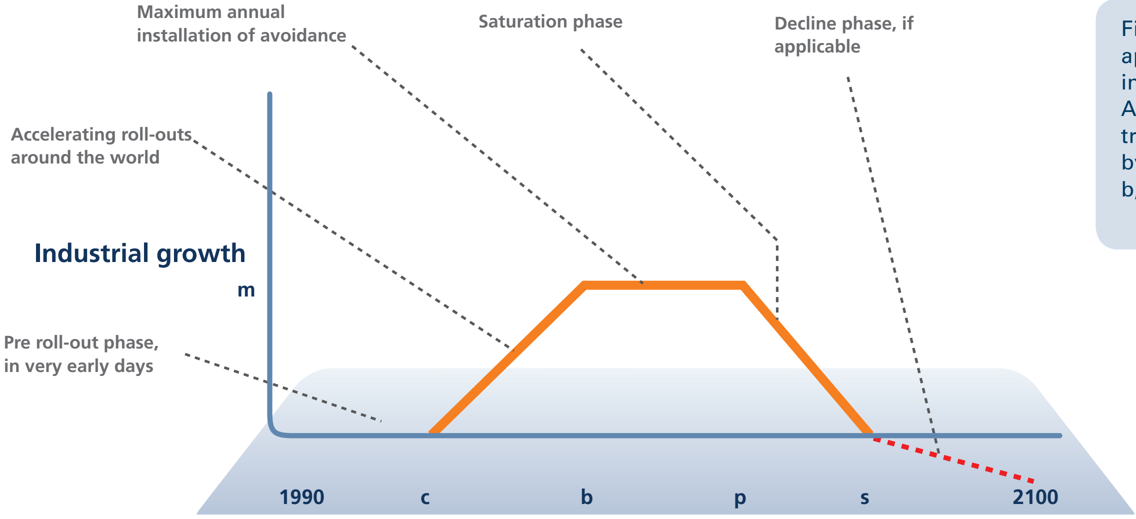


Figure 11: Trapezoid approximation of industrial growth. Any climate solution trapezoid can be defined by the set of variables, c, b, p, s and m.

The growth of any industry follows a typical pattern. It starts small, but can grow rapidly. It is, of course, easy to double in size when an industry is small. But eventually the industry's size stabilises so that it is in equilibrium with the size of its resource and/or market.

By way of example, the wind industry started small and has grown quickly. At some stage it will reach a state where the industry has harnessed all of the suitable wind resources, at which point the industry will only be of a size required to maintain and replace this stock of power stations.

In terms of the trapezoid approximation of industry growth (see Figure 11), the progression of industry development can be summarised into the following phases:

1. The growth phase (also referred to as the critical development period), in which the industry growth is accelerating towards the maximum growth rate (i.e. in each successive year more units are produced per annum).

2. The stable phase, in which the industry growth rate is constant and the maximum number of new units (m in Figure 11) are produced each year.

3. The saturation phase, in which the industry growth rate decreases and fewer new units are produced each year.

4. The decline phase, in which the total size of the industry starts to decrease (i.e. existing installed units are taken out of service and not replaced).

Each industry may have a different industry growth profile depending on the relative size of these periods. For all emerging technologies examined in this report, these are set at 0–20% for the growth phase (critical development period), 20–80% for the stable phase and 80–100% for the saturation phase. Nuclear energy is the only low-emissions technology assumed to enter into the decline phase prior to 2050.

These settings reflect the concept that a participating company will want a sufficiently long period of production from an existing factory to recover the investment, i.e. an industry will not keep growing indefinitely or right up to the point that a resource is saturated.

The Case of Oil: An Empirical Example of Industry Growth Phases

The fossil fuel oil industry is a mature industry with an established industry growth S-curve, as shown below in Figure 12. The dashed line in this figure approximates the stable phase of industry growth for the oil industry. The section prior to this corresponds to the growth phase, also referred to as the critical development period. Ultimately, if not already, the stable phase of oil industry development will enter the saturation phase and finally a decline phase.

Figure 12 shows that the critical development period for oil continued until about 20% of the maximum production volume was reached (assuming the oil industry is currently close to maximum production). Similarly, the modelling used in this report assumes that the critical development period for all low-carbon energy generation technologies continues until they have utilised 20% of their total available resource.

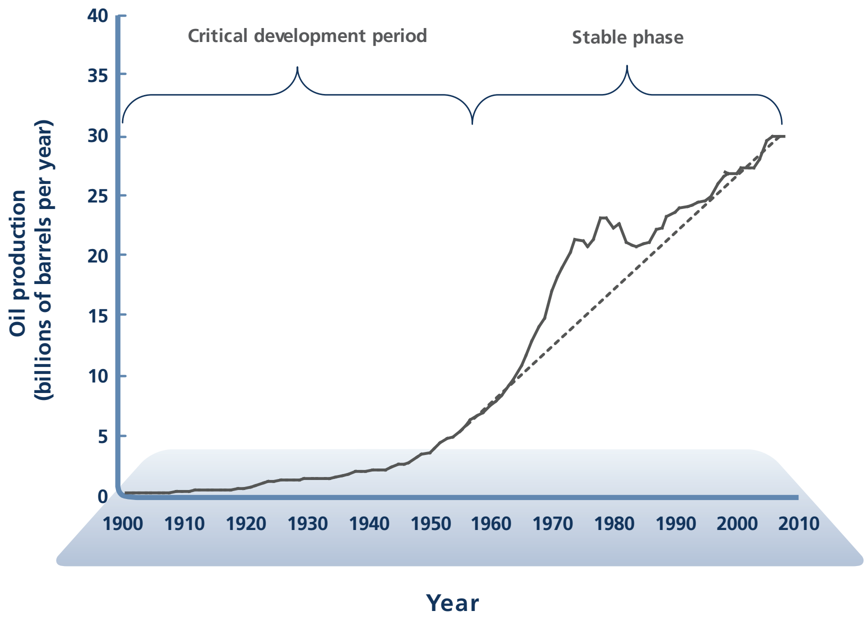


Figure 12: The historical growth profile for oil production from 1900 to 2008 (BP 2009). The dashed line approximates the linear stable phase characterised by constant growth.

Oil production in this figure includes crude oil, shale oil, oil sands and NGLs (the liquid content of natural gas, where this is recovered separately). Liquid fuels from other sources, such as biomass and coal derivatives, are not included.

3.3.8 Form of Outputs and Results

All model results may be expressed as probability distributions, in the form of a histogram for a given output parameter (see Figure 13). For simplicity, the results for multiple parameters shown together are expressed using the mean output over several thousand runs.

Emissions reductions and outcomes are shown in a wedge format, as are energy sector changes. In the case of the emissions wedge diagrams, the emissions abatements from various industries and sectors are shown in a range of colours, whereas any residual emissions from fossil fuels are shown in black (see Figure 14). Similarly, for energy wedge diagrams, energy generated or avoided by low-emissions technologies and efficiency measures are shown in different colours, with residual fossil fuel energy (not including CCS) shown in black (see Figure 15).

Using the energy generation data for each industry, along with the cost data described above in Section 3.3.2, it is possible to determine annual and cumulative cost data for low- and zero-emissions industries relative to their fossil fuel competition (see Figure 16).

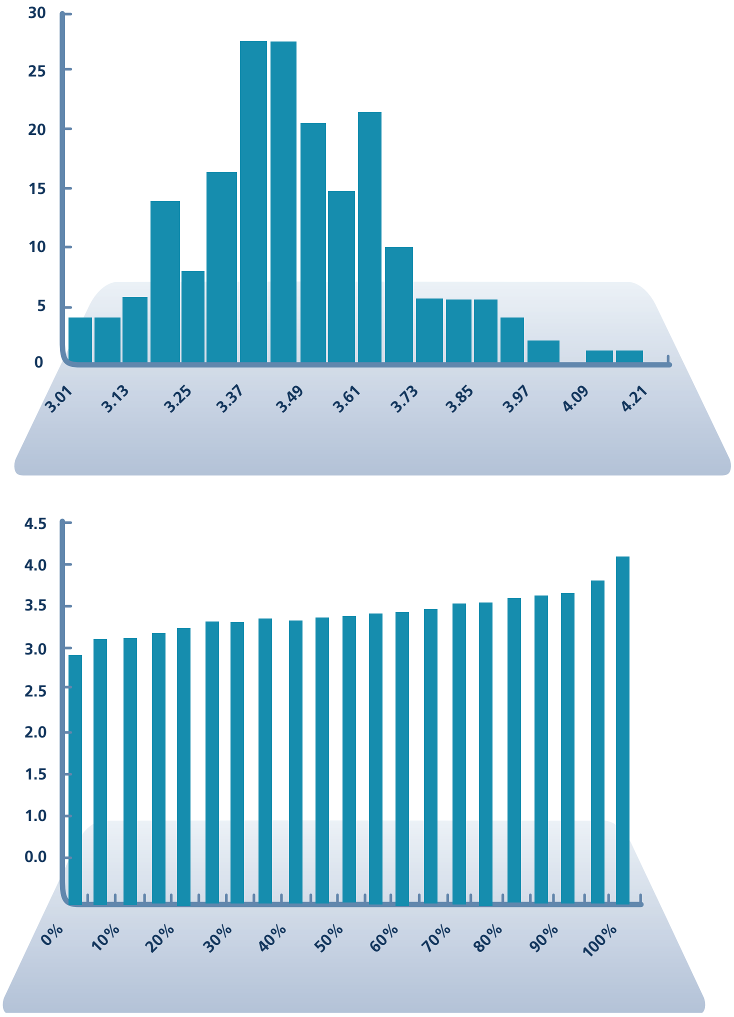


Figure 13: An example distribution of data obtained for a given output parameter of the model, presented as a histogram and percentile distribution. These indicate the range of possible outcomes, the most likely outcomes and a probability distribution for any given output.

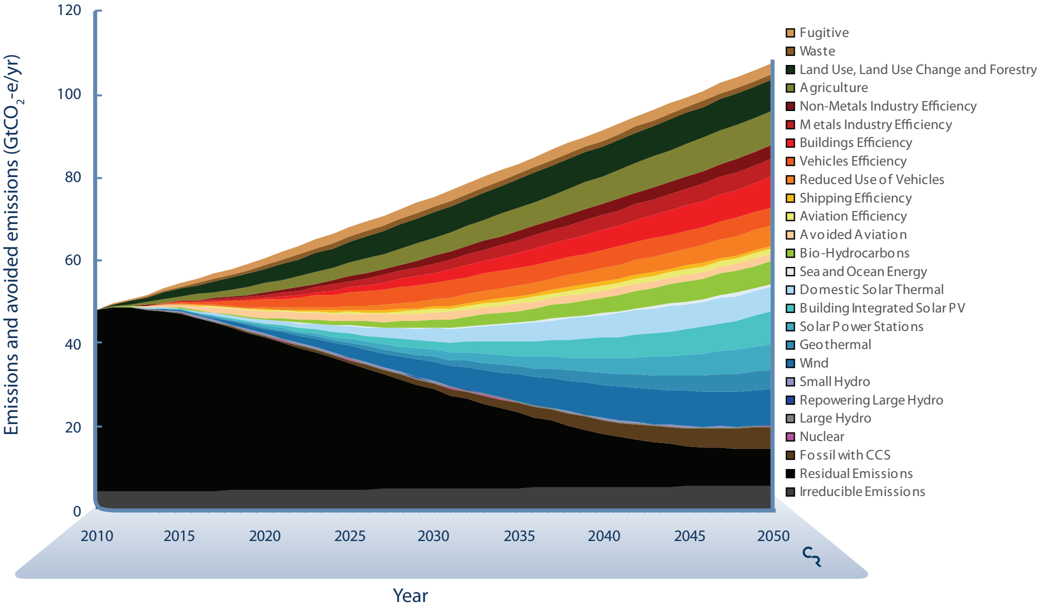


Figure 14: An example emissions output from the CRISTAL model. The emissions wedges show the contribution of the major sectors of emissions abatement subtracted from the A1FI baseline.

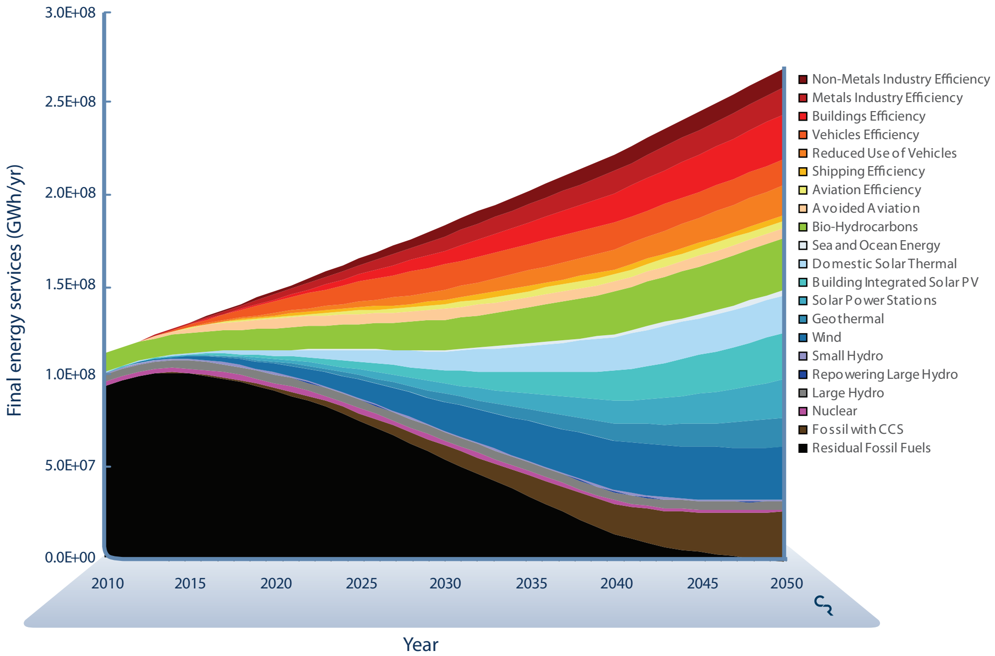


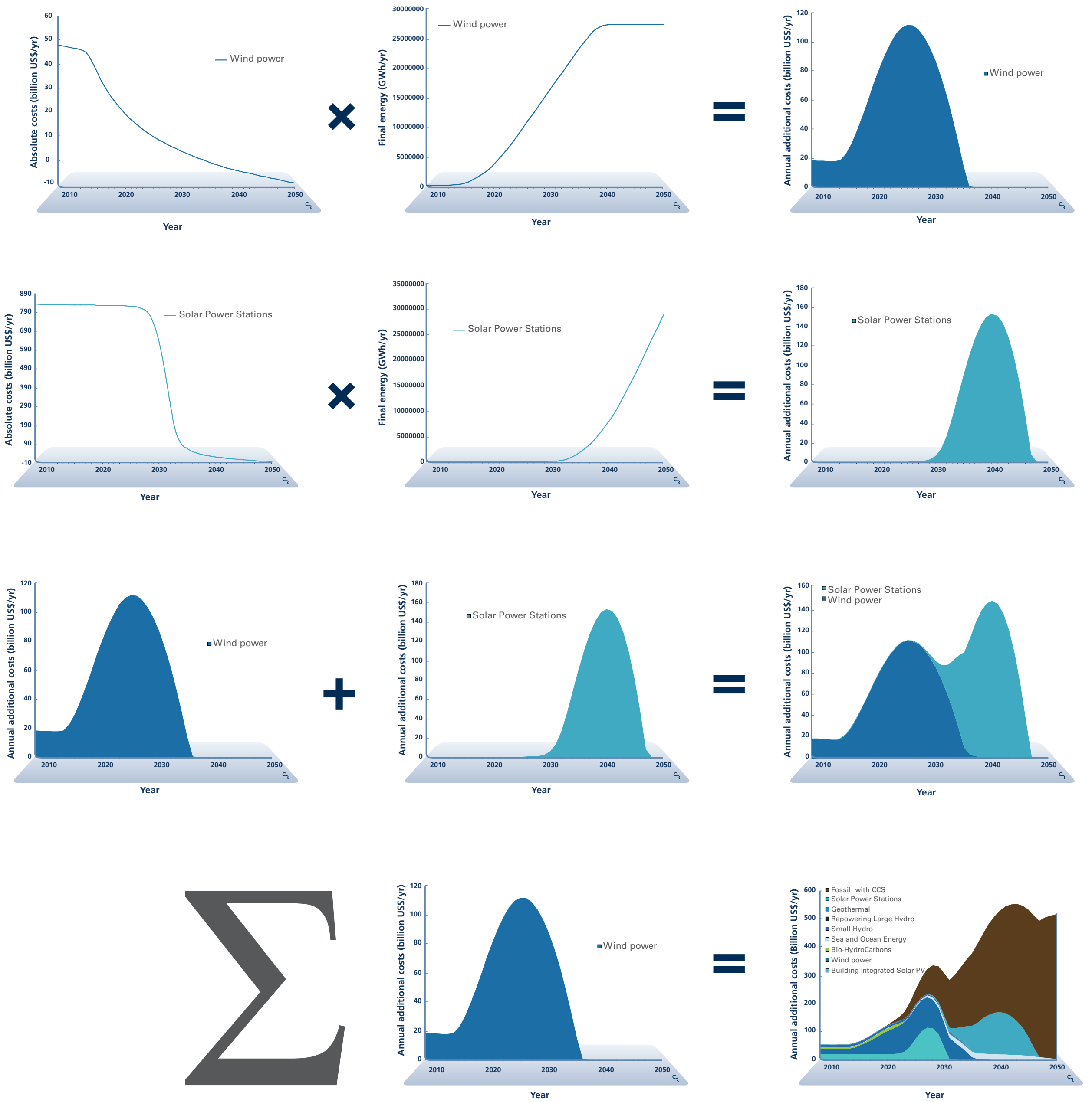
Figure 15: An example energy output from the CRISTAL model. The energy wedges are expressed in GWh of final energy as subtracted from the A1FI final energy demand projections to 2050.

Figure 16: The method for creating the combined investment cost curves. Note these show specifically the cost shortfall between the cost of conventional energy and the costs of the low-carbon resources.

The absolute cost for each technology is used to determine the additional cost relative to the fossil fuel status quo.

The annual final energy supplied by each technology.

The annual additional cost of the actual energy supplied by each technology relative to the fossil fuel status quo.



The combined annual relative costs of all low-emissions technologies.

3.4 Emissions Abatement Sectors

The main emissions abatement sectors considered in the CRISTAL model are comprised as follows:

3.4.1 Zero- and Low-Emissions Energy

This sector includes heat and electricity generated using renewable energy technologies and also non-renewable low-emissions energy sources, such as nuclear and CCS. It should be noted that geothermal energy production in this report includes both electricity and heat generation. See Chapter 14 and Chapter 17 for more details on the resource assumptions for hydroelectricity, bio-hydrocarbons, natural gas and nuclear energy.

3.4.2 Energy Efficiency Measures

This sector includes process and equipment improvements in industry (divided into metals and non-metals), buildings and transport. Avoidance of emissions within the transport sector through the reduced use of vehicles and the adoption of alternatives to business travel (such as teleconferencing and telework) are also included.

In each energy efficiency category, the modelled abatement wedge evolves over time based on the size of the efficiency reduction opportunity, the length of the product replacement lifetimes and the impact of any regulatory incentives/requirements.

3.4.3 Agriculture

This category considers the emissions abatement from improved agricultural practices, with the exception of biomass replacing fossil fuels (since biomass is already considered in the zero- and low-emissions energy section).

3.4.4 Land Use, Land Use Change and Forestry (LULUCF)

The IPCC (2007) approach is used for this category, which considers LULUCF net emissions abatements to involve:

- "maintaining or increasing the forest area through reduction of deforestation and degradation and through afforestation/reforestation;
- maintaining or increasing the stand-level carbon density (tonnes of carbon per hectare) through the reduction of forest degradation and through planting, site preparation, tree improvement, fertilisation, uneven-aged stand management, or other appropriate silviculture techniques;
- maintaining or increasing the landscape-level carbon density using forest conservation, longer forest rotations, fire management, and protection against insects; and
- increasing off-site carbon stocks in wood products and enhancing product and fuel substitution using forest-derived biomass to substitute products with high fossil fuel requirements, and increasing the use of biomass-derived energy to substitute fossil fuels."

Additional information on LULUCF assumptions can be found in Chapter 14 and Chapter 17.

3.4.5 Waste

This area primarily involves improved methane recovery from landfill sites, with some additional contribution from thermal processes for waste-to-energy.

3.4.6 Fugitive

In accordance with the IPCC (2007) approach, it is assumed in this sector that waste greenhouse gases emitted in the production of fossil fuels are constrained to their current levels.

3.4.7 Replacing High-Carbon Coal with Low-Carbon Natural Gas

In the short-term (particularly prior to the effective operation of CCS), an increase in the use of natural gas as a "transition fuel" can play a significant part in avoiding the locking in of higher emissions from coal, thereby buying more development time for other energy solutions to grow. While this is more applicable in some countries than others, gas would have to be scaled up in the short-term (where it can enable the avoidance of coal use), without bringing about negative biodiversity impacts.

If used with CCS technology, the carbon emissions from natural gas will be further reduced. In this way, natural gas can act as a bridging fuel for important applications, provided that energy security issues can be resolved.

In this report, it has been assumed that, within the residual emissions block, natural gas usage follows the business-as-usual production forecasts until all proven reserves are essentially depleted by 2050. So while the overall share of energy generated by fossil fuels decreases as renewable energy sources take a greater share of energy generation, the amount of energy generated by natural gas initially continues to increase.

To achieve this outcome, renewable energy preferentially displaces coal-fired power stations and petroleum-based road transport. Simultaneously, natural gas displaces coal from electricity generation in the short-term. It is assumed that carbon emissions from natural gas energy generation facilities are sequestered within the CCS wedge as the technology comes on-line.

3.5 Emissions Abatements Not Considered

This study does not include many potential emissions reductions which are, at this point in time, difficult to quantify. However, in years to come these activities could add further reductions in the sectors of energy use, energy efficiency, land use and "irreducible emissions".

3.5.1 Lifestyle and Behavioural Changes

A full or partial switch of dietary habits towards less land-consuming, non-meat products is particularly beneficial for the climate. It is well known that cattle ranching, in particular, requires much more land per unit calorie and per unit protein produced than legumes or cereals. Increased cattle ranching and fodder production in developing countries requires land clearing, often in precious ecosystems and rainforests. Also, ruminants contribute substantively to non-CO_2 greenhouse gas emissions (particularly methane) during digestion. Furthermore, growing fodder for conventional meat production often involves substantial fertiliser use, releasing the potent greenhouse gas N_2O.

A wider adoption of carbon-efficient farming techniques (such as low-tillage practices and minimising the use of pesticides and fertilisers) could also provide significant opportunities for improved emissions abatements in the agricultural sector. Such actions could also significantly reduce the overhead costs incurred by farmers and minimise other environmental impacts associated with the agricultural industry.

Use of low-carbon and efficient public transport for both passengers and freight is the key component for a transport modal shift. This requires significant investments in overland and urban transport infrastructure, particularly for rail-based transport. High-speed trains between major cities, as well as a functioning local "tube" system, will help to replace short to medium distance flights as well as private car and lorry-based freight travel.

Lifestyle changes around the home are also a means of achieving significant emissions and cost savings. Reducing air-conditioning and allowing for warmer room temperatures in summer, as well as scaling down heat consumption in winter to allow for cooler rooms will also greatly reduce fossil fuel-based CO_2 emissions.

Moderation and smaller scales in daily life decisions can also contribute to lifestyle related emissions savings. Large emissions savings are possible if the growing global "consumer class" is able to scale back the unnecessary use of products and services. Some examples of the type of lifestyle questions in this area include:

- Could holidays be taken in geographically closer regions?
- Do office buildings need to be lit up the whole night?
- Is an extra-large freezer necessary or can a normal refrigerator do the job?
- Is a large, high fuel consumption car really required or is a smaller, more fuel efficient car sufficient most of the time?

3.5.2 Material Efficiency, Recycling and Material Change

Many consumer products are becoming less durable and are being replaced earlier. Longer-life products and the ability to repair them is an integral aspect of material efficiency. This will not only save energy during manufacturing but also the consumption of scarce non-energy resources, many of which are associated with production and refining processes that have a negative impact on greenhouse gas emissions and the environment in general.

Increased recyclability at the end of a product's service life can also help reduce unnecessary greenhouse gas emissions from production, refining and landfill. There are also collateral benefits for the environment and conservation of limited resources. This is particularly true for energy- and carbon-intensive products such as aluminium, whose full recycling saves more than two-thirds of the energy required to produce primary aluminium from its ore.

Many materials currently in use are sub-optimal for their given purpose. For example, not all houses need to be built with high-emissions cement. Low-carbon cement and renewable wood offer superior building alternatives from a greenhouse gas perspective. Similarly, biomass-based products, mainly from woody materials, can replace carbon-intensive and oil-based plastics. Not only do wood and other organic materials avoid the emissions associated with their fossil fuel alternatives, but they also effectively act as carbon sinks as long as they are preserved.

3.5.3 Negative Emissions Through Extensive Biomass Use and/or Biochar

Biochar is a recently discussed pyrolysis technology for returning biomass to the environment in a relatively carbon-stable form. It is hoped that biomass treated in this way will be able to contribute to soil quality with minimal decomposition into greenhouse gases (i.e. acting as a kind of carbon sink). As such, it is hoped that the use of biochar may increase soil fertility and water availability in degraded lands, alleviate the need for artificial fertiliser use and reduce the need for further land clearing. Still, there are many questions about its practicability that have not yet been resolved.

In this report, biomass (in addition to its present uses) is mainly used as a substitute for oil-derived products that are hard to replace with conventional renewable energy, such as in aviation and shipping. Any waste biomass from the process of producing these necessary bio-hydrocarbons fuels could feasibly be used for biochar. In this report, it is assumed that heating, cooling, electricity production and road transport will be ultimately fuelled by non-biomass renewable energies.

Another potential carbon sink is the use of biomass to generate energy in conjunction with CCS. In this way, carbon absorbed from the atmosphere by the biomass is not released back into the atmosphere when it is converted into energy. However, the assumptions used in this report that biomass is a) preferentially used in shipping and aviation, and b) does not compete with food production, limits the use of biomass in this way.

4 Defining the Climate and Emissions Requirements

4.1 From Dangerous to Runaway

This report moves beyond a critical climate turning-point definition that entails avoiding "dangerous" climate change, to one that considers severely non-linear or "runaway" climate change. Working from the standpoint of dangerous climate change has two weaknesses with regard to the goals at hand.

Firstly, it may be subjectively interpreted, depending on where one stands on the globe; indeed the effects of climate change are already dangerous for many societies (e.g. those in which individuals have lost lives in unprecedented extreme weather, or incomes to crop failure from sustained drought).

Secondly, dangerous climate change may imply a level of manageability, in that all people live with a level of danger, such as from crossing the road or war and conflict. However, what is considered important in this project is the point of fundamental divergence from the manageability of climate-related risks.

Therefore, this report seeks to identify the level of climate change at which the impacts exceed plausible manageability – the point at which climate change veers "out of control". This concept is often inferred by the use of several other terms, including "irreversible", "non-linear" and "runaway" climate change.

This report uses the term "runaway climate change" to encompass aspects of irreversibility and non-linearity, but also to capture the point at which severe positive feedbacks exceed negative feedbacks, i.e. the destabilising influences exceed the stabilising mechanisms.

Herein, runaway climate change is taken to be "when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause" (NRC 2002).

4.2 The Tipping Elements to Runaway Climate Change

The threshold for runaway climate change, sometimes referred to as the "climate tipping point", is, in simplified terms, the threshold beyond which the self-compounding effects of runaway climate change cannot be stopped. On closer examination, the climate tipping point comprises several possible tipping elements. These tipping elements are large-scale components of the Earth's system that have a major stabilising or de-stabilising effect on climate dynamics. Either alone or in combination, the behaviour of these tipping elements may determine if the climate system crosses the threshold into runaway climate change.

4.2.1 Feedback Systems

A negative feedback is a process that tends to dampen a perturbation – as a shock absorber dampens a car from bouncing when it passes over a bump. A climate-related example is the ability of many tree species to absorb more carbon dioxide from the atmosphere as

"There are tipping points in the climate system, which we are very close to, and if we pass them, the dynamics of the system take over and carry you to very large changes which are out of your control."

James Hansen 2008

concentrations of this greenhouse gas rise, providing a living "sink" for this carbon.

A positive feedback, on the other hand, is a process that tends to amplify or perpetuate an initial perturbation. A climatic example is the dynamic whereby rising temperatures increase the frequency and intensity of wild fires, leading to significant carbon dioxide emissions while simultaneously weakening the ability of forested land to act as a sink for atmospheric carbon.

The interdependency of various natural and physical systems means that it is very hard to separate one system from another. Equally, it is difficult for scientists to identify with confidence those systems that will operate as negative feedbacks or positive feedbacks. However, several reasonably certain positive feedback tipping elements have been identified that may act as milestones toward the threshold of runaway climate change. Some key positive feedback tipping elements are as follows.

4.2.2 The Albedo Effect

Albedo refers to the extent that surfaces reflect radiation from the sun. With a low-albedo surface, for example, less radiation is reflected, and more solar radiation is absorbed, thereby contributing to planetary warming. For example, the loss of high-albedo Arctic sea ice exposes much darker (low-albedo) ocean surfaces that absorb more solar radiation than would otherwise be the case. This process creates a positive feedback that amplifies global warming. The loss of arctic ice, both seasonal and permanent, is well documented (NASA 2009). The most optimistic view holds that the threshold for this tipping element – i.e. an irreversible loss of polar reflectivity – may be very close at hand. However, some researchers suggest this point may already have been passed (Lindsay and Zhang 2005).

Melting of the Greenland Ice Sheet and the collapse of the West Antarctic Ice Sheet would further accelerate positive feedbacks. These two ice sheets are land-based, and their loss would mean that greater amounts of solar radiation would be absorbed by the land surface (rather than the ocean). In addition, their loss would lead to significant sea level rise. The Greenland Ice Sheet tipping point (the global average surface temperature at which it would be certain to completely melt) could be as little as a 1.7°C global increase. The Greenland Ice Sheet's meltdown could lead to a sea level rise of up to seven metres (Hansen *et al.* 2007a; Hansen *et al.* 2007b; IPCC 2007). The collapse of the West Antarctic Ice Sheet could potentially be triggered within this century and could lead to upward of five metres of sea level rise (Lenton *et al.* 2008).

4.2.3 Terrestrial Carbon Sink Efficiency

Large carbon sinks hold major volumes of carbon that would otherwise be released into the atmosphere. They also extract carbon dioxide from the atmosphere and fix it into the biosphere.

Any deterioration in the efficiency of global sinks weakens their ability to capture atmospheric carbon. A more serious issue is the possibility that such terrestrial carbon sinks may change their net behaviour – from carbon sink to carbon source.

Several large terrestrial sinks, in particular forests (including soils), are being adversely affected by increasing global temperatures and human activities that cause vegetation loss and soil disturbance. The resulting release of terrestrial carbon into the atmosphere creates a positive feedback that intensifies climate change impacts and further reduces terrestrial sink performance.

One particularly important terrestrial sink is the Amazon rainforest. Deforestation of the Amazon leads to local reductions in precipitation, lengthening of the dry season, and increases in summer temperatures. This occurs because a large fraction of precipitation in the Amazon Basin is recycled by forested ecosystems. In this way, the loss of forest cover creates a positive feedback, causing escalating rainforest dieback and carbon release in this globally significant carbon sink (Zeng *at al.* 1996, Kleidon and Heimann 2000).

The Boreal forest system is the largest terrestrial sink and at risk of dieback due to its sensitivity to the interplay of tree physiology, permafrost and fire. Increased water stress, peak summer heat, decreased reproduction rates and vulnerability to disease and fire under climate change could cause large-scale dieback of this large, global carbon reservoir (Lucht *et al.* 2006).

4.2.4 Ocean Sinks

It is estimated that roughly 18% (plus or minus 15%) of the increase in the growth of carbon dioxide concentrations in recent decades is due to the decreased efficiency with which oceans can act as sinks. These ocean sinks are becoming less capable of removing atmospheric carbon dioxide (which is rising as a result of human activities) due to carbon dioxide saturation and warming of the sea surface layers (Canadell *et al.* 2007).

Recent reports indicate that ocean sink efficiencies are deteriorating particularly in the Southern Ocean. Scientist Corinne Le Quéré and co-workers estimate that "the Southern Ocean sink of CO_2 has weakened between 1981 and 2004 by 0.08 PgC/yr per decade relative to the trend expected from the large increase in atmospheric CO_2" (Le Quéré *et al.* 2007).

This weakening is attributed to the "observed increase in Southern Ocean winds resulting from human activities" that have caused climate change and is projected to continue in the future. The greater energy in ocean winds caused by climate change influences the processes of mixing and upwelling in the ocean. This, in turn, causes an increase in the amount of carbon dioxide released from the ocean back into the atmosphere. As a result, the net absorption of carbon dioxide from the atmosphere into the ocean is reduced.

Since the winds causing the problem increase as climate change intensifies, a positive feedback is established, whereby ocean sink deterioration exacerbates climate change effects.

As for the consequences, in addition to the reduced short-term efficiency of the ocean to act as a carbon dioxide sink, there is also the possibility that, over coming centuries, atmospheric carbon dioxide emissions may stabilise at higher levels than they would have otherwise (Le Quéré *et al.* 2007).

4.2.5 Methane Deposits

Thawing of permafrost regions due to global warming releases not only carbon dioxide but also other greenhouse gases, such as methane. Similarly, increasing ocean temperatures can lead to the release of methane from the ocean floor, where it lies frozen in deposits (Mascarelli 2009). Methane is a very potent greenhouse gas, so the breakdown of these sinks has the potential to cause severe climate change feedbacks. It has been postulated that the recent jump observed in atmospheric methane levels (see Figure 17) may be related to the triggered release of these methane deposits (Rigby *et al.* 2008).

4.2.6 Climate System Changes

Changes in large climatic system behaviour – such as monsoonal rainfall and the El Niño-Southern Oscillation (ENSO) – have the potential to generate positive feedbacks through similar impacts on ocean and terrestrial sink efficiencies to those described

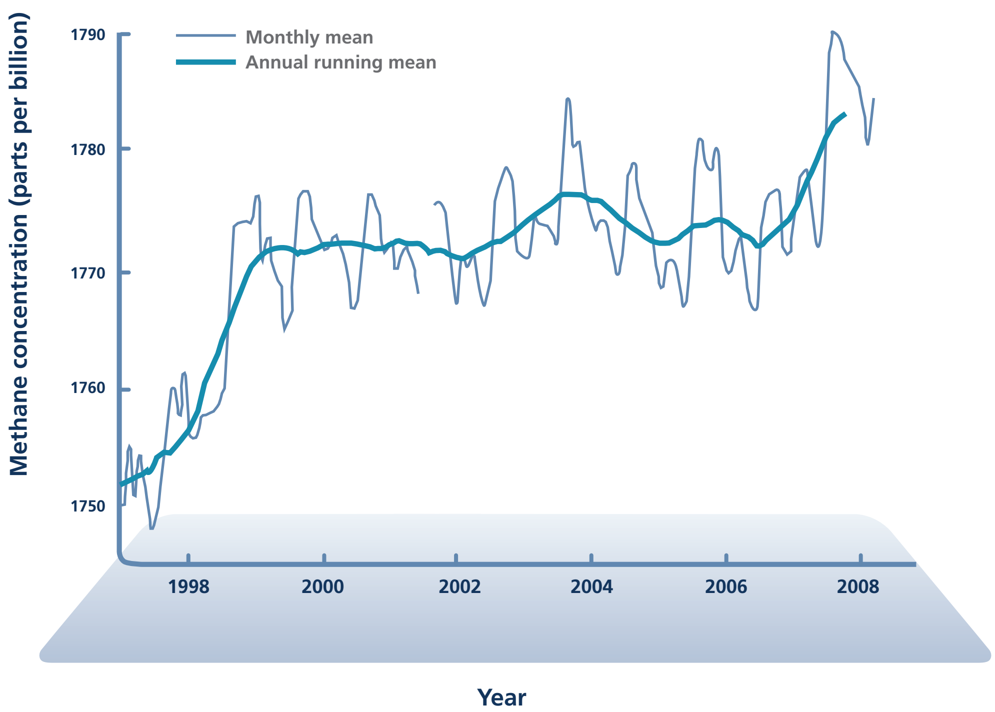


Figure 17: A plot of the average atmospheric concentration of methane, showing how it has undergone a large increase since 2007, after having remained stable for the previous decade (Rigby *et al.* 2008).

above. Large-scale changes in climate conditions can be expected to have a net detrimental effect on local ecosystems. This is because climatic conditions shift beyond the natural range of variability to which vegetation in these ecosystems has evolved to optimise growth (i.e. growth that allows for absorption of carbon dioxide from the atmosphere).

Some research predicts that the amplitude and/or frequency of the ENSO will be significantly increased as a result of increased ocean heat uptake (Timmermann *et al.* 1999). Monsoon behaviour (such as the Indian Summer Monsoon and the Sahara/Sahel and West African Monsoon) appears to be more difficult to predict under climate change, though large-scale changes are possible (Lenton *et al.* 2008).

4.2.7 Water Vapour

As the Earth's atmosphere warms, ocean evaporation increases and this water enters the atmosphere as vapour. Like other greenhouse gases, water vapour traps heat, further contributing to global warming through this positive feedback loop (Soden and Held 2006).

A related impact is the loss of cloud cover in some regions through the effects of global warming. Clouds reflect radiation back into space, thus their loss may provide a positive feedback if land or ocean surfaces reflect less radiation. However, this theory is still subject to debate. This is because clouds reflect radiation back to Earth, as well as into space, providing both a warming and a cooling influence, respectively. Which of these competing effects dominates remains a matter of contention and the subject of further research (Soden and Held 2006, Lin *et al.* 2002, Lindzen *et al.* 2001).

4.2.8 Non-linearity of Positive Feedbacks

An important point regarding the behaviour of feedback systems is that they are unlikely to behave in a linear way. Because these non-linear effects are more challenging to communicate, "society may be lulled into a false sense of security by smooth projections of global change", according to Lenton *et al.* (2008). For this reason, work is currently underway to develop early warning systems to determine when key positive feedbacks are reaching critical thresholds.

Of the tipping elements described above, Lenton *et al.* (2008) have concluded that "the greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point".

4.3 Avoiding Runaway Climate Change

Considerable uncertainty still surrounds the critical temperature threshold for climate change tipping elements, beyond which runaway climate change would take hold. NASA climatologist James Hansen and co-workers suggest that 1.7°C above pre-industrial temperatures should be regarded as an appropriate upper limit for human-

> "The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point."
>
> Lenton *et al.* 2008

induced warming (Hansen *et al.* 2007a; Hansen *et al.* 2008; Hansen 2005; Hansen 2007). This can be compared with a level of warming of over 0.7°C since 1900 (NCDC 2008, IPCC 2007). Climatologist Timothy Lenton and his co-workers take a more severe view, arguing that the threshold for the complete loss of the Arctic summer sea-ice "if not already passed, may be very close" (Lenton *et al.* 2008).

Other opinions suggest that the threshold temperature for runaway climate change may be higher. A number of experts, governments and organisations have set out positions regarding dangerous climate change. These have been compiled by Macintosh and Woldring (2008), who suggest this threat is closely linked to feedback triggers:

> "The risks associated with major tipping elements have been extremely influential in the choice of 2°C and corresponding atmospheric concentration targets as thresholds for DCC [dangerous climate change]. Warming of 2°C above pre-industrial levels is unlikely to be without risk or harm. Several important tipping points may be reached with increases in the global average surface temperature of significantly less than 2°C" (Macintosh and Woldring 2008).

Staying well below a 2°C change in global surface temperatures is also broadly accepted as consistent with the threshold to avoid most of the tipping points described above and the triggering of runaway climate change (SEG 2007, ICCT 2005, den Elzen *et al.* 2007, European Council 1996, European Council 2005). For example, more than 100 nations, including the European Union, the world's largest economic bloc, are asking for global warming to be limited to below 2°C. In their 2009 summit, the Group of Eight (G8) also acknowledged that they "recognise the broad scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2°C" (G8 2009).

Recently, the Group of Least Developed Countries (LDC) and the Alliance Of Small Island States (AOSIS) urged the ongoing international climate negotiations to conclude with results consistent with staying below 1.5°C compared to pre-industrial temperatures (UNFCCC 2009).

For this project, a 2°C increase in global average surface temperature is taken to be the upper limit for temperature increases in industrial modelling. This recognises expert opinion that suggests this is an optimistic view of the integrity of the climate system. Beyond this 2°C level of warming, it is assumed that the risks fall in favour of runaway climate change.

"Beyond this 2°C level of warming, it is assumed that the risks fall in favour of runaway climate change."

4.4 Avoiding 2°C of Warming

Figure 18 indicates that stabilising greenhouse gas emissions in the long-term at 450 ppm CO_2-e leaves a 54% chance of failing to stabilise global warming below 2°C, and therefore an almost equal chance of exceeding the 2°C threshold (Meinshausen 2006). Preventing a temperature increase above 2°C thus implies reduction well below 450 ppm CO_2-e.

Current greenhouse gas levels in the atmosphere are estimated[1] at 463 ppm CO_2-e atmospheric concentration (IPCC 2007, Tans 2009).

However, analysis indicates that the ability of the biosphere and ocean to absorb greenhouse gases does make a long-term stabilisation below 450 ppm CO_2-e possible (Meinshausen 2006). Meinshausen's analysis indicates that a stabilisation at 400 ppm CO_2-e reduces the chance of exceeding 2°C of warming to 28%.

More recent developments find that "an average minimum warming of ≈1.4°C (with a full range of 0.5–2.8°C) remains for even the most stringent stabilisation scenarios," according to Van Vuuren *et al.* (2008). The best-case-scenario in this work finds an average temperature increase of 1.4°C over 1990 levels[2], which corresponds to a 1.9°C increase over pre-industrial levels. This finding implies that all but the most ambitious emissions reduction efforts will likely exceed 2°C above pre-industrial levels.

Van Vuuren *et al.* (2008) also note that while the most stringent emissions reduction scenarios required to avoid a 2°C temperature change might be technically feasible, "they clearly require socio-political and technical conditions very different from those now existing".

Turning to what the 2°C threshold represents in terms of emissions, the recent work of Meinshausen *et al.* (2009) indicates that there is a likelihood of 15–51% (with a default likelihood of 33%) of exceeding a 2°C temperature increase for cumulative emissions between 2000 and 2049 of 1678 $GtCO_2$-e (see Figure 19). If the cumulative emissions in this time period are reduced to 1500 $GtCO_2$-e, the likelihood of exceeding a 2°C temperature increase drops to 10–43%, with a default likelihood of 26% (Meinshausen *et al.* 2009).

1 The atmospheric concentration of greenhouse gases was calculated using the ratio between the concentration of CO_2 (379 ppm) and all long-lived greenhouse gases (455 ppm) that was used by the IPCC for 2005 in its 4th Assessment Report (IPCC 2007). This gives a ratio of approximately 1:1.2, which when applied to the 2009 CO_2 atmospheric concentration (386 ppm) yields a CO_2-e atmospheric concentration of 463 ppm for 2009.

2 i.e. the average over 1980–2000.

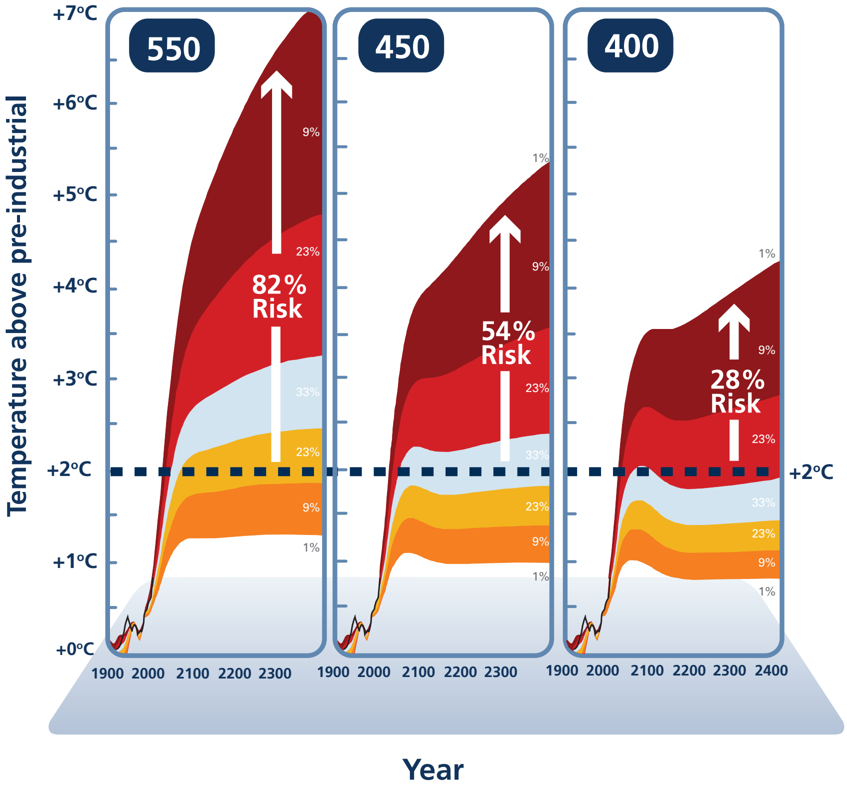


Figure 18: Stabilising atmospheric greenhouse gas concentrations in the long-term at 450 ppm CO_2-e leaves a 54% chance of exceeding 2°C of global warming (Meinshausen 2006).

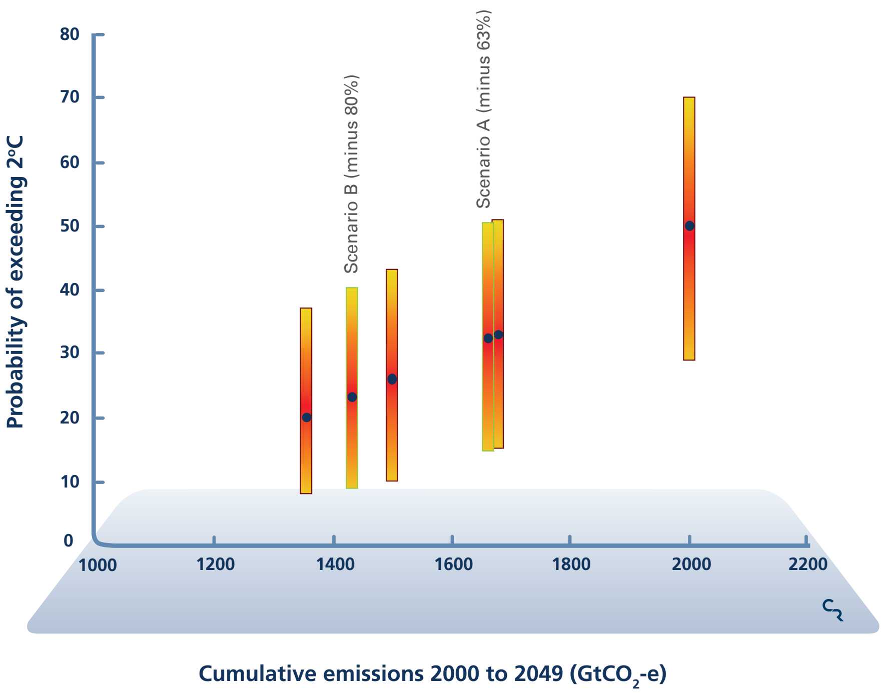


Figure 19: There is not a single probability of avoiding 2°C for a fixed cumulative emissions level. Rather, there is a range of possible probability outcomes. This figure shows the exceedance probability ranges for various cumulative emissions levels in the half century to 2050 based on the work of Meinshausen *et al.* (2009).

4.5 The Concept of Overshoot and Return

4.5.1 Current Atmospheric Greenhouse Gas Concentrations

The amount of carbon dioxide, alone, in the atmosphere in 2009 stands at 386 ppm CO_2 (see Figure 20), having risen 2.28 ppm over the previous year. Using the ratio between CO_2 and CO_2-e reported by the IPCC (2007) permits us to conclude that the total concentration of long-lived greenhouse gases (including carbon dioxide) in the atmosphere has risen from 455 ppm CO_2-e in 2005 to in excess of 463 ppm CO_2-e now (IPCC 2007, Tans 2009).

Despite these current greenhouse gas concentrations in excess of 463 ppm CO_2-e, there is potential for their re-absorption by the biosphere (land and oceans). Analysis also indicates that in the short-term the full warming potential (radiative forcing) of greenhouse gases is being reduced by certain aerosol emissions (some conventional air pollution, such as sulphur dioxide and particles, which have a short- and medium-term cooling effect on regional climates) released mainly from inefficient burning of fossil fuels and biomass.

4.5.2 Concentration Pathways

Therefore, although atmospheric greenhouse gas concentration levels are higher than 450 ppm CO_2-e now, researchers suggest there exists a pathway for stabilisation of the greenhouse gas concentration at 400 ppm CO_2-e, following a peak at 475 ppm CO_2-e (see Figure 21).

> Using the ratio between CO_2 and CO_2-e reported by the IPCC (2007) permits us to conclude that the total concentration of long-lived greenhouse gases (including carbon dioxide) in the atmosphere has risen from 455 ppm CO_2-e in 2005 to in excess of 463 ppm CO_2-e now.

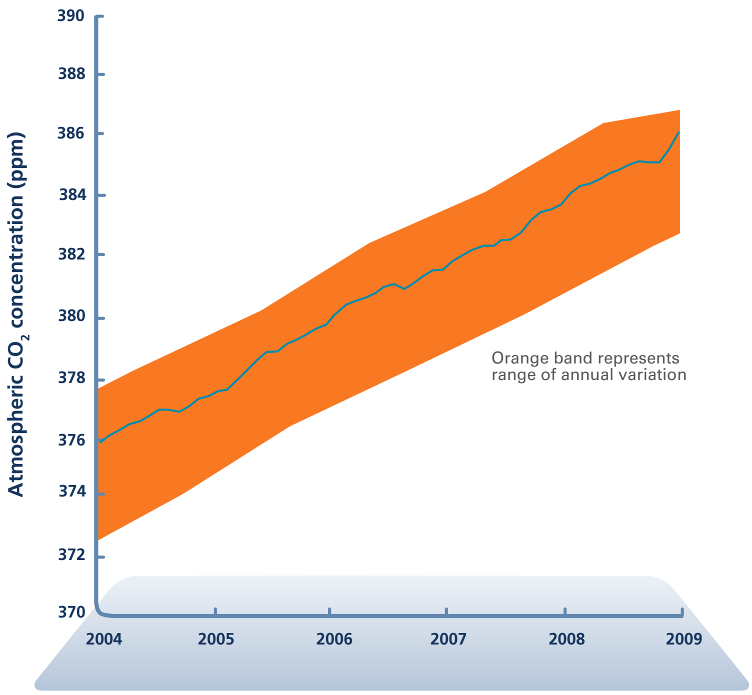


Figure 20: Recent monthly mean atmospheric carbon dioxide concentrations globally averaged over marine surface sites, as reported by the Global Monitoring Division of NOAA/Earth System Research Laboratory (Tans 2009).

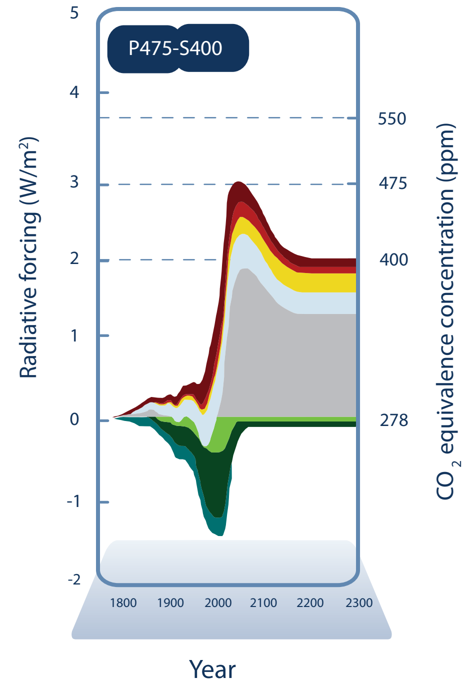


Figure 21: Some gases have a warming effect and others have a cooling effect. This figure shows the net warming effect of various greenhouse gases and aerosols and their influence on radiative forcing. P475-S400 shows that emissions peak at 475 ppm CO_2-e before stabilising at 400 ppm CO_2-e, the reduction being due to the uptake of atmospheric carbon by the ocean and biosphere (Meinshausen 2006).

Though technically the overshoot and return process should be possible, not only is the current level of 463 ppm CO_2-e disconcertingly close to the 475 ppm CO_2-e emissions peak described by Meinshausen (2006), but the rate of increase in greenhouse gas emissions (see Figure 20) has not slowed – if anything, it is increasing. At the current rate of increase in greenhouse gas levels, the 475 ppm CO_2-e peak will be reached by 2015.

Furthermore, the recent findings described above show decreasing sink efficiencies and movement toward tipping element thresholds. These findings imply a compromised ability to overshoot limits and return greenhouse gas concentrations to lower levels. That is, the ability of the climate system to return to lower greenhouse gas levels via processes of re-absorption is becoming impaired with increasing average global temperatures. “As a result, meeting climate targets based on atmospheric concentration of carbon dioxide will be more difficult, requiring a greater reduction in emissions than would otherwise be necessary,” according to Macintosh and Woldring (2008).

4.6 What 2050 Emissions Level will Avoid 2°C of Warming?

The IPCC Fourth Assessment Report Working Group 3 indicates that a temperature increase range of 2.0-2.4°C (above pre-industrial levels) is consistent with global greenhouse gas emissions reductions of 85% to 50% below their levels in the year 2000 (IPCC 2007). Global emissions in that year (including land use change, forestry and bunker fuels) were 44,000 MtCO_2-e.

“Not only is the current level of 463 ppm CO_2-e disconcertingly close to the 475 ppm CO_2-e emissions peak described by Meinshausen (2006), but the rate of increase in greenhouse gas emissions has not slowed – if anything, it is increasing. At the current rate of increase in greenhouse gas levels, the 475 ppm CO_2-e peak will be reached by 2015.”

Thus the 85% and 50% reduction figures translate into a need to reduce annual emissions levels to between 6,650 and 22,170 $MtCO_2$-e. Based on a projected global population of 9.2 billion in 2050 (UNPP 2006), these 85% and 50% reductions would be consistent with per capita annual emissions levels of 0.74 tCO_2-e and 2.4 tCO_2-e, respectively, in 2050. Although these figures are based on probability distributions, staying below 400 ppm CO_2-e implies per capita emissions at, or below, the bottom of this range.

Baer and Mastrandrea (2006) estimate that sub-370 ppm concentrations of carbon dioxide (not CO_2-e) would be required by 2100 to keep the chance of exceeding a 2°C increase in average global temperatures to 12–32%. To achieve this, they estimate that emissions reductions of about 81% on 1990 levels would be required by 2050, with the rate of growth of CO_2 emissions beginning to decline in 2010 and the peak rate of emissions being reached in 2013 (Baer and Mastrandrea 2006). This emissions trajectory would involve a peak carbon dioxide concentration of 421 ppm CO_2 before returning to about 366 ppm CO_2 by 2100.

Meinshausen (2006) estimates that stabilisation at 400 ppm CO_2-e requires an emissions cut of 55% from 1990 levels by 2050 (Meinshausen 2006). Assuming global emissions in 1990 were 42,000 $MtCO_2$-e/yr, a 55% reduction would leave annual emissions at approximately 19,000 $MtCO_2$-e in 2050, or 2.1 tCO_2-e/yr per person.

James Hansen and his co-workers state that "if humanity wishes to preserve a planet similar to that on which civilisation developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm" (Hansen *et al.* 2008).

The most recent work published in *Nature* by Meinshausen *et al.* (2009) has been used as the basis of the cumulative and annual emissions settings for 2050 in this report. The paper focuses on the carbon budget to 2020 and the carbon budget to 2050. Figure 22 summarises the probability of avoiding 2°C of warming above pre-industrial levels based on cumulative emissions in the first half of the century.

4.7 Scenarios

4.7.1 Scenario A (Minus 63%):

In Scenario A (minus 63% on 1990 levels) an annual carbon dioxide equivalent emissions level in 2050 of 14.7 $GtCO_2$-e/yr has been used. This emissions target is consistent with an interpolated probability of exceeding 2°C of warming between 10% and 40%, with a default of about 24% (Meinshausen *et al.* 2009).

The associated cumulative emissions are 1664 $GtCO_2$-e from 2000 to 2049. This cumulative emissions level is consistent with an exceedance probability of about 15–50%, with a 32% default (Meinshausen *et al.* 2009).

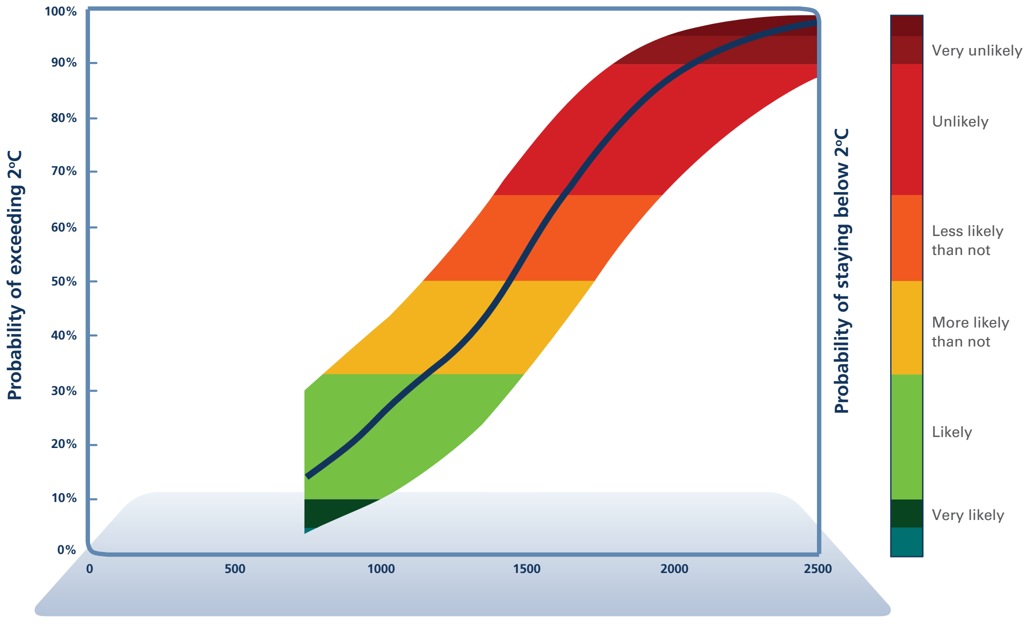


Figure 22: Effect of cumulative CO_2 only emissions in the first half of the century on the probability of avoiding a warming of 2ºC above pre-industrial levels (Meinshausen *et al.* 2009).

For ease of thinking about such figures, a useful number to bear in mind is that based on a population of 9.2 billion people in 2050 (UNPP 2006) this scenario equates to a per capita emissions level of 1.6 tonnes of CO_2-e/yr per person in 2050 (which is the middle of the plausible per capita range determined from IPCC results; 0.74 tCO_2-e/yr to 2.4 tCO_2-e/yr).

4.7.2 Scenario B (Minus 80%):

The minus 80% scenario models an annual carbon dioxide equivalent emissions level in 2050 of approximately 7.9 $GtCO_2$-e/yr. This emissions target is below the lowest scenario reported by Meinshausen *et al.* (2009) in their recent work (10 $GtCO_2$-e/yr) and is equivalent to an extrapolated exceedance probability range of 4–29%, with a default of 13%.

This scenario equates to a per capita emissions level of 0.9 tonnes of CO_2-e/yr per person in 2050 (positioning this scenario at the lower end of the plausible per capita range determined from IPCC results). The cumulative emissions level for 2000 to 2049 in this scenario is about 1432 $GtCO_2$-e, which is approximately consistent with an exceedance probability of 9–40% (with a 23% default) when interpolated from the data of Meinshausen *et al.* (2009).

The summary emissions data for Scenario A and Scenario B are shown below in Table 2. The probability distributions for 2050 annual emissions under each scenario are also given in Figure 23.

Table 2: Summary data for the two main scenarios used in this report.

Scenario	2050 Annual Emissions ($GtCO_2$-e/yr)	2000 to 2049 Cumulative Emissions ($GtCO_2$-e)
Scenario A (minus 63%)	14.7	1664
Scenario B (minus 80%)	7.9	1432

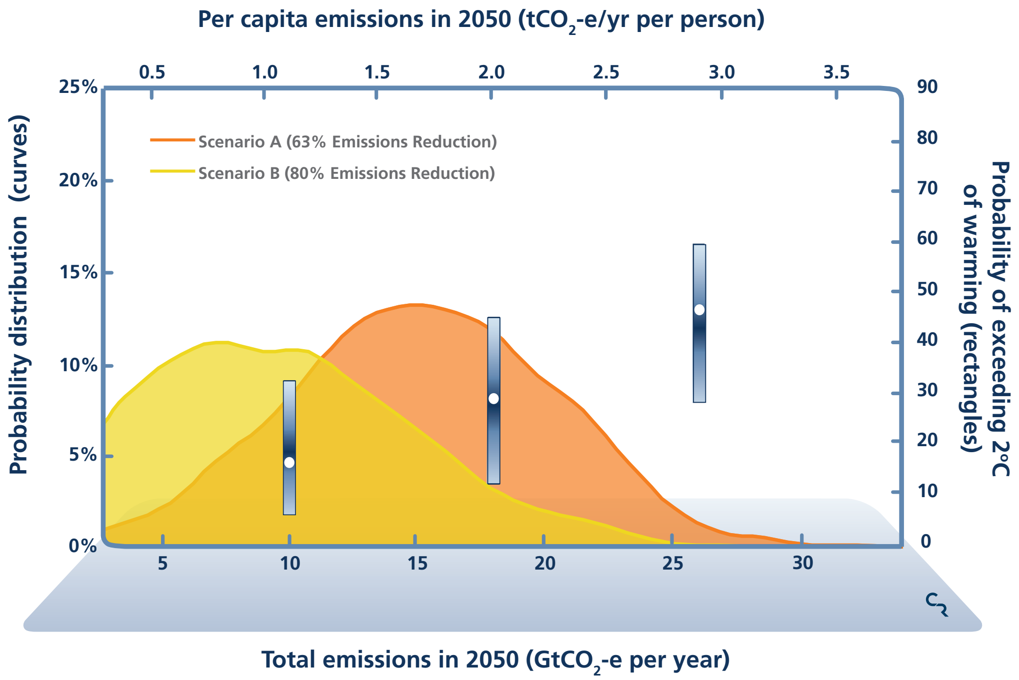


Figure 23: This figure shows two things. The first is the probability distributions for each of the scenarios modelled in this report. The second is the position of the these distributions with respect to the probability of exceeding 2°C of warming as reported by Meinshausen *et al.* (2009).

5 Scenario A (Minus 63%): Emissions and Energy

In this analysis, extensive modelling was performed to consider numerous scenarios. However, to keep the presentation of the results relevant and succinct, only results pertinent to the objectives are presented. With this goal in mind, two major scenarios are presented:

- Scenario A, equivalent to emissions levels 63% below 1990 levels by 2050.
- Scenario B, equivalent to emissions levels 80% below 1990 levels by 2050.

This section presents the main results for Scenario A, which models the delivery of an emissions outcome of 14.7 $GtCO_2$-e/yr (1.6 tCO_2-e/yr per person) in 2050. The cumulative emissions between 2000 and 2049 for this scenario are 1664 $GtCO_2$-e, which, based on Meinshausen *et al.* (2009), is associated with a probability of exceeding 2°C of warming of 15–50%, with a default probability of 32%.

Both scenarios examined in this report use an emissions baseline from the IPCC's SRES A1FI, which is consistent with the current high levels of emissions growth.

In this section, emissions, energy and non-energy industry sector responses are presented. In the next section, the modelling results are presented for costs and returns to the global economy.

5.1 Emissions

The results shown in Scenario A were calculated using a 2050 greenhouse gas emissions target of 14.7 $GtCO_2$-e/yr (1.6 tCO_2-e per person). To achieve the modelled emissions target for 2050, the CRISTAL model determined that low-carbon industries would need to grow at an average rate of 22% per annum from 2010 through the critical development period, assuming the same start time and full concurrent development.

Similarly, all emissions abatement for non-energy sectors were assumed to advance at their maximum possible rate of uptake from 2010 onwards. These rates are unique to each non-energy sector low-carbon resource.

The CRISTAL model forecast for emissions abatement against the business-as-usual baseline is shown in Figure 24 out to 2050 and further summarised by abatement sector in Figure 25. The sectoral breakdown for emissions abatements is shown for 2020, 2030, 2040 and 2050 in Figure 26.

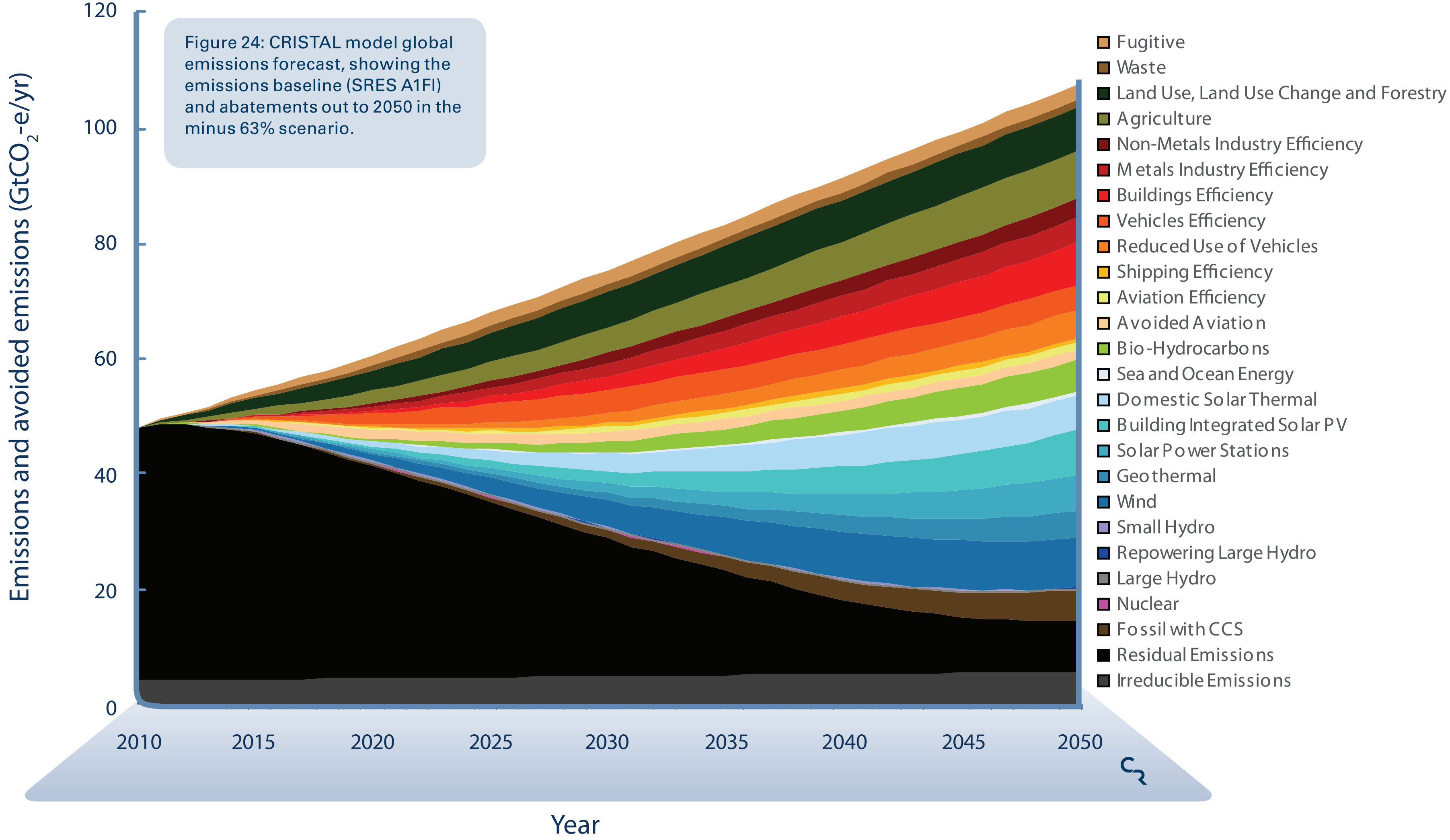


Figure 24: CRISTAL model global emissions forecast, showing the emissions baseline (SRES A1FI) and abatements out to 2050 in the minus 63% scenario.

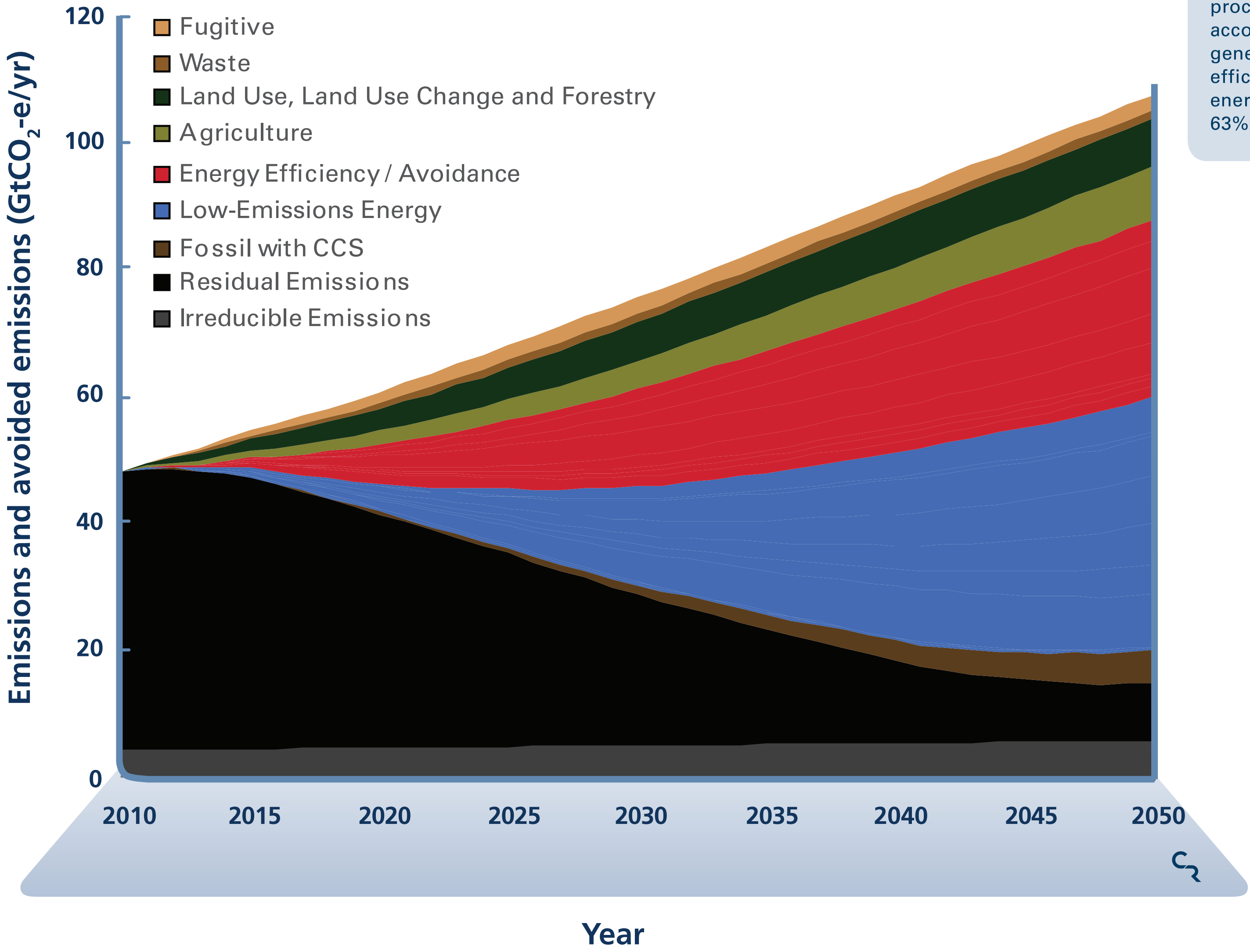
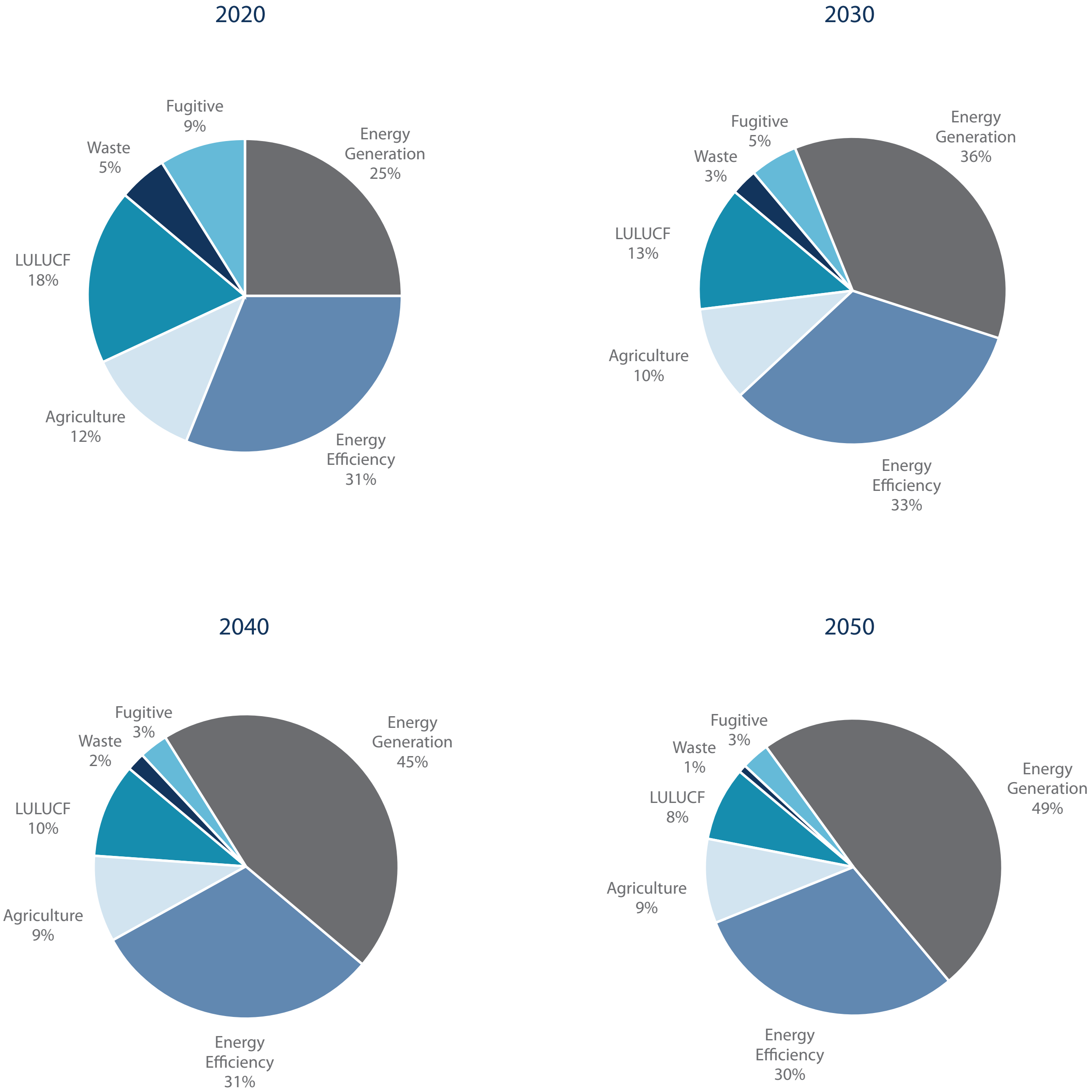


Figure 25: The low-carbon re-industrialisation process, grouped according to energy generation, energy efficiency and non-energy in the minus 63% scenario.

Figure 26: The sectoral composition of emissions abatement in each of the years shown for the minus 63% scenario.



5.2 Final Energy

Assuming that all low-carbon industries grow at 22% per annum from 2010 until each has harnessed 20% of its resource, the model indicates that all energy-sector energy needs can be generated from zero- or low-emissions sources by 2050 (Figure 27 and Figure 28). That is, no power is generated using fossil fuel sources without the application of CCS facilities.

With regard to the transport sector, it is important to note that both Scenario A and Scenario B assume that energy demand from the land-based transport sector is met through grid-connected renewable sources (e.g. providing energy for electrical or hydrogen-fuelled vehicles). This is because, while the modelling indicated that in 2050 there will be sufficient bio-hydrocarbon resources (18000 TWh/yr) to meet the modelled needs of aviation (6200 TWh/yr in Scenario A and 3900 TWh/yr in Scenario B) and shipping (2800 TWh/yr in Scenario A and 2500 TWh/yr in Scenario B), there are insufficient biofuel resources to stretch to the 2050 needs of land-based transport (32500 TWh/yr in Scenario A and 18000 TWh/yr in Scenario B).

Since there are alternatives for land-based transport – but not for air and sea, as it stands today – the priority allocation of sustainable biofuels must be to the aviation and shipping sectors to achieve the scenario outcomes (see Section 17.3 for more information). The current amount of bio-hydrocarbons used in stationary energy (including the traditional use of biomass) is assumed to stay constant at today's levels.

It should be noted that the focus of bio-hydrocarbon use in the aviation and shipping sectors is not based on these sectors continuing to grow as per business-as-usual. Rather, substantial reductions in energy use are assumed to take place through efficiency (such as decreased ship speeds) and reduced usage (such as the utilisation of advanced telepresence to avoid business travel). Transport efficiency and the reduced use of aviation and vehicles are treated as abatement wedges in their own right within the energy efficiency grouping.

In this scenario, by 2050 the amount of energy generated by many low-carbon industries has reached a maximum, given their individual resource limitations (Figure 27). However, in the case of solar power stations, building integrated solar PV, domestic solar thermal, wind and geothermal energy generation, there is room for continued expansion beyond 2050.

While CCS energy generation could also be expanded to accommodate increased baseline demand for electricity, the residual emissions from CCS prove to be a limiting factor. However, industrial processes for which there are not low-carbon alternatives will still require CCS facilities.

It should be noted that nuclear power (fission) is included in the presented scenarios based on existing plants and plants currently under construction. Planned facilities and other expansion are not included (see Section 17.5 for further explanation of this assumption). Consequently, almost all plants in the examined scenarios cease operation at the end of their design lives by 2050.

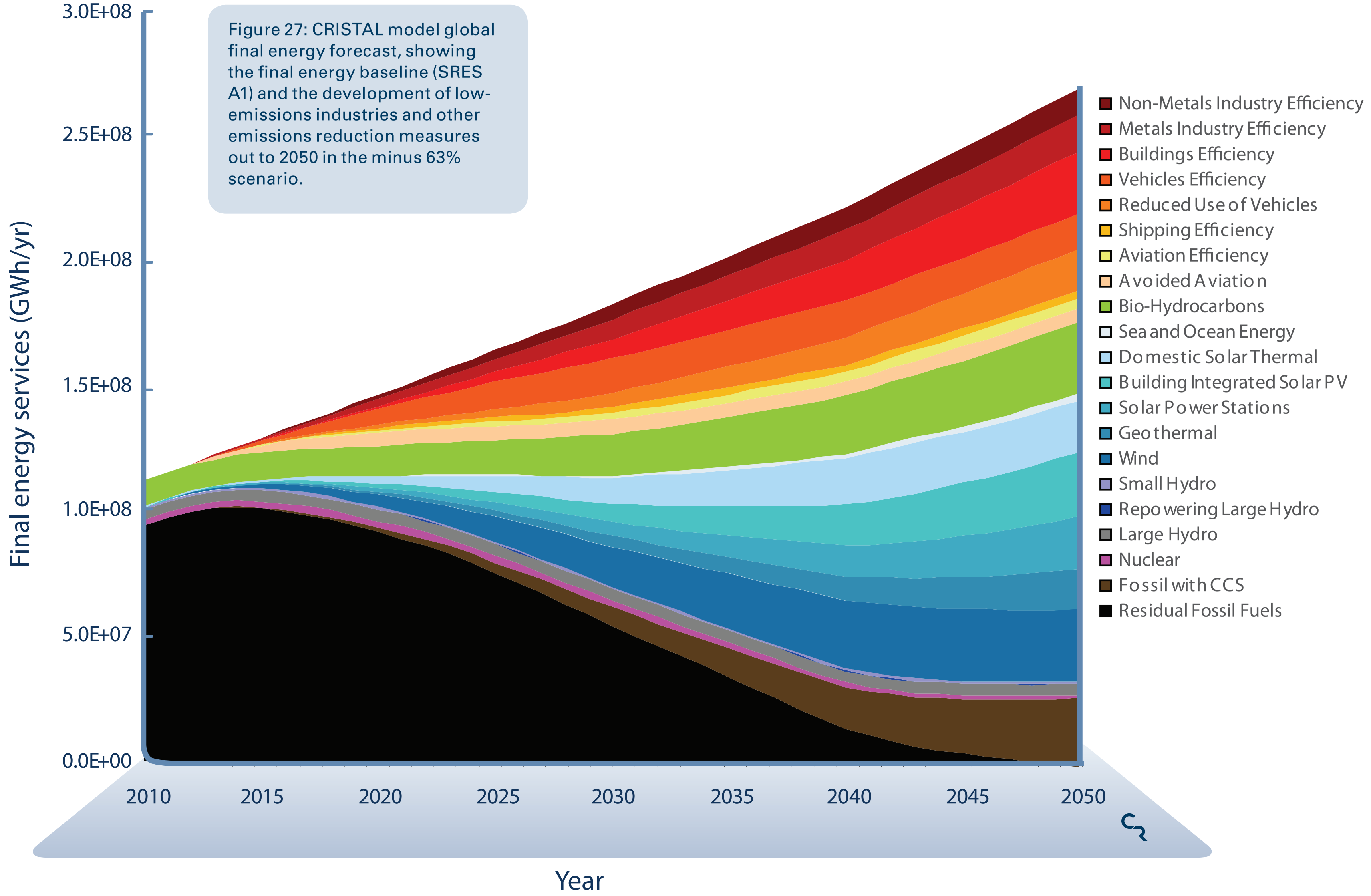


Figure 27: CRISTAL model global final energy forecast, showing the final energy baseline (SRES A1) and the development of low-emissions industries and other emissions reduction measures out to 2050 in the minus 63% scenario.

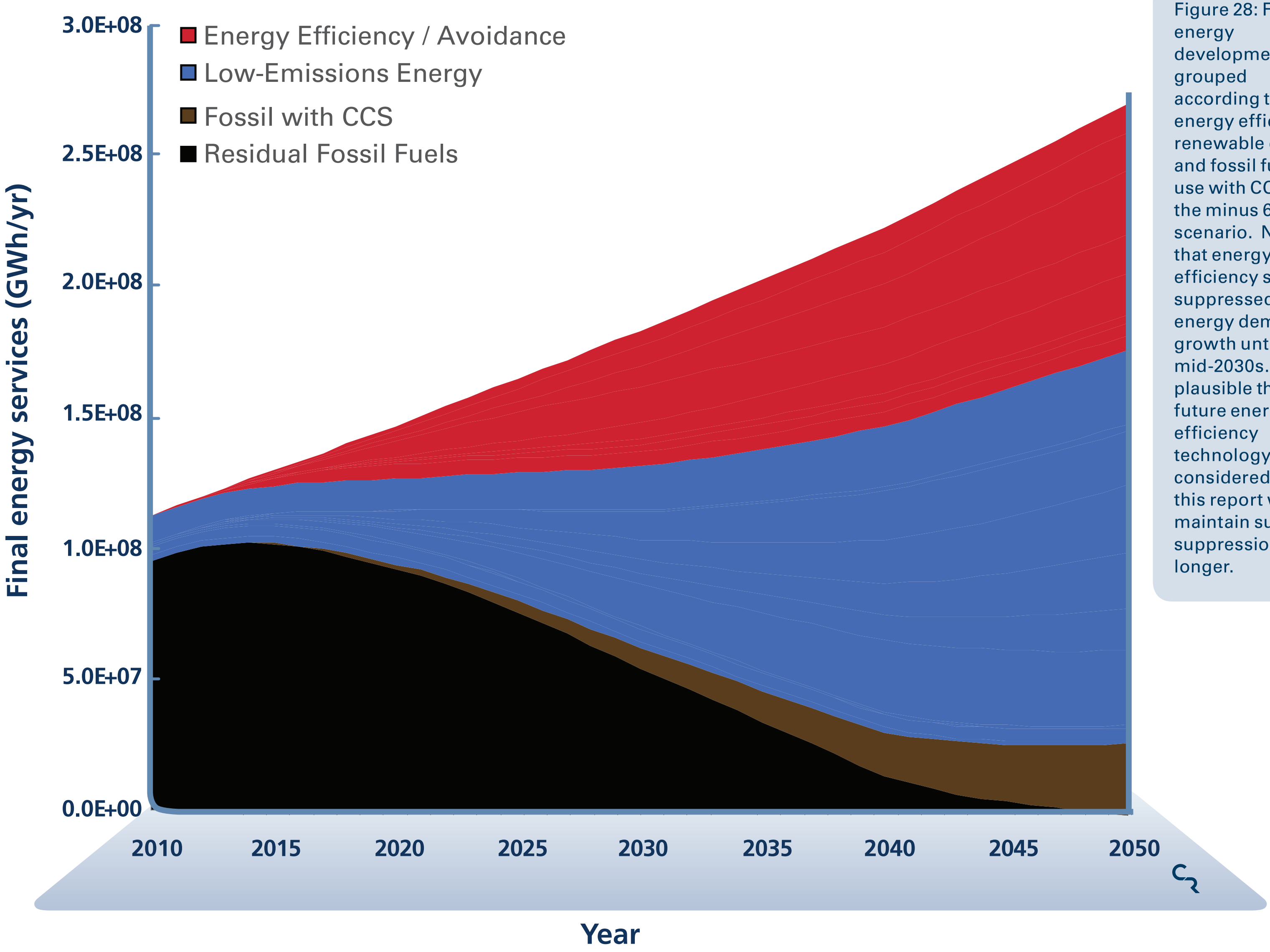


Figure 28: Final energy development, grouped according to energy efficiency, renewable energy and fossil fuel use with CCS in the minus 63% scenario. Note that energy efficiency strongly suppressed final energy demand growth until the mid-2030s. It is plausible that future energy efficiency technology not considered in this report would maintain such suppression even longer.

5.3 Non-Energy

The specific emissions abatement wedges from non-energy sources are shown in greater detail below (see Figure 29). Again, it is assumed that all emissions abatement strategies in non-energy sectors are advancing at their maximum possible rate of uptake from 2010 onwards.

Within the land use, land use change and forestry (LULUCF) sector, the opportunities for emissions avoidance by foregoing deforestation can be acquired relatively quickly, assuming international financial compensation schemes are established in sufficient time. Such schemes are essential for the avoidance of deforestation in developing countries, which would otherwise suffer an opportunity cost.

Agricultural emissions abatements develop gradually as improved farming techniques are adopted, such as low-tillage practices and improved livestock diet and waste management practices.

Fugitive emissions decrease as the intensity of fossil fuel usage decreases and improved extraction, transportation and containment techniques are used. However, if a greater reliance on fossil fuel usage persists in industry or via the more prevalent use of CCS, then fugitive emissions would also increase above those reported here.

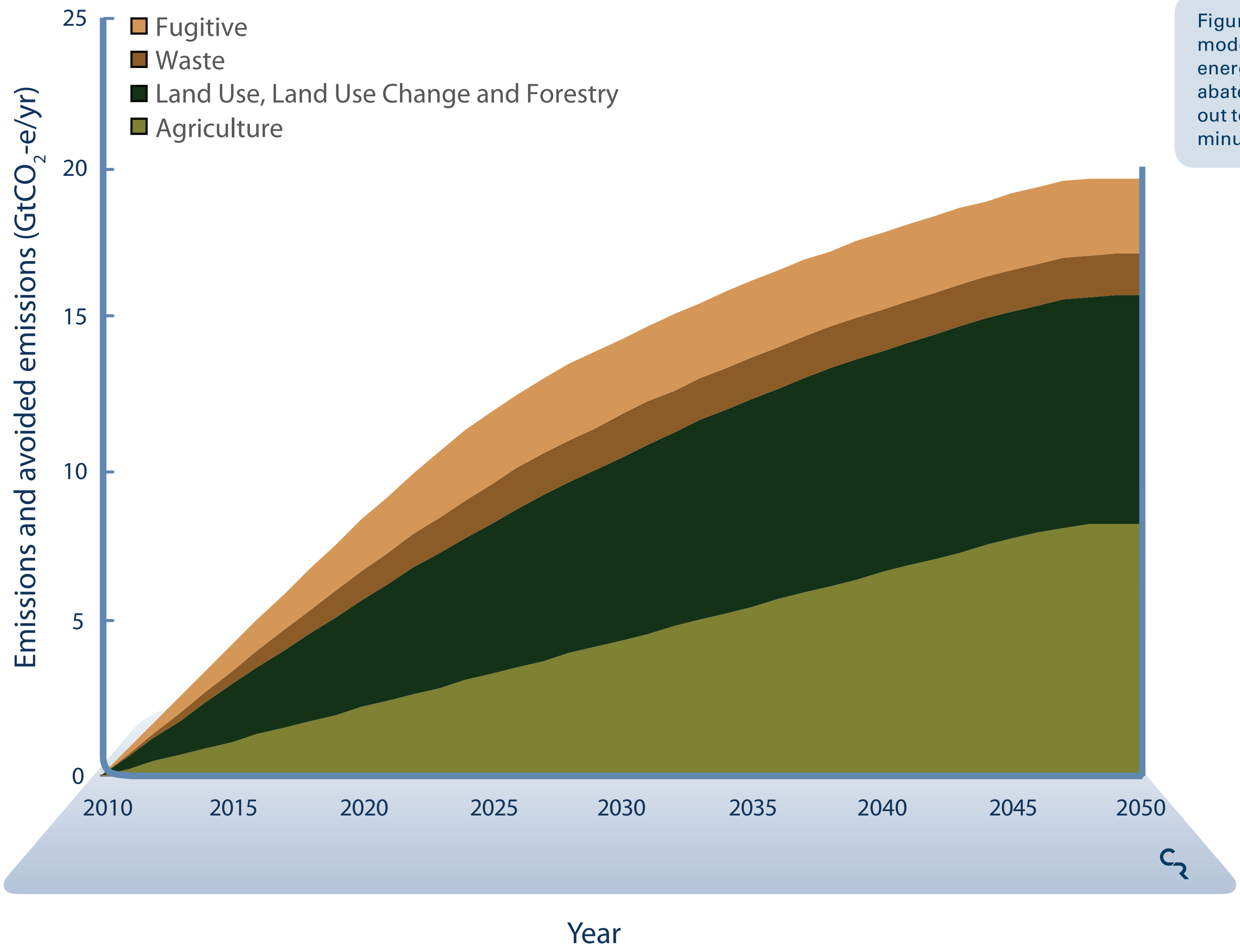


Figure 29: CRISTAL model global non-energy emissions abatement forecast out to 2050 in the minus 63% scenario.

6 Scenario B (Minus 80%): Emissions and Energy

The minus 80% scenario is based on Scenario A in all aspects except for:

- The speed for industrial growth has been changed to 24% annual growth per annum in the critical development period (until 20% of resource is harnessed).
- The emissions abatement obtained from the LULUCF segment out to 2050 is expanded by 80%.
- The emissions abatements by 2050 from energy efficiency and avoidance measures are all increased by 10%.

It is important to realise that expansion of the LULUCF and energy efficiency abatements in this scenario are crucial to meeting the minus 80% emissions target in 2050. These expansions move the abatement levels for these two areas close to their maximum plausible levels. However, these changes also mean that the growth rate required for low-emissions industries is not as high as would otherwise be the case without these abatement expansions.

The effect of these changes is that the emissions level reached in 2050 changes from 14.7 $GtCO_2$-e/yr to approximately 7.9 $GtCO_2$-e/yr, which is about 20% of 1990 global emissions. In per capita terms, this is a change from 1.6 tCO_2-e/yr per capita to approximately 0.9 tCO_2-e/yr per capita.

The total cumulative emissions between 2000 and 2049 in this scenario are 1432 $GtCO_2$-e, which is consistent with a probability of exceeding 2°C of warming of about 9–40%, with a default of 23%.

This section presents the main results for the minus 80% scenario, which models the delivery of an emissions outcome consistent with a higher probability of avoiding runaway climate change than Scenario A (minus 63%).

In this section, emissions, energy and non-energy industry sector responses are presented. In the next section, the modelling results are presented in light of cost and investment returns.

6.1 Emissions

The results shown in this report were calculated using increased growth rates compared to Scenario A. To achieve the modelled emissions target for 2050, the CRISTAL model determined that low-carbon industries would need to grow at an average rate of 24% per annum from 2010 until deployment scale has been achieved (20% of resource is harnessed), assuming the same start time and full concurrent development. Similarly, all emissions abatement for non-energy sectors are assumed to advance at their maximum possible rate of uptake from 2010 onwards. These uptake rates are unique to each non-energy sector.

The CRISTAL model forecast for emissions abatement against the SRES A1FI baseline is shown in Figure 30 out to 2050 and further summarised by abatement sector in Figure 31. The sectoral breakdown for emissions abatements is shown for 2020, 2030, 2040 and 2050 in Figure 32.

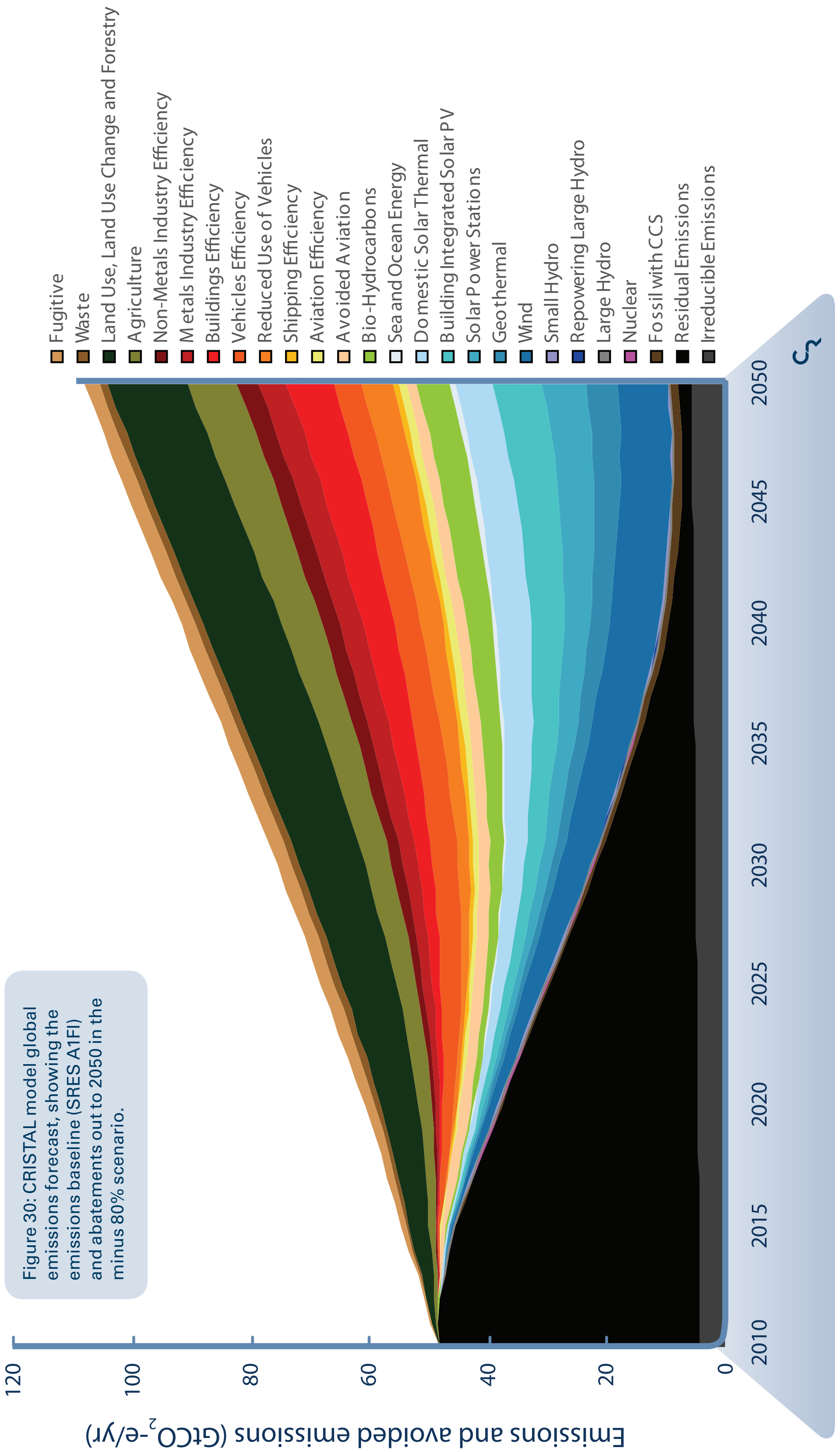


Figure 30: CRISTAL model global emissions forecast, showing the emissions baseline (SRES A1FI) and abatements out to 2050 in the minus 80% scenario.

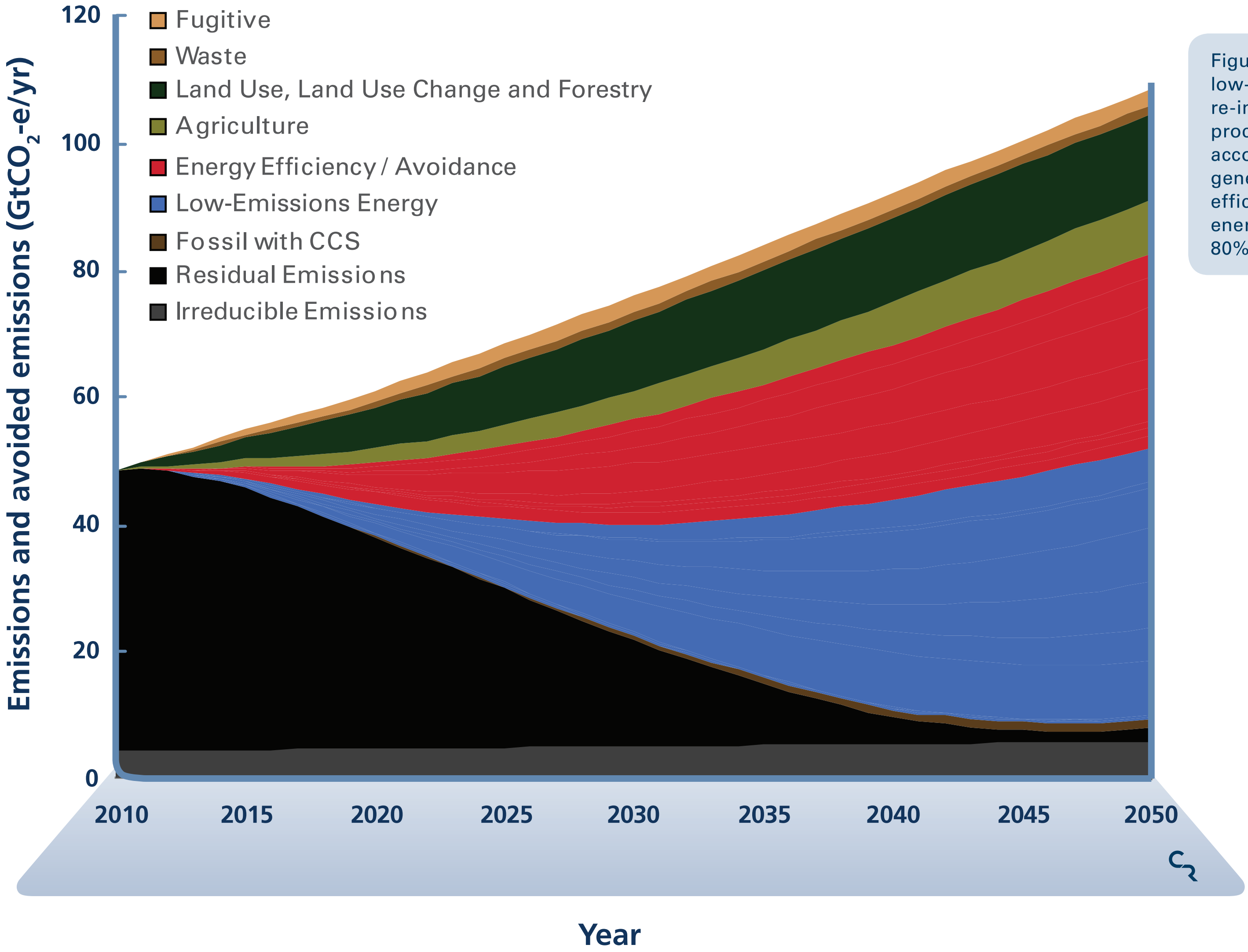
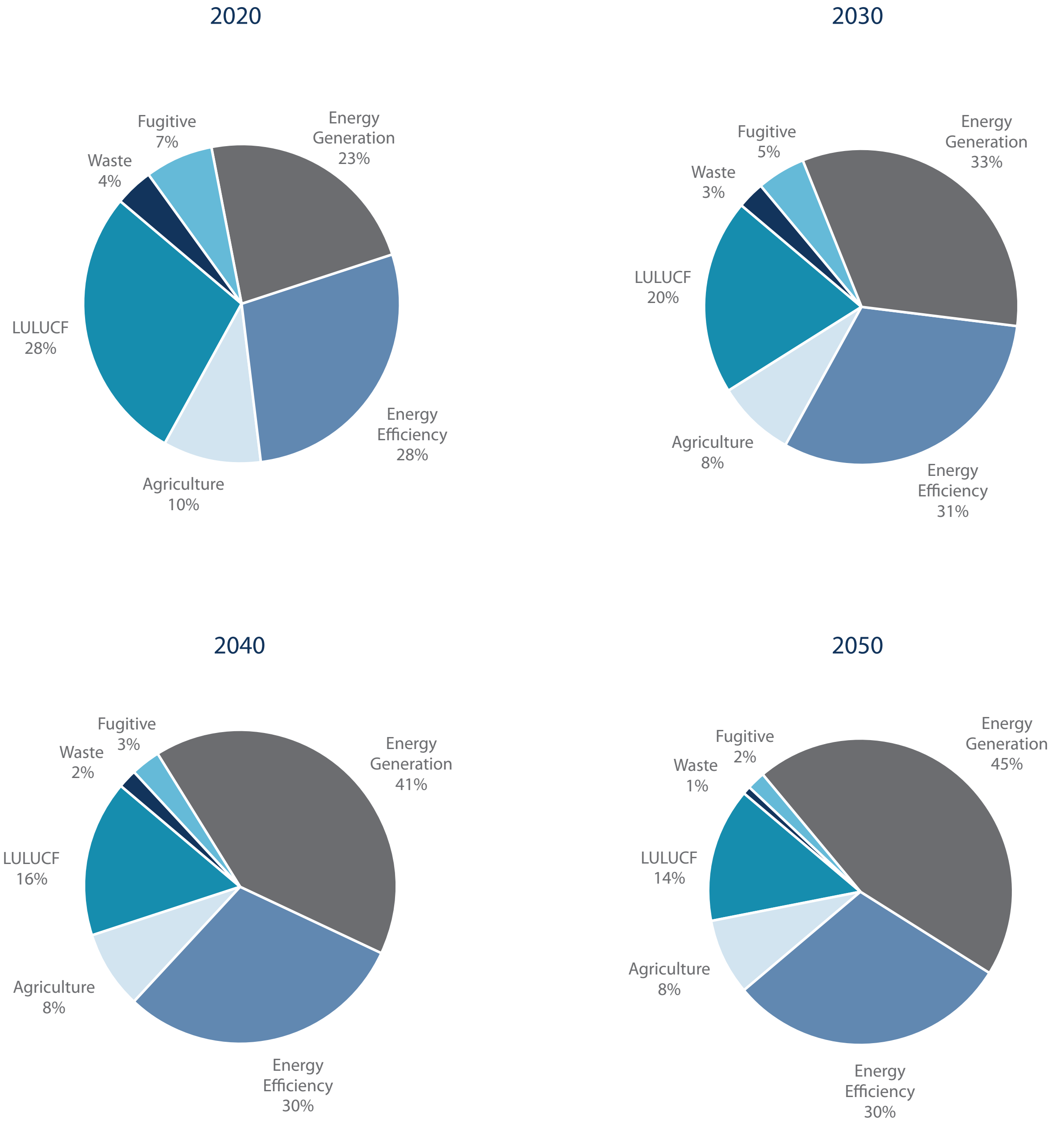


Figure 31: The low-carbon re-industrialisation process, grouped according to energy generation, energy efficiency and non-energy in the minus 80% scenario.

Figure 32: The sectoral composition of emissions abatement in each of the years shown for the minus 80% scenario.



6.2 Final Energy

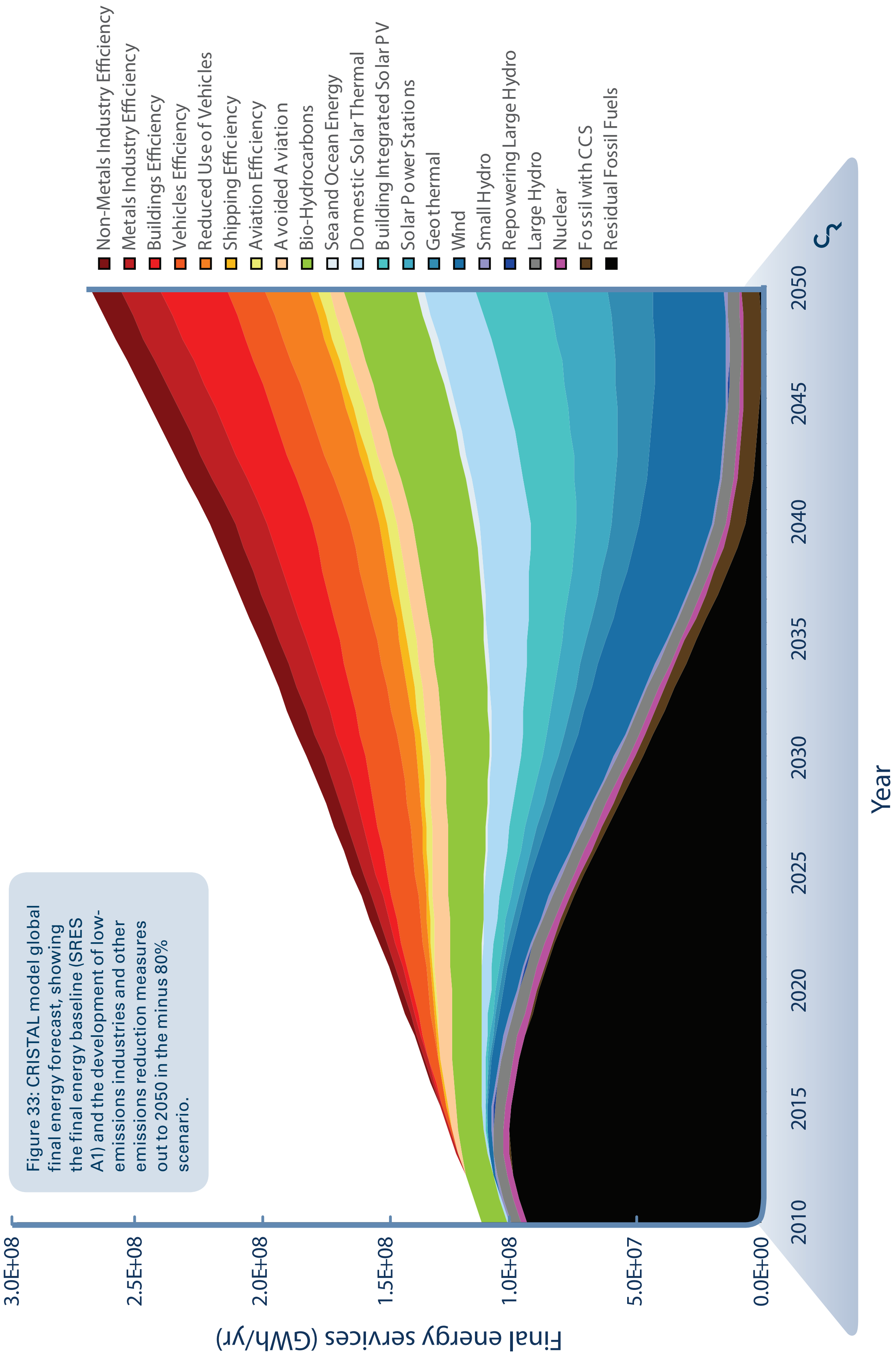


Figure 33: CRISTAL model global final energy forecast, showing the final energy baseline (SRES A1) and the development of low-emissions industries and other emissions reduction measures out to 2050 in the minus 80% scenario.

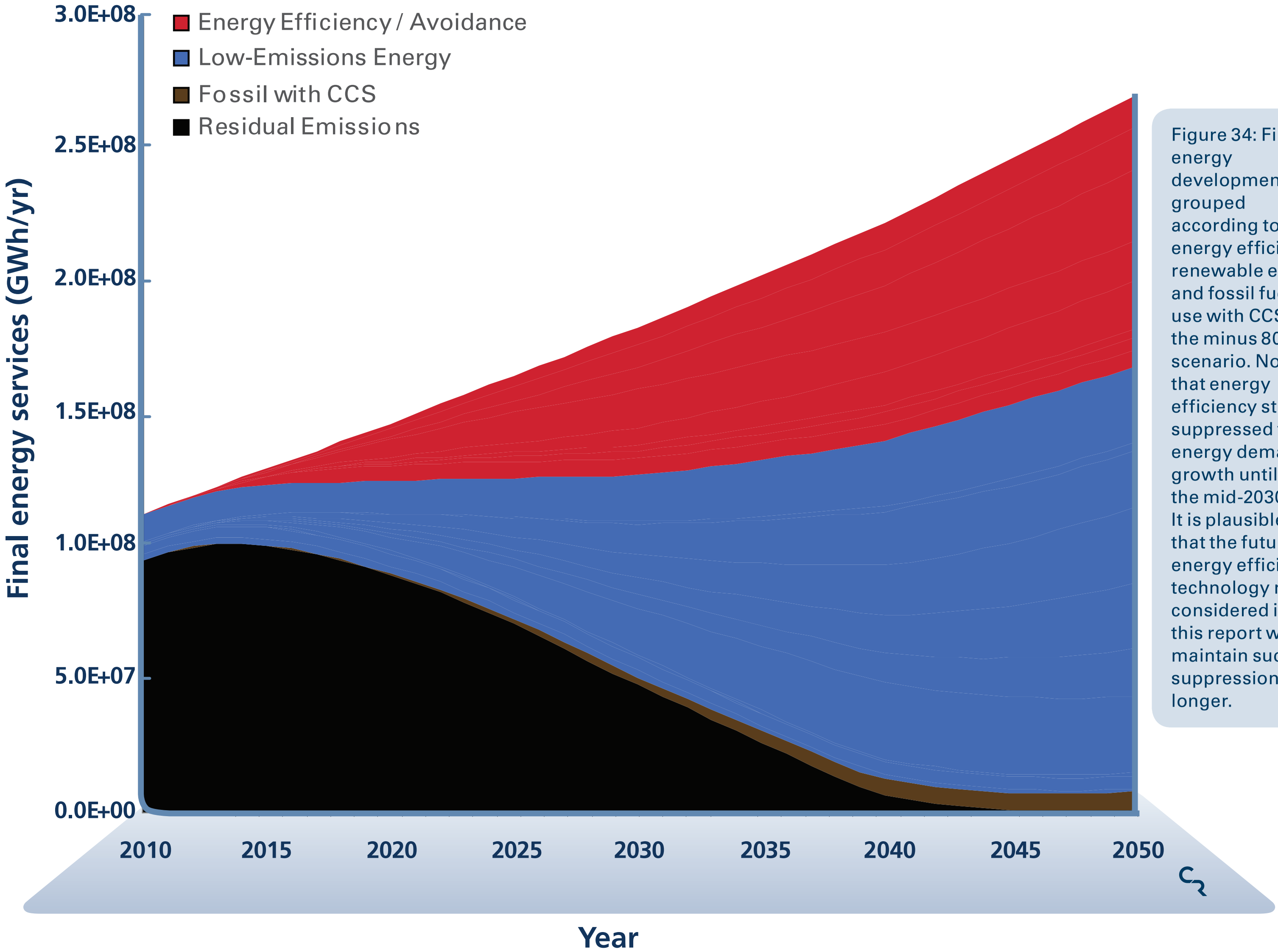


Figure 34: Final energy development, grouped according to energy efficiency, renewable energy and fossil fuel use with CCS in the minus 80% scenario. Note that energy efficiency strongly suppressed final energy demand growth until the mid-2030s. It is plausible that the future energy efficiency technology not considered in this report would maintain such suppression even longer.

6.3 Non-Energy

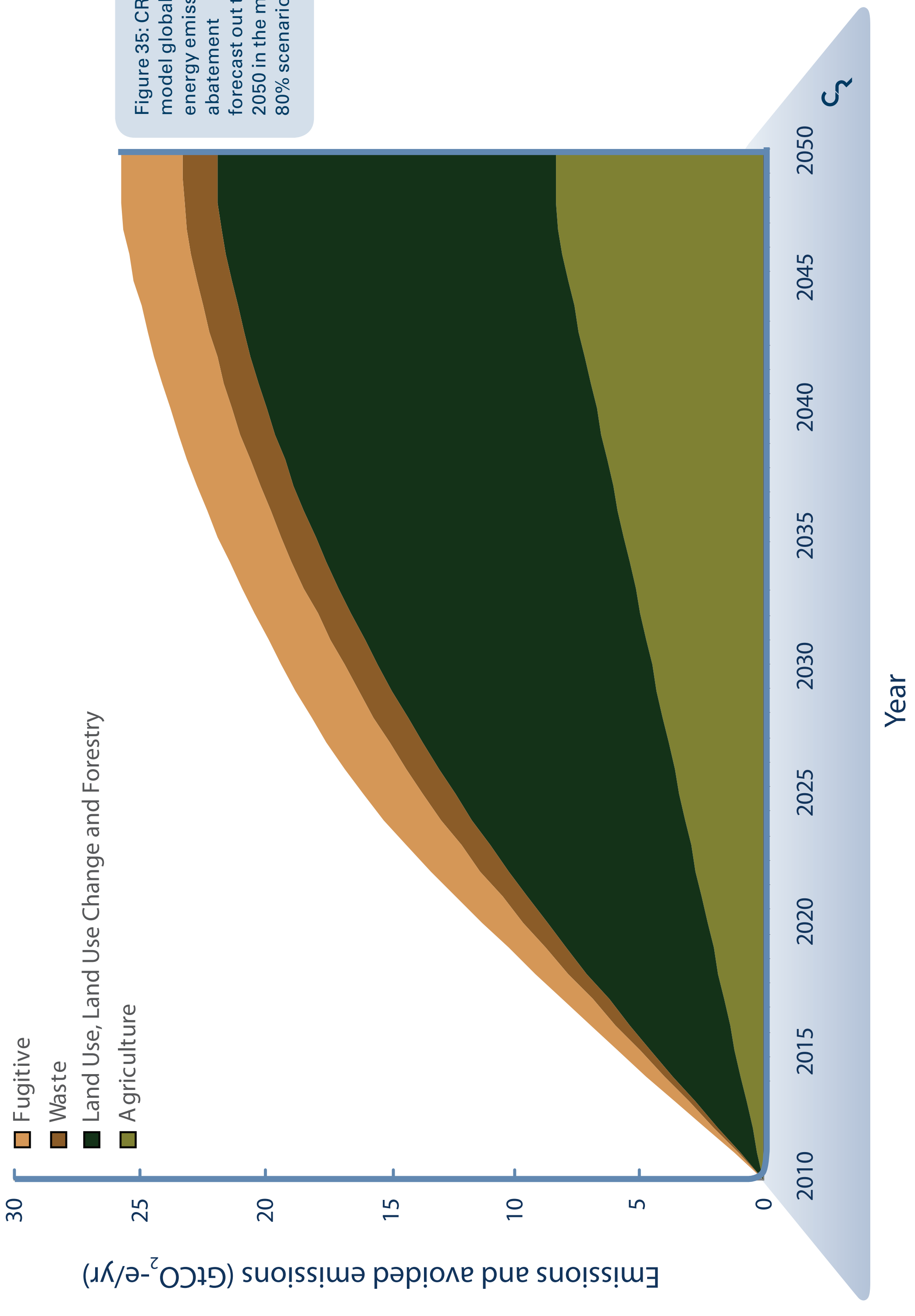


Figure 35: CRISTAL model global non-energy emissions abatement forecast out to 2050 in the minus 80% scenario.

7 Scenario A (Minus 63%): Costs, Investment and Returns

From a cost perspective, relative to business-as-usual (i.e. fossil fuel energy generation), the zero- and low-emissions technologies examined in this report can be divided into the following three categories:

1. Technologies that are already cost neutral or create savings (e.g. domestic solar hot water).

2. Technologies that are initially expensive but go on to create savings as economies of scale are achieved (e.g. buildings integrated with solar PV).

3. Technologies that will always be more expensive (e.g. CCS).

For the second two categories, the investment required to achieve sufficient industry growth to meet the emissions abatement and final energy targets is presented in this section for each technology, on a per annum basis and as a cumulative amount.

7.1 Non-Energy

There are avoided emissions and sinks available, for example, in the form of terrestrial carbon (i.e. that stored in forests or soil). However, their use does not, at this stage, appear to create intrinsic economic returns in the way that energy efficiency or renewable energy can over the long-term. In this sense, terrestrial carbon sequestration represents a net ongoing cost.

The cost of avoided emissions, at a minimum, may reflect the cost of other values for uses of the land, such as paper production from forests or grazing cattle on land cleared of forest. On the other hand, in a traded market this terrestrial carbon may reflect the cost of carbon emissions permits and be treated as an offset. The complexity and uncertainty of such costs put them beyond the scope of this report.

7.2 Efficiency

In this report, it is not assumed that energy efficiency uptake will occur without additional measures that must be implemented to drive uptake. However, these measures generally present no net costs to the economy or create a net benefit. The savings in avoided fuel use only are presented (see Figure 36 and Figure 37), although there may be other financial benefits. However, many efficiency actions have an increased capital cost, which must be counted against the savings. Since energy efficiency actions are diverse in nature and their initial cost, it is beyond the scope of this report to calculate a net saving or net present value for the energy efficiency measures. As with renewable energy, many of the costs associated with energy efficiency will be dramatically reduced through the economies of scale that occur in the process of implementation.

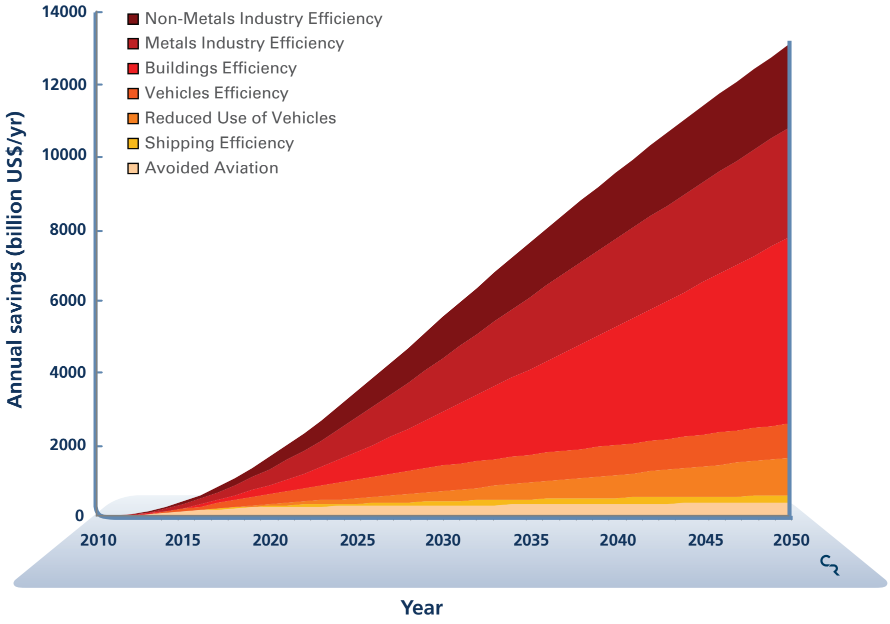


Figure 36: CRISTAL model forecast of gross annual energy cost savings through energy efficiency and avoidance measures in the minus 63% scenario out to 2050. NB: These are gross savings and do not include any costs that may be involved in adopting the efficiency measures.

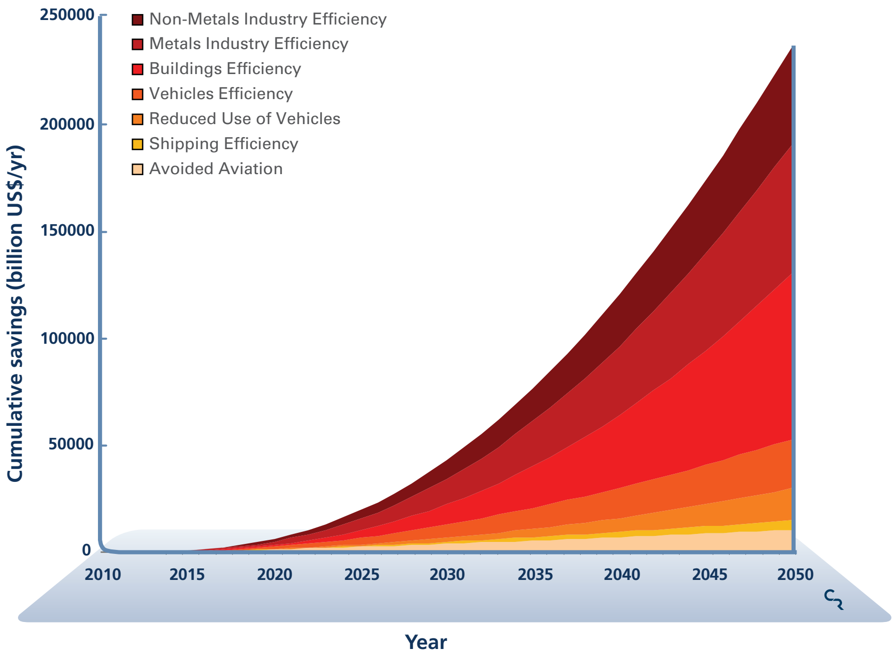


Figure 37: CRISTAL model forecast of gross cumulative energy cost savings for energy efficiency and avoidance measures in the minus 63% scenario out to 2050. NB: These are gross savings and do not include any costs that may be involved in adopting the efficiency measures.

7.3 Renewable Energy Investment

The annual (Figure 38) and cumulative (Figure 39) investment in various renewable resources is calculated based on their historical learning rates (a measure of the reduction in unit costs as production volume doubles; Taylor *et al.* 2006). Here, the amount of investment required is taken as the relative cost of these renewable energy industries compared to their fossil fuel competition. In this way, the relative cost expresses the additional cost of producing energy through renewable energy technology compared to the costs of producing the same amount of energy using fossil fuels. It should be noted that all of the low-emissions industries examined (with the exception of CCS) reach economic self-sustainability (i.e. require no further investment) by 2050. Since averaged global stationary energy prices have been used for the existing fossil fuel energy costs (IEA 2006a, IPCC 2007), there will be some regional variation in the year that each industry reaches economic self-sufficiency.

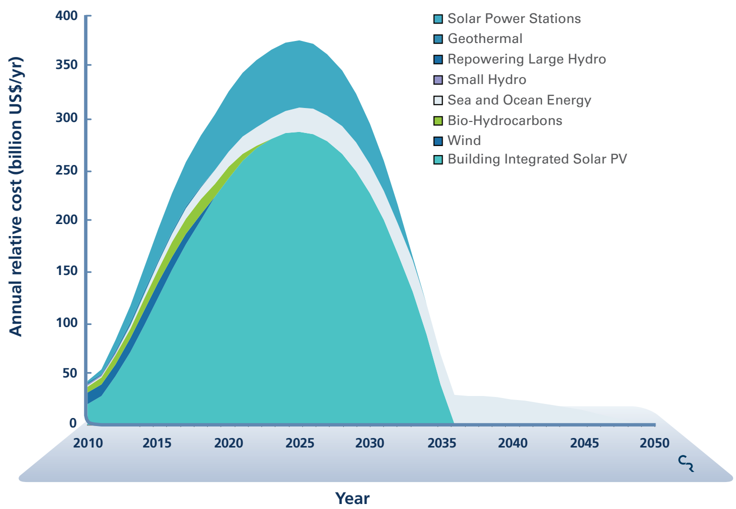


Figure 38: CRISTAL model forecast of the annual relative cost of low-emissions industries (not including CCS) in the minus 63% scenario out to 2050.

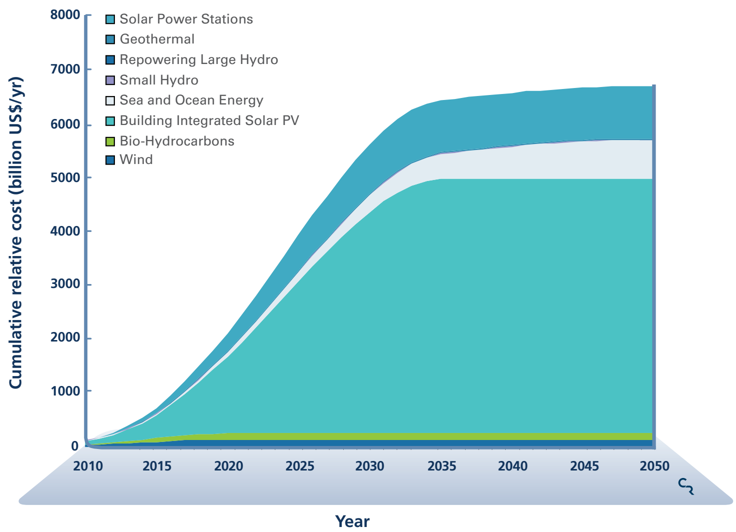


Figure 39: CRISTAL model forecast of cumulative investment requirements for low-emissions industries (not including CCS) in the minus 63% scenario out to 2050.

7.4 CCS Costs

The annual and cumulative relative costs of supporting CCS (i.e. the additional expenses beyond the usual cost of fossil fuel energy generation) are shown below in Figure 40 and Figure 41.

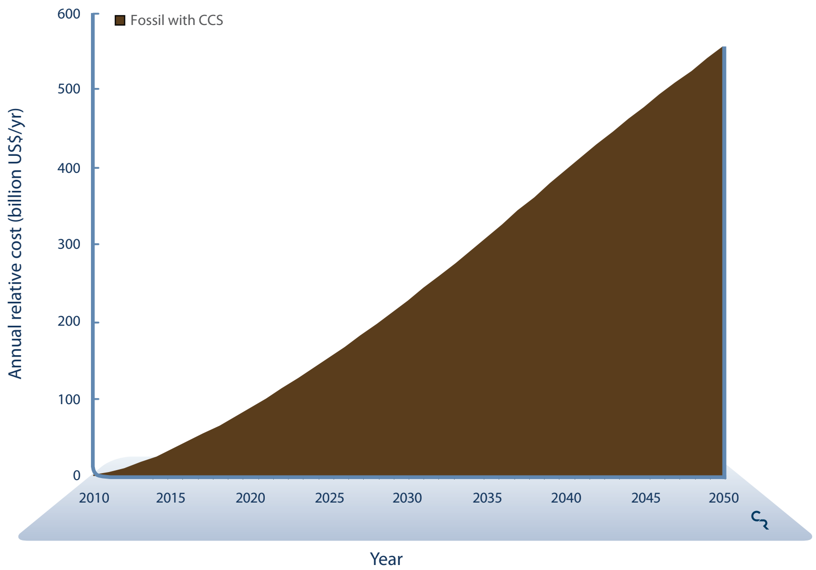


Figure 40: CRISTAL model forecast of the annual relative cost of CCS, alone, in the minus 63% scenario out to 2050.

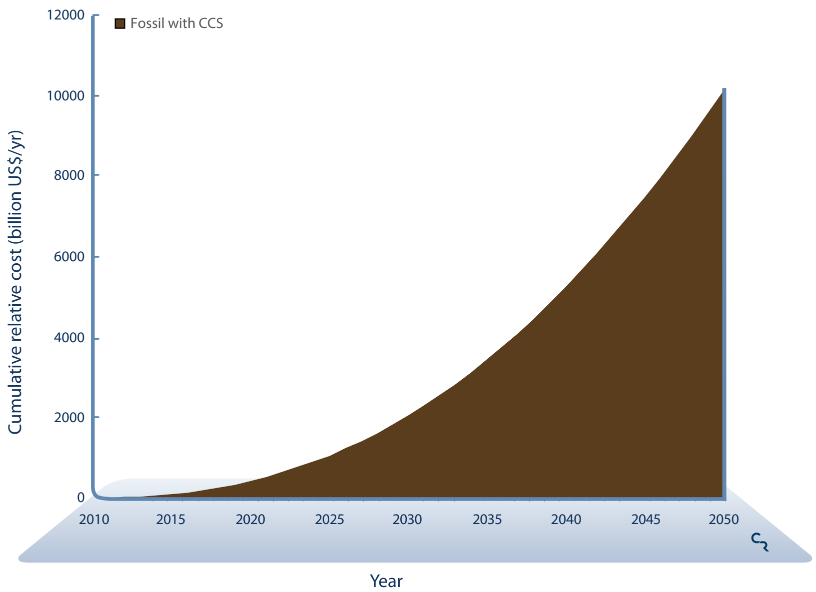


Figure 41: CRISTAL model forecast of the cumulative relative cost of CCS, alone, in the minus 63% scenario out to 2050.

7.5 Renewable Energy and CCS Combined Costs

Combining all zero- and low-emissions technologies yields the annual and cumulative costs shown in Figure 42 and Figure 43, respectively. It can be seen that the cumulative expenditure on renewable energy, alone, is about US$6.7 trillion and when combined with CCS is estimated to total US$16.7 trillion out to 2050 in the minus 63% scenario.

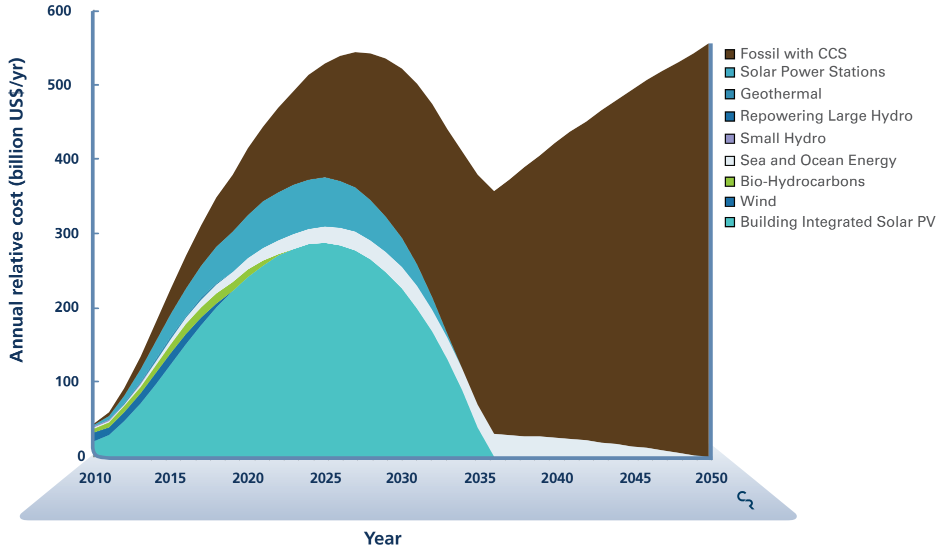


Figure 42: CRISTAL model forecast of the combined annual relative costs of renewable energy technologies and CCS in the minus 63% scenario out to 2050.

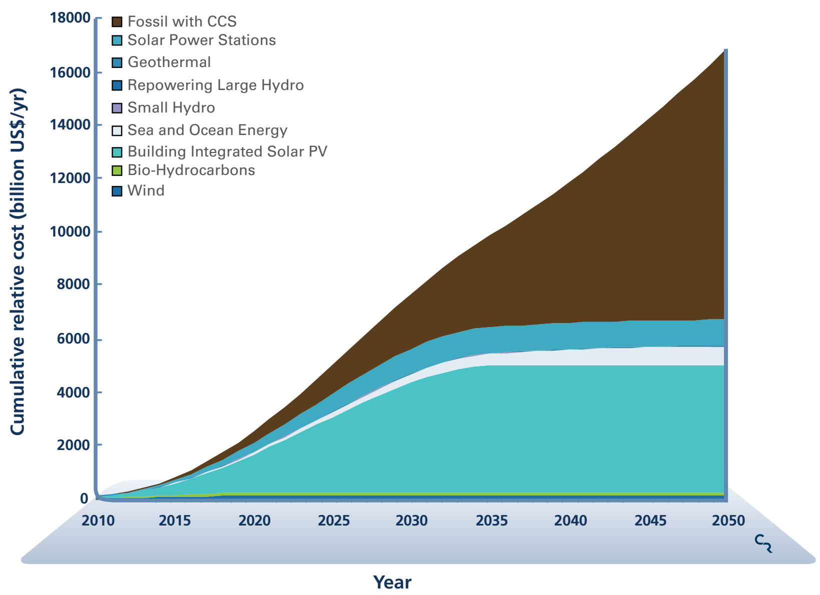


Figure 43: CRISTAL model forecast of the combined cumulative relative costs of renewable energy technologies and CCS in the minus 63% scenario out to 2050.

7.6 Revenue Generation

Once the various renewable energy technologies described in this report achieve sufficient economies of scale, they become a lower cost option than the fossil fuel business-as-usual projection. All the zero- and low-emissions technologies examined in this report (with the exception of CCS) are able to achieve this state of economic self-sufficiency by 2050 provided learning rates are not overly retarded by policy/market instability. CCS, by its very nature, will always represent an additional cost compared to fossil fuel use without CCS. The potential revenue advantage derived from zero- and low-emissions technologies (i.e. the cost saving they offer relative to fossil fuels) when they are able to generate lower-cost electricity than the fossil fuel competition is shown below in Figure 44 and Figure 45.

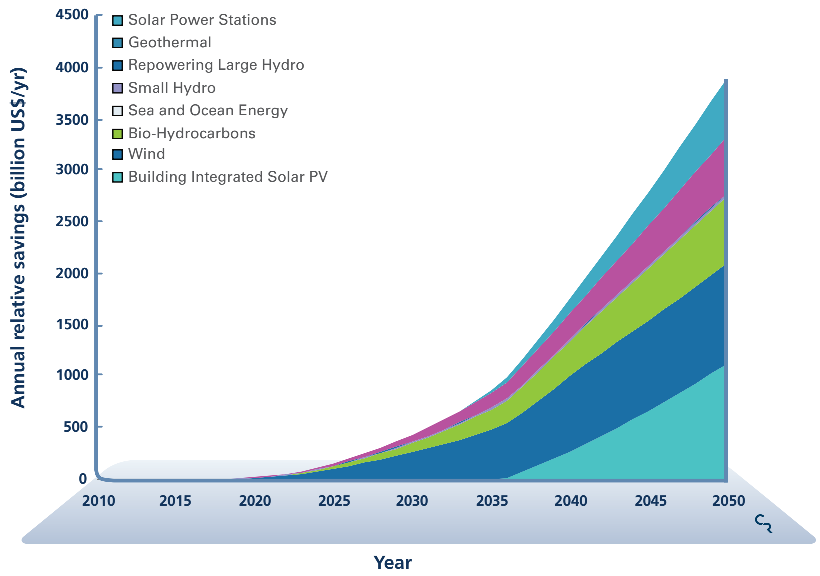


Figure 44: The forecast annual savings for renewable energy technologies relative to the projected cost of fossil fuel-generated electricity in the minus 63% scenario.

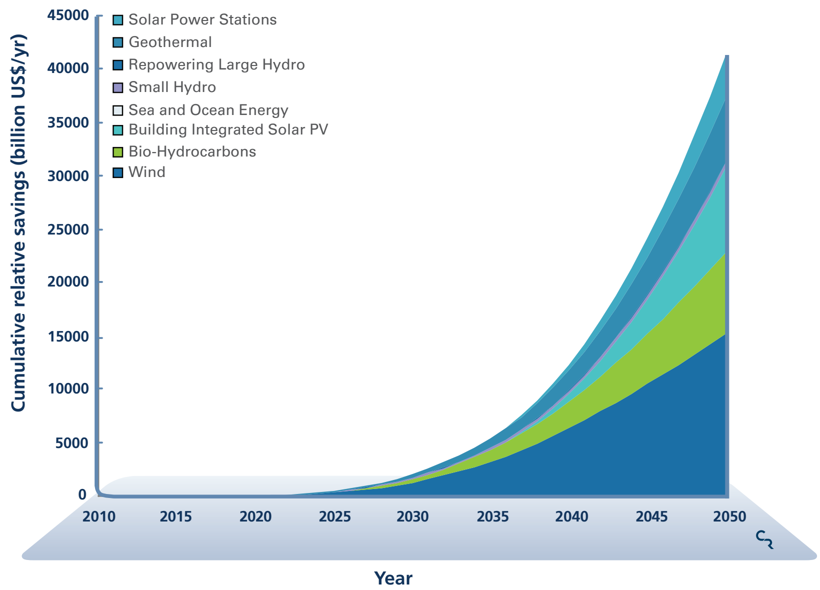


Figure 45: The forecast cumulative savings for renewable energy technologies relative to the projected cost of fossil fuel-generated electricity in the minus 63% scenario.

7.7 Investment/Return Profiles

The cost curves for each zero- and low-emissions technology relative to their fossil fuel competition (without any carbon price) are shown below in Figure 46 to Figure 53. Since the price of energy varies considerably between countries, a shaded band is shown for the cost curves of each energy technology. This band represents one standard deviation to each side of the mean result obtained from the Monte Carlo simulated spread of likely international costs.

In all cases, except for CCS, the cost curve of the low-emissions technology intersects with the fossil fuel competition by 2050 (assuming there is no retardation of learning). The point of intersection between these two cost curves represents the year and energy generation price at which the low-emissions technology reaches a state of economic competitiveness with the relevant fossil fuel (i.e. cost parity) without requiring further assistance.

The spread of years over which the bands of each zero- and low-emissions technology intersect their relevant fossil fuel competition represents the likely range of years in which different countries (with different energy prices) achieve cost convergence. In this way, cost parity between a given zero- or low-emissions technology with fossil fuels is assumed to occur internationally over a range of years.

Given current uncertainty as to the future costs of fossil fuel energy, for simplicity, it is assumed that the cost of coal-fired electricity and fossil diesel energy increase at a linear rate of 2% each year out to 2050. This rate of annual cost increase is considered conservative given that coal and crude oil prices have increased, on average, by more than 5% per annum and 25% per annum, respectively, for the period 1997 to 2007 (these values are even higher if the price spikes in 2008 are included; BP 2009).

It should be noted that only a fraction of the cost of energy from fossil fuels is related to the price of the relevant commodity (e.g. oil, coal or natural gas). The other components of the energy costs (e.g. labour and equipment) are not as prone to fluctuations in commodity prices. Therefore, the rise in the cost of fossil fuel energy is not expected to be quite as high as the rate of increase in the fossil fuel commodity prices.

That being said, if fossil fuel energy costs do grow faster than 2% per annum in future, the economic break-even point for low-carbon technologies will occur earlier than is shown in the figures below.

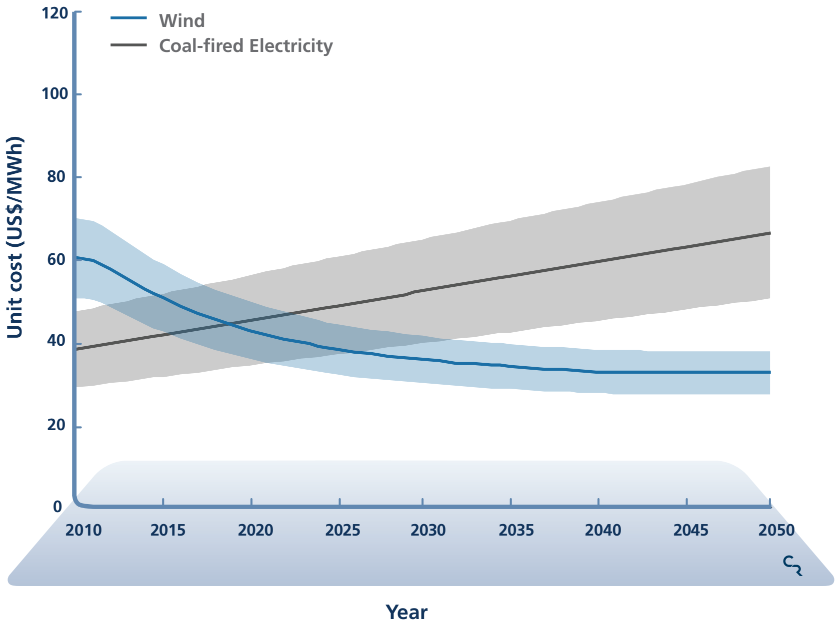


Figure 46: A comparison of the cost curves for wind energy and coal-fired electricity generation in the minus 63% scenario.

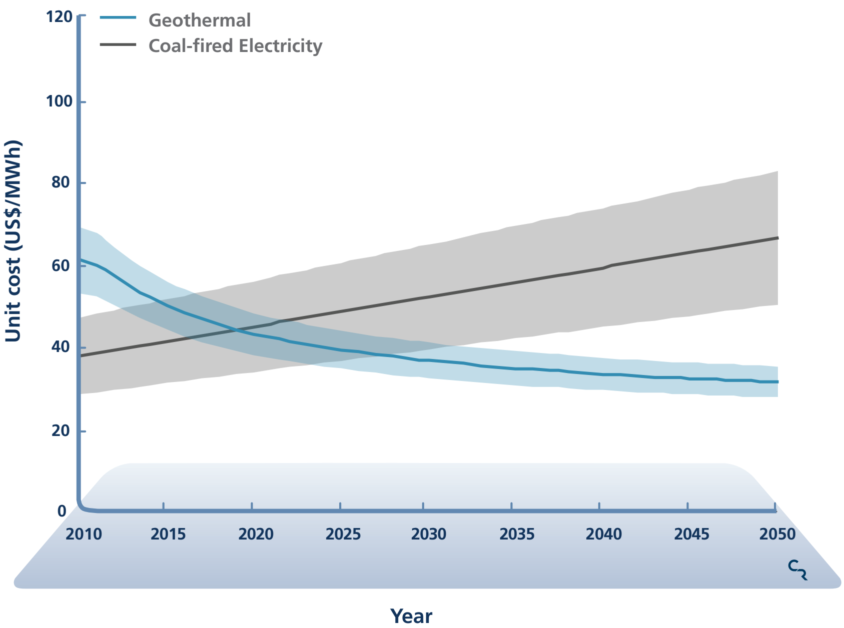


Figure 47: A comparison of the cost curves for geothermal energy and coal-fired electricity generation in the minus 63% scenario.

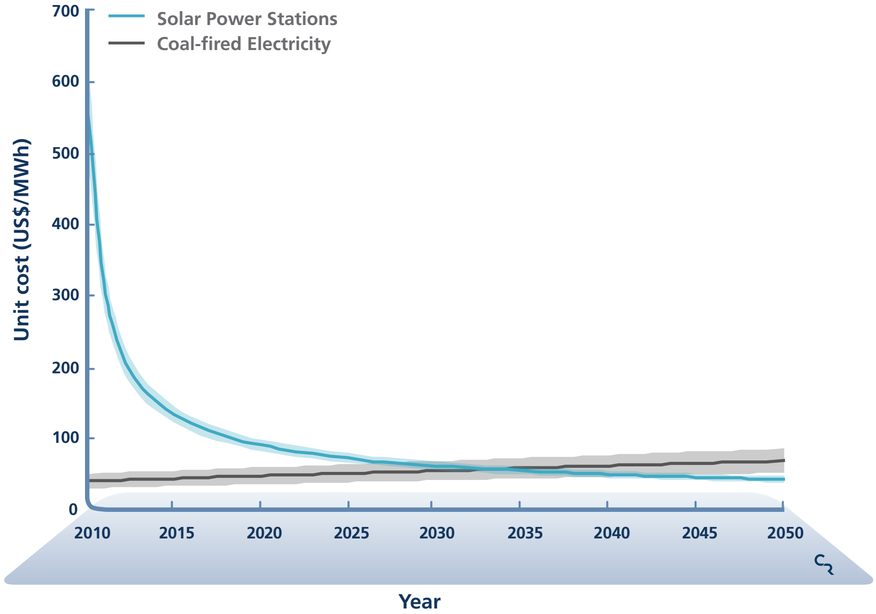


Figure 48: A comparison of the cost curves for solar power stations and coal-fired electricity generation in the minus 63% scenario.

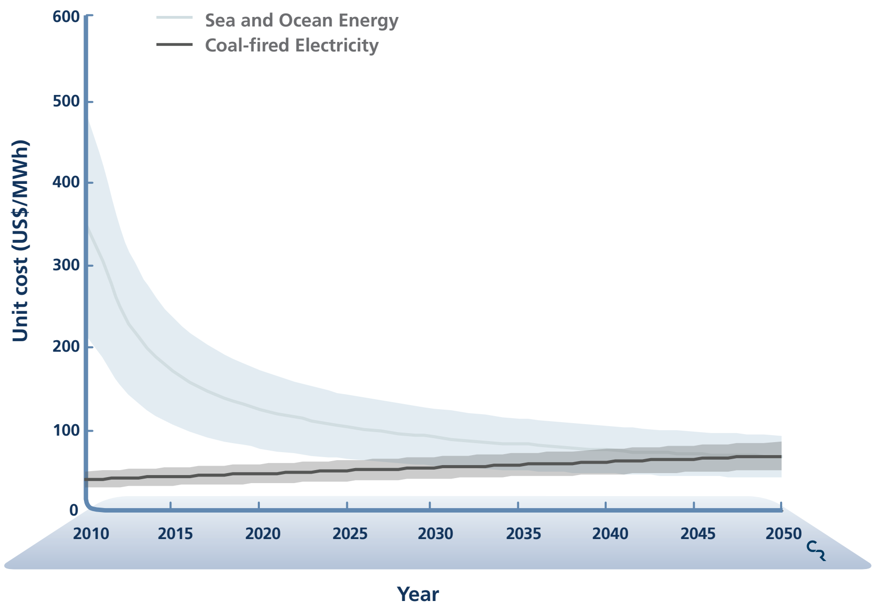


Figure 49: A comparison of the cost curves for sea and ocean energy and coal-fired electricity generation in the minus 63% scenario.

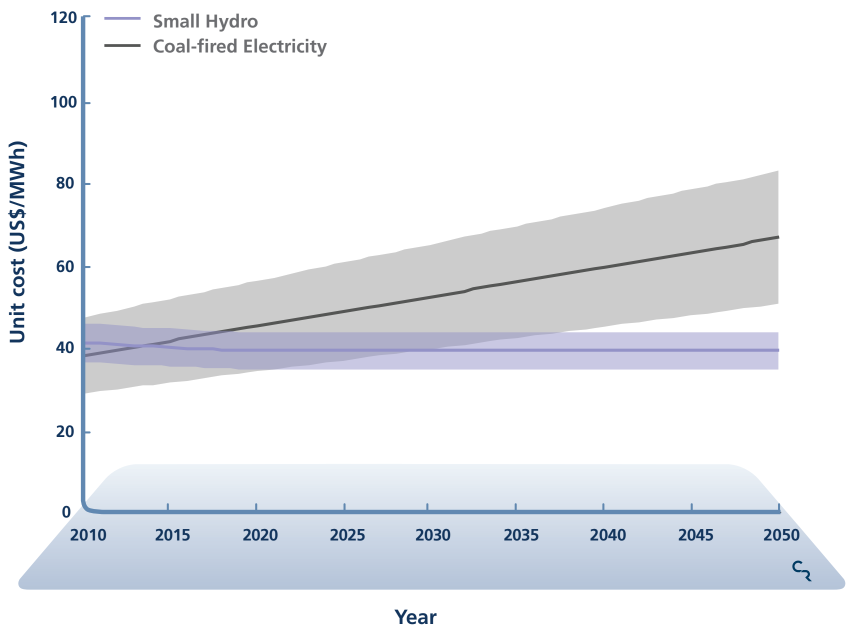


Figure 50: A comparison of the cost curves for small hydro and coal-fired electricity generation in the minus 63% scenario.

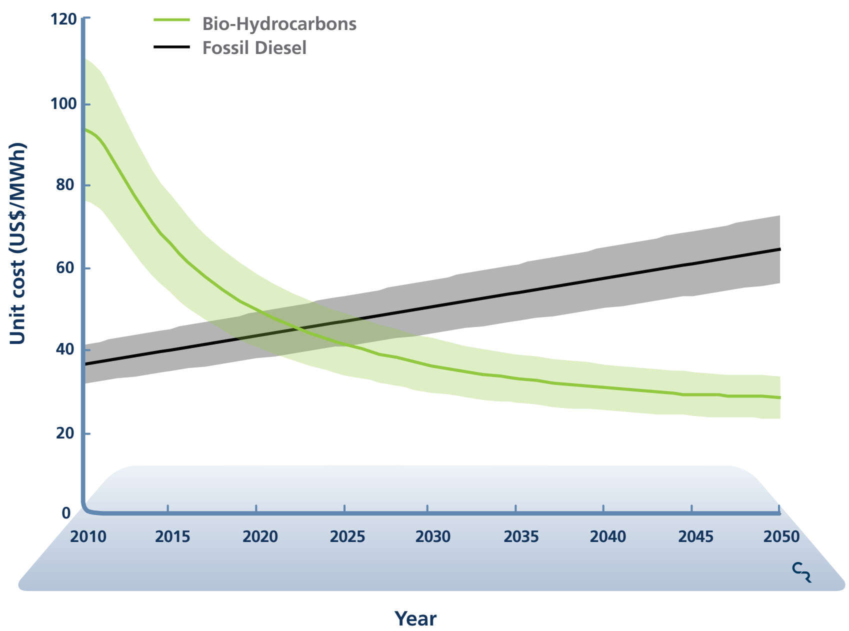


Figure 51: A comparison of the cost curves for bio-hydrocarbons and fossil diesel in the minus 63% scenario.

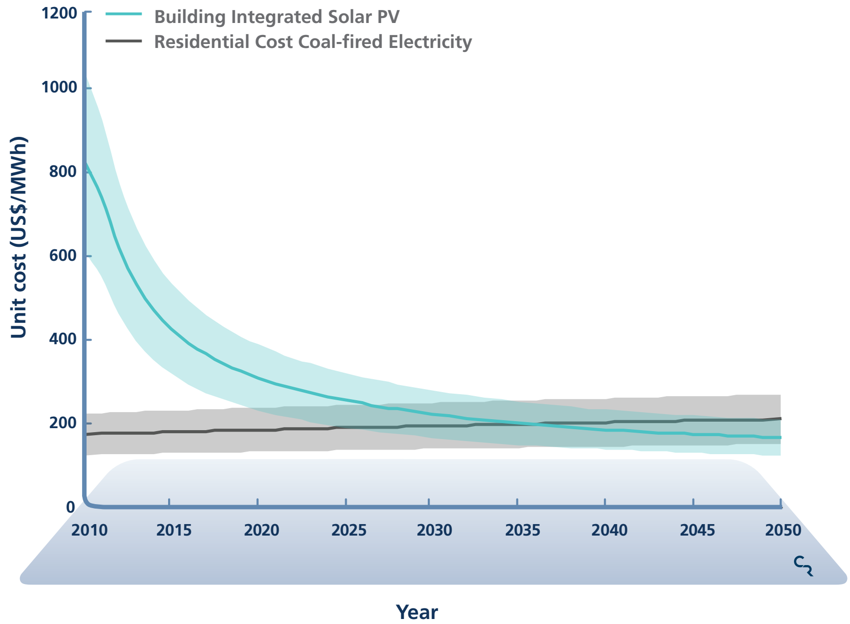


Figure 52: A comparison of the cost curves for building integrated solar PV and the domestic price of coal-fired electricity in the minus 63% scenario.

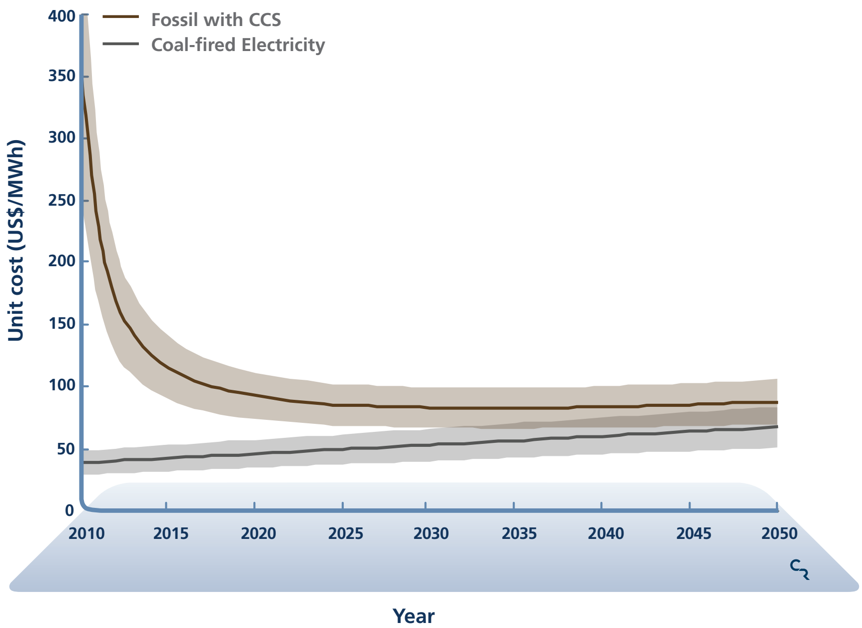


Figure 53: A comparison of the cost curves for CCS coal-fired electricity generation and coal-fired electricity generation with no emissions reduction facilities in the minus 63% scenario.

7.8 Carbon Price

As global agreements on emissions and carbon pricing are not yet in place and the amount and timing of such agreements remains unclear, the scenarios examined in this report do not include a global carbon price. In reality, this is unlikely to be the case, with carbon caps and emissions trading legislation either in development or already in place for many countries.

Consistent with the assumption of a zero carbon price, the projected business-as-usual costs for fossil fuel energy shown in the unit cost diagrams in the section above do not include any cost for carbon emissions. To provide an indication of how these business-as-usual costs for fossil fuel energy (assumed to grow at 2% per annum) would be impacted by various carbon prices, Figure 54 to Figure 56 have been included below.

In Figure 54 to Figure 56 it is important to note that the 2% per year linear increase is only applied to the cost of the fossil fuel energy and not the carbon price. That is, only the fossil fuel component of the unit cost increases by 2% each year and not the carbon price component of the unit cost.

Given the difficulty of predicting the precise development of carbon prices in the next decades, the conservative approach used in this report is helpful in assessing the potentials of renewable, CCS and efficiency technologies.

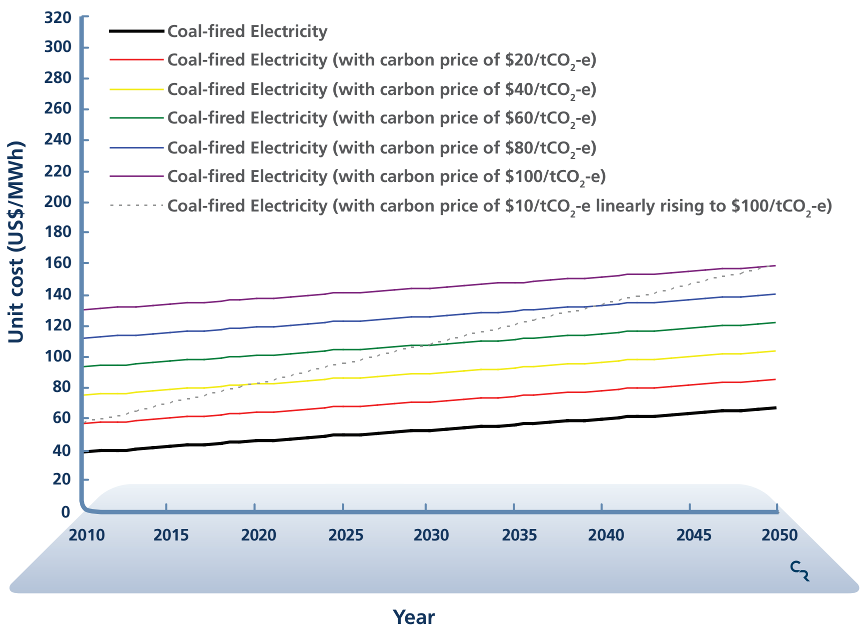


Figure 54: The impact of a range of carbon prices on the cost of producing coal-fired electricity (IEA/OECD 2005).

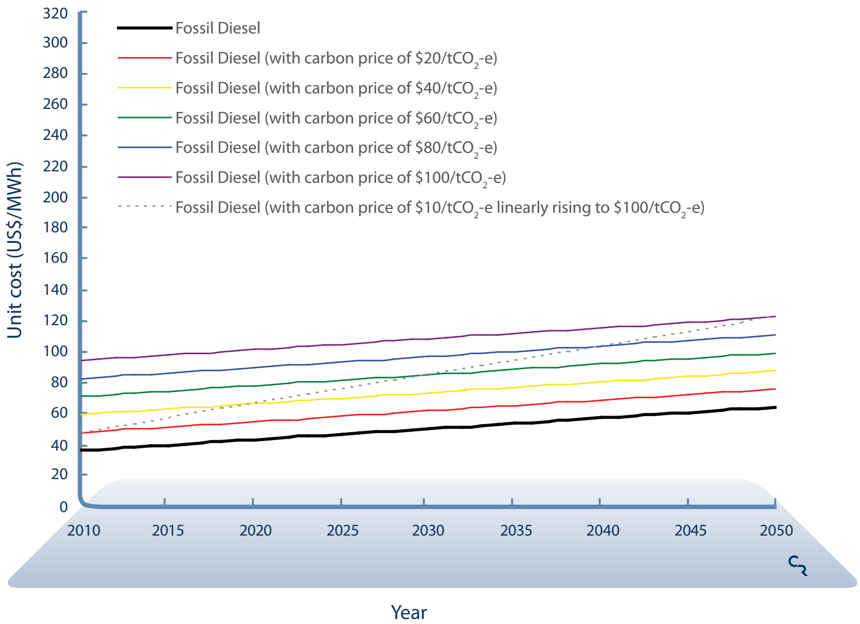


Figure 55: The impact of a range of carbon prices on the cost of fossil diesel (IEA 2009).

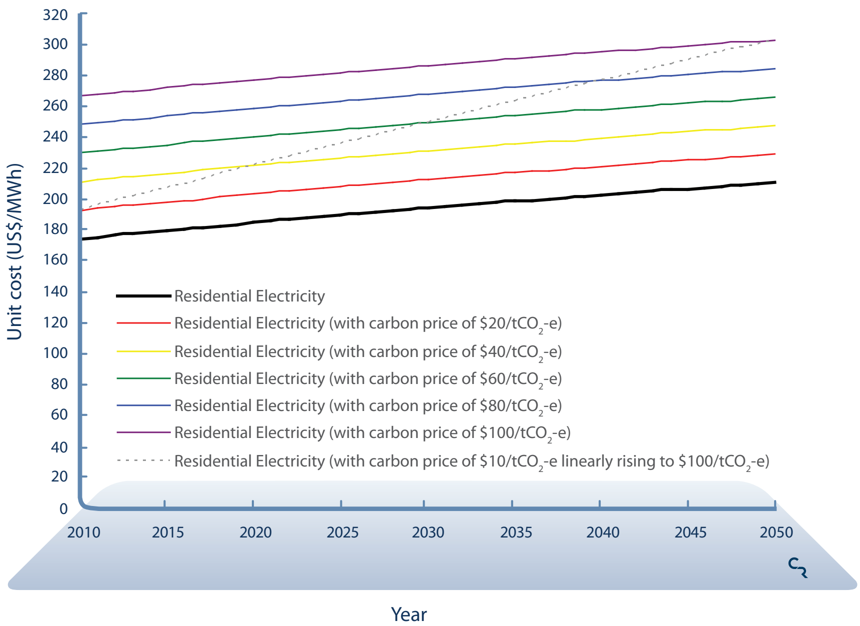


Figure 56: The impact of a range of carbon prices on the residential cost of coal-fired electricity (IEA 2006a).

With the addition of a carbon pricing system, these industries will become cost-effective sooner. For illustrative purposes, the effect of various carbon prices on the annual relative cost of low-emissions energy is shown below in Figure 57 (i.e. Figure 42 with various carbon prices applied).

Figure 57 shows that the use of a global carbon price effectively reduces the relative cost of low-emissions technologies during their critical establishment stages. However, it can also be seen that a carbon price (even a very high one) will not eliminate the annual relative cost of low-emissions technologies in their early roll-out stages. This means that while carbon pricing is an effective and valuable component of achieving emissions targets, it is insufficient on its own to ensure the timely deployment of low-emissions technologies at the pace required to avoid a 2°C increase in temperature.

The reason that a carbon price, alone, does not overcome the barriers to industrial development is that a carbon price (whether a tax, regulation or trading mechanism) necessarily deploys the lowest cost technology or activity first and then waits until constraints of some nature (such as supply limitations or changed market conditions) emerge before commencing the deployment of the next lowest cost technology or activity. This process of sequential deployment creates delays in the implementation of low-emissions technologies. In other words, a global carbon market – even an efficient global market – will not be sufficient, in itself, to deploy technologies and activities at the scale required and in the time available.

“A carbon price (even a very high one) will not eliminate the annual relative cost of low-emissions technologies in their early roll-out stages. This means that while carbon pricing is an effective and valuable component of achieving emissions targets, it is insufficient on its own to ensure the timely deployment of low-emissions technologies at the pace required to avoid a 2°C increase in temperature.”

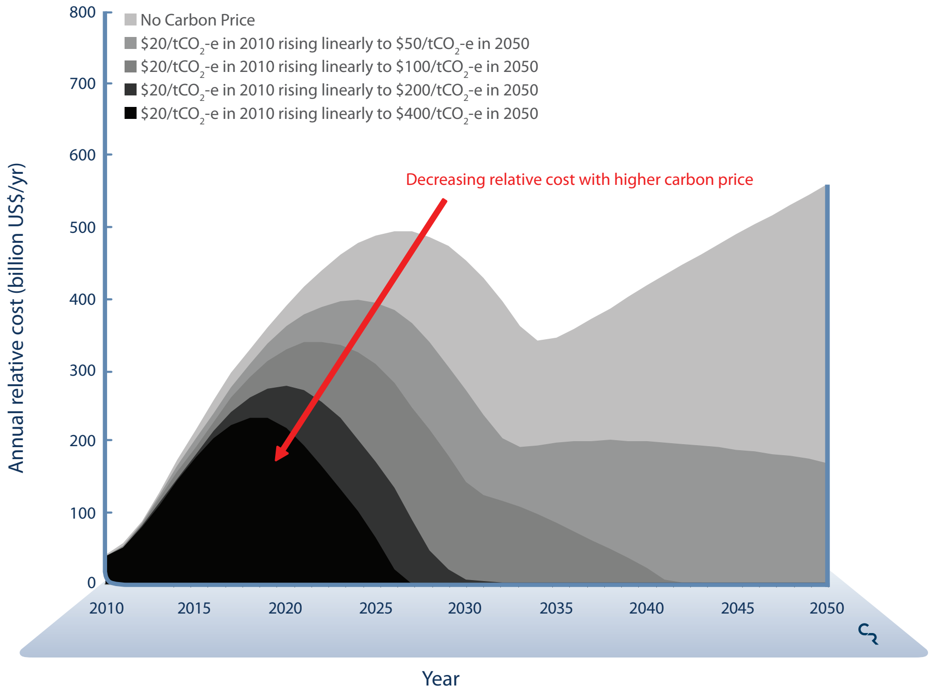


Figure 57: The impact of a range of carbon prices on the annual cost of low-emissions industries relative to fossil fuels in Scenario A.

7.9 Investment and Return Ratios

As the preceding section indicates, the low-emissions resources require investment during their development stages, but then at some point become lower cost than the business-as-usual energy costs. In effect, savings are created that can be considered as returns on the initial investments once economies of scale have been achieved.

In Scenario A, the required investment to support renewable energy industry development was approximately US$6.7 trillion up until 2050. However, a return of over US$41 trillion was created over the period 2013 to 2050, constituting a significant return on costs over the long-term. This ratio between investment and return offers an insight into the de-facto investment and return profile.

However, with such rapid industry growth, learning rates could become somewhat retarded, with scale not providing price drops as quickly as predicted (see Chapter 15). Such outcomes should be avoided, since they severely undermine the ratio of investment and return (see Figure 58). In all scenarios examined in this report, a learning rate retardation of 33% has been applied to buildings integrated PV in response to recent trends (see Chapter 15 for more information). This learning rate retardation takes the very large historical learning rate of buildings integrated PV from 23% down to about 15%.

A healthy ratio of return on investment could provide investment scenarios similar to those found in energy performance contracting, whereby capital to carry out energy efficiency upgrades is provided by a third-party company. The capital is then repaid through savings from reduced energy expenditure.

This picture also parallels the development of major infrastructure projects such as bridges and roads, where multi-billion dollar capital outlays are recouped from tolls over subsequent decades. Such an approach could involve no price disruption to domestic consumers in developed or developing countries.

As discussed earlier, this report conservatively assumes a 2% increase in the cost of all fossil fuel-generated energy each year. However, if the rate of increase in fossil fuel energy costs is slightly higher than this, the ratio between return and investment is significantly improved, as shown in Figure 59.

A similarly conservative stance has been taken in this report by assuming a carbon price of zero. However, it should be noted that the ratio between return and investment would be considerably improved by the implementation of a carbon price. This illustrates the importance and viability of both an investment strategy for renewable energy technologies as well as robust carbon pricing policies.

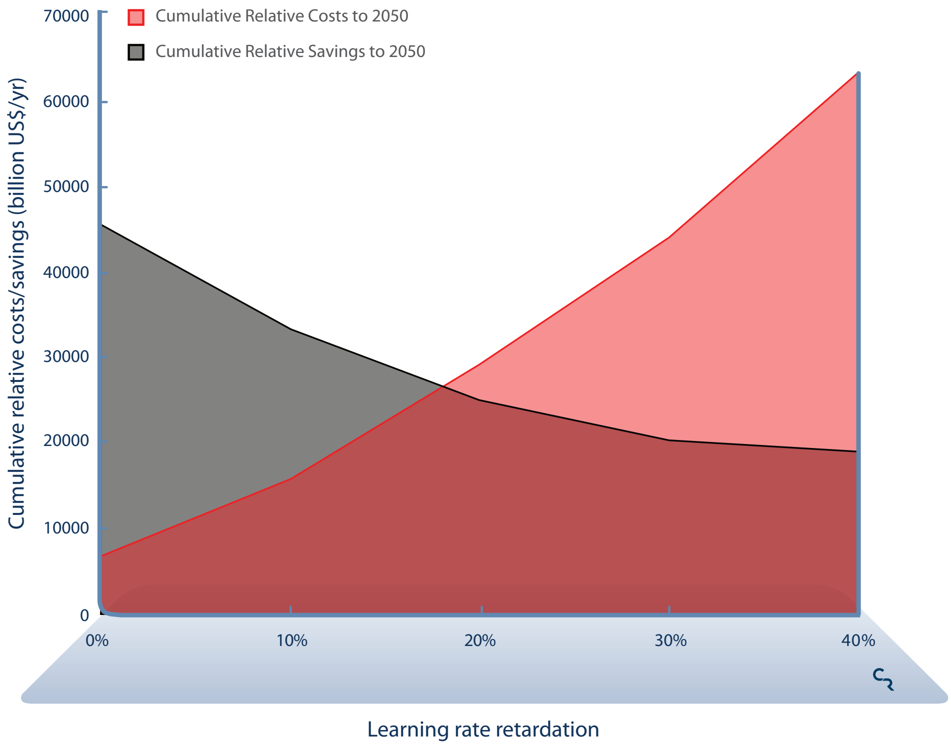


Figure 58: The impact of learning rate retardation on the cumulative relative costs and savings for the renewable energy industries currently requiring support (minus 63% scenario).

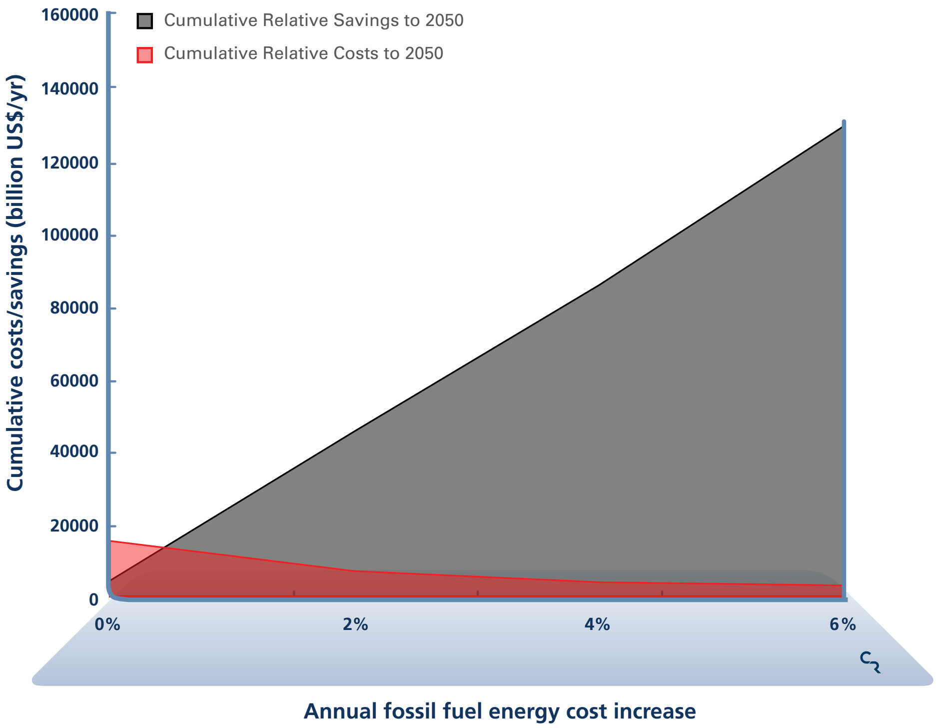


Figure 59: The impact of the rate of increase in fossil fuel energy costs on the cumulative relative costs and savings for the renewable energy industries currently requiring support (minus 63% scenario).

8 Scenario B (Minus 80%): Costs, Investment and Returns

8.1 Efficiency

The gross cost savings from avoided energy use due to various energy efficiency measures are shown below on an annual (Figure 60) and cumulative (Figure 61) basis. The increased savings in this scenario reflects the 10% increase in the energy efficiency measures adopted under Scenario B relative to Scenario A. However, it should be noted that in both scenarios the reported savings do not take into account any financial outlay required to upgrade to the more efficient measures. Such capital outlays are likely to be larger in Scenario B to achieve the greater efficiency gains, thereby offsetting some of the fuel savings advantages observed in Scenario B relative to Scenario A.

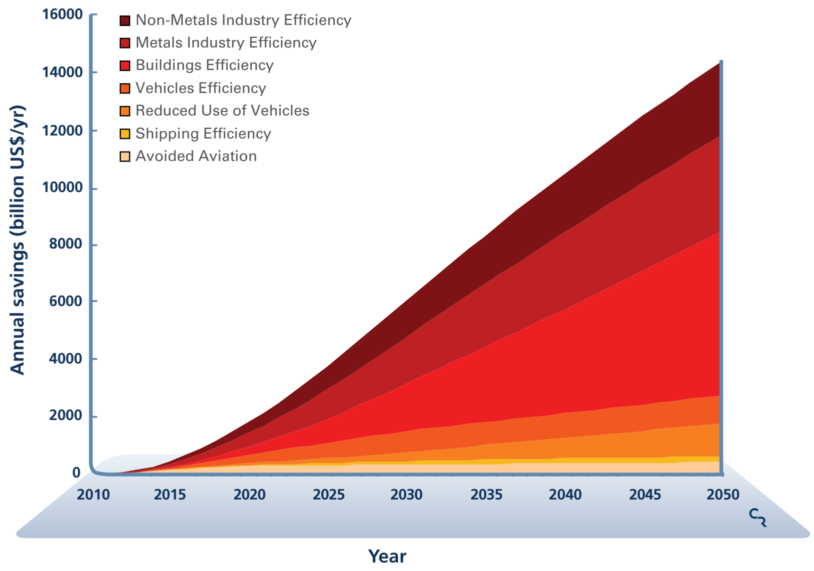


Figure 60: CRISTAL model forecast of gross annual energy cost savings through energy efficiency and avoidance measures in the minus 80% scenario out to 2050. NB: These are gross savings and do not include any costs that may be involved in adopting the efficiency measures.

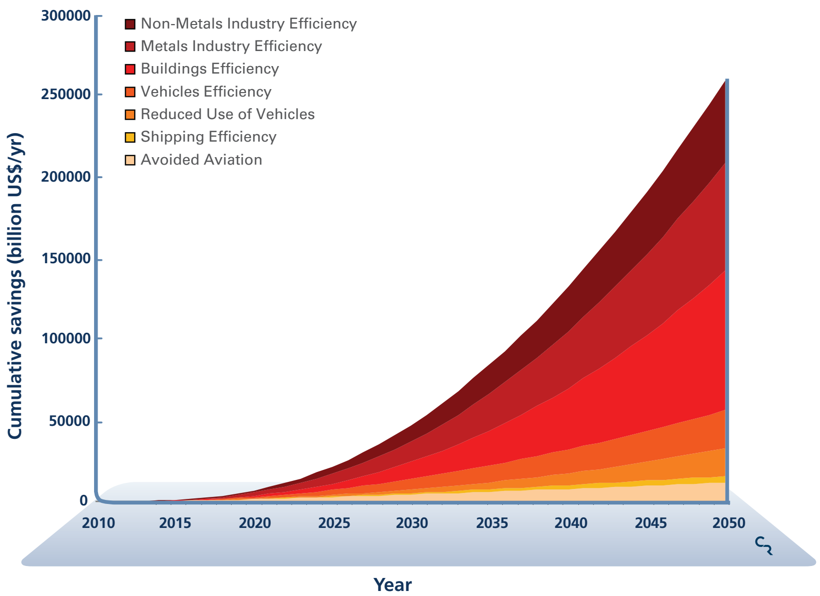


Figure 61: CRISTAL model forecast of gross cumulative energy cost savings for energy efficiency and avoidance measures in the minus 80% scenario out to 2050. NB: These are gross savings and do not include any costs that may be involved in adopting the efficiency measures.

8.2 Renewable Energy Investment

The annual and cumulative investment required for zero-emissions renewable energy industries are shown below in Figure 62 and Figure 63, respectively. As with the previous scenario, these investment requirements represent the cost of renewable energy industries relative to that of their fossil fuel competition (i.e. the additional cost beyond that of fossil fuels for producing the same amount of energy using renewable technologies). All set-up and infrastructure costs have been spread over their operational lifetime and factored into the calculations used to obtain the figures below.

The cumulative relative cost of the renewable energy industries out to 2050 (by which time they will have all reached cost parity with their fossil fuel competition) is US$7.0 trillion. This is slightly higher than the corresponding US$6.7 trillion of scenario A. This is as expected given the increased industry growth rates (24% per annum as compared to 22% per annum) required to meet the tougher minus 80% emissions target of Scenario B relative to the minus 63% emissions target of Scenario A.

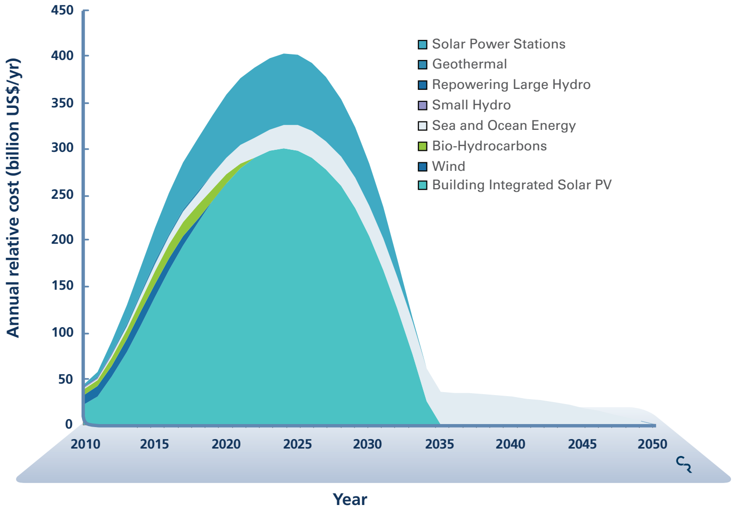


Figure 62: CRISTAL model forecast of the annual relative costs of low-emissions industries (not including CCS) in the minus 80% scenario out to 2050.

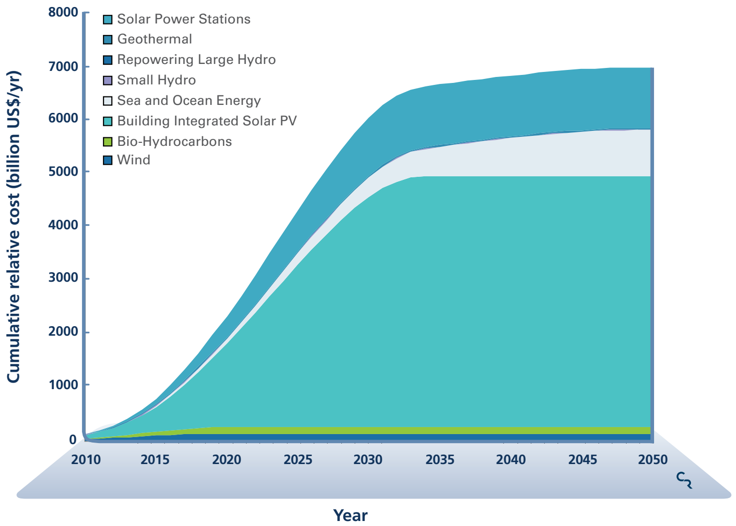


Figure 63: CRISTAL model forecast of the cumulative relative costs of low-emissions industries (not including CCS) in the minus 80% scenario out to 2050.

8.3 CCS Costs

The annual and cumulative relative costs of CCS (i.e. those in addition to the usual cost of fossil fuel energy generation) are shown below in Figure 64 and Figure 65 for Scenario B. The tighter carbon budget of Scenario B means that there is significantly less CCS in the energy supply mix of this scenario. This is because the residual emissions of CCS (between 10% and 40%, depending on the capture efficiency) make it a less effective energy generation option in terms of emissions intensity. Consequently, the costs associated with CCS in Scenario B (US$3.2 trillion) are considerably lower than those of Scenario A (US$10 trillion).

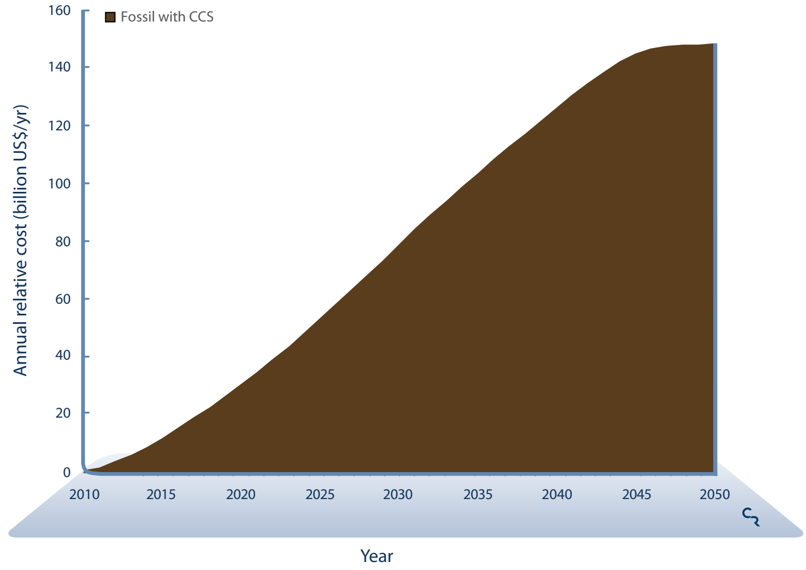


Figure 64: CRISTAL model forecast of the annual relative costs of CCS, alone, in the minus 80% scenario out to 2050.

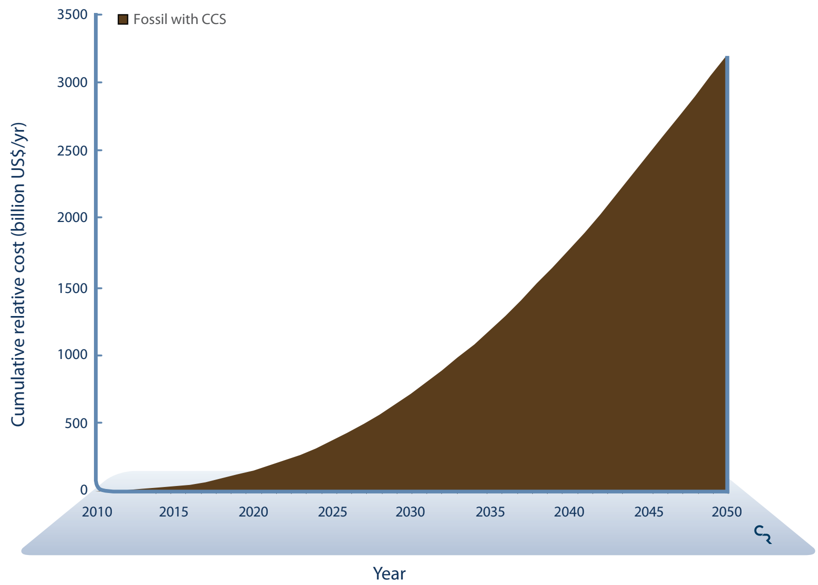


Figure 65: CRISTAL model forecast of the cumulative relative costs of CCS, alone, in the minus 80% scenario out to 2050.

8.4 Renewable Energy and CCS Combined Costs

Combining all zero- and low-emissions technologies for Scenario B yields the annual and cumulative costs shown in Figure 66 and Figure 67, respectively. It can be seen that the cumulative expenditure on renewable energy and CCS combined in the minus 80% scenario is estimated to be about US$10.2 trillion out to 2050. Overall, this figure is slightly lower than that of Scenario A (US$16.7 trillion) owing to the reduced amount of CCS (and the high costs associated with CCS) permitted by the tighter carbon budget in Scenario B.

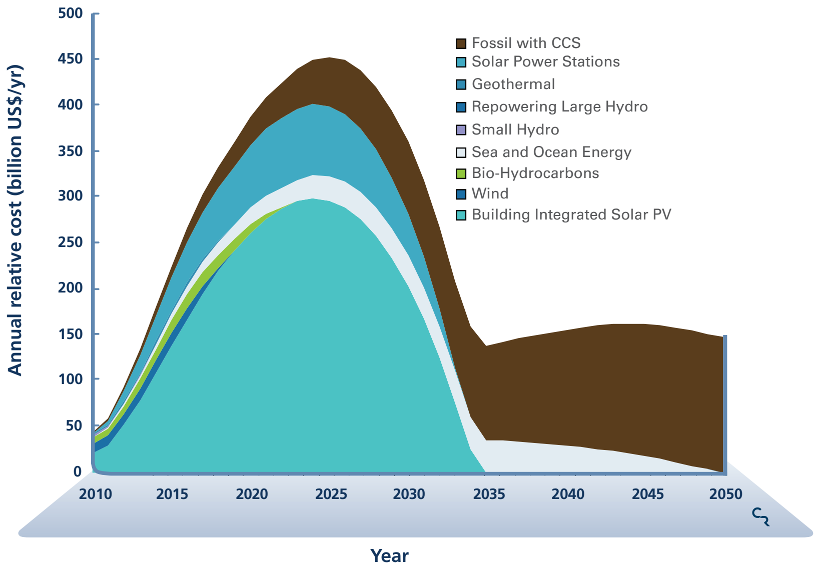


Figure 66: CRISTAL model forecast of the combined annual relative costs of renewable energy technologies and CCS in the minus 80% scenario out to 2050.

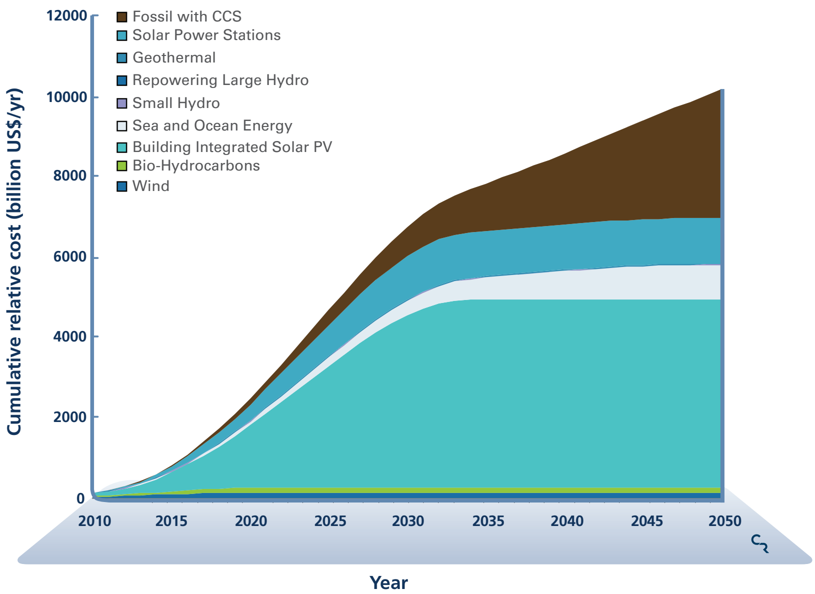


Figure 67: CRISTAL model forecast of the combined cumulative relative costs of renewable energy technologies and CCS in the minus 80% scenario out to 2050.

8.5 Revenue Generation

After achieving sufficient economies of scale, the renewable energy technologies described in this report not only achieve cost parity with their fossil fuel competition but subsequently go on to offer cost savings relative to the fossil fuel alternatives. As with Scenario A, all the zero- and low-emissions technologies examined in this report (with the exception of CCS) reach cost parity with their high-emissions competition prior to 2050. The annual and cumulative relative savings of the renewable energy technologies examined in this report are shown below in Figure 68 and Figure 69 out to 2050 for Scenario B. Consistent with the faster rates of industry growth required by Scenario B, the cumulative savings from renewable energy industries in Scenario B (US$47 trillion out to 2050) are higher than those in the slower growth Scenario A (US$41 trillion out to 2050).

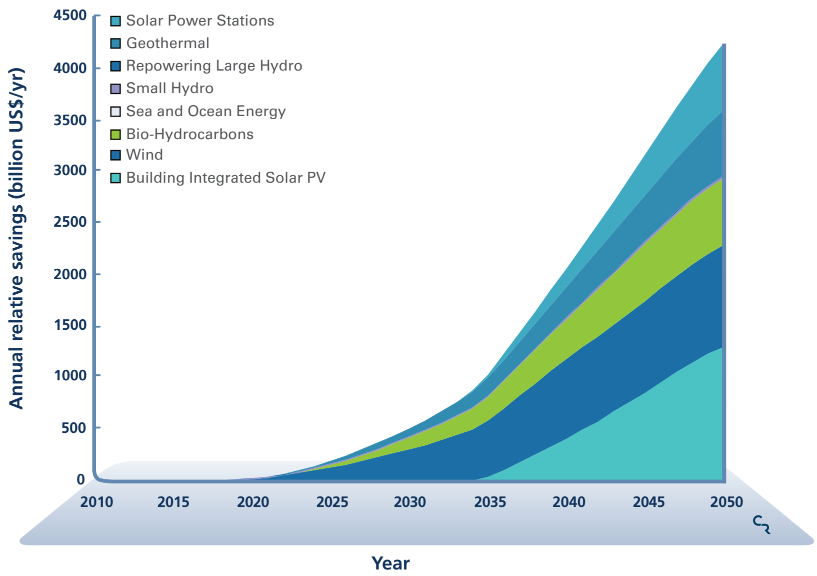


Figure 68: The forecast annual income generated by renewable energy technologies relative to the projected cost of fossil fuel-generated electricity in the minus 80% scenario.

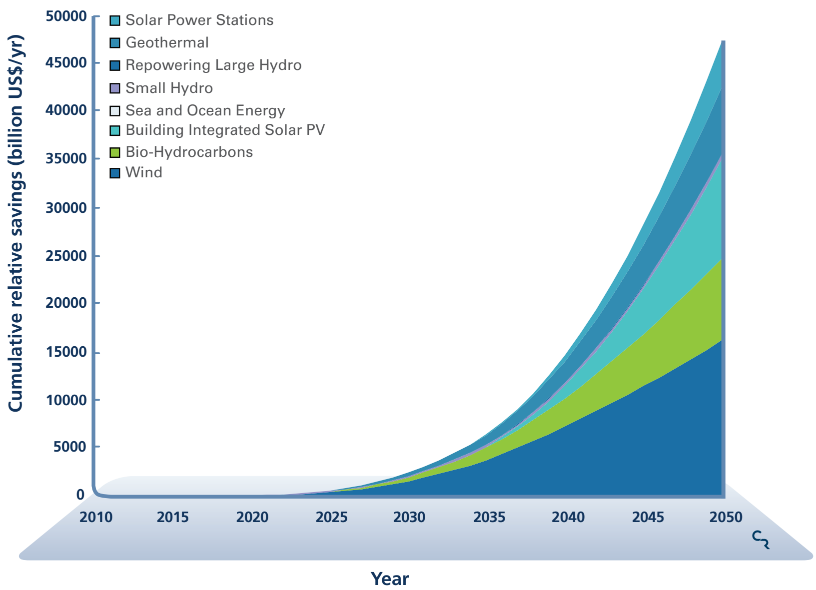


Figure 69: The forecast cumulative income generated by renewable energy technologies relative to the projected cost of fossil fuel-generated electricity in the minus 80% scenario.

8.6 Investment/Return Profiles

The cost curves for each zero- and low-emissions technology relative to their fossil fuel competition are shown below in Figure 70 to Figure 77 for the minus 80% scenario. As with the minus 63% scenario, shaded bands (of one standard deviation to either side of the Monte Carlo simulation mean) are used to illustrate the variability in energy prices between different countries. Again, the cost curves of all low-emissions technologies, with the exception of CCS, intersect the fossil fuel competition by 2050.

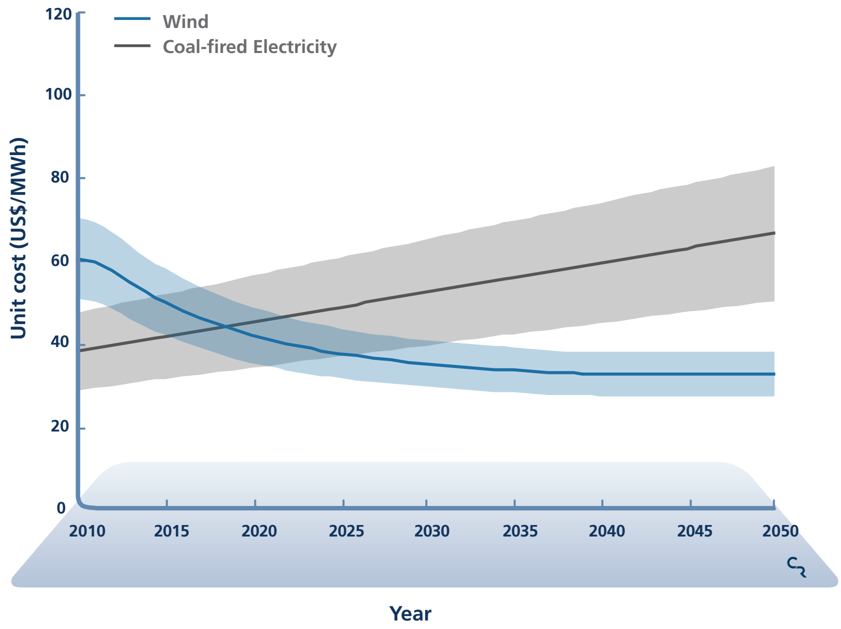


Figure 70: A comparison of the cost curves for wind energy and coal-fired electricity generation in the minus 80% scenario.

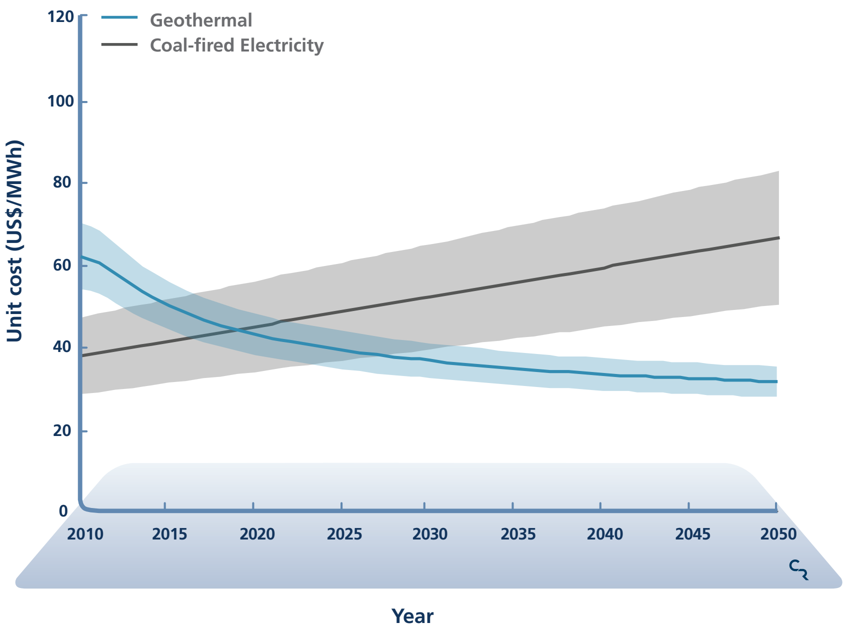


Figure 71: A comparison of the cost curves for geothermal energy and coal-fired electricity generation in the minus 80% scenario.

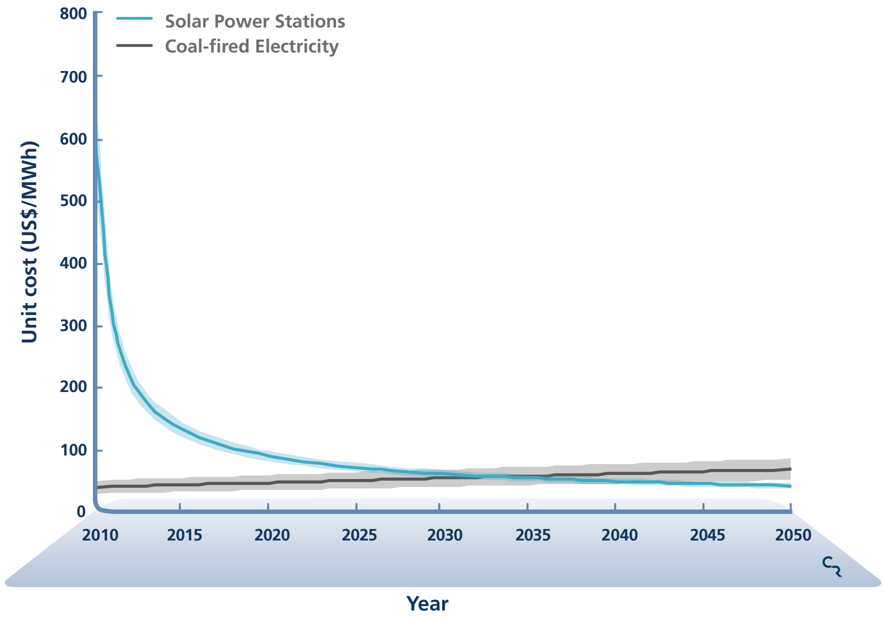


Figure 72: A comparison of the cost curves for solar power stations and coal-fired electricity generation in the minus 80% scenario.

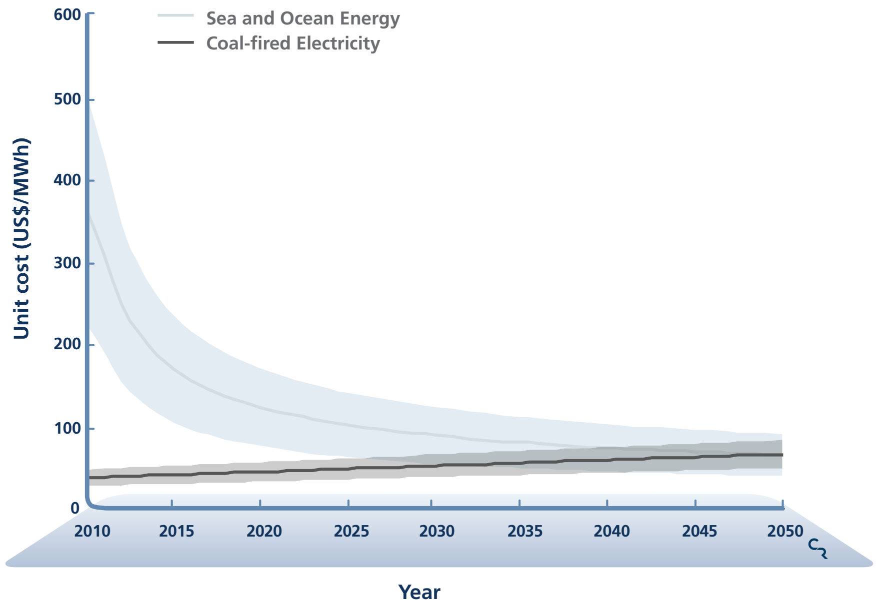


Figure 73: A comparison of the cost curves for sea and ocean energy and coal-fired electricity generation in the minus 80% scenario.

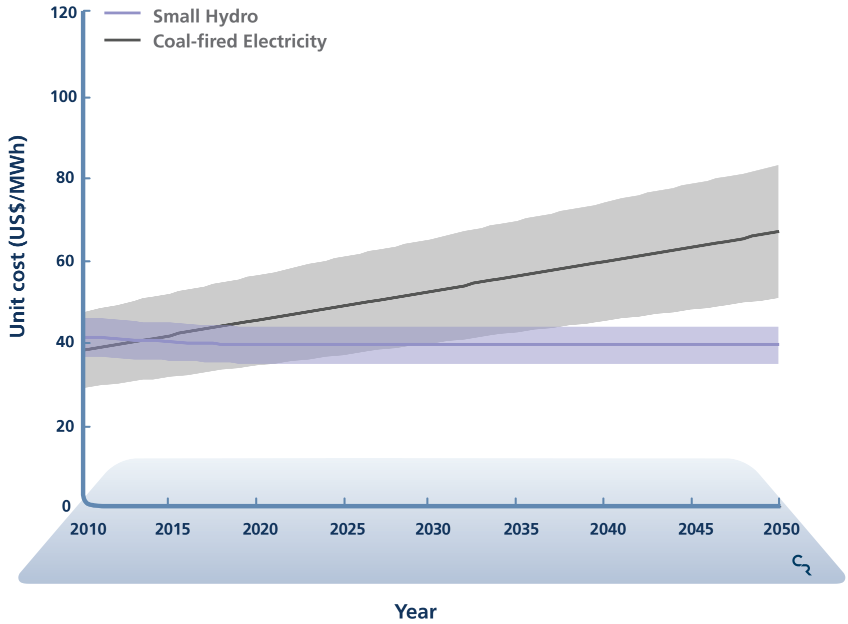


Figure 74: A comparison of the cost curves for small hydro and coal-fired electricity generation in the minus 80% scenario.

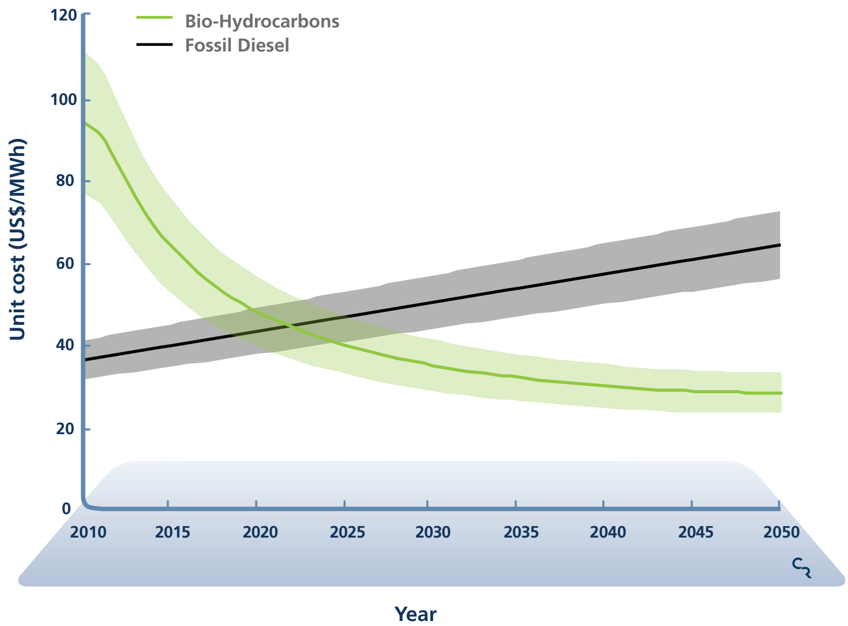


Figure 75: A comparison of the cost curves for bio-hydrocarbons and fossil diesel in the minus 80% scenario.

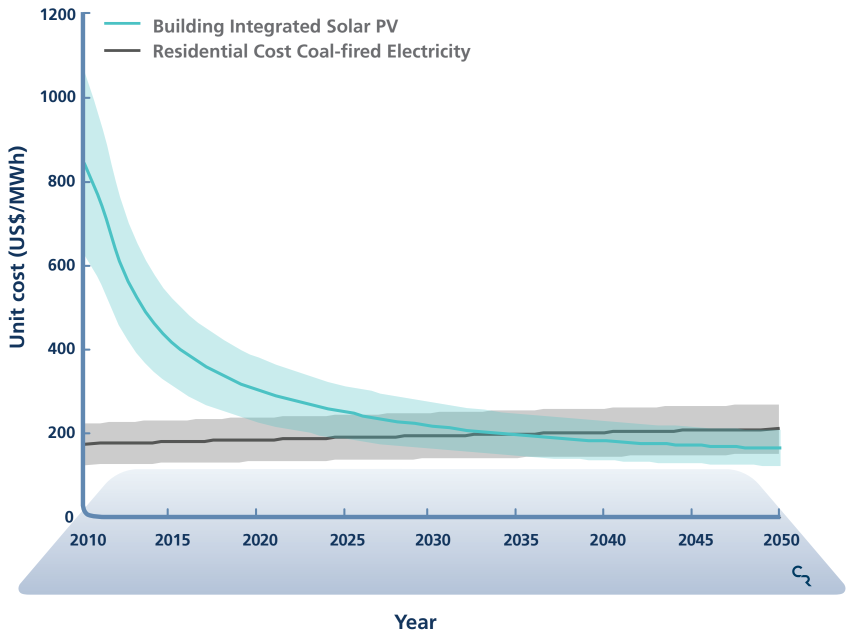


Figure 76: A comparison of the cost curves for building integrated solar PV and the domestic price of coal-fired electricity in the minus 80% scenario.

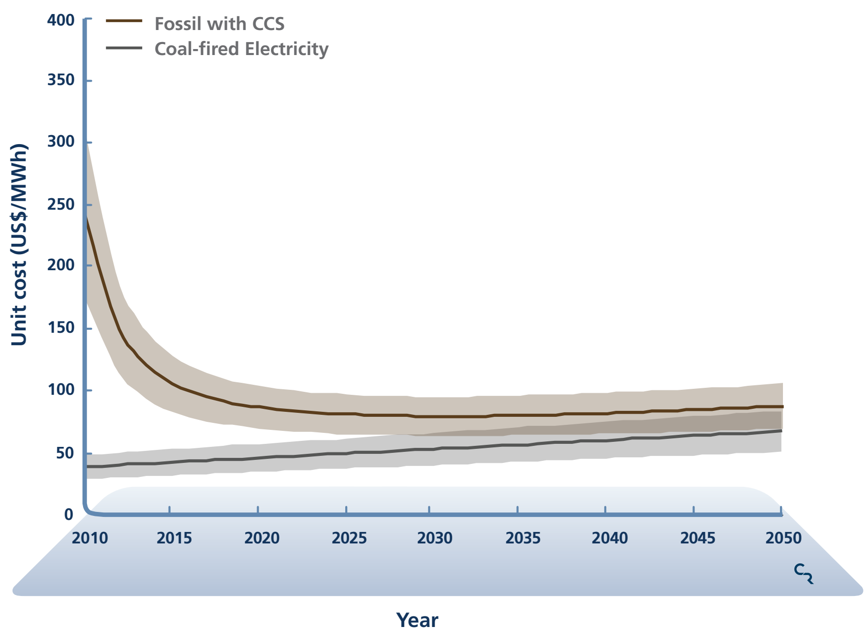


Figure 77: A comparison of the cost curves for CCS coal-fired electricity generation and coal-fired electricity generation with no emissions reduction facilities in the minus 80% scenario.

8.7 Carbon Price

As with the minus 63% scenario, there is no carbon price applied in the minus 80% results shown above. Figure 78 is included below to given an indication of the effect that various carbon prices would have on the annual relative cost of low-emissions energy in the minus 80% scenario. As was found above for Scenario A, the use of a global carbon price effectively reduces the relative cost of low-emissions technologies during their critical establishment stages but does not eliminate it.

This result further supports the assertion that while a carbon price is an essential element of emissions reduction policies, it is not on its own an adequate solution. Additional policy measures will be required to ensure the timely deployment of low-emissions technologies.

The impact of carbon prices on the projected business-as-usual costs for fossil fuel energy in Scenario B are the same as for Scenario A (see Figure 54 to Figure 56).

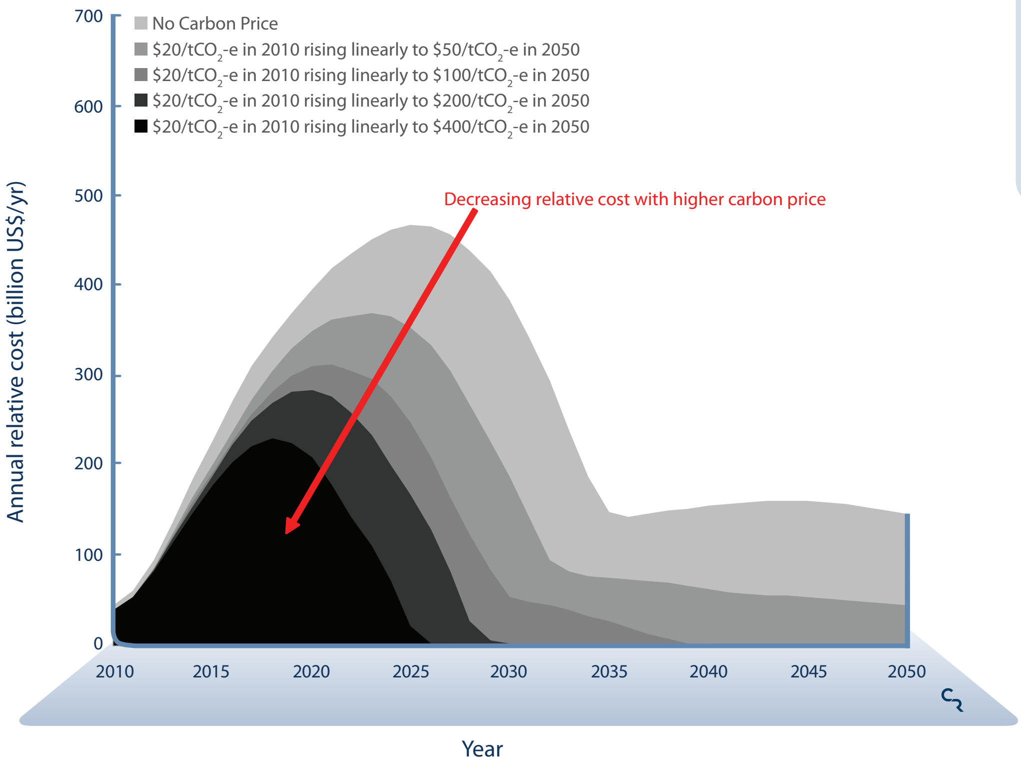


Figure 78: The impact of a range of carbon prices on the annual cost of low-emissions industries relative to fossil fuels in Scenario B.

8.8 Investment and Return Ratios

Figure 79 illustrates the impact of learning rate retardation on the cumulative relative costs and cumulative relative savings for renewable energy industries out to 2050. Comparing this figure for Scenario B to the same figure for Scenario A (see Figure 58) reveals an improved ratio between the return (cumulative relative savings) and the required investment (cumulative relative costs) for renewable energy industries when they grow at the faster rates found in Scenario B.

It can also be seen in Figure 80 that if the cost of fossil fuel energy increases by more than 2% each year the ratio between return and investment is increased. The increase in this ratio is slightly larger than that of the minus 63% scenario.

As previously mentioned, this report conservatively applies a carbon price of zero to all scenarios examined in this report. However, it is anticipated that carbon pricing will be a crucial aspect of achieving emissions reductions.

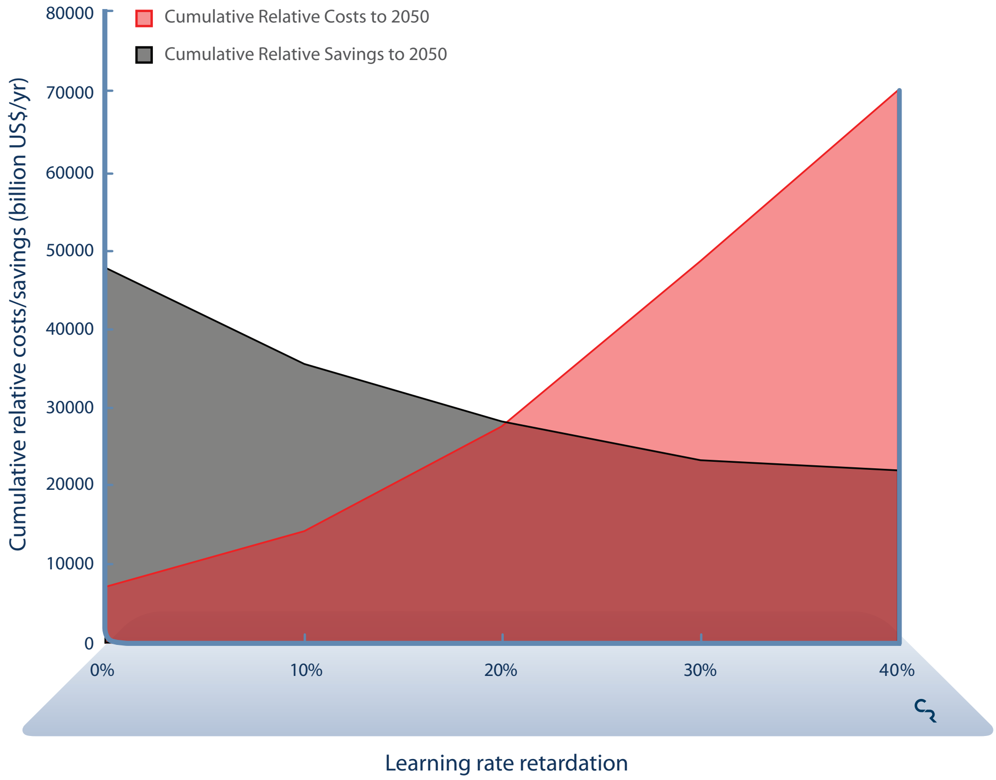


Figure 79: The impact of learning rate retardation on the cumulative relative costs and savings for the renewable energy industries currently requiring support (minus 80% scenario).

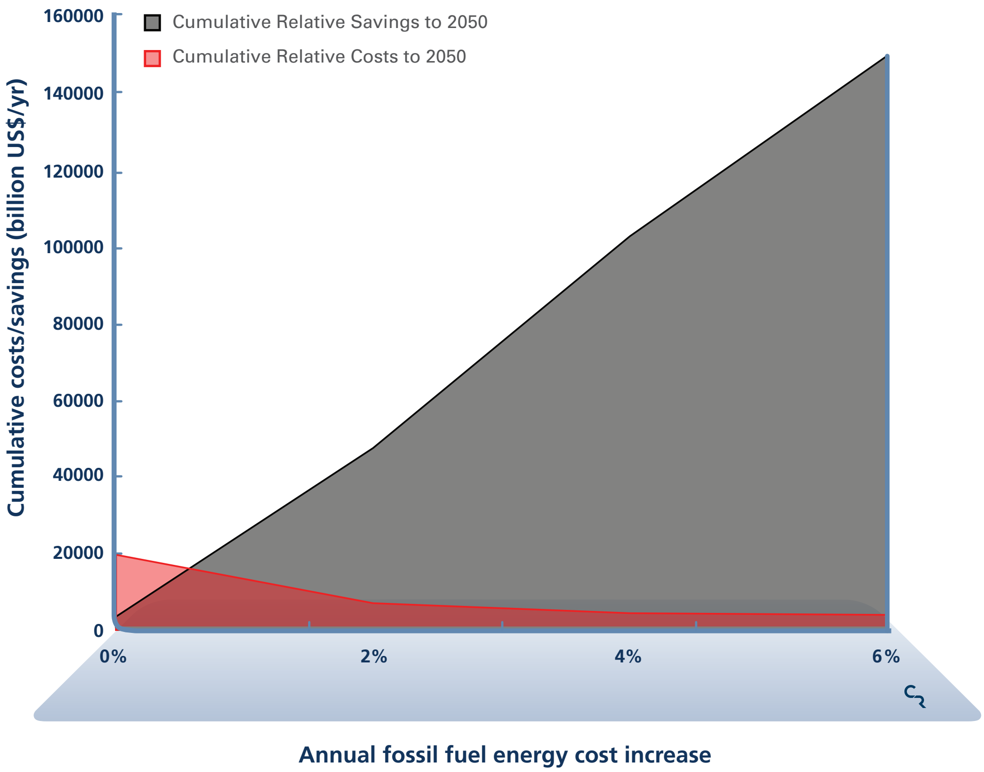


Figure 80: The impact of the rate of increase in fossil fuel energy costs on the cumulative relative costs and savings for the renewable energy industries currently requiring support (minus 80% scenario).

9 Industry Thresholds – The Point of No Return

In this section, the CRISTAL model is used to specifically calculate the time frame available for achieving the future emissions levels required to avoid runaway climate change.

9.1 Defining the Industrial Point of No Return

The calculations presented in this section are not about the response of the climate system and the point at which it may slip past the point of irreversibility. This has been covered in detail earlier in the report (see Chapter 4) and is deemed to be no more than 2°C of warming above pre-industrial levels. This level is in keeping with the scientific and political consensus.

Here, the window available for establishing low-carbon re-industrialisation is calculated based on the development time and industrial growth rate constraints identified earlier in this report.

The point of no return is defined as the latest year for initiating low-carbon re-industrialisation. After this point, there is insufficient time to achieve the required emissions targets for each scenario within the free market constraints used in this report.

The most significant of these free market constraints is the assumption that long-term, year-on-year industry growth rates are unlikely to go beyond 30% due to limitations in the supply of skilled labour, specialised equipment, materials and finance.

The development of low-carbon industries are also assumed to adhere to typical industry growth S-curve dynamics (see Chapter 3) to avoid the occurrence of stranded assets and under-utilised capacity.

This report does not model the "command and control" point of no return threshold, which, in theory, may be slightly later than that of a free market. However, not only is the "command and control" scenario (typically only observed in times of war) considered undesirable, it is also difficult to predict its performance in a modern, highly specialised economy.

While the ability to force the allocation of resources under a "command and control" scenario may allow for slightly higher growth rates or atypical S-curve growth dynamics, the underlying limitations in the economy (such as the availability of specialised equipment, skills and materials) will still apply.

Therefore, preliminary analysis indicates that relying on a "command and control" scenario to extend the point of no return would be unwise. The more prudent response is to ensure an early and comprehensive adoption of low-carbon re-industrialisation within the context of a free market economy.

9.2 Point of No Return Methodology

Prior to the initiation of low-carbon re-industrialisation, low-carbon industries are assumed to continue growing at their current levels. After reaching the modelled start year for re-industrialisation, all low-carbon industries are assumed to grow at whatever rate is required (not exceeding 30%) to meet the 2050 emissions target.

The point of no return is then taken as the latest possible start year for low-carbon re-industrialisation in which the 2050 emissions target can be reached without exceeding industry growth rates of 30%. Results are shown for both the minus 63% scenario and the minus 80% scenario.

It is important to remember that the minus 80% scenario assumes greater emissions abatements from the LULUCF and energy efficiency sectors relative to the minus 63% scenario (see Chapter 14 for more details).

The point of no return results shown in this chapter are for a 50% likelihood of meeting the emissions targets in each scenario. This means that for the start years described in this chapter there is an equal chance of failing to meet the designated emissions targets as there is of achieving them. Therefore, to reduce the likelihood of exceeding 2°C of warming above pre-industrial levels, low-carbon re-industrialisation should be well underway prior to these point of no return years.

9.3 Point of No Return Findings

The emissions trajectories for various re-industrialisation start years are shown below in Figure 81 and Figure 82. Start years that fail to meet the required 2050 emissions target are shown in red (i.e. these start years are beyond the point of no return). The business-as-usual emissions baseline used in this report is also shown. As noted earlier, the emissions and energy baselines used in this report are based on the SRES A1FI forecast with a 3% climate change impact adjustment (see Section 3.2.3 for further information).

For both scenarios, the latest start year, or the point of no return, is 2014. This is the year in which the balance of probability falls in favour of failing to meet the required emissions targets. All emissions abatement industries and sectors need to have been established and be growing at full capacity by 2014, at the latest. This implies that the policies and development mechanisms required to drive these industries must be formulated and agreed upon several years prior to 2014. Indeed, this time frame may already be quite challenging.

Note: The similarity in the point of no return for both scenarios is related to the increased emissions abatements from LULUCF and energy efficiency in the minus 80% scenario. These areas of emissions abatement have been boosted to near their upper plausible limit, representing a challenge in itself. Therefore, the primary difference between the minus 63% and minus 80% scenarios is not the start year per se, but the depth and intensity of emissions abatement efforts that must be undertaken.

“All emissions abatement industries and sectors need to have been established and be growing at full capacity by 2014, at the latest. This implies that the policies and development mechanisms required to drive these industries must be formulated and agreed upon several years prior to 2014. Indeed, this time frame may already be quite challenging.”

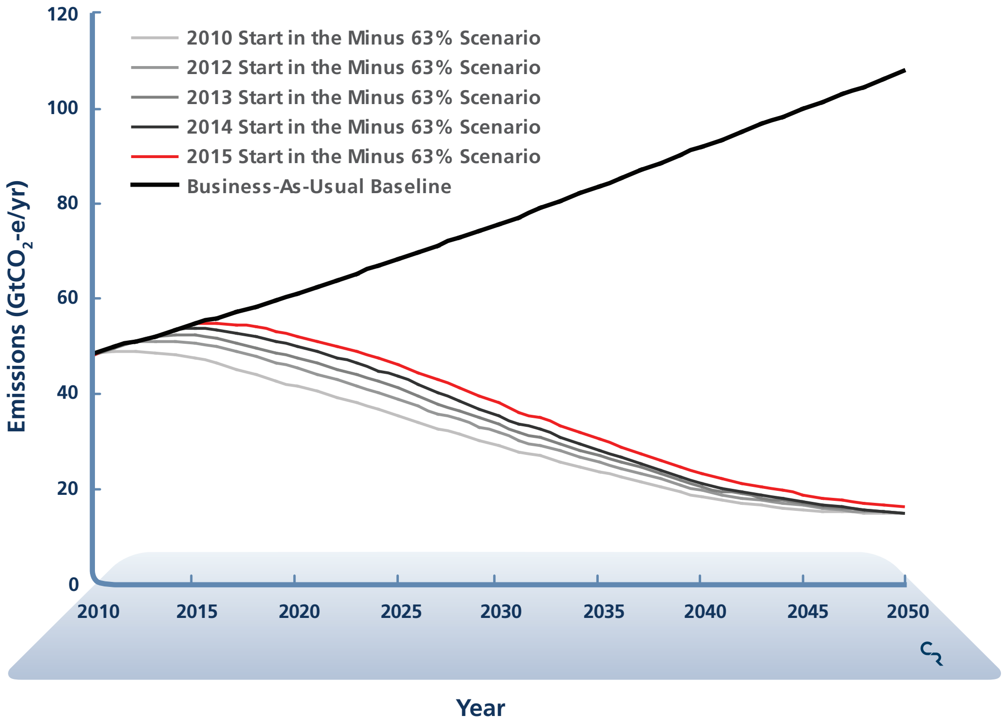


Figure 81: The point of no return. This figure shows the effect of various re-industrialisation start years on the emissions trajectory of the minus 63% scenario. Trajectories shown in red are unable to meet the required emissions target within the assumed free market industry constraints.

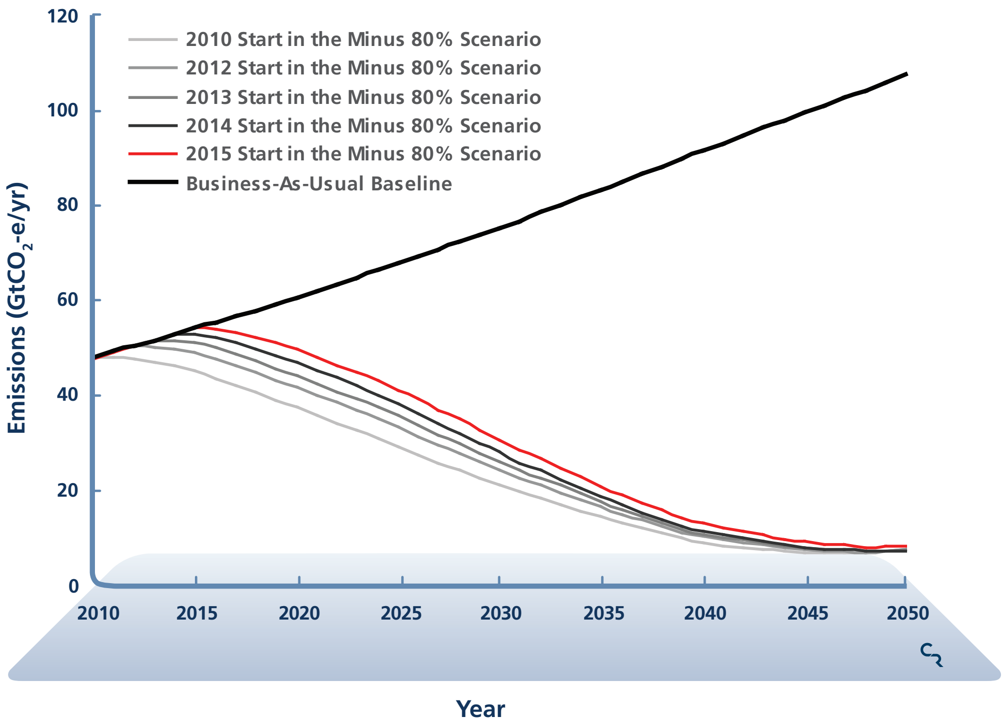


Figure 82: The point of no return. This figure shows the effect of various re-industrialisation start years on the emissions trajectory of the minus 80% scenario. Trajectories shown in red are unable to meet the required emissions target within the assumed free market industry constraints.

10 Discussion of Findings

The following five objectives were identified at the outset of this report:

I. Determine whether it is possible to avoid runaway climate change.

II. Establish the time window available to commence the re-industrialisation of low-carbon industries required to avoid runaway climate change.

III. Determine the critical industrial constraints that must be overcome to provide the necessary emissions levels to avoid runaway climate change.

IV. Compare the costs of low-carbon re-industrialisation versus the costs of business-as-usual development.

V. Identify the implications of the findings for governments, industry and the private sector.

Here, the findings are examined in light of the first four objectives, while the next section discusses the fifth objective relating to policy implications.

10.1 Finding (i): It is Possible to Avoid Runaway Climate Change

The first and paramount objective of this report was to answer the question: Is it possible to avoid runaway climate change? The review of climate and emissions research in Chapter 4 indicates that it may, indeed, be possible to avoid runaway climate change, provided temperatures are stabilised at or below 2°C above pre-industrial levels (though some scientists suggest that this should be as low as 1.7°C; Hansen *et al.* 2007a, Hansen *et al.* 2008, Hansen 2005, Hansen 2007).

Consistent with avoiding exceeding the 2°C warming threshold, two scenarios are considered:

1. Scenario A, with emissions of 14.7 $GtCO_2$-e in 2050, which corresponds to a 10–40% (default of 24%) likelihood of exceeding the 2°C warming threshold according to interpolated Meinshausen *et al.* (2009) data.

2. Scenario B, with emissions of 7.9 $GtCO_2$-e in 2050, which corresponds to a 4–29% (default of 13%) likelihood of exceeding the 2°C warming threshold according to extrapolated Meinshausen *et al.* (2009) data.

To understand whether these levels of emissions are possible, it was necessary to:

a) Demonstrate the availability of low-emissions resources that could meet the projected demand for commodities and services;

b) Demonstrate that emissions levels can be achieved in 2050 consistent with various probabilities of avoiding 2°C of warming;

c) Demonstrate that these industries can be deployed in the time available up to 2050.

Firstly, in response to point (a), the modelling indicates that there are sufficient low-carbon resources and emissions abatement opportunities to meet projected energy and non-energy demands in 2050.

Secondly, in response to point (b), the modelling of associated emissions from all sectors indicates that, on the balance of probabilities, the emissions levels as a result of this deployment can fall below that required by 2050 on an annualised and cumulative basis.

Third, in response to point (c) above, the modelling demonstrates that the required levels of energy and emissions can be met by deploying existing technologies in an adequate time frame. However, as is discussed in detail below, this assumes a prompt start to low-carbon re-industrialisation; concurrent growth of all relevant industries; and average growth rates of at least 22% or 24% per year for Scenario A and Scenario B, respectively (until at least 20% of each low-carbon resource has been harnessed).

Figure 23 illustrates these outcomes with probability distributions for emissions levels in 2050 for both the scenarios examined.

10.2 Finding (ii): Low-carbon re-industrialisation must be implemented promptly

The second objective was to establish the time window available to commence the low-carbon re-industrialisation required to avoid runaway climate change. The findings of the emissions abatement scenario presented in this report assume no delays in the commencement of industrial development of all low-carbon industries. Based on this assumption, low-carbon industries all grow at 22% per annum (for the minus 63% scenario) or 24% per annum (for the minus 80% scenario) from 2010 until each has reached a point where it has harnessed 20% of its resource.

As mentioned earlier, this analysis assumes that the maximum possible year-on-year growth rate achievable by low-carbon industries in the key development stage (i.e. up until 20% of the resource has been harnessed) is 30%. While short periods of industry growth rates of more than 30% may be possible, it is unlikely that these higher growth rates could be sustained over the longer term (i.e. over several decades). Such high growth rates are typically restricted by industry instability and short- to medium-term limitations of resources, skills, finance and facilities.

That said, it is worth noting that prolonged industry growth rates greater than 30% may be possible under a “command and control” type arrangement, as seen in times of war. However, this type of war-footing scenario is not considered in this report.

To determine the importance of the year in which low-carbon re-industrialisation is commenced, the Monte Carlo model was run using industrial growth rates up to the maximum rate (30% per annum), with various commencement years for the re-industrialisation process. This test was run for all commencement years between 2010 and 2015, illustrating the effect of delays in initiating full low-carbon re-industrialisation. As above, the minus 63% scenario was run with a 2050 per capita emissions target of 1.6 tCO_2-e/yr per person, and the minus 80% scenario utilised a 0.9 tCO_2-e/yr per person 2050 emissions target.

This modelling of onset time found that the likelihood of avoiding a 2°C change in average global surface temperatures fell below 50% if global low-carbon re-industrialisation was not underway by 2014 for both scenarios. The start of 2014 represents a practical time limit by which ambitious global low-carbon industry development policies (above and beyond agreements on emissions cuts) must be established and fully operational.

If full-scale low-carbon industry development is not in progress by at least 2014, there will not be enough time to permit the full suite of 24 low-carbon industries and sectors to develop sufficiently. To increase the confidence in avoiding a 2°C change in global surface temperature, suitable policies must be in place well before 2014.

10.3 Finding (iii): Four critical industrial constraints must be overcome to avoid runaway climate change

The third objective was to determine the critical industrial constraints that must be overcome to avoid runaway climate change. Four such constraints were found and are discussed in detail in the following subsections. They are:

1. the maximum industry growth rate constraint;
2. the non-concurrent development constraint;
3. the delayed start constraint; and
4. the incomplete resource development constraint.

> This modelling of onset time found that the likelihood of avoiding a 2°C change in average global surface temperatures fell below 50% if global low-carbon re-industrialisation was not underway by 2014.

10.3.1 Maximum Industry Growth Rate Constraint

This report reveals that the defining industrial constraint that limits the ability to avoid runaway climate change is the real-world upper limits on the growth of low-carbon industries.

This upper limit on viable industrial growth rates restricts the speed that low-carbon industries can be deployed and grow. Therefore, it defines the minimum time necessary to reach the required outcomes. This has very significant implications for the potential to achieve the required emissions, energy and non-energy outcomes in the time frame available.

Global emissions display considerable inertia. Using sensible industrial growth constraints that are inherent within industries shows that, even with adequate resources and technologies, the global economy cannot transform overnight. To meet the required emissions ranges on time and in an orderly manner requires adequate investment flows, stable development frameworks and an early commencement date.

Postponing industry development or failing to provide adequate market certainty requires the implementation of even more rapid changes at a later time. This would result in demand spikes, supply shortages and ultimately high delivery costs from industries characterised by unstable growth. Of even greater concern is the fact that the supply of skills, labour, materials and technology may simply be insufficient, so that even with additional expenditure the necessary growth and installation rates may not be achieved.

To realise the high and prolonged levels of industry growth required to avoid a 2°C change in global temperatures will require concerted and urgent global effort on a scale previously unseen. The CRISTAL model indicates that industry growth rates of 22% every year for the minus 63% scenario (and 24% for the minus 80% scenario) for several decades would be required for all low-carbon industries, even if a globally unified effort was begun on a sufficiently large scale in 2010.

The industry growth rate required escalates to about 29% every year if this cooperative effort is not begun until 2014. Because it is assumed that growth rates cannot be increased beyond 30%, implementing low-carbon re-industrialisation in the years beyond 2014 brings a rapidly deteriorating likelihood of averting runaway climate change.

10.3.2 Non-Concurrent Development Constraint

Various low-carbon industries must be developed in parallel. The urgent need to reduce emissions means there is insufficient time for industries to develop one after the other, or indeed in any way other than with almost completely concurrent development.

Figure 83 compares Scenario A with a scenario in which all other parameters remain the same, but in which industrial

> “This report reveals that the defining industrial constraint that limits the ability to avoid runaway climate change is the real-world upper limits on the growth of low-carbon industries.”

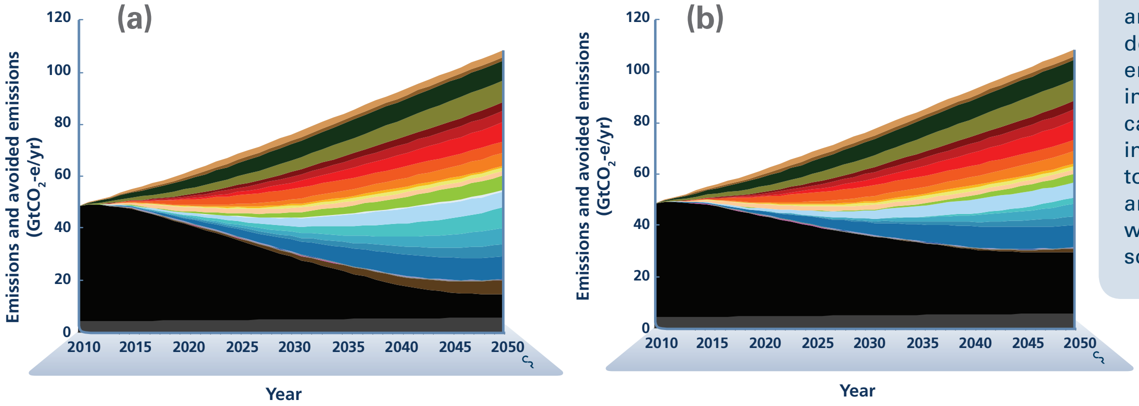


Figure 83: The difference in emissions abatement outcome by 2050 for (a) concurrent and (b) sequential development of emissions abatement industries. In both cases, low-emissions industries are assumed to grow at 22% per annum in accordance with the minus 63% scenario.

development of the low-carbon resources occurs quasi-sequentially. This sequential scenario mimics what would happen under a pure emissions trading approach. The result is that the emissions level in 2050 more than doubles. Thus the target emissions level is completely missed.

This constraint has major implications for policies and measures that put "all the eggs in one basket". For instance, to rely on only one system (such as cap-and-trade) is insufficient to meet the required targets. Irrespective of the perceived costs and carbon prices, the required actions must be homogenous, simultaneous, ambitious and fast-acting in all 24 low-carbon sectors in all countries. Sequential approaches based solely on perceived cost-effectiveness will, on their own, be unable to trigger a prompt start across all low-carbon industries; instead they will foster the development of industries one after the other, with least-cost technologies coming first.

10.3.3 Delayed Start Constraint

If there is a real-world upper limit to industrial growth rates, then it follows that there is a point at which the use of accelerated growth can no longer compensate for implementation delays. As Figure 84 shows, postponement means considerably lower emissions reductions are achieved within the necessary time frame because the biggest part of the emissions reduction wedge is pushed out beyond the 2050 milestone.

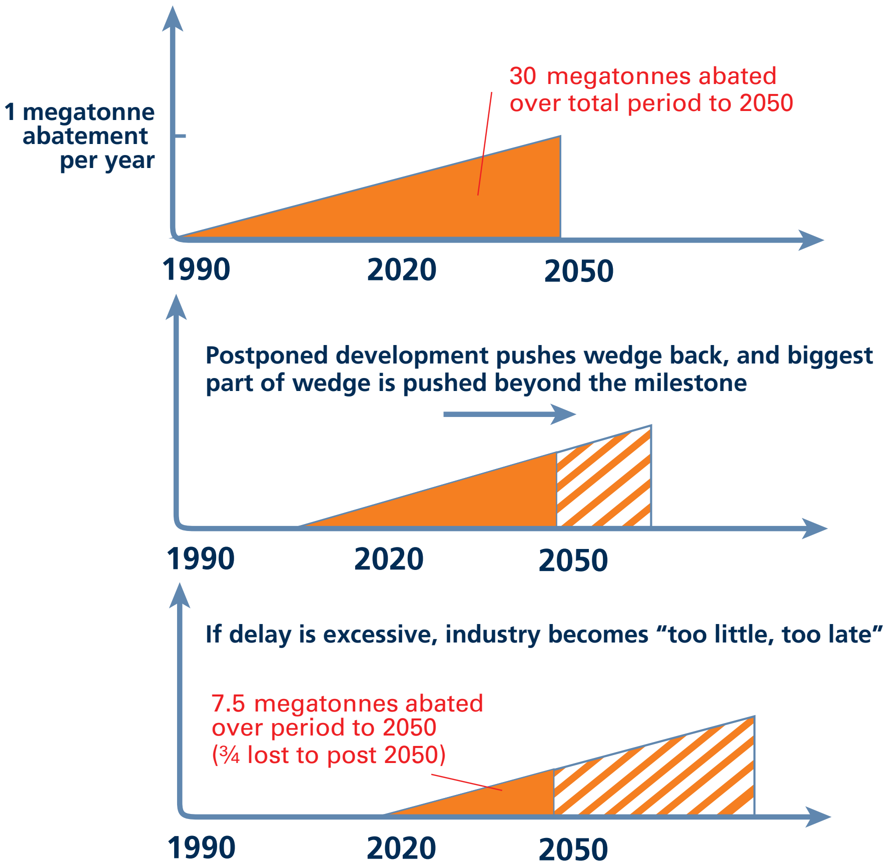


Figure 84: Industry development is limited by its ability to grow at stable rates (due to training, labour availability, materials and so on). This means that delays in starting industrial development reduce the contribution an industry can make over a fixed period. To provide the maximum abatement by 2050, all abatement options need to be started early, as delays may make their contribution too little, too late.

See Finding (ii) above for further discussion on the window of opportunity available to implement low-carbon re-industrialisation.

10.3.4 Incomplete Resource Development Constraint

The results presented for the low-carbon re-industrialisation scenario show that a broad array of low-emissions industries and resources are necessary to achieve the required emissions targets. There is very little resource contingency and there are no dominant resources. This means that all low-carbon services and resources must be developed simultaneously to achieve emissions levels consistent with avoiding runaway climate change.

If a smaller range of industries are developed or if critical transitions in the energy management and transport sectors are not made, then within a few years it will no longer be possible to deepen the trajectory of emissions cuts within the period available, i.e. by 2050. This means that, although global emissions agreements may seek deeper cuts, it may not be possible for industries to deliver on these policies.

Figure 85 illustrates this issue. It shows that to meet abatement targets it is much easier to expand a larger number of established industries than to introduce new industries late in the time frame, especially if greater emissions abatement is required than initially expected. It shows how this approach avoids the possibility that one or more industries would be pushed past viable growth rates.

10.3.5 Transport, Thermal Energy and Fuels Infrastructure

There is an upper limit on the volume of global bio-hydrocarbon resources (even assuming that all waste hydrocarbon from agriculture can be converted

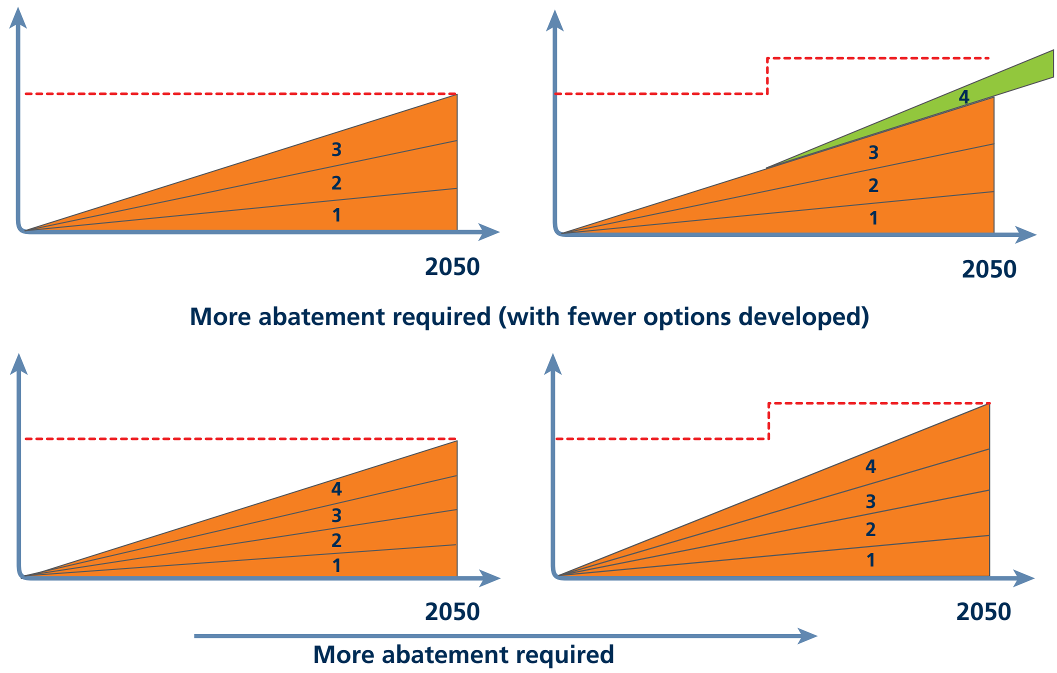


Figure 85: The wedges on the left are both designed to meet the same target. The one with four industries under development is able to expand more easily to meet a more ambitious target than the one with three industries, which would have to develop new industries from scratch late in the piece and push them to very high development rates.

to liquid or gaseous fuels). This has important implications for a low-carbon transition, particularly in the case of low-carbon transport.

Recent tests by Virgin Airlines have made some progress towards demonstrating the suitability of biofuels to larger scale use in commercial aviation. Similarly, biodiesel and its variants have been an effective alternative for diesel and heavy marine fuels in shipping for some time. The specific requirements of these modes of transport for high energy density, transportable fuel means they will need priority access to the bio-hydrocarbon resources identified in this report.

This bioenergy requirement has three important implications:

1. Excluding existing applications of biomass, the use of any additional bio-hydrocarbons for anything other than liquid fuels may be restrictive, given the lack of suitable alternatives in some transport applications. However, any residual biomass from the conversion process to bio-hydrocarbons could potentially be used for increasing soil carbon (e.g. the creation of biochar).

2. Given the prioritisation of liquid bio-hydrocarbon fuels for shipping and aviation (due to the lack of alternatives), the energy needs of land-based transport must be met by other means. The abundance of grid-connected renewable energy sources in the future energy mix makes low-carbon electricity a viable solution. To increase mobility when using grid-based low-carbon electricity, land-based vehicles are likely to make use of on-board energy storage systems such as batteries, hydrogen or compressed air.

3. Industrial applications that use high energy density fuels, especially thermal applications, may need to switch over to other energy carriers such as electricity or hydrogen.

Energy infrastructure planning and transport fuels policy must reflect the priority access of aviation and shipping sectors to biofuels. In addition, this planning must reflect the requisite need for land-based transport (freight, public and personal) and industrial thermal needs to be met from the conversion of low-carbon electricity.

10.3.6 Carbon Capture and Storage

A challenge facing CCS concerns securing investment in a relatively high-cost solution that is important in transition, but is ultimately likely to be phased out of the energy sector. The fact that fossil fuel use with CCS will always be more expensive than using fossil fuels without CCS means that it will always require additional support. As a result, the role of CCS in energy generation will be undermined as other low-emissions renewable energy options become lower costs in the medium- and long-term.

However, while other zero- and low-emissions technologies are being brought to maturity and widely deployed, coal, oil and gas will continue to play a part in the energy supply mix in the short- and medium-term. The model shows that in order to stay within the carbon emissions budget it is highly beneficial if fossil fuel plants are equipped with CCS technology as soon as possible. As other lower-emissions industries (such as wind, geothermal, solar power stations and building integrated solar PV) continue to expand beyond 2050, the market share of fossil fuel power plants (all operating with CCS by this point) appear likely to gradually be reduced and ultimately phased out due to cost and uncaptured emissions.

The importance of CCS for enabling fossil fuels to have an ongoing role in the transition to a low-emissions economy has major and immediate implications for the design, planning, and location of new energy generation plants (and the decommissioning of existing plants). This is because the transport of carbon dioxide to distant storage sites would further increase costs.

While the results make it clear that to pursue CCS for energy generation beyond a transition role would be costly from an emissions and economic standpoint, it should be noted that in its absence the transition phase would place intense and prolonged industrial growth rate pressure on the other lower emissions industries.

A second aspect of CCS is its application to industrial process emissions. From a manufacturing and production perspective (e.g. steel and cement), the absence of CCS for industrial processes would likely mean that the irreducible emissions from industry would be higher than those shown in the results above. In this case, there would be increased pressure on other emissions reduction possibilities for industry (e.g. improved process efficiency, alternative production processes or switching to lower-emissions materials and products) to lower irreducible emissions, particularly beyond 2050.

However, since CCS is as yet commercially unproven, the gamble posed by relying on its performance exposes an even greater risk of failing to achieve emissions reductions targets, should the industry fail to deliver. The dynamics between CCS being seen as a silver bullet and, equally, as a waste of limited resources must be carefully managed. The Economist (The Economist 2009a, The Economist 2009b) recently noted that there is increasing concern that CCS will absorb the crucial funding necessary to establish renewable energy facilities that are more economically viable and key to emissions reductions in the long-term.

10.3.7 Terrestrial Carbon

Stopping and reversing the deforestation and degradation of forest land (e.g. for charcoal or grazing lands), particularly in tropical countries, emerges as a crucial element of the scenarios modelled in this report. It is reasonable to assume that most developed countries will cease deforestation and ideally engage in reforestation as one measure in a suite of emissions reduction activities. However, there remains the important issue of how the economic activity of deforestation will be compensated in developing countries. It is unrealistic to assume that the custodians of these forests seeking to derive income from them will seek to curb their activities without economic recompense for the collective good achieved.

The inclusion of carbon sinks within a carbon trading scheme that includes fossil fuel emissions brings with it perversities in which the prevention of one activity exacerbates the other. Instead, the modelling indicates that a minimum amount of carbon will need to be retained in forest sinks globally, and this cannot be traded off against emissions from fossil fuels if the required emissions outcomes are to be achieved.

10.4 Finding (iv): Low-carbon re-industrialisation provides feasible long-term returns on costs

The fourth objective aimed to compare the costs of low-carbon re-industrialisation with those of business-as-usual development. In this report, these costs excluded major infrastructure investment, i.e. costs that are deemed to have been for changes in the type of infrastructure. The cost of capital stock that provides a short-term return (e.g. energy-efficient appliances) is also excluded.

For renewable energy resources and industries, the results in this report express the costs required to meet the shortfall between the price of fossil fuel-based energy production and that from renewable and CCS sources. For renewable sources, this investment achieves a return against the business-as-usual case, due to the savings created as these industries achieve economies of scale.

In the minus 63% scenario, the required investment to support renewable energy industry development was about US$6.7 trillion for the period up to 2050. A return of over US$41 trillion was created over the period 2013 to 2050, constituting a significant return on costs over the long-term. However, the fast growth rates involved could lead to learning rates being retarded somewhat. If this were the case, increases in scale would not provide price drops as quickly as predicted and the ratio of return to investment would be eroded, as shown in Figure 58 and Figure 79.

It is possible to minimise learning rate retardation through appropriate planning and policy implementation. If this can be achieved, the ratio between investment and return presents a reasonably plausible long-term investment strategy, where short-term price support to achieve economies of scale may be repaid with long-term returns from the cost savings (as shown schematically in Figure 86).

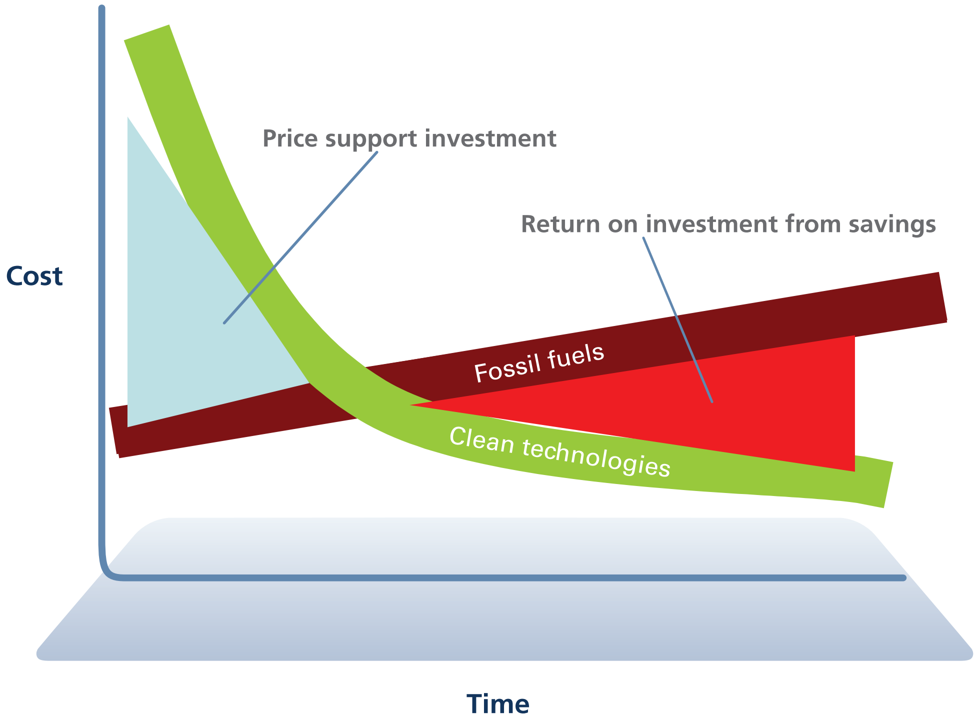


Figure 86: Schematic cost curve diagram, showing the required investment and resulting revenue from the development of renewable energy technologies.

11 Policy Implications and Opportunities

This section sets out a list of policy challenges that cannot remain unaddressed if the obstacles to avoiding 2°C of warming are to be successfully overcome.

In providing these policy insights and suggestions to decision-makers and stakeholders, it should be emphasised that although many of the policy issues put forward here are under consideration, this is not a menu from which only a few pieces can be chosen while the others are set aside. All of the policy challenges identified here must be addressed.

The report identifies 24 low-carbon wedges, which are resources, industries and activities that must be developed at very high growth rates to achieve emissions cuts of up to about 80% by 2050 (relative to 1990 levels). The limits to reasonable growth rates, resource size, and risks of unforeseen delays or failure, mean that policies must ensure that all of these low-carbon resources are developed concurrently, promptly and through to 2050.

11.1 National and International Targets

Problem: Though many low-carbon actions result in a greater degree of economic efficiency, some represent an increase in costs compared to business-as-usual in the short-term. For some industries and countries, this could represent a competitive disadvantage unless all countries participate in emissions reductions, creating a more consistent international market. For this reason, a globally binding international agreement is required. However, as this report identifies, the time window for agreement is very short indeed, requiring such an agreement to be established as quickly as possible.

The Policy Challenge: To implement an effective and binding international agreement within five years that has targets consistent with avoiding 2°C of warming. Obviously the UNFCCC provides the basis for addressing this challenge, providing that the time frame and targets are adequate.

11.2 A Price on Pollution

Problem: In most countries there is no constraint or cost to putting greenhouse gas pollution into the atmosphere.

The Policy Challenge: Greenhouse gases are a pollution problem and therefore mitigation requires restraints to be placed on such pollution by requiring the polluter to pay for the right to pollute, or to face punitive costs for illegal pollution. The leading policy solution for establishing a cost to greenhouse gas pollution is the implementation of national, regional and international emissions trading schemes. Such schemes place a limit on pollution but allow the market to find the appropriate price for the right to emit.

11.3 Sequential Low-Carbon Industry Development Under Emissions Trading

Problem: A price on carbon, alone, will be too slow to achieve the required outcomes. A price on carbon or market-based mechanisms from emissions trading create a steadily increasing price on greenhouse gas emissions. This price increases as the emissions constraint tightens and the right to emit becomes more valuable. The problem is that carbon pricing on its own will lead to least cost, low-carbon resources being developed sequentially, according to cost, while higher cost solutions are delayed. The modelling in this report shows that this means that the emissions goals for 2050 will not be achieved as a result.

The Policy Challenge: Complementary measures are required to ensure that all critical low-carbon resources are not left undeveloped or are developed too slowly, even those that are of higher cost. Mechanisms such as feed-in tariffs and portfolio standards are proven means for deploying higher cost technology, such as renewable energy, and spreading the cost across a wide consumer base. Similar schemes combined with carbon pricing could address CCS cost barriers.

11.4 Non-Economic Barriers to Efficiency

Problem: Though almost all efficiency measures result in net savings to individuals and business (and therefore the economy), many remain undeveloped or actively resisted due to market inertia or vested interests. The energy market, in particular, is universally based on the sale of energy (e.g. kilowatts or litres of fuel) as the key commodity rather than the energy service (e.g. light, heat or transport). This means that most utilities have a disincentive to encourage efficiency. Under these conditions, the diffusion of efficiency may occur too slowly to achieve the emissions targets set out in this report.

The Policy Challenge: Non-economic barriers cannot be substantively overcome by economic incentives or penalties alone. Therefore, non-economic interventions are required to accelerate the diffusion of efficiency. The most rapid efficiency improvement possible is to remove all inefficient devices and practices from the market using regulation and standards. To accelerate the rate at which technology and practices are developed, such standards could be set at an international level to cover multiple countries. Furthermore, regulating energy markets to require the sale of energy services would fundamentally de-couple increasing energy services demand from energy production and escalating emissions.

11.5 Cost of Retaining Forests

Problem: The need to reduce emissions from land use, land use change and forestry is unavoidable, yet may represent an opportunity cost to the countries and land-owners who might otherwise undertake actions that generate greater value than they would receive from a carbon market.

The Policy Challenge: In order to avoid certain deforestation, payments may need to be made to the relevant land-owners to compensate for the lost income or value. This implies that there is a minimum amount of forest carbon that must be in existence in order to contribute to avoiding 2°C of warming. This is the responsibility of all people and nations – not just the ones that have the largest forests – which presents an important international policy challenge. A separate market may need to be established for forest carbon to manage the distribution of such costs.

11.6 Removal of Perversity

Problem: Many markets and tax regimes operate in ways that actively oppose the uptake and diffusion of low-carbon solutions. For example, energy companies make money by selling more power, rather than selling an energy service that would incentivise energy efficiency for profitability. In addition, existing energy subsidies in the fossil fuels sector are estimated to be about US$300 billion each year globally (UNEP 2008).

The Policy Challenge: To dismantle subsidies and perversities in markets that are working against low-carbon uptake without causing economic disruption. It may be necessary to reform energy markets so that supplying energy by volume is phased out and replaced with supplying integrated energy services – heating, cooling, lighting, telecommunications and so forth. Such reform would thus internalise the value of efficiency at the point of sale.

11.7 Opportunity Cost to Developing Countries

Problem: The costs of some low-carbon solutions are higher than those that might otherwise be used, which presents an allocation of resources that might detract from poverty eradication. On the other hand, developing country industrialisation along low-carbon pathways will be critical to avoiding a lock-in of high emissions. In the long-term, this report shows that such a pathway will lead to lower costs than business-as-usual.

The Policy Challenge: The challenge is to find a way of funding the incremental cost of deploying low-carbon projects in developing countries without diverting resources from poverty eradication. The long-term nature of these costs and returns may require the use of long-term "Climate Bonds" that can be used to fund the short- and medium-term cost increments for choosing low-carbon resources (e.g. feed-in tariffs). In turn, these can be repaid using the savings against business-as-usual achieved in the medium- and long-term.

11.8 Enabling Infrastructure

Problem: Changes of mode, such as increased public transport and the switch to electricity-based land transport, will require major investment in new infrastructure. Similarly, building in the ability for grids to move and manage large volumes of renewable energy and accommodate the capture and storage of CO_2 will also require considerable infrastructure investment. The absence of such key enabling infrastructure would prevent or constrain low-carbon re-industrialisation.

The Policy Challenge: To find a mechanism that will successfully allow an entity or entities to identify, fund and implement an enabling infrastructure at national and regional scales. This will require that low-carbon infrastructure be identified as of strategic national and international importance and that its deployment is coordinated by and between governments.

11.9 Liquid Fuel Limitations

Problem: Though many energy needs currently met by fossil fuels can be replaced by using electricity generated with renewable energy, the transport sector presents a particular challenge. The total resource for biofuels (assuming no competition with food production) will not be sufficient to meet all of the demand types currently met by oil. At this stage, the two sectors with the fewest viable alternatives to a liquid fuel are the aviation and shipping sectors.

The Policy Challenge: With significant avoided aviation and shipping there will be adequate bio-hydrocarbons available from agricultural and forestry wastes to meet the remaining needs of these two sectors, but land-based transport needs will have to be met through other energy carriers supplied from renewable energy. Definitive transport energy policy is required to avoid economic dislocations in these sectors. This may require a set of mandatory fuel-use targets to be set to transition the aviation sector to bio-kerosene and shipping to biodiesel supplied from biomass sources that do not compete with food crops. National and international targets may also be established to fully transition the land-based transport sector to energy carriers (such as batteries or hydrogen) supplied by renewable power.

11.10 Leveraging Investment

Problem: This project has identified that the process of low-carbon re-industrialisation will create long-term savings against business-as-usual. These savings represent a major investment opportunity but no financial mechanism currently exists to leverage the trillions of dollars required.

The Policy Challenge: Leveraging such an opportunity will require the participation of three key players:

1. Industry – to rapidly expand production and deployment, and reduce costs through economies of scale.

2. Institutional investors – to finance the industry development until such a time as cost competitiveness is achieved and returns can be achieved.

3. Governments – to provide a secure investment framework for the investors and industry. This framework must ensure that they are able to extract a return on the investment using the savings created from low-carbon industries achieving economies of scale.

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13 Glossary

Abatement – A reduction in greenhouse gas emissions (also see mitigation).

Adaptation – The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (Metz *et al.* 2001).

Anthropogenic – The result of human activities.

Base-load – Normally refers to a power station that runs constantly (24 hours per day, 7 days per week), regardless of energy demand. Due to their slow start-up and shut-down times it is more cost-effective for them to remain on.

BAU – Business-as-usual: Refers to the emissions or energy trajectory associated with undertaking activities without any measures to reduce greenhouse gas emissions. Often greenhouse gas mitigation policies are compared to business-as-usual to show the potential impact of the policy.

Capacity – Maximum rated power of a power station, usually measured in megawatts (MW).

Capacity factor – The percentage of yearly energy generated as a fraction of its maximum possible rated output.

CCS – Carbon capture and storage.

CO_2 – Carbon dioxide, which is one of the primary anthropogenic greenhouse gases.

CO_2-e – Carbon dioxide equivalent: The net effect greenhouse gas emissions are often presented as carbon dioxide equivalent, which is a conversion to the global warming potential of carbon dioxide over a 100-year period. For example, the global warming potential for a tonne of methane is 21 times that of a tonne of carbon dioxide.

Critical development period – The time period up until a low-emissions industry has harnessed 20% of the available resource for that particular technology. This is also sometimes referred to as the growth phase.

Emissions intensity – The emissions generated per unit of input or output.

Fossil fuel – A non-renewable source of energy formed from decayed organic matter millions of years ago. The most predominant fossil fuels are coal, oil and gas.

Fugitive emissions – The emissions that come from the mining, transportation and storage of fossil fuels (but do not include the emissions from fossil fuel combustion).

GDP – Gross Domestic Product: The economic value of a country's annual production of goods and services.

Geosequestration – Refers to the capture and geological (underground) storage of CO_2 emissions.

GHG – Greenhouse gases: Gases in the atmosphere that adsorb and emit infrared radiation, which subsequently lead to global warming. The most common anthropogenic greenhouse gases are carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O) and sulphur hexafluoride (SF_6).

Gt – Gigatonnes: One gigatonne is one billion (10^9) tonnes. Greenhouse gas emissions are often displayed in gigatonnes carbon dioxide equivalent per annum ($GtCO_2$-e/yr).

$GtCO_2$-e – Gigatonnes carbon dioxide equivalent: An internationally recognised measure used to compare the emissions of various greenhouse gases. This measure factors in differences in global warming potential and converts them to a carbon dioxide equivalent. For example, the global warming potential for a tonne of methane over 100 years is 21 times that of a tonne of carbon dioxide.

GWh/yr – Gigawatt hours per year: A gigawatt is one billion (10^9) watts.

LEI – Low-emissions industry.

LULUCF – Land use, land use change, and forestry.

Mitigation – The Intergovernmental Panel on Climate Change (IPCC) defines mitigation as "an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases" (Metz *et al.* 2001).

MRET – Mandatory Renewable Energy Target.

Mt – Megatonnes: One megatonne is one million (10^6) tonnes. Greenhouse gas emissions are often displayed in megatonnes carbon dioxide equivalent per annum ($MtCO_2$-e/yr).

$MtCO_2$-e – Megatonnes carbon dioxide equivalent: An internationally recognised measure used to compare the emissions of various greenhouse gases. This measure factors in differences in global warming potential and converts them to a carbon dioxide equivalent. For example, the global warming potential for a tonne of methane over 100 years is 21 times that of a tonne of carbon dioxide.

Mtoe – One million tonnes of oil equivalent.

MWh/yr – Megawatt hours per year: A megawatt is one million (10^6) watts.

Photovoltaic cell – A renewable energy technology that converts sunlight into electrical energy.

Power – Energy transferred per unit of time. Electrical power is usually measured in watts (W), kilowatts (kW), megawatts (MW) and gigawatts (GW). An appliance drawing 1000 watts (1 kW) for 1 hour is said to have used 1 kilowatt hour (1 kWh) of electricity.

ppm – Parts per million.

PV – Photovoltaic (solar power).

Renewable energy – Energy that comes from natural processes and is replenished in human time frames or cannot be exhausted (sources of renewable energy include wind, biomass, solar radiation, geothermal energy, wave and tidal power).

Runaway climate change – When the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause (NRC 2002).

TWh/yr – Terawatt hours per year: A terawatt is one million, million (10^{12}) watts.

Wind farms – A collection of wind turbines that connect to common substations to feed into the main electrical grid.

Wind turbine – A renewable energy technology that converts air currents into mechanical energy, which is then used to generate electrical energy.

14 Appendix: Model Input Data

Since the CRISTAL model makes use of Monte Carlo methods, most input data used in the model is built up from a range of possible values. Generally, the range of values used for each model input was obtained from widely accepted literature sources available to the general public. The tables shown below list some of the key input ranges used in the CRISTAL model.

It should be noted that the estimates of renewable energy resource are conservative. For example, the resource constraints that have been applied to reflect possible technical limits to uptake for geothermal energy, solar power stations, and sea and ocean energy for 2050 may have actually been removed by that time, in which case the available resource could be significantly larger.

Figure 87 to Figure 89 show the data used to build the Monte Carlo ranges for fossil fuel energy prices.

Table 3: Monte Carlo data ranges used to determine the maximum emissions abatement relative to business-as-usual (BAU) for various sectors by 2050 in the minus 63% scenario.

Sector	Emissions Abatement			Units
	Low	Best	High	
Avoided Aviation	30	35	40	% Reduction on BAU
Aviation Efficiency	20	42	60	% Reduction on BAU
Shipping Efficiency	25	50	75	% Reduction on BAU
Reduced Use of Vehicles	15	40	50	% Reduction on BAU
Vehicles Efficiency	20	30	50	% Reduction on BAU
Buildings Efficiency	28	50	72	% Reduction on BAU
Metals Industrial Energy Efficiency	35	40	50	% Reduction on BAU
Non-Metals Industrial Energy Efficiency	20	35	50	% Reduction on BAU
Agriculture	7.95	8.31	8.67	$GtCO_2$-e/yr
LULUCF	1.3	7.55	13.8	$GtCO_2$-e/yr
Waste	1.45	1.53	1.62	$GtCO_2$-e/yr
Fugitive	2.5	2.5	2.5	$GtCO_2$-e/yr

Sources: Stern 2006, IPCC 2007, IMO 2009

Table 4: Monte Carlo data ranges used to determine the maximum emissions abatement relative to business-as-usual (BAU) for various sectors by 2050 in the minus 80% scenario.

Sector	Emissions Abatement			Units
	Low	Best	High	
Avoided Aviation	33	38.5	44	% Reduction on BAU
Aviation Efficiency	22	46.2	66	% Reduction on BAU
Shipping Efficiency	25	50	75	% Reduction on BAU
Reduced Use of Vehicles	16.5	44	55	% Reduction on BAU
Vehicles Efficiency	22	33	55	% Reduction on BAU
Buildings Efficiency	30.8	55	79.2	% Reduction on BAU
Metals Industrial Energy Efficiency	38.5	44	55	% Reduction on BAU
Non-Metals Industrial Energy Efficiency	22	38.5	55	% Reduction on BAU
Agriculture	7.95	8.31	8.67	$GtCO_2$-e/yr
LULUCF	2.34	13.59	24.84	$GtCO_2$-e/yr
Waste	1.45	1.53	1.62	$GtCO_2$-e/yr
Fugitive	2.5	2.5	2.5	$GtCO_2$-e/yr

Sources: Stern 2006, IPCC 2007, IMO 2009

Table 5: Monte Carlo data ranges used for determining the maximum resource for various energy generation technologies by 2050 for all scenarios.

Sector	Maximum Resource by 2050			Units
	Low	Best	High	
New Large Hydro	4020	5073	5073	TWh
Small Hydro	556	556	556	TWh
Wind Power	28666	97733	166800	TWh
Geothermal	2522	8330	36734	TWh
Solar Power Stations	13900	29190	44480	TWh
Sea and Ocean Energy	2000	3000	4000	TWh
Building Integrated PV	8642	21606	54014	TWh
Domestic Solar Thermal	12089	18133	70518	TWh
Bio-Hydrocarbons	7098	15001	29586	TWh
Nuclear	1466	3124	5186	TWh
Fossil Fuels with CCS	0.28	0.38	0.43	tCO_2/MWh captured

Sources: IPCC 2007, IEA 2008, Nowak *et al.* 2002

Table 6: Current installed capacity and capacity factor ranges for various low-emissions energy technologies used in all scenarios.

Sector	Current Capacity	Capacity Factor		
	(GW)	Low	Best	High
Large Hydro	860.0	0.34	0.45	0.55
Small Hydro	85.0	0.50	0.60	0.70
Wind Power	121.0	0.40	0.50	0.60
Geothermal	10.0	0.40	0.73	0.80
Solar Power Stations	0.5	0.12	0.20	0.28
Sea and Ocean Energy	0.3	0.20	0.35	0.45
Building Integrated PV	13.0	0.10	0.16	0.20
Domestic Solar Thermal	145.0	0.10	0.20	0.25
Bio-Hydrocarbons	32.4	0.35	0.45	0.50
Nuclear	372	0.60	0.70	0.80
Fossil Fuels with CCS	0.0	0.50	0.55	0.70

Sources: REN21 2009, IEA 2008, IPCC 2007

Table 7: Monte Carlo data ranges for historical learning rates (the fraction by which the unit cost is reduced for a doubling of production volume) and current unit costs for various low-emissions energy generation technologies used in all scenarios.

Sector	Historical Learning Rate	Current Cost (US$/MWh)		
		Low	Best	High
Large Hydro	0.01	30	35	40
Small Hydro	0.05	40	55	70
Wind Power	0.1	40	65	90
Geothermal	0.08	40	55	70
Solar Power Stations	0.18	120	150	180
Sea and Ocean Energy	0.15	80	100	400
Building Integrated PV	0.153	200	500	800
Domestic Solar Thermal	-0.043	20	65	200
Bio-Hydrocarbons	0.15	50	80	120
Nuclear	0.058	10	75	120
Fossil Fuels with CCS (additional cost)	0.2	20	90	150

Sources: REN21 2008, IPCC 2007, IPCC 2005, IEA 2000, EIA 2009, Kouvaritakis 2000, Taylor *et al.* 2006

Table 8: Simulation mean result for the annual emissions abatements of low-carbon energy generation in the minus 63% scenario ($GtCO_2$-e/yr).

Year	Residual Emissions	Fossil with CCS	Nuclear	Large Hydro	Repowering Large Hydro	Small Hydro	Wind	Geo-thermal	Solar Power Stations	Building Integrated Solar PV	Domestic Solar Thermal	Sea and Ocean Energy	Bio-Hydrocarbons
2010	48.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
2011	48.67	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.04
2012	48.69	0.01	0.01	0.05	0.00	0.02	0.05	0.01	0.02	0.02	0.03	0.00	0.05
2013	48.18	0.03	0.02	0.10	0.00	0.04	0.11	0.03	0.04	0.05	0.07	0.01	0.07
2014	47.84	0.06	0.03	0.15	0.01	0.06	0.20	0.05	0.06	0.09	0.13	0.01	0.11
2015	47.27	0.09	0.04	0.20	0.01	0.07	0.31	0.08	0.10	0.14	0.20	0.01	0.15
2016	46.12	0.13	0.06	0.25	0.01	0.09	0.45	0.11	0.15	0.20	0.29	0.02	0.20
2017	45.02	0.18	0.07	0.29	0.02	0.11	0.61	0.16	0.20	0.27	0.40	0.03	0.26
2018	43.83	0.23	0.09	0.32	0.02	0.13	0.80	0.20	0.26	0.36	0.52	0.04	0.33
2019	42.57	0.30	0.10	0.33	0.02	0.13	1.01	0.26	0.33	0.45	0.66	0.05	0.41
2020	41.45	0.37	0.12	0.33	0.03	0.13	1.25	0.32	0.40	0.56	0.81	0.06	0.50
2021	40.25	0.44	0.13	0.33	0.03	0.13	1.51	0.38	0.49	0.68	0.98	0.07	0.60
2022	38.98	0.53	0.14	0.33	0.03	0.13	1.80	0.46	0.58	0.81	1.17	0.08	0.71
2023	37.85	0.62	0.15	0.33	0.03	0.13	2.11	0.54	0.68	0.95	1.37	0.10	0.82
2024	36.47	0.72	0.16	0.33	0.03	0.13	2.45	0.62	0.79	1.10	1.59	0.11	0.95
2025	35.27	0.82	0.17	0.33	0.03	0.13	2.80	0.71	0.91	1.26	1.83	0.13	1.08
2026	33.87	0.94	0.17	0.33	0.03	0.13	3.15	0.81	1.03	1.43	2.07	0.15	1.23
2027	32.49	1.06	0.17	0.33	0.03	0.13	3.51	0.92	1.17	1.62	2.31	0.16	1.38
2028	31.33	1.19	0.16	0.33	0.03	0.13	3.86	1.03	1.31	1.81	2.56	0.18	1.55
2029	29.98	1.32	0.15	0.33	0.03	0.13	4.22	1.15	1.46	2.02	2.80	0.20	1.72
2030	28.85	1.47	0.14	0.33	0.03	0.13	4.57	1.27	1.62	2.24	3.04	0.23	1.90
2031	27.52	1.62	0.12	0.33	0.03	0.13	4.93	1.40	1.78	2.47	3.29	0.25	2.09
2032	26.61	1.77	0.10	0.33	0.03	0.13	5.28	1.54	1.96	2.71	3.53	0.27	2.28
2033	25.51	1.94	0.08	0.33	0.03	0.13	5.63	1.68	2.14	2.96	3.78	0.30	2.47
2034	24.41	2.11	0.06	0.33	0.03	0.13	5.99	1.83	2.33	3.22	4.02	0.33	2.67
2035	23.32	2.29	0.04	0.33	0.03	0.13	6.34	1.98	2.52	3.50	4.26	0.35	2.86
2036	22.22	2.48	0.03	0.33	0.03	0.13	6.70	2.15	2.73	3.77	4.51	0.38	3.05
2037	21.34	2.67	0.02	0.33	0.03	0.13	7.05	2.31	2.95	4.05	4.75	0.41	3.25
2038	20.26	2.87	0.01	0.33	0.03	0.13	7.41	2.49	3.17	4.33	4.99	0.44	3.44
2039	19.20	3.07	0.00	0.33	0.03	0.13	7.74	2.66	3.40	4.62	5.24	0.48	3.63
2040	18.21	3.27	0.00	0.33	0.03	0.13	8.03	2.84	3.64	4.90	5.48	0.51	3.82
2041	17.33	3.47	0.00	0.33	0.03	0.13	8.24	3.03	3.88	5.18	5.69	0.54	4.02
2042	16.80	3.68	0.00	0.33	0.03	0.13	8.38	3.21	4.14	5.46	5.85	0.58	4.21
2043	16.20	3.88	0.00	0.33	0.03	0.13	8.44	3.40	4.40	5.74	5.95	0.61	4.40
2044	15.71	4.08	0.00	0.33	0.03	0.13	8.46	3.58	4.67	6.02	6.01	0.65	4.59
2045	15.30	4.28	0.00	0.33	0.03	0.13	8.46	3.77	4.95	6.30	6.02	0.68	4.78
2046	14.92	4.49	0.00	0.33	0.03	0.13	8.46	3.95	5.23	6.59	6.02	0.72	4.96
2047	14.83	4.69	0.00	0.33	0.03	0.13	8.46	4.14	5.52	6.87	6.02	0.75	5.12
2048	14.46	4.89	0.00	0.33	0.02	0.13	8.46	4.33	5.80	7.15	6.02	0.79	5.24
2049	14.60	5.09	0.00	0.33	0.02	0.13	8.46	4.51	6.09	7.43	6.02	0.82	5.32
2050	14.63	5.30	0.00	0.33	0.02	0.13	8.46	4.70	6.38	7.70	6.02	0.86	5.37

Table 9: Simulation mean result for the annual emissions abatements of all non-energy generation sectors in the minus 63% scenario ($GtCO_2$-e/yr).

Year	Avoided Aviation	Shipping Efficiency	Reduced Use of Vehicles	Vehicle Efficiency	Buildings Efficiency	Metals Industry Efficiency	Non-Metals Industry Efficiency	Agriculture	Land Use, Land Use Change and Forestry	Waste	Fugitive
2010	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2011	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.38	0.09	0.17
2012	0.11	0.01	0.01	0.02	0.00	0.02	0.01	0.45	0.75	0.19	0.34
2013	0.30	0.02	0.03	0.09	0.01	0.05	0.04	0.67	1.13	0.28	0.51
2014	0.55	0.03	0.05	0.22	0.02	0.10	0.07	0.89	1.50	0.37	0.68
2015	0.81	0.05	0.09	0.40	0.05	0.16	0.12	1.11	1.87	0.47	0.85
2016	1.06	0.08	0.13	0.64	0.09	0.25	0.19	1.34	2.22	0.56	1.02
2017	1.27	0.12	0.19	0.92	0.15	0.35	0.26	1.56	2.57	0.66	1.19
2018	1.44	0.15	0.25	1.22	0.22	0.46	0.35	1.78	2.91	0.75	1.36
2019	1.56	0.20	0.32	1.53	0.31	0.59	0.44	2.00	3.23	0.84	1.53
2020	1.64	0.24	0.40	1.84	0.41	0.73	0.55	2.23	3.55	0.94	1.70
2021	1.68	0.29	0.50	2.15	0.54	0.87	0.66	2.45	3.85	1.03	1.87
2022	1.69	0.33	0.60	2.45	0.67	1.03	0.77	2.67	4.15	1.12	2.03
2023	1.70	0.37	0.71	2.75	0.83	1.18	0.89	2.90	4.43	1.20	2.17
2024	1.70	0.42	0.82	3.03	1.00	1.35	1.02	3.12	4.69	1.26	2.29
2025	1.70	0.46	0.95	3.29	1.19	1.51	1.14	3.34	4.95	1.31	2.38
2026	1.70	0.51	1.09	3.52	1.39	1.67	1.26	3.56	5.20	1.35	2.44
2027	1.70	0.55	1.24	3.72	1.60	1.84	1.39	3.79	5.43	1.36	2.47
2028	1.70	0.60	1.39	3.89	1.83	2.00	1.51	4.01	5.65	1.37	2.49
2029	1.70	0.64	1.55	4.02	2.07	2.16	1.63	4.23	5.86	1.38	2.50
2030	1.70	0.68	1.71	4.13	2.32	2.31	1.75	4.45	6.06	1.38	2.50
2031	1.70	0.72	1.87	4.20	2.57	2.46	1.86	4.68	6.24	1.38	2.50
2032	1.70	0.76	2.03	4.25	2.82	2.61	1.98	4.90	6.41	1.38	2.50
2033	1.70	0.79	2.19	4.29	3.07	2.75	2.08	5.12	6.57	1.38	2.50
2034	1.70	0.82	2.35	4.31	3.33	2.89	2.19	5.35	6.72	1.38	2.50
2035	1.70	0.84	2.51	4.32	3.58	3.02	2.29	5.57	6.85	1.38	2.50
2036	1.70	0.85	2.67	4.33	3.84	3.15	2.39	5.79	6.97	1.38	2.50
2037	1.70	0.87	2.83	4.33	4.09	3.27	2.48	6.01	7.08	1.38	2.50
2038	1.70	0.87	2.99	4.33	4.35	3.39	2.57	6.24	7.17	1.38	2.50
2039	1.70	0.88	3.15	4.33	4.60	3.50	2.66	6.46	7.25	1.38	2.50
2040	1.70	0.88	3.31	4.33	4.86	3.60	2.74	6.68	7.31	1.38	2.50
2041	1.70	0.89	3.47	4.33	5.11	3.70	2.81	6.90	7.37	1.38	2.50
2042	1.70	0.89	3.63	4.33	5.36	3.79	2.88	7.13	7.41	1.38	2.50
2043	1.70	0.89	3.79	4.33	5.62	3.88	2.95	7.35	7.44	1.38	2.50
2044	1.70	0.89	3.95	4.33	5.87	3.96	3.01	7.57	7.47	1.38	2.50
2045	1.70	0.89	4.11	4.33	6.13	4.04	3.07	7.80	7.48	1.38	2.50
2046	1.70	0.89	4.27	4.33	6.38	4.10	3.12	8.01	7.49	1.38	2.50
2047	1.70	0.89	4.43	4.33	6.63	4.17	3.17	8.18	7.50	1.38	2.50
2048	1.70	0.89	4.59	4.33	6.88	4.23	3.22	8.27	7.50	1.38	2.50
2049	1.70	0.89	4.75	4.33	7.13	4.28	3.26	8.30	7.50	1.38	2.50
2050	1.70	0.89	4.91	4.33	7.37	4.33	3.29	8.31	7.50	1.38	2.50

Table 10: Simulation mean result for annual energy production from low-carbon industries in the minus 63% scenario (GWh/yr).

Year	Residual Fossil Fuels with no CCS	Fossil with CCS	Nuclear	Large Hydro	Repowering Large Hydro	Small Hydro	Wind	Geo-thermal	Solar Power Stations	Building Integrated Solar PV	Domestic Solar Thermal	Sea and Ocean Energy	Bio-Hydrocarbons
2010	9.48E+07	5107	2324791	3591009	0	531392	485764	60870	1840	31846	294414	2333	10395322
2011	9.80E+07	24032	2329659	3636272	481	546383	527684	71540	15408	50654	321685	4235	10411032
2012	1.00E+08	80808	2346580	3767704	3359	591347	653444	103548	56112	107078	403497	9943	10458159
2013	1.01E+08	175435	2373832	3937364	9549	654651	863043	156895	123952	201117	539851	19457	10536706
2014	1.02E+08	307912	2409787	4107754	18787	718397	1156483	231581	218928	332772	730747	32776	10646671
2015	1.01E+08	478240	2452125	4276974	30051	782143	1533763	327605	341041	502043	976184	49900	10788055
2016	1.00E+08	686419	2498325	4436805	42161	845889	1994883	444969	490289	708930	1276163	70830	10960857
2017	9.86E+07	932448	2545689	4572680	54399	909527	2539842	583671	666673	953433	1630684	95566	11165078
2018	9.66E+07	1216329	2592053	4664340	66295	962062	3168642	743712	870194	1235551	2039747	124106	11400717
2019	9.43E+07	1538059	2636402	4695644	77400	980789	3881282	925091	1100850	1555285	2503351	156453	11667775
2020	9.18E+07	1897641	2678101	4697409	87310	982118	4677761	1127810	1358643	1912634	3021496	192604	11966251
2021	8.92E+07	2295073	2716370	4697409	95722	982118	5558081	1351867	1643571	2307600	3594183	232561	12296146
2022	8.62E+07	2730356	2750392	4697409	102407	982118	6522240	1597263	1955636	2740181	4221412	276324	12657460
2023	8.29E+07	3203489	2778762	4697409	107288	982118	7570186	1863998	2294837	3210378	4903183	323891	13050192
2024	7.93E+07	3714474	2799718	4697409	110456	982118	8697731	2152072	2661173	3718191	5639495	375265	13474343
2025	7.54E+07	4263308	2811093	4697409	112132	982118	9876754	2461484	3054646	4263619	6430349	430444	13929913
2026	7.14E+07	4849994	2811184	4697409	112616	982118	11068050	2792235	3475255	4846664	7248474	489428	14416901
2027	6.72E+07	5474530	2797494	4697409	112249	982118	12259800	3144325	3923000	5467324	8066598	552217	14935307
2028	6.29E+07	6136917	2768192	4697409	111315	982118	13451550	3517754	4397881	6125599	8884723	618812	15485125
2029	5.85E+07	6837155	2722432	4697409	110028	982118	14643300	3912522	4899898	6821491	9702848	689213	16065932
2030	5.41E+07	7575243	2659534	4697409	108541	982118	15835050	4328628	5429051	7554998	10520972	763419	16675279
2031	5.00E+07	8351182	2579810	4697409	106962	982118	17026799	4766066	5985340	8326118	11339097	841430	17306269
2032	4.60E+07	9164972	2484667	4697409	105370	982118	18218549	5224797	6568765	9134817	12157222	923247	17949311
2033	4.19E+07	10016612	2379209	4697409	103798	982118	19410299	5704732	7179327	9980684	12975346	1008869	18596231
2034	3.78E+07	10906101	2272718	4697409	102249	982118	20602049	6205680	7817024	10861713	13793471	1098297	19243374
2035	3.36E+07	11833232	2171300	4697409	100725	982118	21793799	6727292	8481857	11772327	14611596	1191530	19890517
2036	2.94E+07	12796079	2075011	4697409	99223	982118	22985549	7268938	9173827	12703161	15429721	1288568	20537659
2037	2.52E+07	13789564	1983572	4697409	97744	982118	24177215	7829549	9892932	13644220	16247845	1389412	21184802
2038	2.10E+07	14805638	1896715	4697409	96288	982118	25362805	8407612	10639174	14588662	17065970	1494061	21831945
2039	1.68E+07	15835147	1814192	4697409	94853	982118	26492620	9001043	11412552	15533839	17884095	1602504	22479087
2040	1.28E+07	16870728	1735767	4697409	93441	982118	27454604	9607097	12213065	16479100	18696523	1714568	23126230
2041	1.00E+07	17908349	1661218	4697409	92050	982118	28170722	10222493	13040714	17424363	19397877	1829570	23773373
2042	7.68E+06	18946271	1590336	4697409	90680	982118	28628485	10843833	13895470	18369626	19926381	1946273	24420516
2043	5.77E+06	19984196	1522924	4697409	89331	982118	28846916	11467995	14777115	19314889	20281937	2063620	25067611
2044	4.21E+06	21022121	1458797	4697409	88002	982118	28904387	12093005	15684731	20260152	20464641	2181117	25712945
2045	2.86E+06	22060046	1397778	4697409	86693	982118	28909239	12718137	16615800	21205415	20497107	2298629	26347602
2046	1.61E+06	23097972	1339703	4697409	85404	982118	28909251	13343251	17565233	22150667	20497108	2416141	26946157
2047	4.52E+05	24135897	1284416	4697409	84135	982118	28909251	13968207	18525892	23095821	20497108	2533653	27470213
2048	0	25173822	1231770	4697409	82885	982118	28909251	14592670	19491171	24039649	20497108	2651165	27883859
2049	0	26211746	1181627	4697409	81654	982118	28909251	15215915	20457697	24975395	20497108	2768677	28168934
2050	0	27249267	1133855	4697409	80442	982118	28909251	15836511	21424374	25881676	20497108	2886189	28334175

Table 11: Simulation mean result for annual energy savings and avoidance from non-energy generation activities in the minus 63% scenario (GWh/yr).

Year	Avoided Aviation	Shipping Efficiency	Reduced Use of Vehicles	Vehicle Efficiency	Buildings Efficiency	Metals Industry Efficiency	Non-Metals Industry Efficiency
2010	0	0	0	0	0	0	0
2011	54568	2800	4582	5129	316	8593	6263
2012	375181	19225	31324	77986	4987	58659	43461
2013	1020603	54426	88526	309020	25147	165624	123362
2014	1858005	108806	176815	732615	74558	330584	246821
2015	2733384	182364	296191	1349567	164502	553502	413808
2016	3553995	275102	446653	2143854	302706	833491	623762
2017	4269445	386969	628203	3074513	493756	1167281	874347
2018	4843374	516700	840839	4084217	739210	1549914	1162035
2019	5252470	659377	1084562	5123829	1039175	1975448	1482456
2020	5503508	808079	1359372	6169253	1393651	2437266	1830860
2021	5632389	958280	1665269	7210741	1802637	2929044	2202489
2022	5687045	1108630	2002252	8236388	2266135	3444613	2592758
2023	5704882	1258983	2370323	9228815	2784140	3978220	2996908
2024	5708629	1409335	2769480	10168063	3356595	4523134	3409907
2025	5708979	1559688	3199724	11035010	3982993	5073416	3827189
2026	5708983	1710033	3661055	11813085	4661615	5624239	4244964
2027	5708983	1860155	4153323	12489839	5388282	6171458	4660314
2028	5708983	2009103	4673194	13056748	6156243	6711801	5070989
2029	5708983	2154952	5207950	13512214	6957144	7242960	5474963
2030	5708983	2295163	5745691	13861603	7781958	7762977	5870759
2031	5708983	2426569	6283542	14115955	8622051	8270320	6257203
2032	5708983	2545782	6821393	14290739	9470731	8763568	6633361
2033	5708983	2650090	7359244	14403339	10323471	9241477	6998377
2034	5708983	2737968	7897095	14470974	11177769	9702976	7351495
2035	5708983	2809180	8434946	14508205	12032517	10147424	7692096
2036	5708983	2864586	8972797	14526149	12887353	10574211	8019552
2037	5708983	2905777	9510648	14533199	13742197	10982588	8333510
2038	5708983	2934775	10048498	14535556	14597041	11371915	8633612
2039	5708983	2954028	10586349	14536126	15451885	11741966	8919363
2040	5708983	2966041	11124200	14536203	16306728	12092855	9190370
2041	5708983	2972991	11662051	14536204	17161572	12424520	9446432
2042	5708983	2976629	12199902	14536204	18016393	12736852	9687130
2043	5708983	2978256	12737753	14536204	18871112	13029401	9912147
2044	5708983	2978837	13275604	14536204	19725323	13301801	10121562
2045	5708983	2978965	13813455	14536204	20578349	13554034	10315558
2046	5708983	2978977	14351305	14536204	21429092	13786706	10494279
2047	5708983	2978977	14889156	14536204	22275710	14000530	10658035
2048	5708983	2978977	15427007	14536204	23115580	14196294	10807251
2049	5708983	2978977	15964858	14536204	23945449	14374702	10942432
2050	5708983	2978977	16502709	14536204	24761460	14536455	11064305

Table 12: Simulation mean result for the annual emissions abatements of low-carbon energy generation in the minus 80% scenario ($GtCO_2$-e/yr).

Year	Residual Emissions	Fossil with CCS	Nuclear	Large Hydro	Repowering Large Hydro	Small Hydro	Wind	Geo-thermal	Solar Power Stations	Building Integrated Solar PV	Domestic Solar Thermal	Sea and Ocean Energy	Bio-Hydrocarbons
2010	48.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
2011	48.36	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.04
2012	48.04	0.01	0.01	0.06	0.00	0.02	0.06	0.01	0.02	0.03	0.04	0.00	0.05
2013	47.18	0.01	0.02	0.11	0.00	0.04	0.13	0.03	0.04	0.06	0.08	0.01	0.08
2014	46.46	0.02	0.03	0.16	0.01	0.06	0.23	0.06	0.08	0.10	0.14	0.01	0.12
2015	45.52	0.04	0.05	0.21	0.01	0.08	0.36	0.09	0.12	0.16	0.22	0.02	0.17
2016	43.97	0.05	0.06	0.26	0.01	0.10	0.52	0.13	0.17	0.24	0.32	0.02	0.23
2017	42.49	0.07	0.08	0.30	0.02	0.12	0.70	0.18	0.23	0.32	0.44	0.03	0.30
2018	40.90	0.09	0.09	0.32	0.02	0.13	0.92	0.24	0.31	0.42	0.57	0.04	0.38
2019	39.26	0.12	0.11	0.33	0.02	0.13	1.16	0.30	0.39	0.53	0.73	0.05	0.48
2020	37.75	0.14	0.12	0.33	0.03	0.13	1.44	0.37	0.48	0.65	0.90	0.07	0.58
2021	36.16	0.17	0.14	0.33	0.03	0.13	1.74	0.45	0.58	0.79	1.08	0.08	0.69
2022	34.50	0.21	0.15	0.33	0.03	0.13	2.07	0.53	0.69	0.94	1.29	0.10	0.82
2023	32.99	0.24	0.16	0.33	0.03	0.13	2.43	0.63	0.81	1.10	1.51	0.11	0.96
2024	31.23	0.28	0.17	0.33	0.03	0.13	2.81	0.73	0.94	1.28	1.76	0.13	1.10
2025	29.67	0.32	0.17	0.33	0.03	0.13	3.19	0.83	1.07	1.47	2.02	0.15	1.26
2026	27.93	0.37	0.17	0.33	0.03	0.13	3.58	0.95	1.22	1.67	2.28	0.17	1.43
2027	26.21	0.42	0.17	0.33	0.03	0.13	3.96	1.07	1.38	1.89	2.55	0.19	1.61
2028	24.72	0.47	0.16	0.33	0.03	0.13	4.35	1.20	1.55	2.12	2.82	0.22	1.80
2029	23.06	0.52	0.15	0.33	0.03	0.13	4.73	1.34	1.72	2.36	3.09	0.24	2.01
2030	21.62	0.57	0.13	0.33	0.03	0.13	5.12	1.48	1.91	2.61	3.36	0.27	2.21
2031	20.00	0.63	0.11	0.33	0.03	0.13	5.50	1.64	2.11	2.88	3.63	0.29	2.42
2032	18.82	0.68	0.08	0.33	0.03	0.13	5.89	1.80	2.31	3.16	3.90	0.32	2.64
2033	17.46	0.74	0.06	0.33	0.03	0.13	6.28	1.96	2.53	3.45	4.17	0.35	2.85
2034	16.12	0.79	0.04	0.33	0.03	0.13	6.66	2.14	2.75	3.75	4.43	0.38	3.06
2035	14.80	0.85	0.03	0.33	0.03	0.13	7.05	2.32	2.98	4.06	4.70	0.41	3.27
2036	13.51	0.90	0.02	0.33	0.03	0.13	7.43	2.50	3.23	4.36	4.97	0.45	3.48
2037	12.47	0.96	0.01	0.33	0.03	0.13	7.80	2.69	3.48	4.67	5.24	0.48	3.69
2038	11.32	1.01	0.00	0.33	0.03	0.13	8.11	2.89	3.74	4.97	5.51	0.52	3.90
2039	10.30	1.07	0.00	0.33	0.03	0.13	8.33	3.09	4.02	5.28	5.77	0.56	4.11
2040	9.46	1.12	0.00	0.33	0.03	0.13	8.46	3.29	4.30	5.58	5.99	0.60	4.32
2041	8.80	1.18	0.00	0.33	0.03	0.13	8.51	3.49	4.59	5.89	6.14	0.63	4.54
2042	8.45	1.23	0.00	0.33	0.03	0.13	8.52	3.69	4.89	6.19	6.23	0.67	4.75
2043	8.03	1.28	0.00	0.33	0.03	0.13	8.52	3.90	5.20	6.50	6.26	0.71	4.95
2044	7.67	1.33	0.00	0.33	0.03	0.13	8.52	4.10	5.51	6.81	6.26	0.75	5.13
2045	7.39	1.36	0.00	0.33	0.03	0.13	8.52	4.30	5.82	7.11	6.26	0.79	5.28
2046	7.18	1.39	0.00	0.33	0.03	0.13	8.52	4.50	6.14	7.41	6.26	0.82	5.38
2047	7.27	1.40	0.00	0.33	0.02	0.13	8.52	4.70	6.45	7.71	6.26	0.86	5.44
2048	7.15	1.41	0.00	0.33	0.02	0.13	8.52	4.90	6.77	7.98	6.26	0.90	5.46
2049	7.50	1.41	0.00	0.33	0.02	0.13	8.52	5.10	7.08	8.20	6.26	0.94	5.47
2050	7.78	1.41	0.00	0.33	0.02	0.13	8.52	5.28	7.40	8.36	6.26	0.98	5.47

Table 13: Simulation mean result for the annual emissions abatements of all non-energy generation sectors in the minus 80% scenario ($GtCO_2$-e/yr).

Year	Avoided Aviation	Shipping Efficiency	Reduced Use of Vehicles	Vehicle Efficiency	Buildings Efficiency	Metals Industry Efficiency	Non-Metals Industry Efficiency	Agriculture	Land Use, Land Use Change and Forestry	Waste	Fugitive
2010	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2011	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.68	0.09	0.17
2012	0.13	0.01	0.01	0.02	0.00	0.02	0.01	0.45	1.36	0.19	0.34
2013	0.34	0.02	0.03	0.10	0.01	0.05	0.04	0.67	2.04	0.28	0.51
2014	0.61	0.03	0.06	0.23	0.03	0.10	0.08	0.89	2.71	0.37	0.68
2015	0.90	0.05	0.10	0.42	0.05	0.17	0.14	1.11	3.37	0.47	0.85
2016	1.17	0.08	0.15	0.67	0.10	0.26	0.21	1.34	4.01	0.56	1.02
2017	1.41	0.12	0.21	0.96	0.16	0.37	0.29	1.56	4.64	0.65	1.19
2018	1.59	0.15	0.28	1.27	0.24	0.49	0.39	1.78	5.25	0.75	1.36
2019	1.72	0.20	0.36	1.59	0.34	0.63	0.49	2.01	5.85	0.84	1.53
2020	1.80	0.24	0.45	1.92	0.45	0.77	0.61	2.23	6.43	0.94	1.70
2021	1.84	0.29	0.55	2.24	0.59	0.93	0.73	2.45	6.98	1.03	1.87
2022	1.86	0.33	0.66	2.56	0.74	1.10	0.86	2.68	7.51	1.12	2.03
2023	1.87	0.38	0.78	2.87	0.91	1.27	0.99	2.90	8.02	1.19	2.18
2024	1.87	0.42	0.91	3.16	1.09	1.45	1.13	3.12	8.51	1.26	2.29
2025	1.87	0.47	1.05	3.42	1.30	1.62	1.27	3.34	8.98	1.31	2.39
2026	1.87	0.51	1.20	3.66	1.52	1.80	1.40	3.57	9.42	1.35	2.44
2027	1.87	0.56	1.36	3.87	1.76	1.98	1.54	3.79	9.84	1.36	2.48
2028	1.87	0.60	1.54	4.04	2.01	2.16	1.68	4.01	10.24	1.37	2.49
2029	1.87	0.64	1.71	4.18	2.27	2.33	1.81	4.24	10.61	1.38	2.50
2030	1.87	0.69	1.89	4.28	2.54	2.50	1.94	4.46	10.96	1.38	2.50
2031	1.87	0.72	2.07	4.36	2.81	2.66	2.07	4.68	11.29	1.38	2.50
2032	1.87	0.76	2.24	4.41	3.09	2.83	2.19	4.90	11.59	1.38	2.50
2033	1.87	0.79	2.42	4.45	3.37	2.98	2.31	5.13	11.88	1.38	2.50
2034	1.87	0.82	2.60	4.47	3.64	3.14	2.42	5.35	12.14	1.38	2.50
2035	1.87	0.84	2.77	4.48	3.92	3.28	2.53	5.57	12.38	1.38	2.50
2036	1.87	0.86	2.95	4.48	4.20	3.43	2.64	5.80	12.59	1.38	2.50
2037	1.87	0.87	3.13	4.49	4.48	3.56	2.74	6.02	12.78	1.38	2.50
2038	1.87	0.88	3.30	4.49	4.76	3.69	2.84	6.24	12.95	1.38	2.50
2039	1.87	0.88	3.48	4.49	5.04	3.82	2.93	6.47	13.09	1.38	2.50
2040	1.87	0.89	3.66	4.49	5.32	3.93	3.02	6.69	13.21	1.38	2.50
2041	1.87	0.89	3.83	4.49	5.60	4.05	3.10	6.91	13.31	1.38	2.50
2042	1.87	0.89	4.01	4.49	5.88	4.15	3.18	7.13	13.38	1.38	2.50
2043	1.87	0.89	4.19	4.49	6.15	4.25	3.25	7.36	13.44	1.38	2.50
2044	1.87	0.89	4.36	4.49	6.43	4.34	3.32	7.58	13.49	1.38	2.50
2045	1.87	0.89	4.54	4.49	6.71	4.43	3.38	7.80	13.52	1.38	2.50
2046	1.87	0.89	4.72	4.49	6.99	4.50	3.44	8.02	13.54	1.38	2.50
2047	1.87	0.89	4.89	4.49	7.27	4.58	3.49	8.19	13.55	1.38	2.50
2048	1.87	0.89	5.07	4.49	7.54	4.64	3.54	8.28	13.56	1.38	2.50
2049	1.87	0.89	5.25	4.49	7.81	4.70	3.58	8.31	13.56	1.38	2.50
2050	1.87	0.89	5.42	4.49	8.08	4.76	3.62	8.31	13.56	1.38	2.50

Table 14: Simulation mean result for annual energy production from low-carbon industries in the minus 80% scenario (GWh/yr).

Year	Residual Fossil Fuels with no CCS	Fossil with CCS	Nuclear	Large Hydro	Repowering Large Hydro	Small Hydro	Wind	Geo-thermal	Solar Power Stations	Building Integrated Solar PV	Domestic Solar Thermal	Sea and Ocean Energy	Bio-Hydrocarbons
2010	9.48E+07	5113	2321828	3603448	0	530974	484065	60880	1839	31869	293532	2338	10395322
2011	9.79E+07	12554	2327147	3650919	501	546670	532297	73340	17874	53805	323617	4568	10413697
2012	1.00E+08	34876	2345536	3788456	3411	593744	676992	110719	65977	119614	413871	11258	10468823
2013	1.01E+08	72080	2375182	3963624	9609	659130	918151	173017	146149	229295	564295	22407	10560698
2014	1.01E+08	124165	2414360	4139292	18827	724839	1255774	260235	258390	382848	774888	38017	10689324
2015	1.01E+08	191132	2460475	4313494	30069	790547	1689860	372371	402699	580274	1045651	58086	10854699
2016	9.92E+07	272980	2510230	4476532	42151	856256	2220410	509427	579078	821572	1376583	82616	11056825
2017	9.72E+07	369710	2560604	4610664	54337	921523	2847423	671403	787525	1106743	1767685	111605	11295701
2018	9.49E+07	481322	2609941	4690939	66205	969772	3570900	858297	1028042	1435785	2218956	145054	11571327
2019	9.23E+07	607815	2657263	4710891	77329	982264	4390841	1070111	1300627	1808701	2730396	182963	11883703
2020	8.94E+07	749189	2701693	4711148	87300	982630	5307245	1306844	1605280	2225488	3302006	225331	12232830
2021	8.64E+07	905445	2742168	4711148	95764	982630	6320113	1568497	1942003	2686148	3933786	272160	12618707
2022	8.31E+07	1076582	2777457	4711148	102473	982630	7429440	1855068	2310795	3190681	4625735	323448	13041333
2023	7.94E+07	1262601	2805957	4711148	107355	982630	8633216	2166559	2711655	3739085	5377853	379197	13500710
2024	7.54E+07	1463502	2825705	4711148	110493	982630	9906840	2502970	3144584	4331363	6190141	439405	13996837
2025	7.11E+07	1679284	2833914	4711148	112116	982630	11200726	2864299	3609582	4967512	7062599	504073	14529714
2026	6.66E+07	1909947	2826945	4711148	112545	982630	12495538	3250548	4106649	5647534	7965141	573201	15099342
2027	6.20E+07	2155344	2802003	4711148	112137	982630	13790349	3661716	4635785	6371428	8867683	646789	15705706
2028	5.74E+07	2414338	2757816	4711148	111173	982630	15085161	4097804	5196989	7139195	9770225	724836	16348147
2029	5.26E+07	2684215	2694142	4711148	109868	982630	16379972	4558808	5790262	7950834	10672768	807344	17022872
2030	4.79E+07	2961237	2613106	4711148	108367	982630	17674784	5044716	6415605	8806339	11575310	894311	17720190
2031	4.35E+07	3241807	2517554	4711148	106785	982630	18969595	5555480	7073016	9705578	12477852	985738	18427832
2032	3.92E+07	3523612	2412871	4711148	105189	982630	20264407	6090962	7762495	10647348	13380394	1081625	19137143
2033	3.49E+07	3805646	2309054	4711148	103614	982630	21559219	6650819	8484044	11626632	14282936	1181972	19846461
2034	3.05E+07	4087687	2210222	4711148	102062	982630	22854030	7234299	9237661	12632938	15185478	1286779	20555779
2035	2.62E+07	4369728	2116137	4711148	100534	982630	24148822	7840131	10023348	13653591	16088021	1396046	21265098
2036	2.19E+07	4651768	2026556	4711148	99030	982630	25439411	8466440	10841103	14678966	16990563	1509772	21974416
2037	1.77E+07	4933809	1941244	4711148	97548	982630	26674721	9110583	11690927	15705217	17893105	1627942	22683734
2038	1.36E+07	5215849	1859983	4711148	96089	982630	27716145	9769202	12572819	16731540	18795647	1750319	23393052
2039	9.88E+06	5497890	1782565	4711148	94653	982630	28463569	10438324	13486779	17757865	19680856	1875930	24102370
2040	6.64E+06	5779890	1708792	4711148	93238	982630	28904473	11113461	14432762	18784189	20399998	2003182	24811688
2041	4.79E+06	6060598	1638480	4711148	91845	982630	29077479	11790915	15410357	19810514	20909347	2130921	25520763
2042	3.33E+06	6334184	1571452	4711148	90473	982630	29106261	12468878	16417821	20836839	21208901	2258730	26225219
2043	2.15E+06	6589144	1507542	4711148	89122	982630	29106990	13146885	17450377	21863163	21303178	2386539	26906031
2044	1.20E+06	6809924	1446593	4711148	87791	982630	29106990	13824814	18499877	22889444	21304050	2514349	27520177
2045	4.35E+05	6982255	1388456	4711148	86481	982630	29106990	14502426	19557311	23914949	21304050	2642159	28015523
2046	4.35E+05	7100183	1332989	4711148	85190	982630	29106990	15179057	20616945	24933490	21304050	2769969	28357820
2047	4.35E+05	7168732	1280059	4711148	83919	982630	29106990	15853016	21676923	25920098	21304050	2897778	28552600
2048	4.35E+05	7200899	1229540	4711148	82668	982630	29106990	16520564	22736922	26822041	21304050	3025588	28633695
2049	5.15E+04	7212319	1181312	4711148	81435	982630	29106990	17175228	23796921	27573688	21304050	3153398	28651622
2050	6.68E+05	7214912	1135261	4711148	80222	982630	29106990	17807379	24856920	28125142	21304050	3281208	28652230

Table 15: Simulation mean result for annual energy savings and avoidance from non-energy generation activities in the minus 80% scenario (GWh/yr).

Year	Avoided Aviation	Shipping Efficiency	Reduced Use of Vehicles	Vehicle Efficiency	Buildings Efficiency	Metals Industry Efficiency	Non-Metals Industry Efficiency
2010	0	0	0	0	0	0	0
2011	63132	2791	5070	5741	347	9154	7112
2012	421270	19145	34668	82789	5837	61940	48630
2013	1135932	54339	97884	325372	28833	175107	137888
2014	2060263	108784	195400	769942	83998	349979	275918
2015	3026460	182478	327217	1416978	182977	586532	462663
2016	3934351	275422	493334	2248232	334386	883968	697280
2017	4723282	387553	693752	3220225	543386	1239268	977273
2018	5348011	517558	928471	4272733	811925	1647265	1298225
2019	5787671	660643	1197491	5356633	1140156	2102265	1655157
2020	6056553	809879	1500811	6446486	1528080	2597927	2042624
2021	6195209	960630	1838433	7531038	1975695	3127647	2455522
2022	6253781	1111519	2210354	8596970	2483003	3684892	2888465
2023	6272575	1262411	2616577	9625859	3050003	4262730	3336057
2024	6276656	1413302	3057100	10597179	3676655	4854122	3793197
2025	6277097	1564193	3531924	11492031	4362445	5452560	4255107
2026	6277107	1715073	4041049	12294166	5105381	6052256	4717422
2027	6277107	1865677	4584331	12990021	5901190	6648927	5176637
2028	6277107	2015004	5158059	13571280	6742585	7239082	5630020
2029	6277107	2161292	5748330	14036431	7619960	7820042	6075365
2030	6277107	2301975	6341982	14391243	8523014	8389950	6510953
2031	6277107	2433912	6935767	14648028	9442589	8947523	6935638
2032	6277107	2553715	7529553	14823571	10371674	9491464	7348473
2033	6277107	2658571	8123338	14936200	11305367	10020282	7748478
2034	6277107	2747055	8717123	15003902	12241001	10532797	8134984
2035	6277107	2818850	9310908	15041219	13177344	11028090	8507484
2036	6277107	2874663	9904694	15059299	14113850	11505273	8865374
2037	6277107	2916096	10498479	15066662	15050367	11963502	9208022
2038	6277107	2945279	11092264	15068917	15986884	12401979	9534781
2039	6277107	2964602	11686049	15069278	16923401	12819633	9845210
2040	6277107	2976550	12279834	15069297	17859918	13215815	10139078
2041	6277107	2983410	12873620	15069297	18796435	13590373	10416426
2042	6277107	2986964	13467405	15069297	19732944	13943022	10677235
2043	6277107	2988503	14061190	15069297	20669363	14273372	10921257
2044	6277107	2989001	14654975	15069297	21605448	14581080	11148315
2045	6277107	2989103	15248760	15069297	22540460	14866233	11358507
2046	6277107	2989113	15842546	15069297	23472994	15129133	11552152
2047	6277107	2989113	16436331	15069297	24400965	15370250	11729667
2048	6277107	2989113	17030116	15069297	25321581	15590272	11891673
2049	6277107	2989113	17623901	15069297	26231429	15790138	12038837
2050	6277107	2989113	18217687	15069297	27126643	15970897	12171878

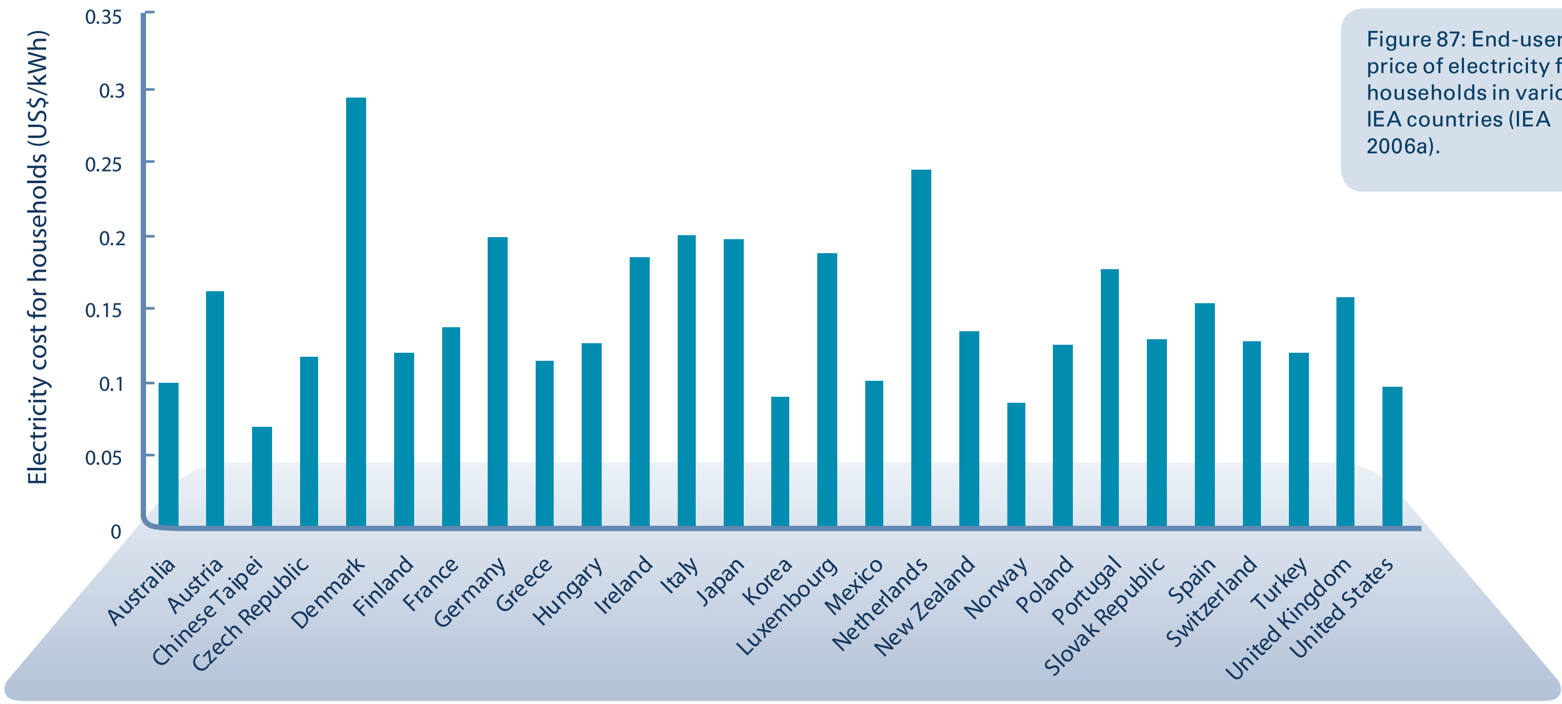

Figure 87: End-user price of electricity for households in various IEA countries (IEA 2006a).

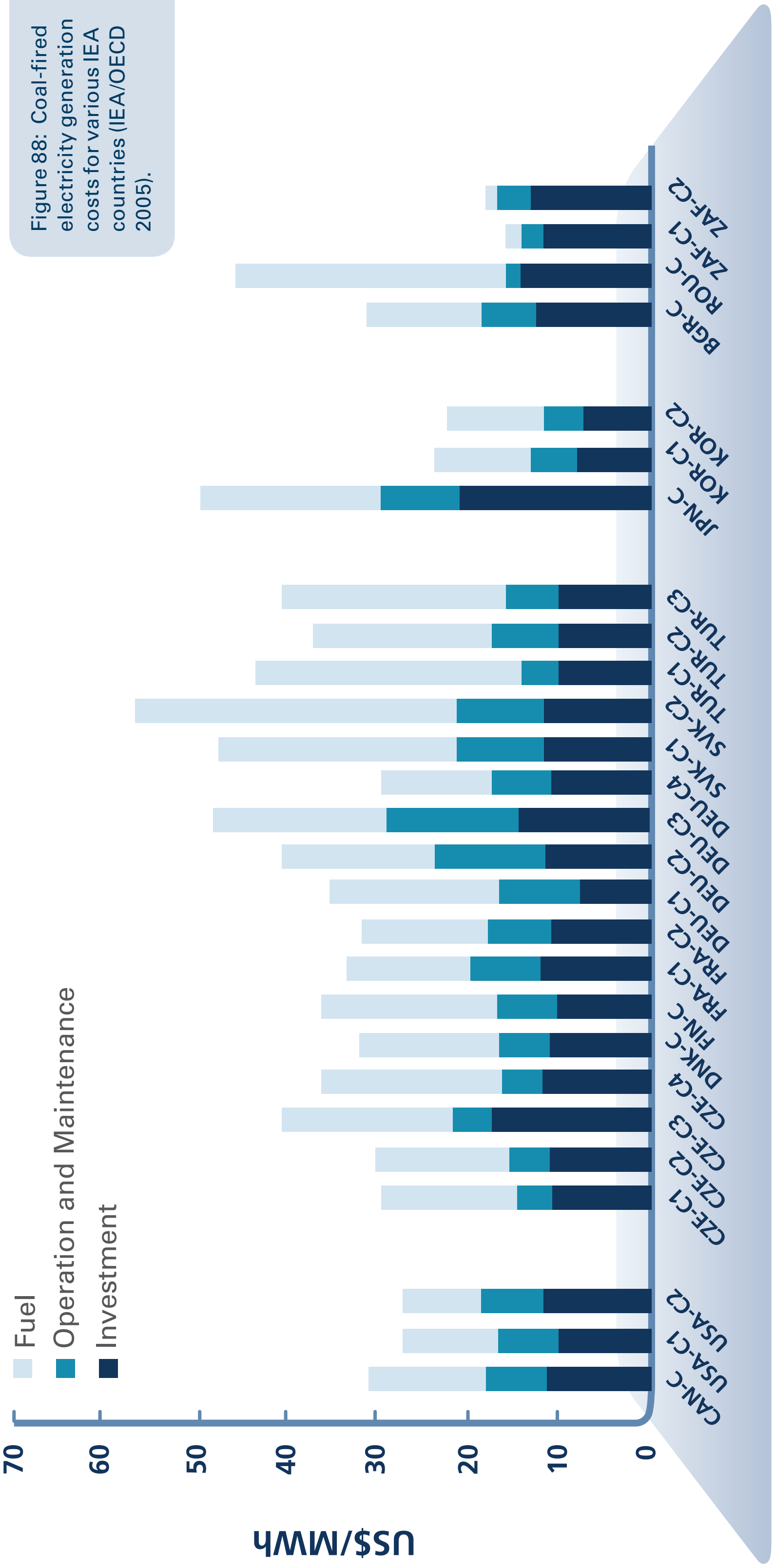

Figure 88: Coal-fired electricity generation costs for various IEA countries (IEA/OECD 2005).

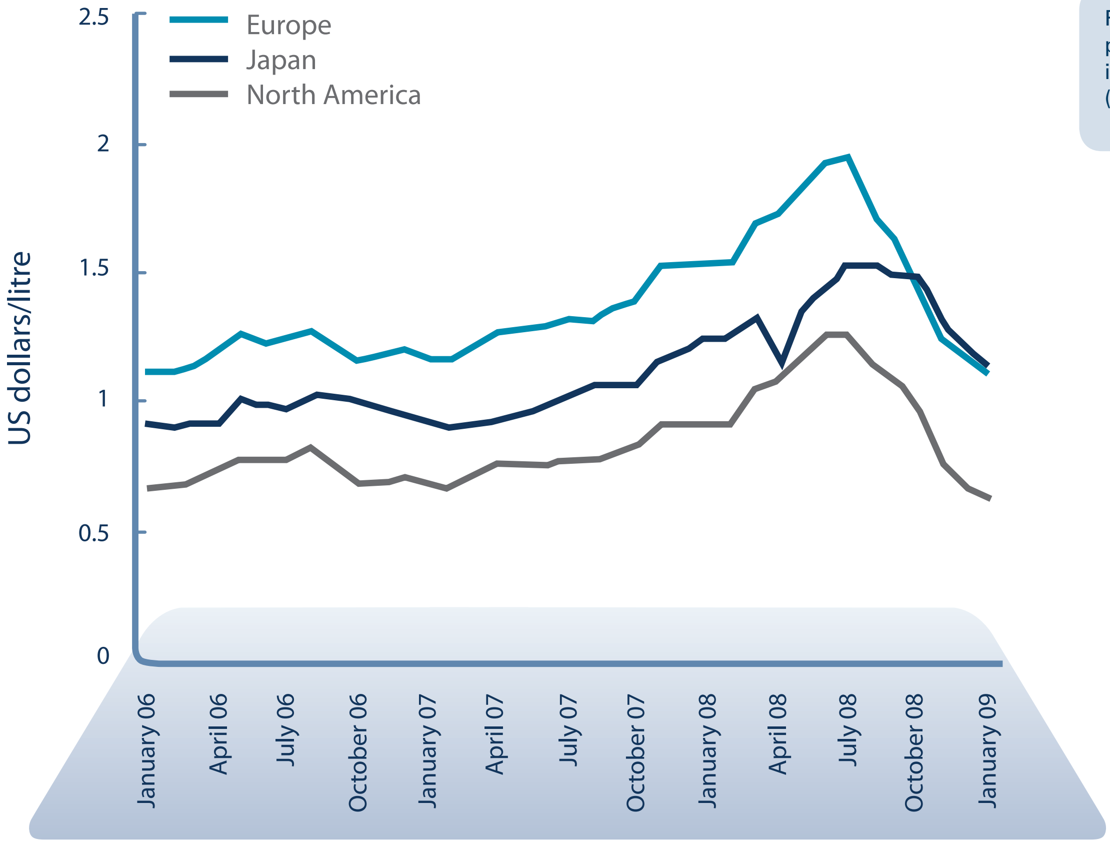

Figure 89: End-user prices for fossil-diesel in various world regions (IEA 2009).

15 Appendix: Learning Rate Retardation

For most emissions abatement solutions, the price of the technology or commodity decreases as the production volume increases (i.e. a positive learning rate; Taylor *et al.* 2006, IEA 2000). However, in some cases, there can be a zero reduction in price or even an increase in prices with increased production (i.e. a negative learning rate). This scenario has been a serious concern for some renewable energy technologies, such as wind, building integrated photovoltaics (PV) and domestic solar thermal energy (Navaro 2008, Taylor *et al.* 2006).

From the 1970s to the early 2000s, wind energy and photovoltaic energy both exhibited positive learning rates. However, more recently these technologies have suffered price increases due to supply shortages. For example, photovoltaics have experienced manufacturing and materials constraints consistent with supply shortage. Figure 90 illustrates the resultant rise in the photovoltaic module price as production increased.

Similarly, supply shortages and commodity prices have impacted on the wind industry where "the price of offshore turbines rose 48 percent to 2.23 million euros (US$3.45 million) per megawatt in the past three years [and] land-based rotors cost 1.38 million euros per megawatt after rising 74 percent in the same period" (BTM Consult 2008).

In the case of domestic solar thermal, the increase in the unit cost with increased production is thought to be related to increases in materials and labour costs that were not overcome by the modest technical improvements over the same period (Taylor *et al.* 2006).

When examining the effect of relatively moderate learning rate retardations in the minus 63% scenario (see Figure 91 to Figure 95), it can be seen that the cumulative cost of renewable energy technologies out to 2050 jumps from US$6.7 trillion for no learning rate retardation, to US$63.3 trillion for 40% learning rate retardation (or from US$16.7 trillion to US$79.9 trillion when the ongoing costs of CCS are included). It is worth noting that learning rate retardations in excess of 40% are quite possible (as evidenced by the greater than 100% learning rate retardations shown above for PV modules).

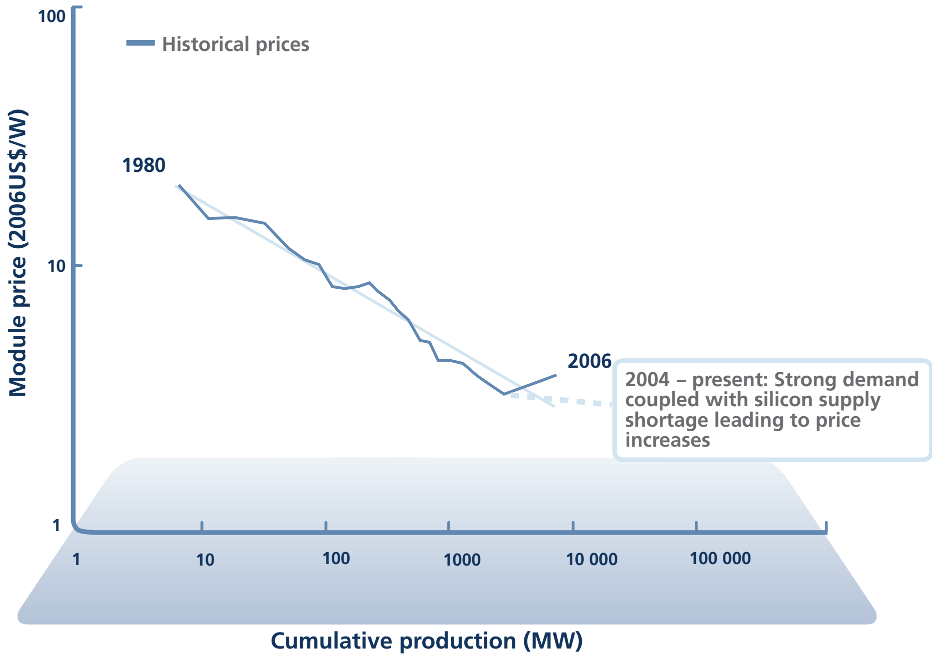

Figure 90: Persistent silicon shortages and high demand have caused prices of PV modules to rise in recent years, even as production has increased (Navaro 2008).

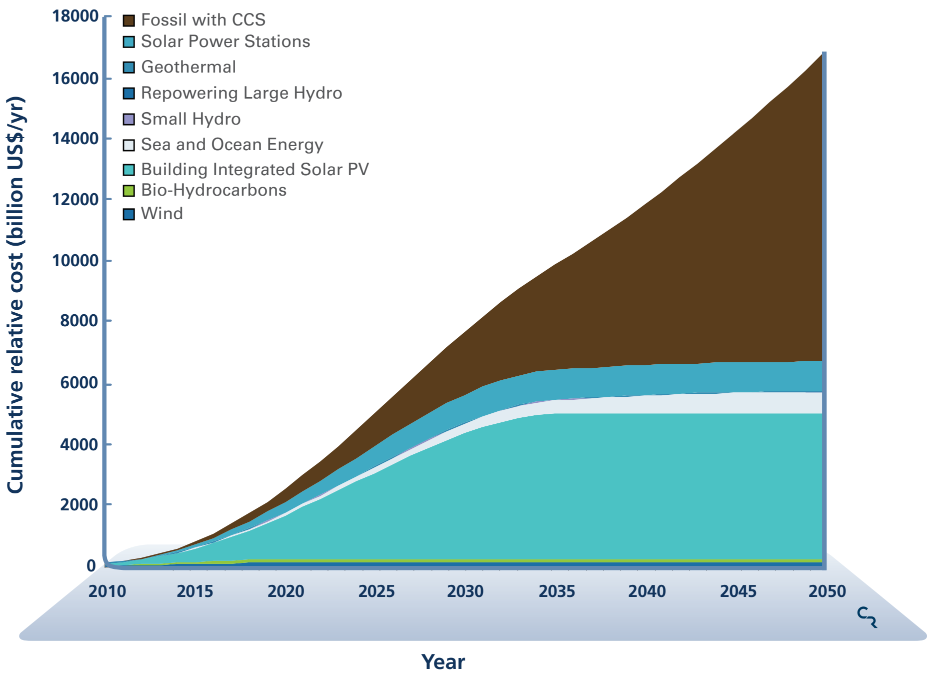

Figure 91: Cumulative relative cost of low-emissions technologies out to 2050 with no learning rate retardation in the minus 63% scenario.

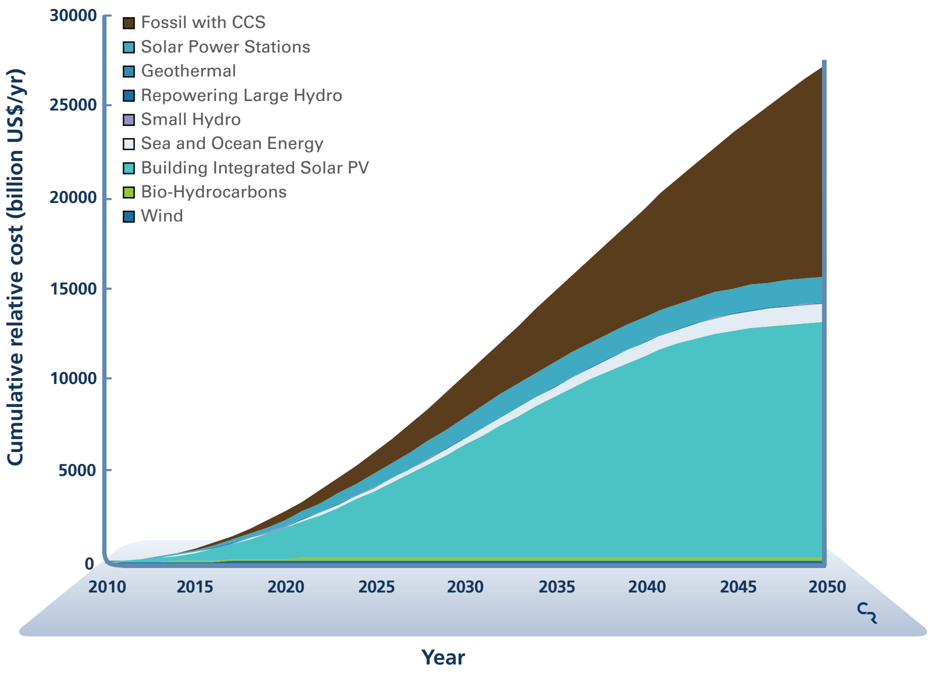

Figure 92: Cumulative relative cost of low-emissions technologies out to 2050 for a 10% learning rate retardation in the minus 63% scenario.

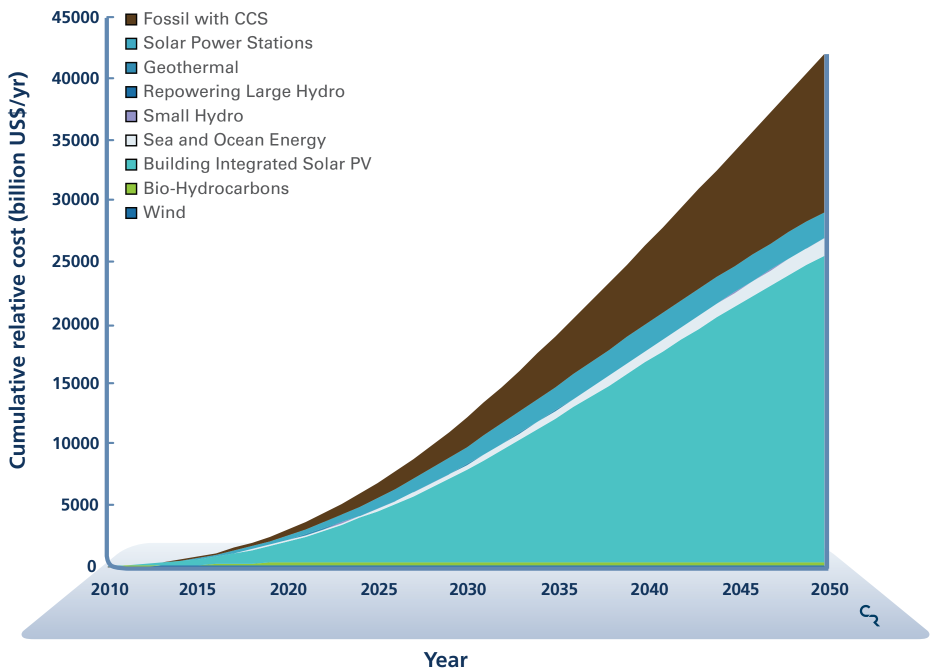

Figure 93: Cumulative relative cost of low-emissions technologies out to 2050 for a 20% learning rate retardation in the minus 63% scenario.

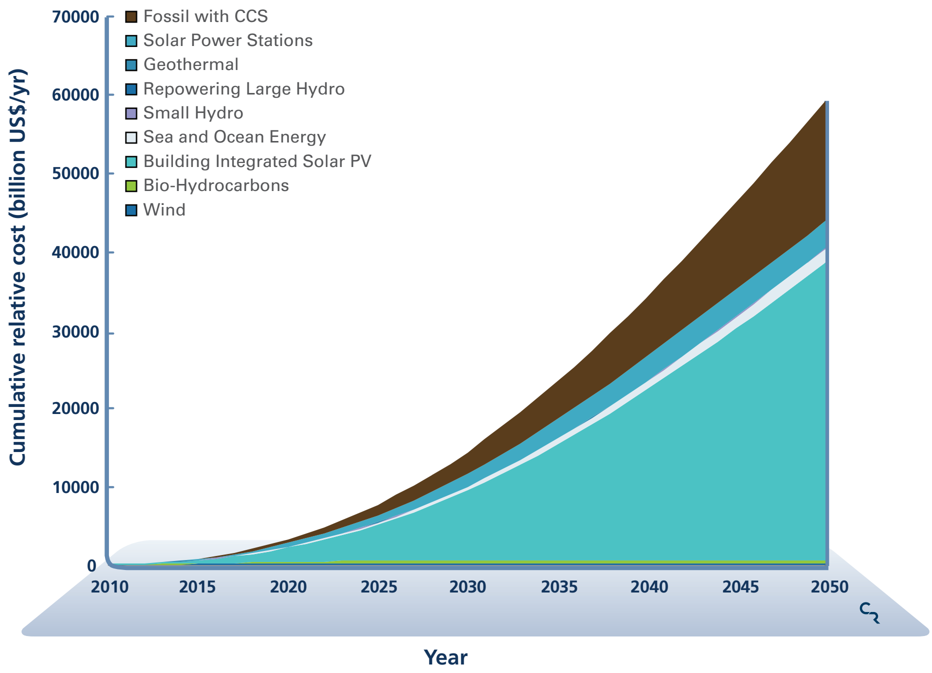

Figure 94: Cumulative relative cost of low-emissions technologies out to 2050 for a 30% learning rate retardation in the minus 63% scenario.

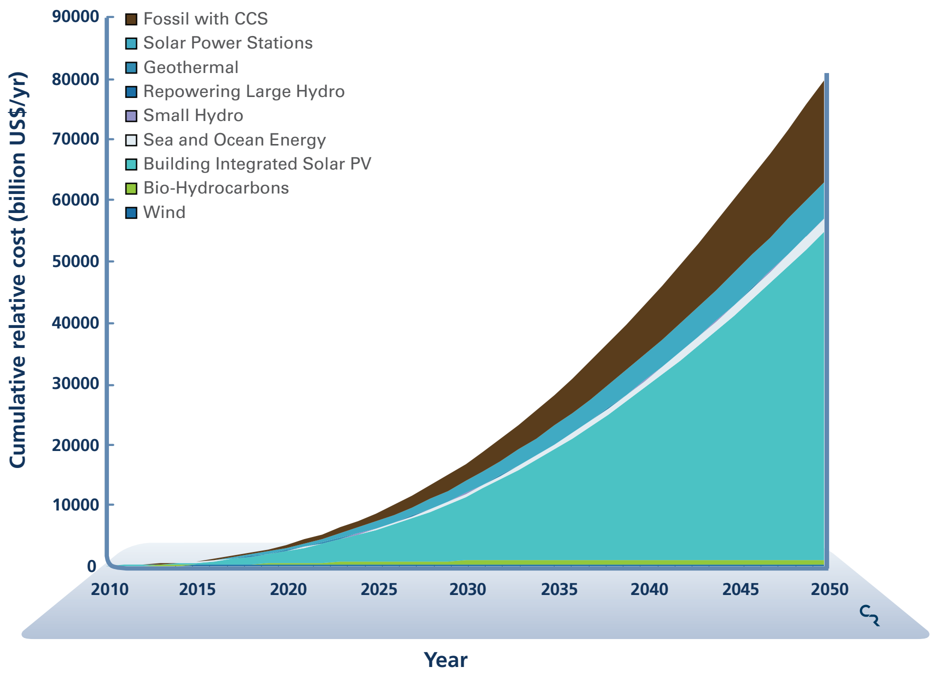

Figure 95: Cumulative relative cost of low-emissions technologies out to 2050 for a 40% learning rate retardation in the minus 63% scenario.

16 Appendix: Sustainable Industry Growth Rates

Limitations in manufacturing capacity, resource development, labour and skills generally restrict the stable expansion of new industries. While exceptions may exist in the short-term, consistent annual growth rates higher than a certain threshold start to result in supply dislocations that cause temporary price increases. In this report, this threshold is assumed to occur at sustained annual growth rates of 30% (as described in Chapter 15). This leads to retardation in the expected learning rates of these industries as increases in production volumes do not achieve the previously obtained price reduction. Even if the price increases caused by supply shortages could be tolerated, industrial limitations in the materials, labour and skills required to expand production mean that growth rates higher than 30% are generally physically unsustainable over the long-term.

As illustrated in Figure 96, the three industries operating at average annual growth rates greater than 25% (solar PV, biodiesel and wind) have all recently experienced supply limited price increases and hence learning rate retardations (Navaro 2008, BTM Consult 2008). This phenomenon is manifested via component shortages within the wind and photovoltaic industries, and demand-related increases in the cost of grain and oil feedstock for biodiesel. Where the ultimate resource can be expanded (this may not be the case for biodiesel feedstock that competes with food), short-term supply dislocations will generally be corrected over time and commensurate price reductions achieved. However, where excessively high industry growth rates are maintained, the process of equilibration will continue to be hampered as incremental supply increases are quickly outstripped by demand.

It is important to note that growth rates higher than 30% are possible under a "command and control" scenario, as has been observed historically during times of war. However, any potential increase in annual growth rates achieved by forcing the reallocation of resources under such a scenario would still be limited by the finite nature of the underlying resources in the economy. Given the undesirable nature of such an outcome, this scenario has not been considered in this report.

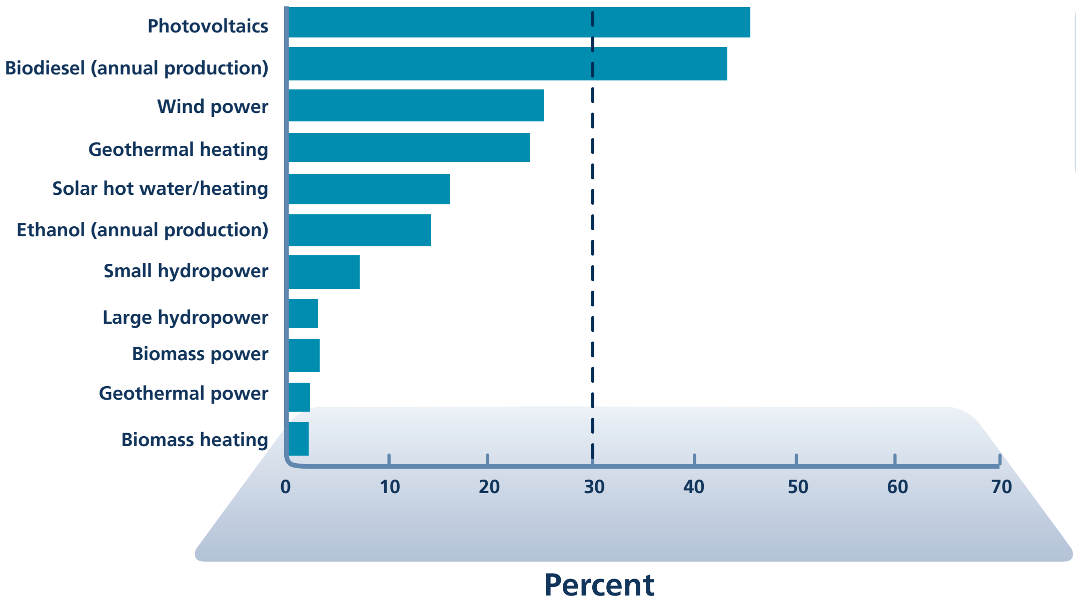

Figure 96: Average annual growth rates of renewable energy capacity from 2002 to 2006 (REN21 2008).

17 Appendix: WWF Definitions of Viable Resource Levels

As an organisational expert in conservation of the natural environment, WWF has provided this project with access to expertise and analysis on the degree of exploitation of natural resources to replace fossil fuel use that is compatible with the ongoing environmental integrity of those resources. The analysis shown in this chapter was first presented in *Climate Solutions 1* and has been reproduced and updated here[3]. The findings of this analysis have been used to define the resource levels for environmentally sensitive resources in this report.

17.1 Deforestation

17.1.1 Significance

Deforestation is responsible not only for significant ecosystem and species loss but, also importantly, for about 20% of global greenhouse gas emissions. Ten countries account for 87% of global deforestation, with Brazil and Indonesia, alone, accounting for 54% of deforestation emissions.

In general, tropical forests tend to experience the greatest rate of deforestation. It is estimated that tropic forests hold over 210 GtC in their vegetation and almost 500 GtC in their soils (which is often released when land-use changes).

Rates of deforestation have remained constant over the past two decades and without significant, concerted action these could result in emissions of 10 Gt of carbon dioxide per year for 50–100 years. Forests also absorb carbon dioxide, so increasing forest cover can increase carbon sequestration. However, the positive impact of increasing forest cover is far outweighed by the negative impact of deforestation (IPCC 2000) on atmospheric carbon dioxide, let alone wider ecosystem impacts. So, while restoring forest cover is of benefit, the primary opportunity for emissions abatement is in reduced deforestation[4].

17.1.2 Challenges

- The causes of deforestation are wide-ranging and vary from country to country. They include agricultural expansion, cattle ranching, infrastructure development and logging. These activities are driven by both population pressures and increased levels of local and foreign consumption. They are further exacerbated by poor governance and inadequate land-use planning. Governments and a wide range of market factors must be effectively influenced to reduce these threats.

- The current data provided by national governments is not globally consistent. Establishing accurate data and, in particular, agreeing on new globally consistent definitions of deforestation and degradation at a forest biome level, is essential.

- Bioenergy is potentially CO_2 neutral. However, the expansion of palm oil and tropical crops, such as sugarcane, for biofuel production could become a significant driver of deforestation. Bioenergy developments must therefore be appropriately regulated to prevent further deforestation.

3 The contributions of the following authors are gratefully acknowledged: Jean-Philippe Denruyter (Bioenergy); Gary Kendall & Paul Gamblin (Natural Gas); Richard Mott (Nuclear Energy); Jamie Pittock (Hydroelectricity) and Duncan Pollard (Deforestation).

4 The sustainable use of forests, while protecting and maintaining their overall structure and ecosystem functions, is not in question.

17.1.3 Rate of Change Achievable

It is plausible to halve the current rate of deforestation by 2015 and achieve a zero rate by 2020. This would lead to cumulative emissions reductions of 55 Gt carbon dioxide by 2020 and 155 Gt by 2030. In contrast, to halve the rate of deforestation by 2020, and achieve a zero rate by 2030, would result in cumulative emissions reductions of 27 Gt carbon dioxide by 2020 and 105 Gt by 2030 – a significantly lower benefit.

Halting land clearance is a far more effective intervention than planting trees. Reforestation with fast-growing trees at the rate of three million hectares per year (equal to current rates) would result in a cumulative absorption of only approximately 10 Gt carbon dioxide by 2020.

The IPCC (2007) reports that "bottom-up regional studies show that forestry mitigation options have the economic potential at costs up to US$100/t$CO_2$-e to contribute 1.3-4.2 GtCO_2-e/yr (average 2.7 GtCO_2-e/yr) in 2030. About 50% can be achieved at a cost under US$20/ t$CO_2$-e (around 1.6 Gt$CO_2$-e/yr) with large differences between regions. Global top-down models predict far higher mitigation potentials of 13.8 GtCO_2-e/ yr in 2030 at carbon prices less than or equal to US$100/t$CO_2$-e".

These IPCC (2007) findings are used as the basis for emissions abatements from LULUCF by 2050 in this report. The minus 63% scenario (Scenario A) uses a Monte Carlo data range of 1.3 to 13.8 GtCO_2-e/yr for LULUCF by 2050, with a best estimate of 7.6 GtCO_2-e/yr. For the minus 80% scenario (Scenario B), the range used for LULUCF is 2.3 to 24.8 GtCO_2-e/yr, with a best estimate of 13.6 GtCO_2-e/yr.

17.2 Hydroelectricity

17.2.1 Significance

This brief covers three related technologies with a proposed capacity of +400 GW: repowering old hydro dams (+30 GW proposed) and installing new small (+100 GW) and medium and large hydro projects (+270 GW). Hydroelectricity currently provides nearly 20% of the world's electricity. At particular sites, hydroelectricity can provide low-greenhouse gas emissions electricity that is particularly useful for meeting peak loads.

17.2.2 Challenges

Issues that arise or constraints that should apply to its widespread deployment:

- Dams destroy the ecology of river systems by changing the volume, quality and timing of water flows downstream, and by blocking the movement of wildlife, nutrients and sediments. Less than 40% of the world's longest rivers remain free-flowing and there are over 1,400 large dams planned or under construction (e.g. 105 in the Yangtze River basin ecoregion and 162 in northern India).

- Dams have enormous social impacts, with 40–80 million people displaced so far. Large dam proposals at many sites have been opposed by local people.

- Undeveloped (but not necessarily low-impact or sustainable) hydropower capacity is unevenly distributed: 60% in Asia, 17% in Africa and 13% in South America. Small hydropower is mostly used in decentralised systems.

17.2.3 Development/Deployment Potential

Repowering old hydropower dams – retrofitting them with modern equipment that can produce more power – is generally benign and can be an opportunity to reduce the original environmental impacts. While the total contribution is relatively small (+30 GW), the repowering of dams can happen quickly and form the basis for a broader dialogue between civil society and financiers, industry and governments. This 30 GW contribution estimate is based on the numbers of 20+ year-old hydropower-only dams on the International Committee on Large Dams' register and assuming a conservative 10% increased production between now (~20 GW) and 2025 (+10 GW), based on a mixture of light, medium and full upgrading opportunities.

Small, low-impact, financially feasible hydropower potential is estimated at 190 GW globally, with 47 GW developed so far. WWF estimates that a realistic development level is around 100 GW over 50 years, continuing the current 2 GW/yr growth rate.

New dam proposals are controversial. Based on impacts in countries with different degrees of hydropower development, WWF estimates that it may be possible to develop 30% of the economically feasible hydropower capacity in most river basins or nations without unacceptable impacts, in accordance with the World Commission on Dams guidelines[5].

Around 770 GW has been installed out of a global economically feasible large hydropower capacity of 2,270 GW. Around 170 GW are currently under construction and 445 GW are planned over 30–40 years, including many dams with unacceptable environmental impacts. WWF estimates that of the 445 GW, 250 GW of large hydropower sites could be developed with relatively low impacts. Using a similar process, a further 20 GW of medium hydropower potential has also been identified.

17.3 Bioenergy

Biomass is the totality of plants in the terrestrial and marine biosphere that use carbon dioxide, water and solar energy to produce organic material. It also includes animals and agents of decomposition – such as bacteria and fungi – whose activity releases carbon dioxide into the atmosphere. Bioenergy can be derived from biomass in the form of liquid biofuels (processed usually from energy-rich crops), wastes (including renewable municipal waste), solid biomass (wood, charcoal and other biomass material) or gases (derived from biomass decomposition).

5 WWF advocates social and environmental safeguards that are based on the guidelines of the World Commission on Dams (2000): http://www.dams.org/

17.3.1 Significance

Globally, biomass currently provides around 46 EJ of bioenergy. This share is estimated to be about 10% of global primary energy supply, though the volume of traditional biomass consumed in developing countries is uncertain (IPCC 2007). Applications vary widely, from traditional biomass use (such as cooking on open fires) in the poorest countries to highly efficient electricity and heat production or transport fuels. About 110 EJ to 250 EJ produced from biomass would remove about 8–19 Gt carbon per year from the atmosphere if it is used to displace fossil fuels. However, this assumes the same efficiency for all biomass and that it is all produced sustainably and replanted so as to be carbon neutral. Since much biomass is used less efficiently, the actual savings would be lower.

17.3.2 Issues and Constraints

Uncontrolled development of bioenergy crops can have dramatic impacts on humans and the environment. What, where and how the raw materials are produced and processed will define whether bioenergy projects are environmentally and socially sustainable on all fronts. WWF believes that key principles and criteria[6] that must be taken into account for sustainable bioenergy production and use include the following:

Bioenergy must deliver greenhouse gas and carbon life-cycle benefits over conventional fuels

Energy crops to be used for bioenergy must be selected on the basis of the most efficient carbon (soil and air) and energy balance, from production through to processing and use. This is not always achieved. For example, energy-intensive fertiliser input increases emissions of nitrous oxide (N_2O), a highly potent greenhouse gas, and intensive cropping may contribute to the release of soil-bound carbon dioxide. Some conventional crops, such as sugarcane or woody biomass, can provide net benefits if sustainably produced and processed, and are already available for use as bioenergy. However, future investments and research should be oriented towards ligno-cellulosic or other crops that offer better options to reduce carbon dioxide emissions, as well as a reduced impact on the environment.

Bioenergy developments must ensure positive natural resource use and careful land-use planning

Permanent grasslands, natural forests, natural floodplains, wetlands and peatlands, important habitats for threatened species and other high conservation value areas (HCVA), must not be converted into intensive forest or farmland, even if to produce a potential environmental good, such as a bioenergy crop. Biomass production requires agricultural and forestry management techniques that can guarantee the integrity and/ or improvement of soil and water resources, avoiding water and soil pollution, the depletion of soil carbon and the over-extraction of water resources for irrigation.

6 These principles and criteria, established by WWF, are subject to further definition and are not meant to be exhaustive.

Competition for land use and social impacts

The unplanned, opportunistic development of bioenergies could lead to damaging land-use competition in some regions. This may compromise a range of key environmental needs (floodplains, forest cover and high nature value lands), reduce access to land for poorer or start-up farmers and create competition with food and fibre production. Many of the bioenergy commodities currently used are also food and feed crops. The interest in bioenergy has already led to price increases for several crops, which can challenge the capacity of poor farming communities to afford these commodities for their own needs.

17.3.3 Development/Deployment Potential

In this report it is assumed that about 110 EJ (low estimate) to 250 EJ (high estimate) bioenergy can be produced globally without any competition with food production by 2050. These figures are in agreement with estimates by the IPCC (2007) and the most conservative bioenergy scenario results for bottom-up bioenergy modelling (Smeets *et al.* 2004). The potential for an even greater bioenergy resource in 2050 is illustrated by the alternative scenario results produced by Smeets *et al.* (see Figure 97) under the assumption that there is "no deforestation, no competition for land between bioenergy production and food production and protection of biodiversity and nature conservation"

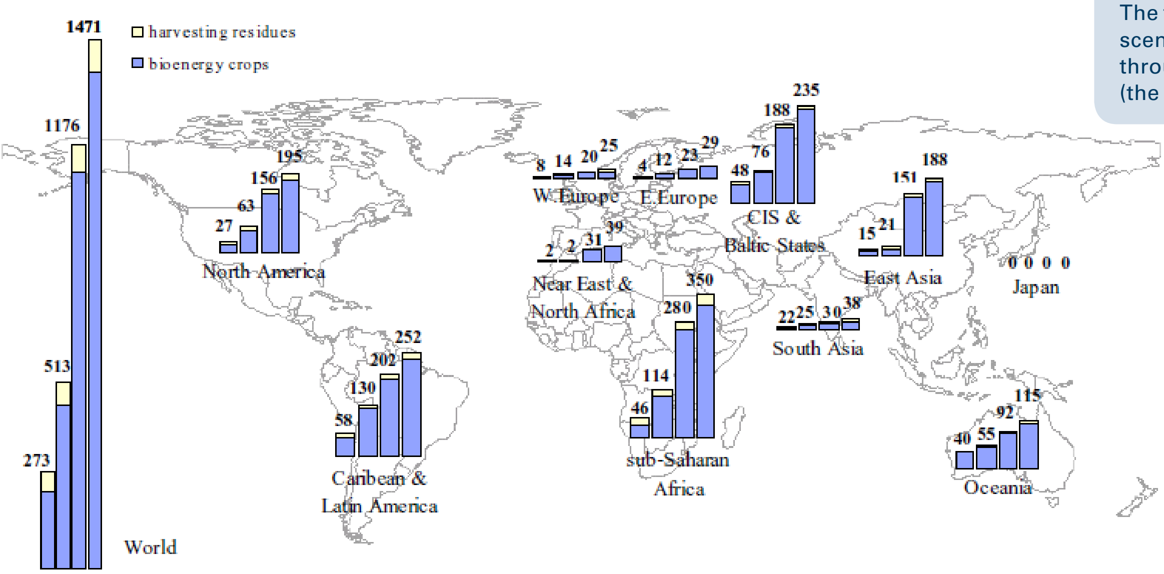

Figure 97: Total bioenergy production potential in 2050 for scenarios 1 to 4 of the study by Smeets *et al.* (2004). Results are expressed in EJ/yr. The four bars refer to scenario 1 (the left bar) through to scenario 4 (the right bar).

(Smeets *et al.* 2004). However, this report adopts a position at the most conservative end of these estimations, in line with the IPCC stance (IPCC 2007).

17.4 Natural Gas Replacement for Coal

17.4.1 Gas and Climate Change Targets

As a source of energy, natural gas has a carbon footprint about half that of coal (EIA 1998). Currently, coal supplies 26% of the world's primary energy, yet contributes over 40% of global greenhouse gas emissions (IEA 2008). In the power sector, the International Energy Agency (IEA) projects that coal consumption will almost double by 2030, with China and India accounting for about 65% of this increase (IEA 2008). Whatever the exact figure, it is clear that coal use will increase hugely if alternative sources of energy are not made commercially available.

Natural gas may be part of the medium-term solution. Some modern conventional power plants can be easily modified to switch fuel sources, delivering immediate carbon dioxide savings when gas is substituted for coal. Furthermore, modern Combined Cycle Gas Turbine (CCGT) installations emit only 40% of the carbon dioxide produced by a conventional coal-fired power station (IPCC 2001).

Therefore, displacing coal with natural gas in the power sector can reduce short- and medium-term emissions, buying time for the deployment of truly sustainable zero-emissions solutions and reducing the overall atmospheric loading from greenhouse gas pollution from coal.

For such an outcome to occur, it is critical that:

1. Gas replaces only coal use.

2. The use of gas does not slow or hinder renewable energy development in the same markets.

3. Gas power facilities are either converted to CCS or decommissioned as lower emissions sources become available.

17.4.2 Issues and Constraints

Renewable Energy Overlap

In some cases, market conditions that price carbon will tend to favour gas (which is a competitive energy supply in most markets) over renewables, which would need a higher carbon price to compete directly with gas. This competition between two low-emissions supply sources is highly inefficient and counter-productive in the longer term.

Competing Uses

To deliver maximum carbon dioxide abatement potential, the world's finite natural gas resources would need to be deployed to avoid coal emissions where possible. Competing uses, such as extraction of oil from tar sands, have serious negative consequences for the climate and should be avoided.

Shrinking Sources of Supply

Gas resources have been available in many areas and are often close to the markets that use them, such as North Sea gas in Europe. However, as these reserves are used up, the focus moves to the remaining large gas reserves in areas remote from current and future high-growth energy demands. The global leader, by volume proven, is Russia (47.57 trillion cu m), followed by Iran (26.62 trillion cu m) and Qatar (25.77 trillion cu m). European production is now in severe decline, with increasing dependency upon Russian supplies. This raises challenges for transportation and energy security.

Energy Security

In the coming decades, most new power generation will be installed in rapidly developing Asian economies such as China and India, which have generous coal deposits but limited gas. In addition, liquid natural gas receiving ports, storage capacity and transmission infrastructure are very limited. With energy security a political priority, these countries will naturally favour the development of coal-fired power over increasing their reliance on imported gas, unless other compelling reasons or incentives prevail.

Similarly, European nations may try to avoid dependence on piped gas from Russia, whose political relations with transit countries (such as the Ukraine) are strained. The emergence of resource nationalism also challenges capital flows, so that global energy companies become loath to risk having stranded assets. This may slow the development of reserves in many markets and shift the focus away from gas.

17.4.3 Rate of Development/ Deployment

In 2008, an estimated 63 years of proven natural gas reserves remained globally, based on current consumption (BP 2008). However, the predicted increase in natural gas consumption (such as the Energy Information Administration's forecasts; see Figure 98) indicates that these proven resources are likely to be consumed much faster.

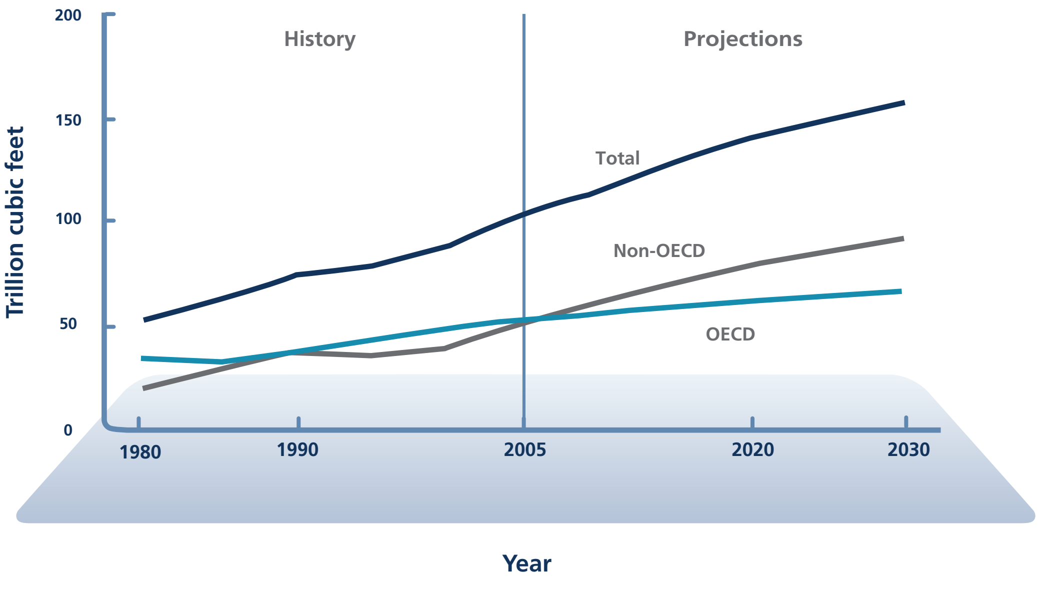

Figure 98: World natural gas consumption history and forecast 1980–2030 (EIA 2007, EIA 2008b).

Extrapolating the EIA forecast for natural gas consumption out to 2050 reveals that the current proven reserves of natural gas (about 6,186 trillion cubic feet; Figure 99) are expected to be exhausted by 2048. This is a conservative estimate, since it does not take into account unproven natural gas contributions to the available natural gas resource.

The finite reserves of natural gas mean that switching from coal to gas for power generation must be viewed as a temporary measure that reduces short- and medium-term emissions, yet is consistent with possible CCS in the longer term and the overall carbon budget of 63% or 80% emissions cuts on 1990 levels by 2050.

17.4.4 Essential Key Measures for These Expectations to be Realised

- The world's limited natural gas resources must be used wisely in order to maximise carbon dioxide savings while avoiding CH_4 leakage emissions and wider environmental impacts;
- Investments in natural gas infrastructure are most important in the short-term – whether pipeline or liquid natural gas – to reduce the take-up of coal, allow source diversification and alleviate security of supply concerns;
- For imported gas to compete with domestic coal, the full external costs of coal use must be internalised, together with a strengthening of carbon markets and/or other fiscal mechanisms that provide compelling economic incentives for fuel switching. Developing country markets will need to ensure that such measures do not cut across development goals.

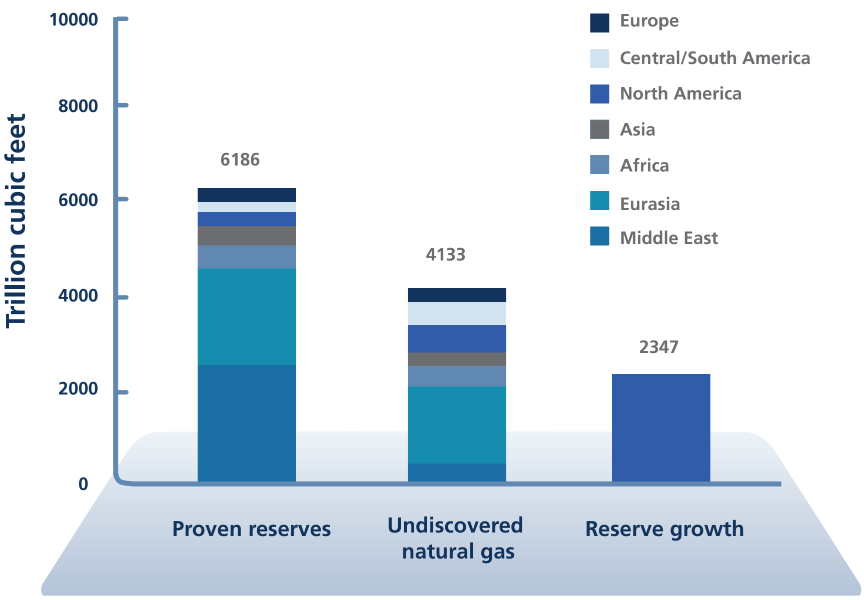

Figure 99: World natural gas resources by geographic region for 2008–2025 (USGS 2000, OGJ 2007, EIA 2008a).

17.5 Nuclear Energy

17.5.1 Significance

Nuclear fission, the conventional means for generating nuclear power, remains among the most controversial and contested sources of energy. In the past 50 years, nuclear energy has risen to generate 16% of global electricity (roughly 6.5% of world primary energy consumption) from nearly 450 reactors in 30 countries, including Europe, Asia, and the United States (IPCC 2007). The International Energy Agency recently projected nuclear capacity to increase to about 433 GW by the year 2030 in their business-as-usual scenario, compared to 372 GW today (IEA 2008).

However, within OECD Europe, a decline of net nuclear capacity is projected by 2030 in the business-as-usual scenario (IEA 2008). In China, growth in nuclear capacity from the current 6 GW to 31–50 GW nuclear capacity is predicted by 2030 (IEA 2006b). But nuclear may still only contribute 3–6% of all electricity generated in China by 2030. Similarly, in India, nuclear-positive estimates project future nuclear to cover less than 10% of all electricity needs in that country by 2030 (IEA 2006b). In order to save 1Gt of carbon emissions, displacing 770 GW of fossil fuel energy, approximately 1,200 new reactors of conventional capacity would need to be built.

Public and political support for nuclear energy, which in many western countries has waned in recent years, is seeing some resurgence as concerns over climate change and energy supply security intensify. In many OECD countries, claims that nuclear is a low- or no-carbon fuel form the basis for promoting a new generation of reactors.

While nuclear energy is unquestionably low-carbon, the real debate is whether other concerns over safety, security, proliferation of weapons, public acceptability and particularly cost mitigate in favour of pursuing alternative technologies for controlling carbon emissions, and what the trade-offs among those options may be.

WWF has long opposed nuclear power on environmental grounds (see Caring for the Earth: A Strategy for Sustainable Living, 1991).

17.5.2 Challenges

Briefly summarising the analysis, the chief environmental concern is that nuclear energy generates radioactive wastes that stay dangerous for up to 25,000 years and must be contained and actively managed. Related safety concerns include radiotoxic emissions from fuel mining and processing, transport, routine releases during use, the prospect of leaks during accidents and potential attacks on facilities.

One of the biggest challenges in using nuclear power to address climate change will be the issue of weapons proliferation. If nuclear power were to be used to displace fossil fuels around the world, it would mean building nuclear reactors in many countries that do not currently have nuclear power or weapons. Many of these countries are not politically stable or free from conflict.

Given that fuel and waste from nuclear reactors can be used to make weapons, a massive expansion in nuclear power would expose a major risk for weapons capability and proliferation. This is reinforced by the fact that regulators already have limited ability to monitor and regulate the use and movement of nuclear fuel and waste materials.

Implementing nuclear power also faces obstacles relating both to the long build-time and regulatory delays that have led to construction blow-outs of up to 20 years. For instance, since 2000, China, Russia and the Ukraine have announced plans to build 32, 40 and 12 reactors, respectively, by 2020. Of this total of 84 reactors, only 19 had started construction by 2009 (WNA 2009). Build-time overruns have been common and although improved nuclear designs could speed implementation, unanticipated problems or delays seem equally possible. In the United States, 51 repeated shutdowns of nuclear power plants for a year or longer led to power shortages and increased costs.

Implementation will also be affected by new concerns over terrorism and geopolitical stability. The significant deployment of nuclear power in developing countries would require regulatory infrastructure, capacity-building and the development of supporting industry.

Economically, nuclear energy is difficult to cost for a number of reasons. Historically, it has been heavily subsidised through direct government support and by limitations on liability and insurance. In direct terms, nuclear has received high, if not the highest rate of subsidy of all fuels within many OECD countries. Between 1947 and 1999 in the USA, alone, nuclear received US$145 billion – or 96% of all energy subsidies. This compares with subsidies for solar of US$4.5 billion and wind US$1.2 billion between 1975 and 1999 (REPP 2000). In the former EU-15, nuclear subsidies still amount to US$2 billion per year (EEA 2004).

Future costs – decommissioning and the management of wastes – are not factored into the current pricing for nuclear and appear likely to increase substantially over time. The cost of any accidents will be large, but borne by governments (in the USA, about US$600 billion for a single major accident). One study suggested that a successful terrorist attack on a reactor near New York could cause up to US$2 trillion damage, in addition to 44,000 short-term and 500,000 long-term deaths (UCS 2004).

In conclusion, this report does not include the expansion of nuclear power and shows that meeting the required emissions outcomes is not dependent on the inclusion of nuclear power.






Climate Risk Pty Limited (Australia)
Sydney: + 61 2 8243 5767
Brisbane: + 61 7 3040 1621

Climate Risk Europe Limited
London: + 44 752 506 8331

www.climaterisk.net

Climate Risk