SHELL SCENARIOS

Sky

MEETING THE GOALS OF THE PARIS AGREEMENT

2050 2055 2060 2065 2070 2075 20

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CHAPTER 1

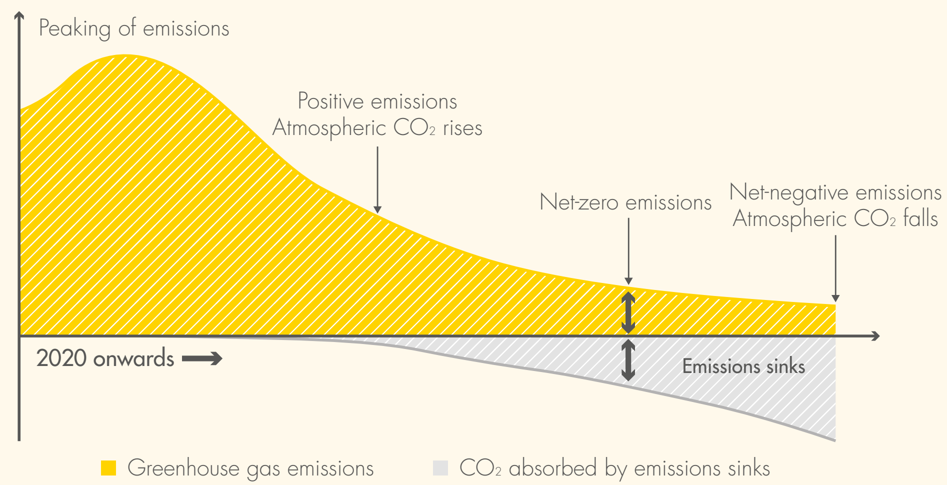
WELL BELOW 2°C: THE PARIS AMBITION

1. WELL BELOW 2°C: THE PARIS AMBITION

The December 2015 Paris Agreement on climate change is a remarkable document. In just 25 pages it offers a pragmatic blueprint for resolving one of the toughest issues society faces. The aim of the Agreement is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

In pursuit of this goal, the Agreement calls for a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century." This emphasis on "a balance" – or what is also referred to as "net-zero emissions" – is a critical development because it recognises that surface temperature warming is directly related to the cumulative total of carbon dioxide (CO_2) emitted to the atmosphere. If total cumulative emissions overshoot a threshold, it may be necessary to go beyond net-zero emissions to achieve "net-negative" emissions, where more CO_2 is extracted from the atmosphere than continues to be released. In such a case, the global average surface temperature can fall.

THE PARIS AGREEMENT CALLS FOR AN EARLY PEAK IN EMISSIONS, THEN A DECLINE TO NET-ZERO EMISSIONS DURING THE SECOND HALF OF THE CENTURY



Source: Shell schematic

Implementation of the Agreement is now under way, with most national governments responding quickly to the call for ratification and the delivery of their first national contributions. New coalitions have also formed around government-led carbon pricing and coal phase-out, but the task is only just beginning. Success is hoped for but is not a given.

The context for a pathway forward

Our 2016 publication, **A Better Life with a Healthy Planet**, recognised the desire of a large part of the world's population to have a better life – which means that energy demand will rise in relatively poor countries even as it may fall in relatively rich ones. Within this context of a better life for all, we highlighted the key changes in each main sector of the economy – industry, transport, buildings, and power generation – that were required to deliver a world of net-zero CO_2 emissions from energy.

While we know, in general, what key conditions and energy system changes are required for net-zero emissions, it would be helpful to have a pathway to achieving that goal by 2070 – a timeframe compatible with holding the increase in the global average temperature to well below 2°C. Because the future is unpredictable, especially when it comes to complex global societal systems over an extended period involving technology, government policy, and consumer behaviour, the best approach to exploring this pathway is to use scenarios.

Energy scenarios for the pathways forward

Scenarios are alternative stories of the future that help us learn useful lessons for the present. They are not policy proposals – they do not argue for what should be done. Nor are they forecasts – what will be done, by society, industry, or anyone else. They offer descriptions of what could be done – plausible pathways for the future and useful insights along the way.

For over two decades Shell scenario thinking has incorporated the issue of climate change, with different scenarios showing varying levels of success in addressing this critical global issue. But with typical forward-looking timeframes of 25 years in the 1990s and reaching to 50 years in the early 2000s, the full resolution of the climate issue through complete transformation of the global energy system was never clearly visible.

> **In Sky, the rate of decline in global emissions after 2035 exceeds the rate of growth we've seen for this century – an eye-watering achievement.**

That transformation has always been, and remains, a journey measured in generations, now extending out to the end of this century.

In 2013 Shell published its **New Lens Scenarios** comprising two outlooks named **Mountains** and **Oceans**. For the first time, the scenarios featured energy-system modelling stretching to 2100, which allowed long-term transitions to be seen in their entirety. While exploring very different socio-political contexts, the scenarios show that persistent and widespread application of CO_2-targeted policy frameworks, including large-scale switching to renewable energy and extensive use of CCS (carbon capture and storage), would lead to net-zero emissions in the energy system. However, in the two scenarios, that outcome is achieved around the end of the century, which means that they fall short of the temperature goal of the Paris Agreement.

Looking beyond Mountains and Oceans

Drawing lessons from that previous work and additional analyses, we now present a possible pathway for decarbonising the global economy with the societal aim of achieving net-zero emissions from energy use by 2070 – a scenario called "**Sky**."

Sky recognises that a simple extension of current efforts, whether efficiency mandates, modest carbon taxes, or renewable energy supports, is insufficient for the scale of change required. The relevant transformations in the energy and natural systems require concurrent climate policy action and the deployment of

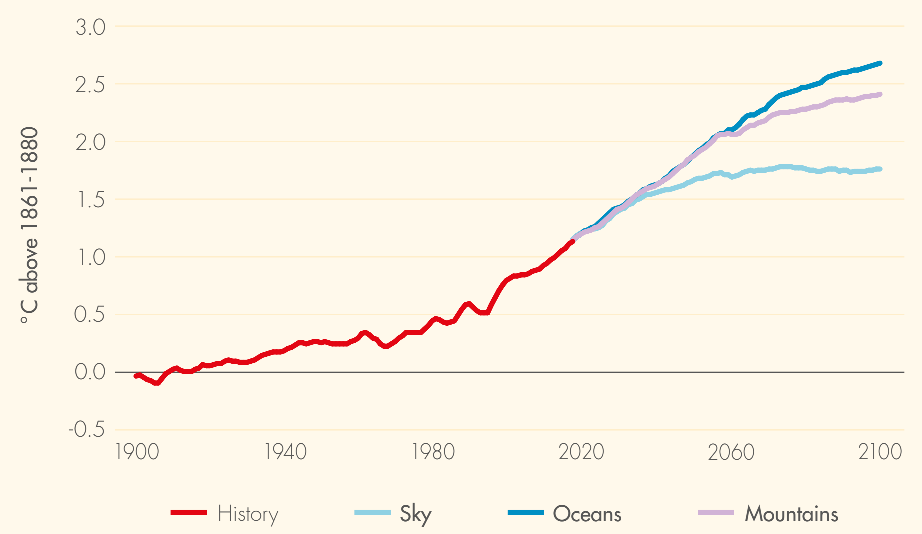
Introducing **Sky** – an ambitious scenario to hold the increase in the global average temperature to well below 2°C.

This requires a complex combination of mutually reinforcing drivers being rapidly accelerated by society, markets, and governments.

From now to 2070 –

1. A change in consumer mindset means that people preferentially choose low-carbon, high-efficiency options to meet their energy service needs.
2. A step-change in the efficiency of energy use leads to gains above historical trends.
3. Carbon-pricing mechanisms are adopted by governments globally over the 2020s, leading to a meaningful cost of CO_2 embedded within consumer goods and services.
4. The rate of electrification of final energy more than triples, with global electricity generation reaching a level nearly five times today's level.
5. New energy sources grow up to fifty-fold, with primary energy from renewables eclipsing fossil fuels in the 2050s.
6. Some 10,000 large carbon capture and storage facilities are built, compared to fewer than 50 in operation in 2020.
7. Net-zero deforestation is achieved. In addition, an area the size of Brazil being reforested offers the possibility of limiting warming to 1.5°C, the ultimate ambition of the Paris Agreement.

SHELL SCENARIOS COMPARED – GLOBAL AVERAGE SURFACE TEMPERATURE RISE



Note: The MIT Joint Program on the Science and Policy of Global Change modelled the climate impacts of **Sky** in comparison with those of **Mountains** and **Oceans**. All series are five-year moving averages.

Source: MIT

disruptive new technologies at mass scale within government policy environments that strongly incentivise investment and innovation. No single factor will suffice to achieve the transition. Instead, **Sky** relies on a complex combination of mutually reinforcing drivers being rapidly accelerated by society, markets, and governments.

Because climate challenges arise from the total accumulation of greenhouse gases in the atmosphere, there are an infinite number of possible pathways for the annual reduction of emissions over the coming decades that can result in an outcome consistent with the Paris ambition. Of course, some of these pathways are much more plausible than others – you wouldn't expect that the global economy can be completely re-wired overnight.

Sky begins with the current structure of economic sectors and government policies and the capacity for change that exists now. It then assumes very aggressive, but plausible, capacity-building and ratcheting of policy commitments through the first two five-year review cycles embodied in the Paris agreement. Beyond that time-frame, there are naturally rather greater uncertainties about how policies and technology may be developed and implemented globally. So, the scenario progressively becomes driven simply by the ambitious goal to achieve net-zero emissions by 2070, taking full account of the characteristics of scale, technological substitution, and investment in the various sectors of different national economies. Such a goal-driven scenario is sometimes referred to as "normative."

By adopting an approach grounded in the current reality of the energy system but then combined with a specific long-term goal, we intend **Sky** to be both an ambitious scenario and a realistic tool for practical considerations today.

Additionally, we are publishing extensive quantitative data sets for the **Sky** scenario, so that others can inspect and make more use of this information themselves.

The Paris Agreement has sent a signal around the world; climate change is a serious issue that governments are determined to address. By 2070, there is the potential for a very different energy system to emerge. It can be a system that brings modern energy to all in the world without delivering a climate legacy that society cannot readily adapt to. That is the essence of the **Sky** scenario.

Link to **quantitative data sets**

CHAPTER 2

CHALLENGES FOR A 21ST CENTURY SCENARIO

2. CHALLENGES FOR A 21ST CENTURY SCENARIO

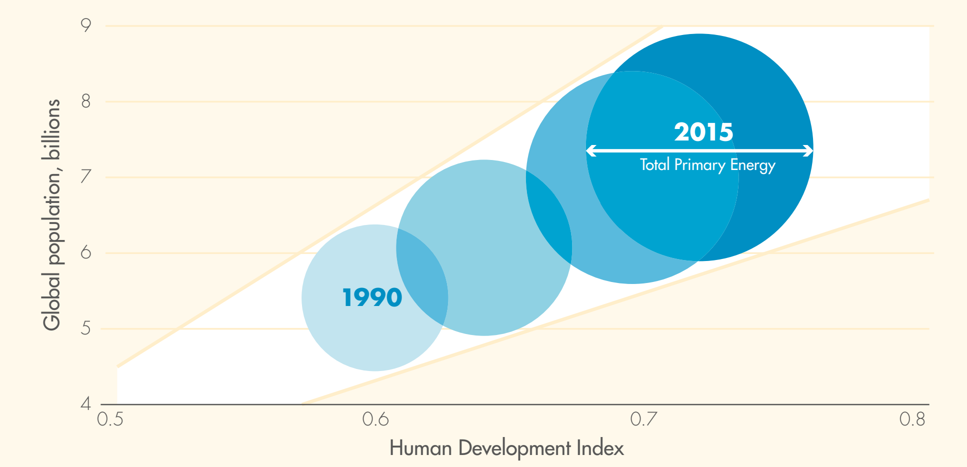
Challenge: Energy demand is rising

Energy enables the whole economy to function. It is needed and used everywhere – in homes, factories, shops, schools, personal transport, freight, sanitation, water systems, agriculture, and construction. It is a vital hidden ingredient in manufacturing and delivering almost all the products and services modern society takes for granted.

Through the course of the 20th century, global energy demand increased ten-fold as population more than tripled, economic growth and development surged, extended mobility became commonplace, and a wide range of new energy services appeared, from refrigeration at the beginning of the century to data-related services at its end. But in the context of the UN Sustainable Development Goals, several billion people are still pursuing a better life through much-needed access to clean water, sanitation, nutrition, health care, and education. Energy is a key enabler for these basic needs.

On a per capita annual basis, the range of primary energy use today is from 20 gigajoules (GJ) in a country such as Kenya, to about 300 GJ in the US. The global average currently stands at nearly 80 GJ but is expected to rise as near universal access to modern energy services is achieved during this century.

WORLD ENERGY DEMAND RISES WITH POPULATION AND DEVELOPMENT

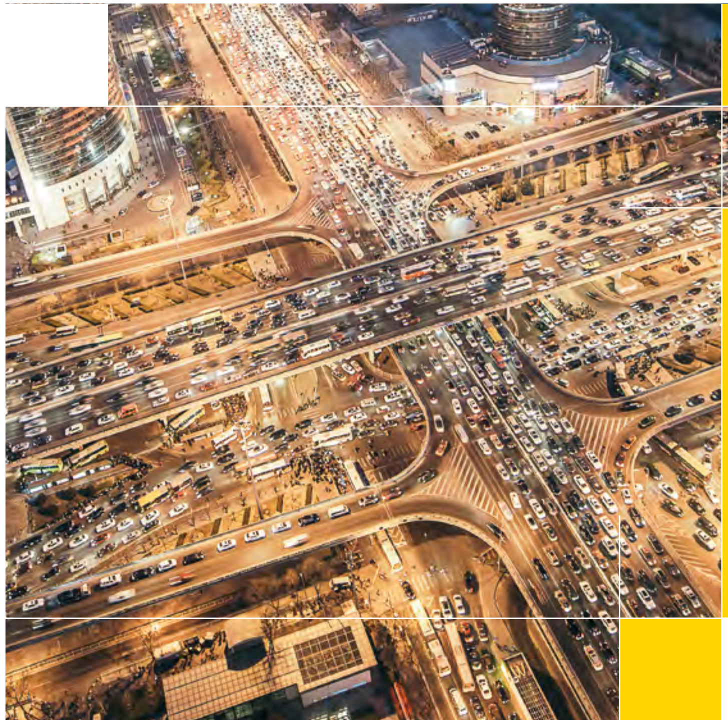


Source: Shell analysis, IEA, UN

New energy services will feature in the 21st century as well, from extensive use of artificial environments in which people live and work in comfort to trillions of connected devices within the "internet of things." As an early example, the connections people make through international travel have already doubled in the first two decades of this century (measured in terms of international air travel arrivals). Population growth, much-needed development, new energy services, and the extended use of existing services will all contribute to energy demand growth.

Challenge: Efficiency can have unexpected consequences

Without limiting the availability of energy services, energy demand growth can potentially be slowed through rapid improvement in the efficiency of such services. While this will inevitably happen it can be a double-edged sword. On the one hand, increased efficiency has been one of the economic growth engines of the 20th century, with the manufacturing cost and energy consumption of appliances such as air conditioners falling consistently over the decades. But on the other hand, these lower costs have also led to increasing uptake by consumers.



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In 2016, vehicle ownership in North America and Europe varied from 500 to 800 per 1000 people. China was 154 per 1000 people, with India at 42 per 1000, and inevitably set to grow.

For example, the most recent energy service to see large efficiency gains is lighting, with LEDs rapidly replacing incandescent, halogen, and fluorescent bulbs. But there is now clear evidence of growth in lighting services as a result, even in cities where lighting saturation was presumed to have been reached. Advertising is being transformed with LEDs, moving from street displays to giant billboards.

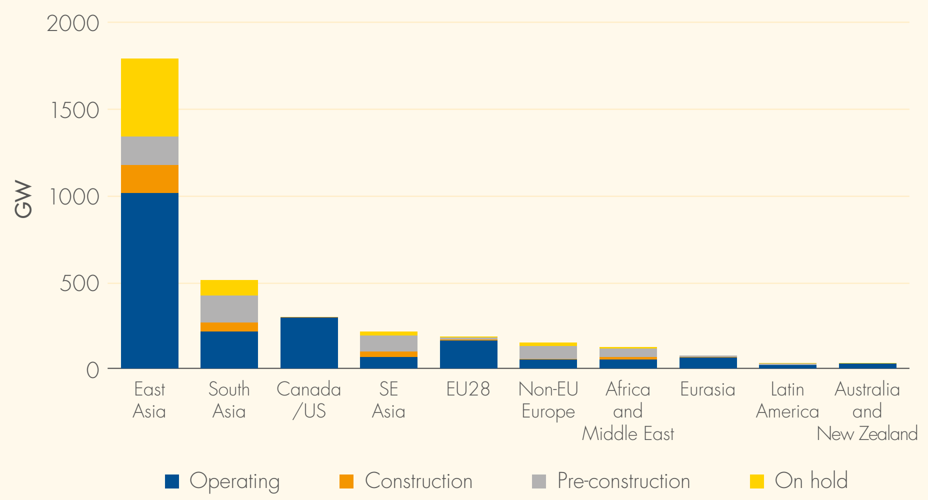
Challenge: Coal remains popular

Limiting the rise of CO_2 in the atmosphere will require moving away from fossil fuels to other sources of energy as well as utilising CCS. But new energy sources will be challenged to expand fast enough to meet both rapid demand growth and the need to back out of existing emitting sources quickly enough. Continued high demand growth can also put upward pressure on energy prices, which, in turn, could encourage further extraction of coal, oil, and gas, and discourage the transformation or modification of existing infrastructure.

Although the world is beginning to act, substantive progress towards the Paris goal will be challenging, partly because of coal. As renewables and natural gas increasingly dominate the energy sector in developed countries, bringing down emissions, coal use is increasing in some economies as new generation capacity is required for development. Vietnam is one such economy, with several large coal-fired power stations under construction in 2018.

A stark reality of the early 21st century is the lack of a clear development pathway for an emerging economy that doesn't include coal. Coal is a relatively easy resource to tap into and make use of. It requires little technology to get going but offers a great deal, including electricity, heating, industry,

COAL ELECTRICITY GENERATION CAPACITY



Note: Coal remains popular. New projects outside China could potentially exceed those under construction in the country.

Source: Global Coal Plant Tracker, January 2017, endcoal.org

and, very importantly, smelting to make iron. Although solar PV and wind offer clean, distributed electricity, benefiting households, electricity alone is currently insufficient for rapid urbanisation and industrialisation, including the construction of cities and the manufacture of products such as automobiles and appliances.

Challenge: Some parts of the energy system are "stubborn"

Not all economies will reach net-zero emissions at the same time. The EU or North America may need to consider this as an objective for the 2050s, in part to balance countries that arrive at this point much later in the century. As a progressive country within a progressive region, Sweden has already set its eyes on 2045. But net-zero emissions in almost any industrial economy in the 2050s is a tough ask. The apparent lack of low-carbon solutions for aviation, shipping, cement manufacture, some chemicals processes, smelting, glass manufacture, and others means that significant sectors of the industrial economy won't trend rapidly to zero emissions. Even the power sector could still need support from conventional thermal generation in 2050.

Challenge: Some technologies are "stalled"

Some promising technologies are currently stalled, with hydrogen, perhaps, being the notable example. Coming into this century it was seen as the future fuel in road transport, but hydrogen has now been eclipsed by battery electric vehicle developments. More recently, hydrogen has been proposed as a possible solution for industrial processes requiring intense heat, the metallurgical sector (where coal is the staple), home heating, and air transport, where battery storage is severely limited owing to weight.

Another sector where progress has been slower than originally anticipated is biofuels technology, which has the potential to provide essential, high-energy density, low-carbon footprint fuels for certain transport applications. Biofuel production could also be developed as a route to negative emissions, as seen in the US today, where CCS has been attached to a bio-ethanol plant.

Challenge: Systems transformations are unpredictable and take time

Limiting warming in line with the Paris Agreement means achieving net-zero emissions by 2070, just over 50 years from now. In energy transition terms, a decade is the blink of an eye, and a century might typically see just a handful of major transformations, although not all follow expected pathways.

As the 20th century arrived, an electric car was the preferred choice on American roads, but by 1920 the world was in the middle of the Ford Model T combustion engine era. Four billion cars later, the essential technology remains largely the same, yet with electric mobility emerging again.

Even electricity itself, which continues to transform our world, has not been a fast-paced energy technology. The first electricity grid appeared in New York in September 1882, over 135 years ago. Although the technology has spread globally and appears ubiquitous, it makes up less than 20% of final energy use today; so, 80% of the energy we use now isn't electricity but fossil and bioenergy hydrocarbons. Over the course of the last few decades, electrification of final energy has moved relatively slowly, at around 2%-points per decade – for example, it was about 17% in 2005 and 19% in 2015.

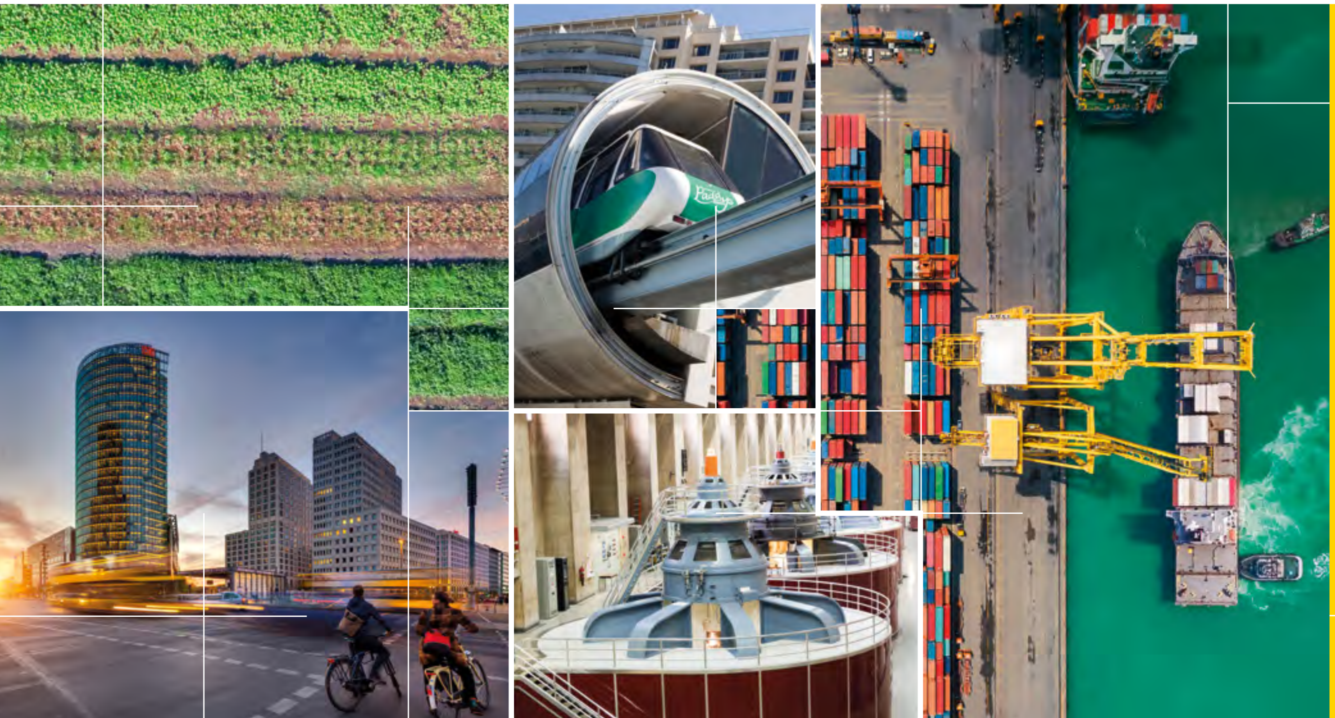
By the 1960s a nuclear power revolution seemed possible, but it had stalled completely by the 1990s. Similarly, in the 1960s, solar PV began to appear in highly specialist applications, but it has taken 50 years to pass 1% of global electricity production.

> **The photovoltaic (PV) effect was discovered in 1839, then eventually deployed on satellites as solar PV from 1962. Four decades later, only two GW of capacity existed globally, but in the following fifteen years capacity increased two-hundred fold.**

One reason systems transformations take time is that the success of one transformation – from horses to the international combustion engine, for example – can impede the progress of the next. A legacy of successful development is the potential for lock-in of the resource on which the current system was built. This potential for lock-in stems from the resistance to stranding the original capital investments and losing the jobs that have been created.

Challenge: Given the time frame of 2070, there can be no slippage

Achieving net-zero emissions in just 50 years leaves no margin for interruption, stalled technologies, delayed deployment, policy indecision, or national back-tracking. Rather, it requires a rapid acceleration in all aspects of an energy transition and particularly robust policy frameworks that target emissions. Success can be accomplished only through a broad process that is embraced by societies, led by governments, and lightly coordinated by organisations including the UNFCCC, the EU, ASEAN, and others.



CHAPTER 3
FROM MOUNTAINS AND OCEANS TO SKY

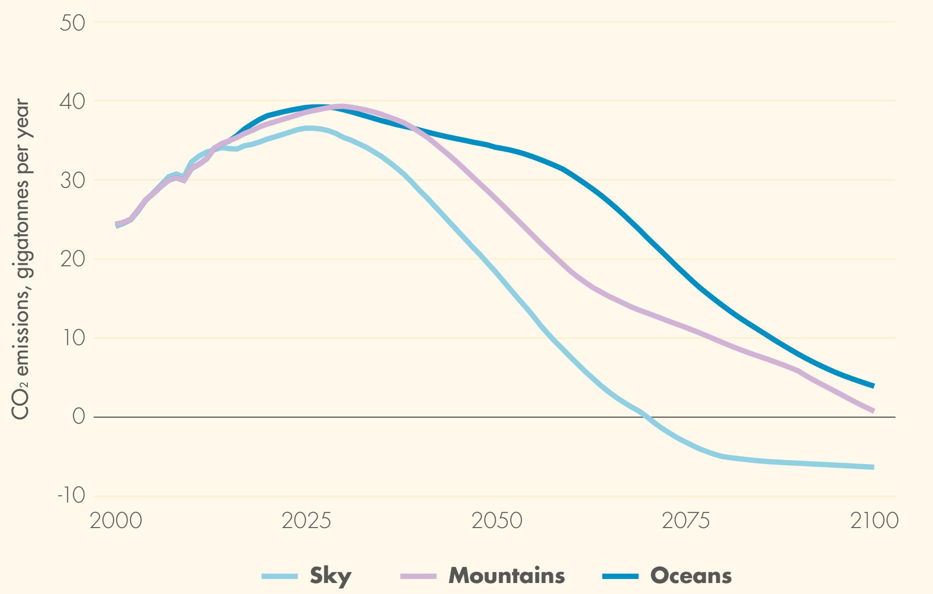
3. FROM **MOUNTAINS** AND **OCEANS** TO **SKY**

In the original New Lens Scenarios, we explored two possible ways the 21st century could unfold, taking several pressing global trends and issues and using them as "lenses" through which to view the world.

Mountains and **Oceans** provided a detailed analysis of current socio-political trends and their possible trajectories into the future, with **Mountains** more government-led with a top-down approach and **Oceans** more bottom-up with a market-driven outcome.

The **Sky** scenario brings further to the surface the emerging possibility of better multi-lateral collaboration to tackle climate and air-quality issues. In this regard, it combines the most progressive elements of both **Mountains** and **Oceans**. This collaborative approach has been seen in previous real-life incarnations, such as in the Montreal Protocol on ozone-depleting substances, but true long-term international co-operation and a willingness to combine national self-interest with the differing interests of other nations has generally eluded society as a lasting trend. Nevertheless, the Paris Agreement is built on such a model, albeit with a strong element of peer review and challenge.

SHELL SCENARIOS COMPARED – WORLD ENERGY-RELATED CO_2 EMISSIONS

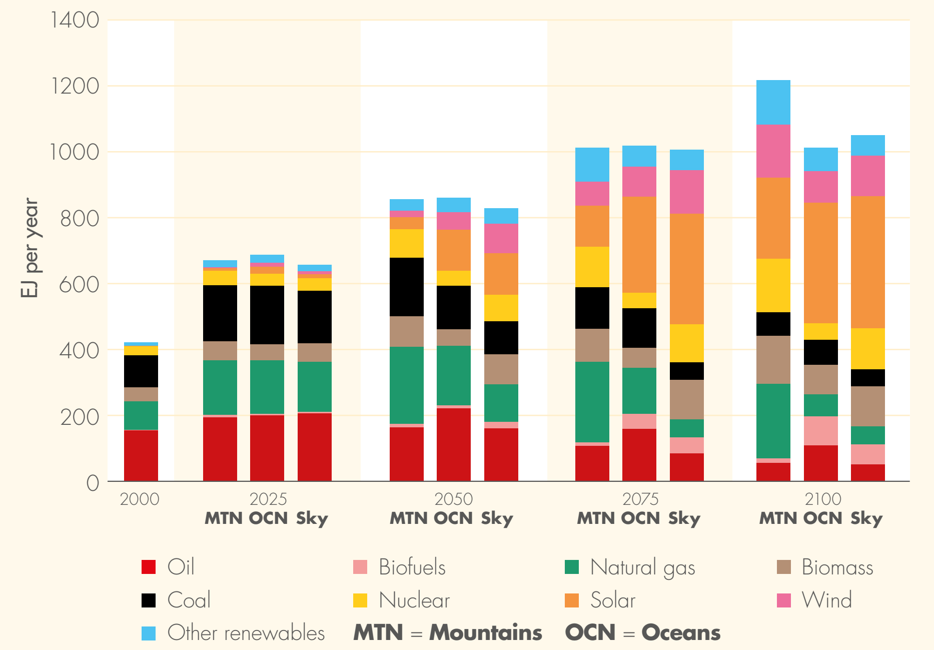


Source: Shell analysis

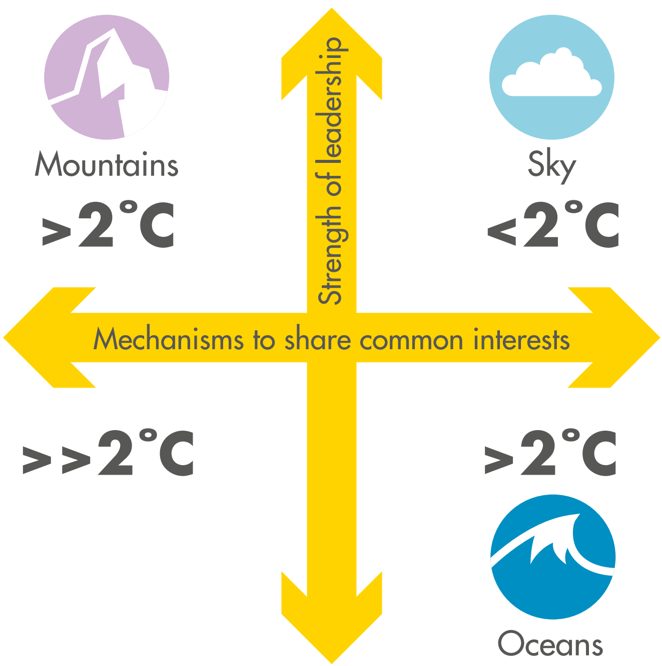
Leadership to create a shared vision was an essential element of the Paris Agreement, as demonstrated through bilateral agreements between several heads of government in the two years before the final negotiation. But so, too, was listening and responding to those most at risk from climate change, such as the Alliance of Small Island States (AOSIS) with its deep concerns in relation to sea level rise. Responding to these concerns, a "high ambition coalition" emerged in Paris and was responsible for the incorporation of a stretch goal within the Paris Agreement to limit warming to 1.5°C.

These developments introduce the notion of a framework for resolution of global issues within which various scenarios could be positioned. That framework is not solely dependent on trends such as technological change, which features at an accelerated or even breakneck pace in almost any 21st century story, but is born out of long-term self-interest and the way society listens and reacts to the issues of the day.

PRIMARY ENERGY BY SOURCE IN THE THREE SCENARIOS



Source: Shell analysis



Sky requires both leadership and emerging coalitions from all sectors of society. The issue of climate change is a global commons problem requiring a solution that deals with the complexity of multiple public and private interests.

Oceans imagines a world where influence stretches far and wide, power is devolved, competing interests are accommodated, and commerce is king. Leadership is not strong, but an evolving recognition of common interests is a feature of commerce. Economic potential is unleashed with technology deployment and efficiency improvements driven by the commercial engine.

By contrast, **Mountains** is a world with status quo power locked in and held tightly by those already influential. Stability is highly prized, and the powerful align interests to unlock resources steadily and cautiously, not solely dictated by immediate market forces. Economic growth is somewhat moderated, but centralised authority offers the prospect of city transformation, a revolution in modes of transport, and widespread use of CCS – features that are important for limiting overall emissions.

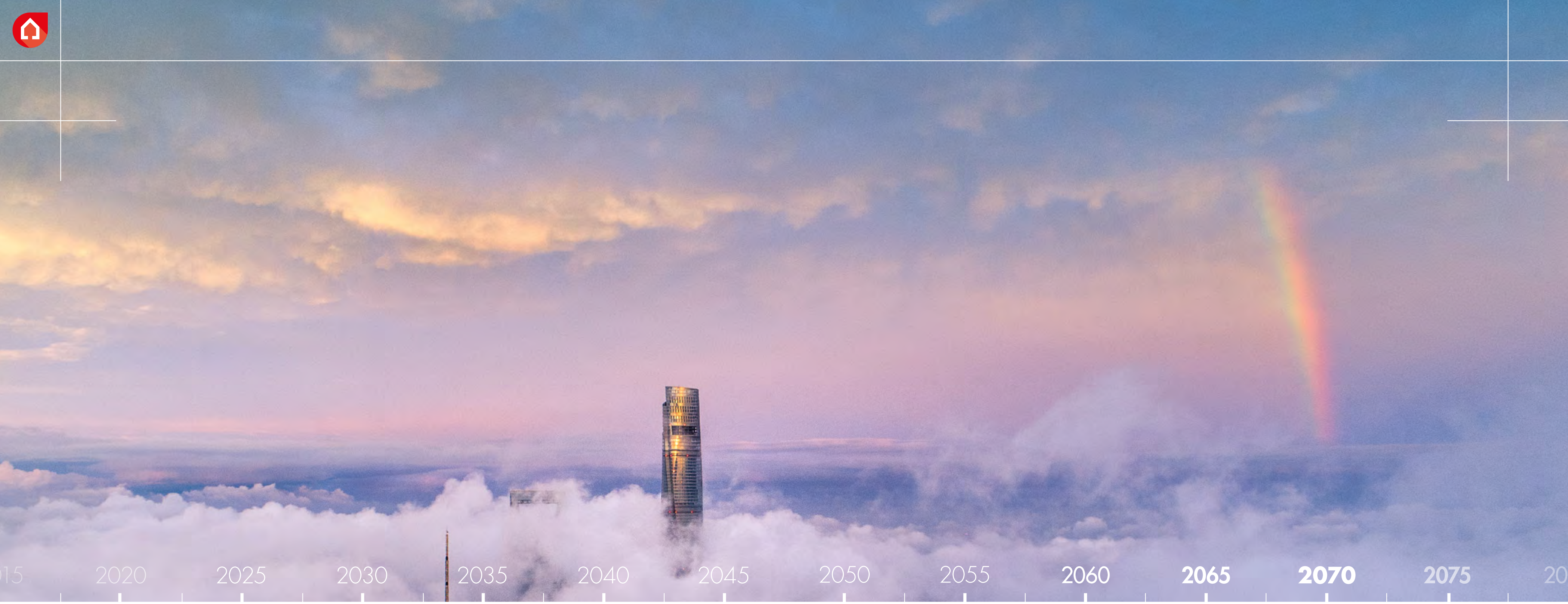
MOUNTAINS, OCEANS AND SKY: HOW DO THEY DIFFER IN APPROACH?

The modelling-and-development of the **Sky** scenario differs from the methodology applied in earlier Shell scenario work, such as for **Mountains** and **Oceans**. It also differs from the approach taken by most energy organisations that have developed 2°C scenarios.

Mountains and **Oceans** both started life through a series of workshops that sought to identify key societal trends that had the potential to shape the landscape of the 21st century. From that work, narrative storylines emerged that formed the basis of the two scenarios. These storylines were then tested by energy modelling to fully explore the impact of the trends in each scenario on the energy system. That modelling included feedback and checks, such that a plausible and consistent scenario emerged where the narrative and the energy numbers stood solidly together. The scenarios were open-ended and not goal-seeking, so outcomes such as warming of the climate system emerged from the realpolitik of the scenarios and the energy choices made as a result.

In contrast, a narrow 2°C scenario establishes that level of warming as a given target from the outset, irrespective of the prevailing political and social conditions at any point in time. An energy pathway and storyline then develop as the outcome, both of which may need to challenge plausibility to meet the limit set on warming. This approach to scenario building is known as "normative."

As noted in the introduction, **Sky** takes a hybrid approach aimed at being helpful to those in society making decisions today. From 2018 to around 2030, there is clear recognition that the potential for dramatic short-term change in the energy system is limited, given the installed base of capital across the economy and available technologies, even as aggressive new policies are introduced. But the period is also assumed to include significant capacity-building and technology cost reductions, following two five-year nationally determined contribution (NDC) cycles of the Paris Agreement, such that after 2030, deployment can proceed at an accelerated pace to ensure a result well below 2°C.



CHAPTER 4

A SCENARIO FOR SUCCESS – SKY

4. A SCENARIO FOR SUCCESS – **SKY**

Sky begins with the actions taken in the first decade of the Paris Agreement. Governments respond positively to the rapid cycle of assessment, review, and improvement of national contributions, as set up under the Paris Agreement. Prior to the 2023 stocktake, there is wide resubmission of national contributions, with the notable change by China to a falling emissions pledge. In Sky, by the 2028 stocktake, all contributions have been radically improved, with India now indicating an emissions plateau in the 2030s.

During the 2020s in Sky, emissions reduction progress is relatively slow while capacity builds. But beginning in 2030, the speed of transformation accelerates rapidly as key sustainability challenges of the 21st century begin to be met.

Success: Energy for all

In Sky, the global population grows from 7.5 billion in 2017 to 10 billion by 2070, after which it stabilises. Energy demand also rises throughout the century, with a near plateau from 2080. Importantly, per capita usage remains relatively low in Sky because of unprecedented efficiency gains for energy services – an approximate tripling in efficiency is seen over the course of the century. As a result, per capita primary energy demand converges near 100 GJ per year – far below the numbers seen today in industrialised economies but nevertheless a level that provides the broad range of energy services required for a better life. As a reference, a modern energy-efficient refrigerator will consume just over one GJ per year.

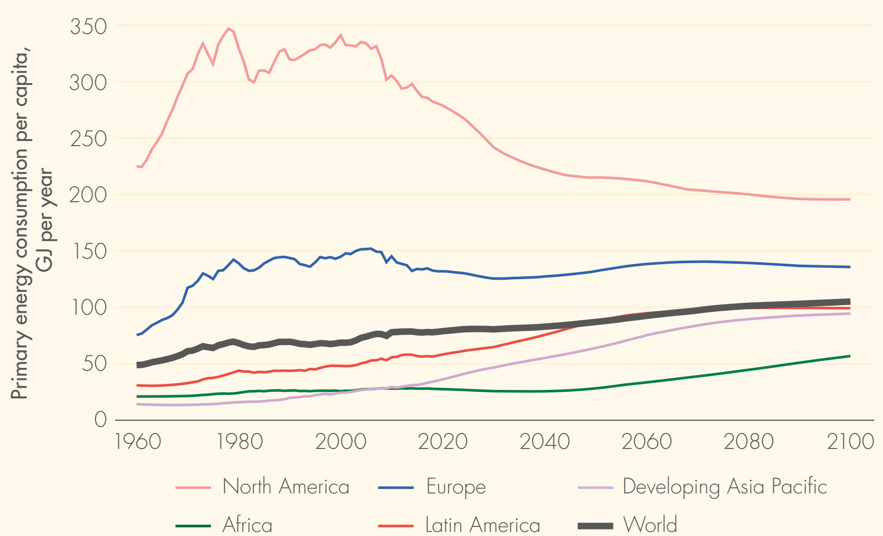
With the global population at 10 billion late in the century and per capita energy use rising, the energy system in Sky is approximately double its 2010 size.

Success: Dealing with coal

At COP23 in 2017, 25 countries and states formed the Powering Past Coal Alliance, pledging to phase out existing traditional coal power in their jurisdictions. In the next few years, in Sky, a significant number of other countries join the Alliance with the result that coal for power generation diminishes in all parts of the world. In Vietnam and even in India, new coal for power construction ends before 2030. By the 2030s, additional solar and wind meet all incremental electricity demand.

China's push to accelerate the phase-out of coal in Sky means global peak coal demand is now behind us, with rapid decline ahead, although coal remains important in some Asian

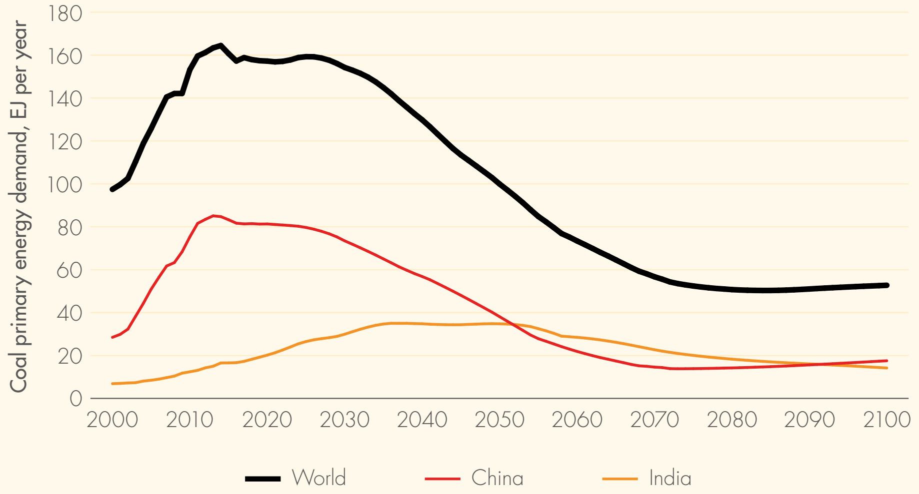
A BETTER LIFE FOR ALL



Note: Today, a better life for all can be achieved for an average of 100 GJ per capita. Later in the century, efficiency gains mean that a better life can be achieved at still lower figures.
Source: Shell analysis, IEA (historical data)

In Sky, absolute CO_2 emissions peak before 2040 in India, by then the most populated country on earth.

PEAK COAL USE IS BEHIND US IN **SKY**, WITH TOTAL CONSUMPTION FALLING RAPIDLY FROM THE EARLY 2030s ONWARDS



Source: Shell analysis, IEA (historical data)

countries, and metallurgical coal continues as a critical input for smelting. By 2070, coal's share of global primary energy falls to around 6%, down from 25% in 2020.

Success: Transformation of stubborn and stalled technologies

In the first decade following the Paris Agreement, energy system CO_2 emissions are largely locked in by existing technologies, capital stock, and societal resistance to change. But by 2030 in **Sky**, the system is opening, triggered in the 2020s by significant advances in energy technologies and scale of manufacture leading to price falls for consumers and businesses. This is facilitated by targeted government intervention in research and development and the important early commercialisation phase, with major gains in battery storage technology, CCS, and advanced biofuels.

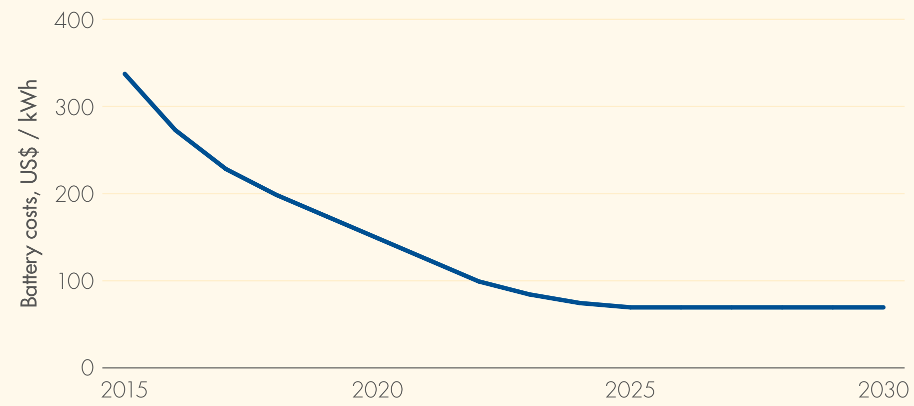
Success: Governments step up the pace

In **Sky**, governments around the world implement legislative frameworks to drive efficiency and rapidly reduce CO_2 emissions, both through forcing out older energy technologies and through promoting competition to deploy new technologies as they reach cost effectiveness.

For example, at the national and sub-national level, governments speed up the energy transition by adapting power markets to new renewable technologies and putting a meaningful price or constraint on carbon emissions from conventional thermal generation. Legislation in many jurisdictions forces grids towards 100% renewable energy by the 2040s.

Appliances, commercial and residential buildings, and personal transport are all targeted with aggressive efficiency or emission standards. The creation of low-emission zones

BATTERY COSTS FALL RAPIDLY IN **SKY**, IN PART DUE TO GOVERNMENT FUNDING OF NEW TECHNOLOGIES



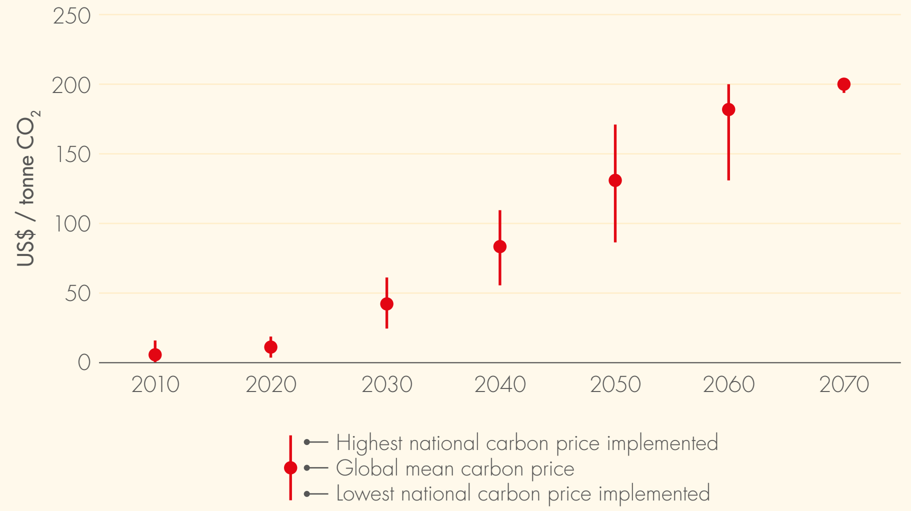
Source: Shell analysis, Bloomberg New Energy Finance (historical data)

by city authorities forces older vehicles off the road, and in many cities electric vehicles become the natural replacement due to their convenience and the wide availability of recharging points. Scrappage incentives speed up the replacement of out-dated, less efficient equipment in homes and offices. But the most significant emissions-targeted action taken by governments around the world is the adoption of effective implicit or explicit carbon-pricing mechanisms.

Since Paris, government-led carbon-pricing approaches have been gaining traction. At the 2017 OnePlanet Summit, several countries and states within the Americas committed to expand their use of these mechanisms. During the same year, China announced the launch of its nationwide emissions trading system, starting with the power sector. And by the beginning of 2018, California, Quebec, and Ontario were operating under linked emissions trading systems.

> **In Sky, solar PV maintains strong average growth rates of 20% per year, exceeding 6500 GW installed capacity by 2035. This will cover an area of 100,000 km², equivalent to an area the size of South Korea. From then on to 2070, nearly 1000 GW will have to be added every year, when solar PV's global footprint approaches the area of Spain.**

GOVERNMENTS RAPIDLY ADOPT CARBON-PRICING MECHANISMS THROUGHOUT THE WORLD IN THE 2020s; COMPLETE HARMONISATION IS ACHIEVED BY 2070



Source: Shell analysis

In **Sky**, government-led carbon pricing emerges as a suite of taxes, levies, and market mechanisms. Surprisingly quickly, a common understanding is reached between governments as to the appropriate level of the cost of emissions.

By 2030 in **Sky**, government-led carbon pricing is firmly established throughout the OECD and China, with Russia and India forming the second wave of entrants to carbon markets. Global implementation of carbon pricing by governments is complete by the late 2030s, with all systems then achieving a credible limit to deter emissions.

In **Sky**, carbon pricing has two other significant consequences. First it speeds up the adoption of CCS for large emitters while driving the deployment of net-negative technologies like bioenergy with CCS.

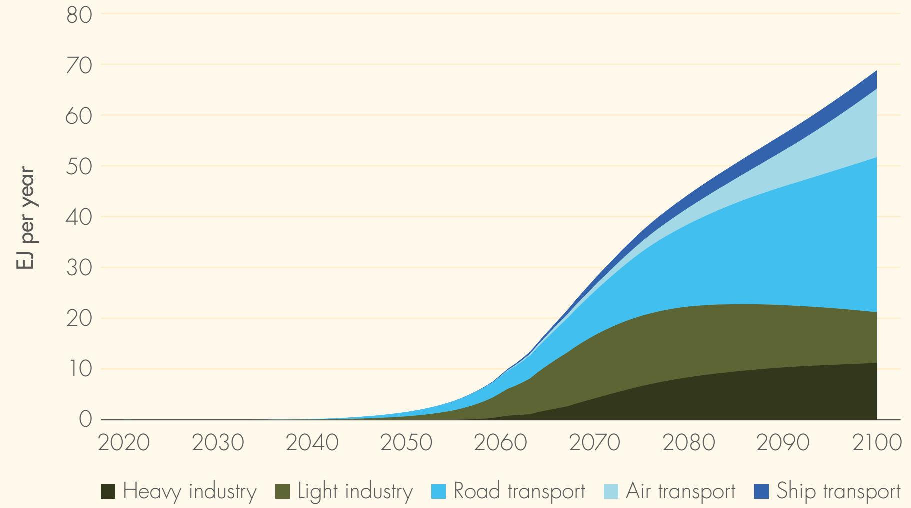
Second, carbon pricing encourages emissions reduction across the whole economy, especially through improving energy efficiency, thus generating significant shifts in consumer and producer behaviour.

Success: New energy systems emerge

Onshore and offshore hydrogen electrolysis systems also begin to emerge around the world in **Sky**. Initially, they make use of the growing off-peak surplus of electricity from renewable sources, but later become fully integrated base-load systems. As a result, after 2040, hydrogen emerges as a material energy carrier, steadily growing to account for 10% of global final energy consumption by the end of century.

As oil and gas use falls over time in **Sky**, redundant facilities are repurposed for hydrogen gas storage and transport. Indeed, the growing LNG supply in the early decades

IN **SKY**, HYDROGEN EMERGES AS A MATERIAL ENERGY CARRIER AFTER 2040, PRIMARILY FOR INDUSTRY AND TRANSPORT



Note: By 2100, hydrogen supplies a quarter of all transport energy demand and over 10% of industrial energy

Source: Shell analysis

Hydrogen grows as an energy carrier from 2040 in Sky, with 800 million tonnes per year global capacity by 2070 – more than double the current global LPG market.

of the century has enabled hydrogen to gain a foothold and develop scale. An immense build-out of electricity networks and hydrogen pipelines ensures secure and affordable electricity and hydrogen supply, which stimulates switching across sectors, particularly in transport and industry.

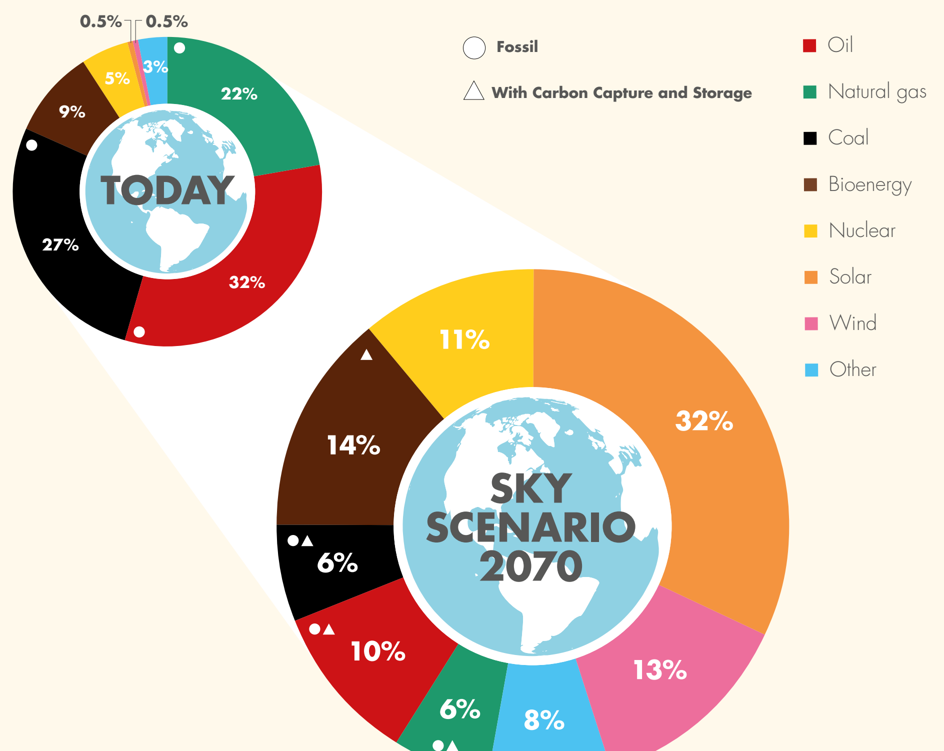
Even though aviation and shipping continue to rely on crude oil for the first decades of **Sky**, fuel synthesised from biomass begins to take more and more of the market share. **Sky** assumes that this is in the form of liquid biofuels, given its greatest flexibility, but if the conversion to methane proves the more successful, then this equally could be in the form of compressed or liquefied bio-gas for ship, rail, and road uses. In the latter stages of the transition, hydrogen emerges as a new energy carrier, particularly for aviation.

Success: Paris works

In **Sky**, the Paris Agreement succeeds, driven by government implementation of targeted energy policy at every level in parallel with aggressive action across the global economy, including the energy sector.

These and similar actions multiply rapidly. At first, government leadership is responsible for the speed of change, but increasingly,

IN A NET-ZERO EMISSIONS WORLD IN 2070, SOLAR, BIOENERGY, AND WIND DOMINATE RENEWABLES SUPPLY WHILST OIL REMAINS THE LARGEST FOSSIL ENERGY SOURCE

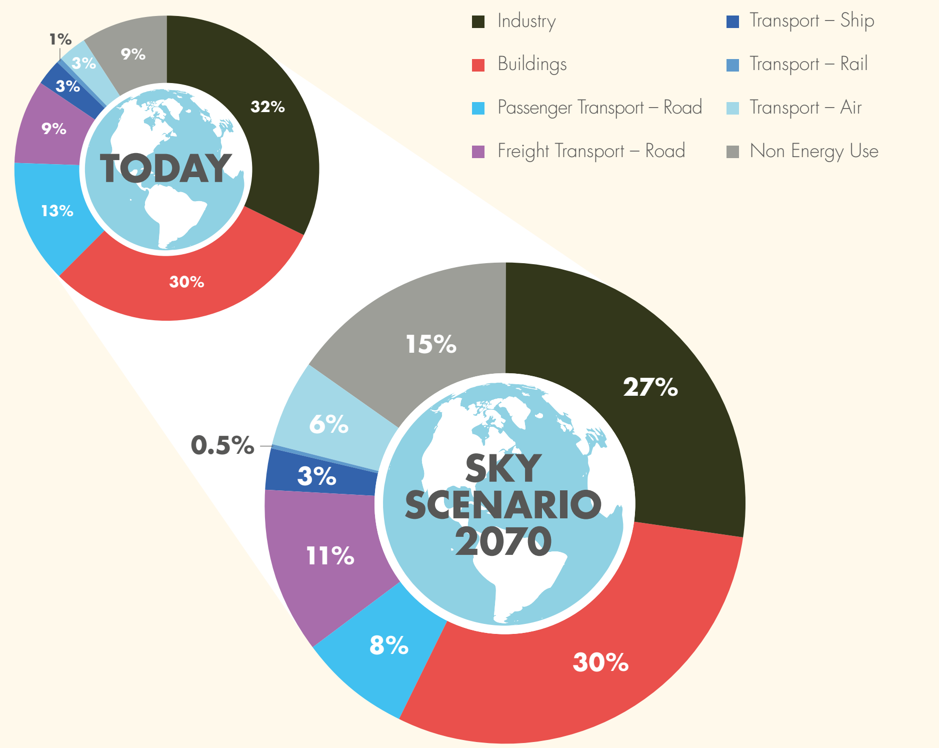


Source: Shell analysis

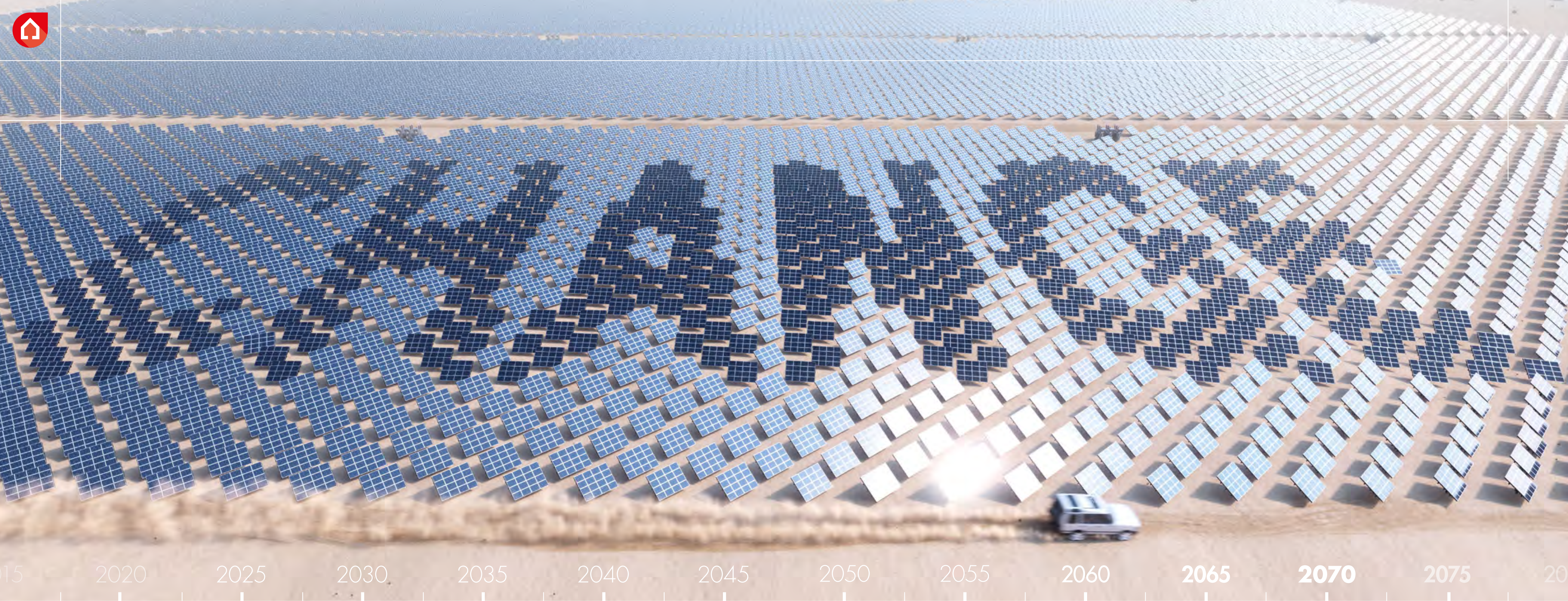
peer pressure provides the push in response to the transparency framework embedded in the Paris Agreement. New technologies become increasingly cost-competitive by themselves as mass deployment increases. The five-year ratchet mechanism works in the **Sky** scenario.

Not all countries have reached net-zero emissions by 2070. But beginning in 2020, progressive countries follow Sweden's earlier legal commitment to reach net-zero emissions by 2045. Along with Brazil and other big economies, most European countries reach net-zero by 2060, with some seeing continued falls such that their economy-wide emissions become negative – in other words, drawing down CO_2 from the atmosphere. This is achieved by combining the use of biomass for energy with CCS. These countries are then able to offer negative emission transfers to those countries still in positive territory, thereby achieving the global balance called for under the Paris Agreement.

WORLD TOTAL FINAL ENERGY CONSUMPTION BY SECTOR IN **SKY**



Source: Shell analysis



CHAPTER 5
SECTOR TRANSFORMATIONS

5. SECTOR TRANSFORMATIONS

In **Sky**, the route to net-zero emissions in 2070 involves change at every level of the economy and energy system, from urban configuration to consumer demand for energy to the breakthroughs in technology required to deliver viable and cost-effective alternatives to fossil fuels. And in the world of **Sky**, transformation of the energy system to produce fewer greenhouse gases is matched by transformations in other sectors that produce the remaining one-third of greenhouse gas emissions.

One of the most important energy system trends in **Sky** is electrification – the increasing replacement of fossil fuels (such as natural gas for cooking and gasoline for mobility) by electricity.

A successful transport revolution

By 2020, the foundation has been created for a revolutionary transformation of the transport system. The global Clean Energy Ministerial, which emerged in 2009 after the Copenhagen Climate Conference to encourage the transition to a global clean energy economy, had already adopted an Electric Vehicle Initiative as one of its early actions, with the target of 20 million electric vehicles deployed globally by 2020 and 30% new vehicle sales by 2030. And the UK had pledged to phase out the sale of internal combustion engine passenger cars by 2040.

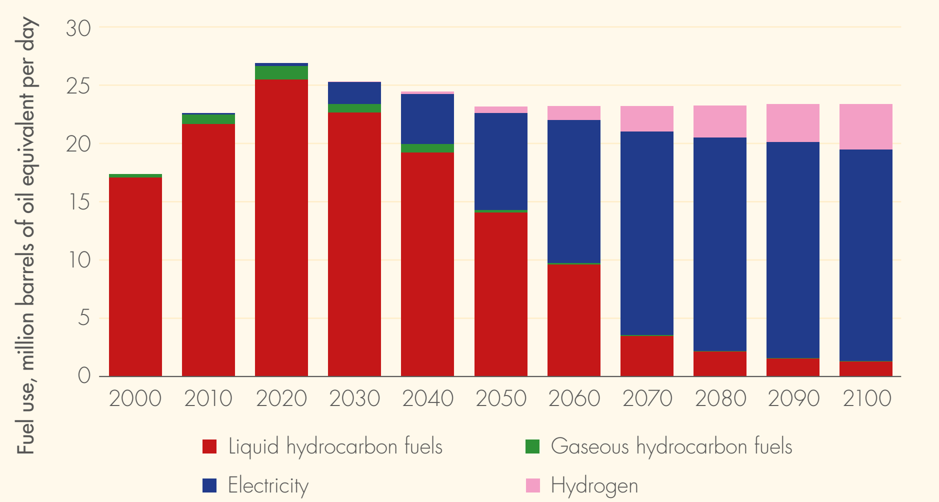
In **Sky**, this transformation occurs more rapidly than many expect; as early as 2030, more than half of global car sales are electric, extending to all passenger cars by 2050. One reason is that in some prosperous large cities, workers enjoy the freedom and convenience that the fleets of autonomous electric vehicles provide. Another reason for the rapid increase of electric vehicles has to do with the exciting new options being offered. For example, in **Sky**, a standardised chassis design emerges in combination with battery or fuel-cell (FCEV) architecture, being shipped in almost flatpack form to local design companies for bespoke body fabrication using 3D printing techniques. And a specialised CarOS (Operating System) evolves, including battery management and autonomous operation, supplied as a single universal interface box.

In this way, electric vehicle penetration accelerates on the back of a new manufacturing approach and customer value proposition that offers complete customisation, a welcome reward for the loss of differential engine performance. The change is as profound as the arrival of the assembly line.

Across all forms of transport, biofuels play a critical role in the energy transition in **Sky**. With continued reliance on liquid fuels as the high energy density fuel of choice, but set against the need to reduce CO_2 emissions, biofuel use expands rapidly. While first generation fuels such as sugar cane ethanol continue to mid-century before

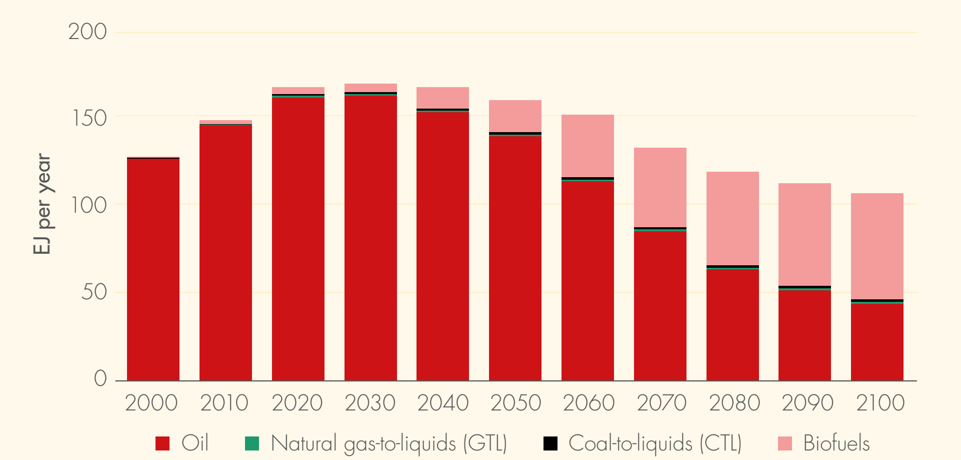
In Sky, passenger electric vehicles reach cost parity with combustion engine cars by 2025. By 2035, 100% of new car sales are electric in the EU, US, and China, with other countries and regions close behind.

THE FUEL MIX FOR PASSENGER VEHICLES SHIFTS RAPIDLY IN **SKY**, WITH ELECTRICITY DOMINATING BY 2070 AND LIQUID FUELS NEARLY HALVING FROM 2020 TO 2050



Source: Shell analysis

ADVANCED BIOFUELS GROW RAPIDLY IN **SKY**, MEETING AN ONGOING NEED FOR LIQUID HYDROCARBON FUEL.



Note: By 2100, biofuels production has reached some 30 million barrels of oil equivalent per day.
Source: Shell analysis

diminishing, the impetus comes from new synthesis pathways that produce drop-in equivalent fuels for aviation, road freight, and shipping. These fuels can be derived from a wider range of bio-feedstocks, reducing the dependency on food crops.

In **Sky**, the passenger vehicle transformation is largely complete by 2070. Liquid hydrocarbon fuel consumption almost halves between 2020 and 2050 and falls by 90% by 2070 in the sector. And even though road freight holds on to diesel into the 2050s, because of the need for a high-energy-density fuel, this sector also experiences its own transformation, split along biodiesel, hydrogen, and electrification lines.

> **US domestic refrigerator efficiency has tripled since 1970. To offer a better life for all but also manage energy demand, Sky matches these successes across the economy.**

The built environment

Changes in the built environment, covering both homes and commercial properties, evolve over decades, but the foundations are established in the 2020s. During this period, governments implement radical changes in building codes, set high efficiency standards for appliances, establish new infrastructure for district and regional heating needs, and establish practices that encourage attractive compact urban development.

The efficiency drive is so effective that final energy demand for residential services, which include heating, cooking, lighting, and appliance use, remains steady at around 90 EJ for all the century, even as most of the growing global population gain access to these amenities.

Electrification of the building stock proceeds rapidly, with local use of natural gas declining progressively from 2030. By 2070 in North America and much of Europe, natural gas is no longer used for residential heating and cooking.

Industrial transformation

The shift in industry required for net-zero emissions follows a more incremental path, largely driven by the progressive implementation of government carbon-pricing systems and the ratcheting up of the resultant price that occurs as governments respond to the Paris Agreement. The transformation is profound and follows three distinct routes:

- Efficiency improves continuously, with most industrial processes approaching thermodynamic and mechanical efficiency limits by the 2050s.
- Some processes shift towards electricity, particularly for light industry, where electricity use doubles from 2020 to 2040. Hydrogen also emerges as an important fuel for light industry by 2050 as natural gas use declines. But a similar change for heavy industry doesn't emerge until after 2050, with hydrogen, biomass, and electricity substituting for natural gas and some coal use.
- Coal remains important in the metallurgical sector and some other processes right through the century, but with government-implemented carbon prices rising, CCS emerges as the solution.

Industry also benefits from an increased focus on the circular economy, which sees large-scale recycling expand throughout the century, to the extent that some resource extraction declines as a result.

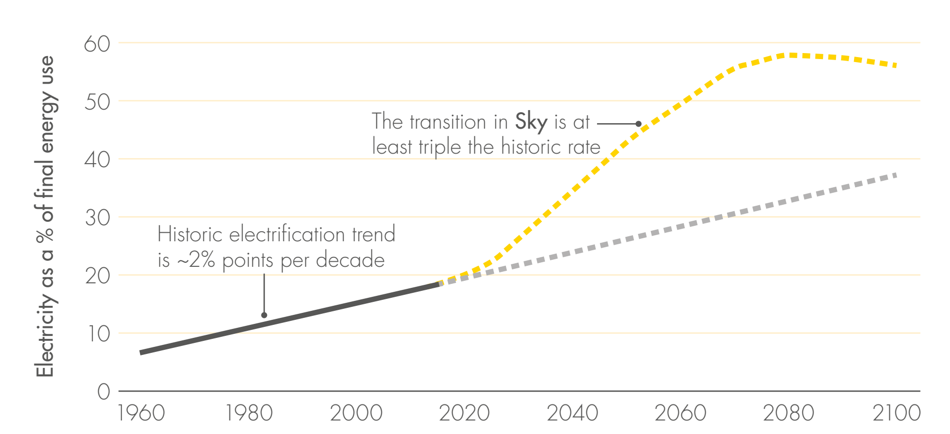
An electric world

As electricity makes its way rapidly into transportation, home heating and cooking, and industrial processes, its role in the energy system grows. By the 2070s, electricity exceeds 50% of end-use energy consumption, compared with less than 20% in the 2010s.

With renewables penetration increasing, issues associated with renewable intermittency and grid infrastructure receive policy attention. Utility-scale and distributed electricity both increasingly compete head-to-head with conventional thermal generation, leading electricity prices in some markets to fall below the variable cost of less efficient coal and gas plants, thus hastening their decommissioning.

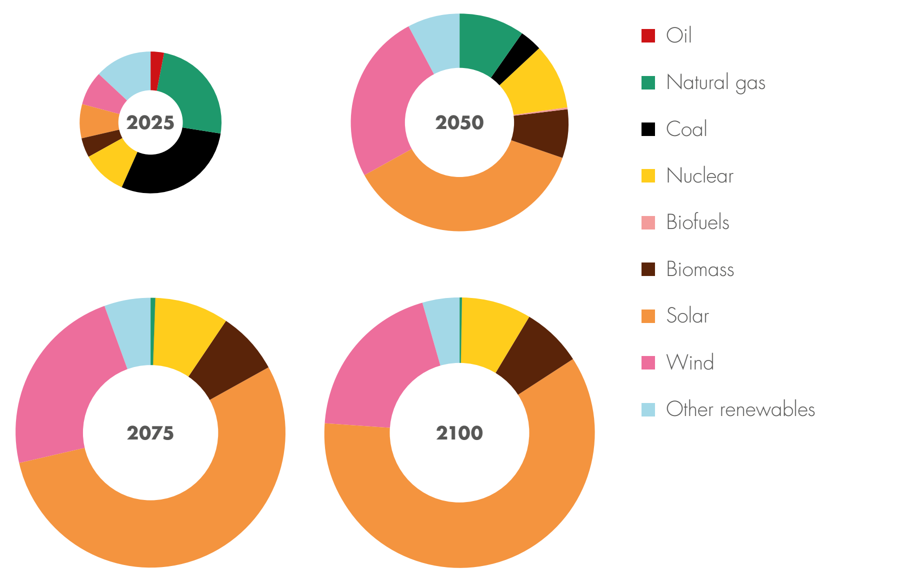
> **In Sky, nuclear power grows steadily, with 1,400 GW of capacity by 2070, up from 450 GW in 2020.**

CURRENT ELECTRIFICATION TRENDS ARE NOT SUFFICIENT FOR **SKY**



Source: Shell analysis, IEA (historical data)

THE ELECTRICITY MIX SHIFTS HEAVILY TO SOLAR THROUGH THE CENTURY

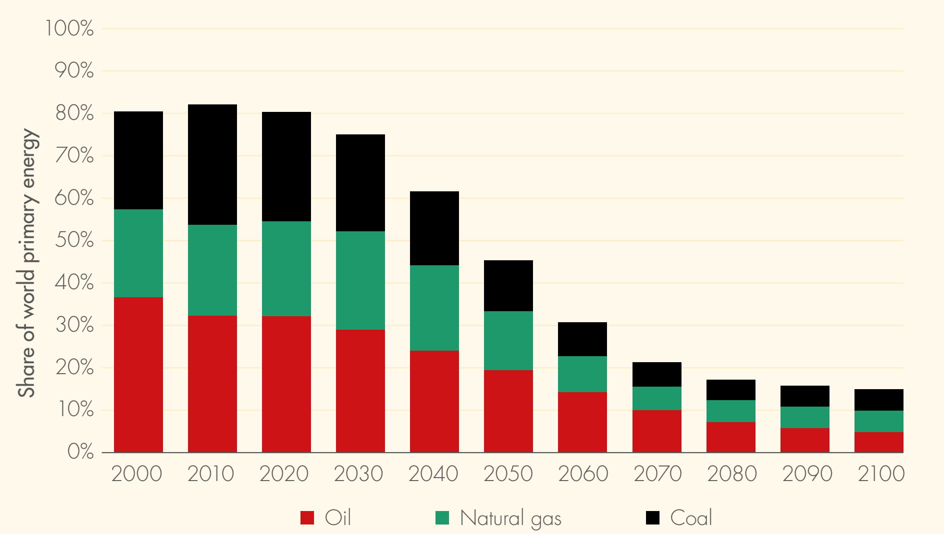


Note: The diameter of the pie chart represents the total electricity demand.
Source: Shell analysis

ELECTRICITY IN THE 21ST CENTURY

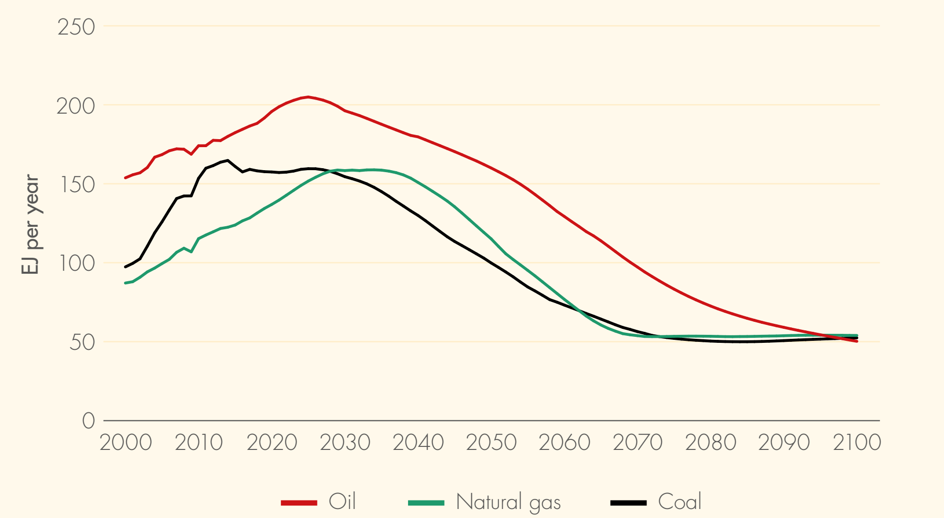
Today, global electricity demand stands at some 22,000 terrawatt hours (TWh) per year. In **Sky** it rises to around100,000 TWh per year during the second half of the century, or the addition of about 1,400 TWh of generation per year from now on. As a reference, when complete, the 3.3 GW Hinkley Point nuclear power station being constructed in the UK will add about 29 TWh, so this pace of development is equivalent to some 50 giant power stations globally each year, or one additional such facility per week. Global generation from wind and solar was around 1,300 TWh in 2016, with about 200 TWh added from 2015 to 2016 against total added electricity generation of some 600 TWh. So, new solar and wind are not yet close to meeting additional generation demand. Although both are rising quickly, thermal power stations will continue to be needed to at least mid-century. This also means that emissions from electricity generation globally will only fall in the medium term to the extent that natural gas and nuclear can displace coal.

IN **SKY**, BY MID-CENTURY FOSSIL ENERGY FINALLY RELINQUISHES ITS MAJORITY SHARE OF THE GLOBAL ENERGY SYSTEM



Source: Shell analysis

IN **SKY**, PEAK COAL DEMAND IS ALREADY BEHIND US, PEAK OIL DEMAND FOLLOWS IN THE 2020s, AND AFTER A PLATEAU, GAS DEMAND FALLS RAPIDLY FROM 2040



Source: Shell analysis

In Sky, electricity reliability issues are largely managed through a combination of improved market design (for example, capacity markets), grid integration (for example, cross-border integration in Europe), demand-side management (for example, smart grids), and deployment of cost-effective heat, battery, and hydrogen storage. Falling capital costs ensure that the renewables build-out is affordable, being well within historical spending on the new energy system as a share of global GDP.

By the 2070s, the power generation sector has progressed through two radical transformations. The first is one of scale, with electricity approaching a five-fold increase over 2017 levels. The composition of sources has also changed, with fossil fuels effectively absent from the sector and solar meeting over half of global electricity needs in 2070 and still increasing. A new addition to the sector is generation from biomass combustion, which is linked with CCS to offer an important carbon sink.

A new energy system

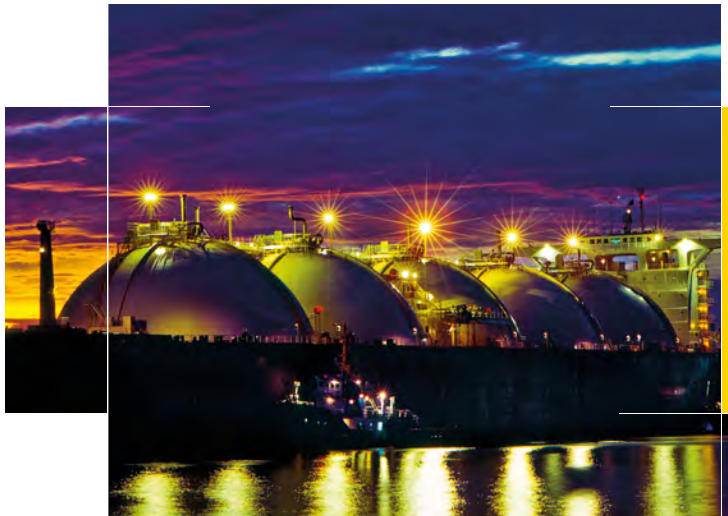
In Sky, the first clear signs of the transition emerge in the 2020s, with oil demand stagnating, coal declining, natural gas growing as it replaces coal, and solar closing in on nuclear as the largest non-fossil part of the energy system.

By 2070, oil production remains at some 50-60 million barrels per day due to the broad swathe of services that it still supplies. Non-road transport continues to make significant use of liquid hydrocarbon fuels, with overall growth through to 2070. Biofuels supplement the liquid fuel mix, with hydrogen playing an increasing role after 2050.

Natural gas, both as pipeline gas and LNG, plays an important early role in supplanting coal in power generation and backing up renewable energy intermittency as wind and solar grow in the power sector. But as solar PV expands rapidly, as battery costs fall, and as the high cost of carbon emissions bites, even natural gas succumbs to the transition. It is the last fossil fuel to peak, with demand falling rapidly after 2040. By 2055, natural gas use for power generation is back to 2015 levels globally.

By the middle of the century the energy mix is starting to look very different, with solar emerging as the dominant primary energy supply source by around 2055.

Energy system CO_2 emissions peak in the mid-2020s at around 35 gigatonnes (Gt), after which a continuous decline sets in.



Global natural gas demand reaches a plateau by 2028 in Sky at 4,600 billion cubic metres per year (bcma) – up from 3,700 bcma in 2017.

Other greenhouse gases and non-energy sectors

Sky arrives at net-zero CO_2 emissions for the global energy system by 2070, although with a varied distribution among different sectors and countries. That covers all the carbon contained within the coal, oil, and gas used for energy, but excludes feedstock for non-energy products, such as plastics.

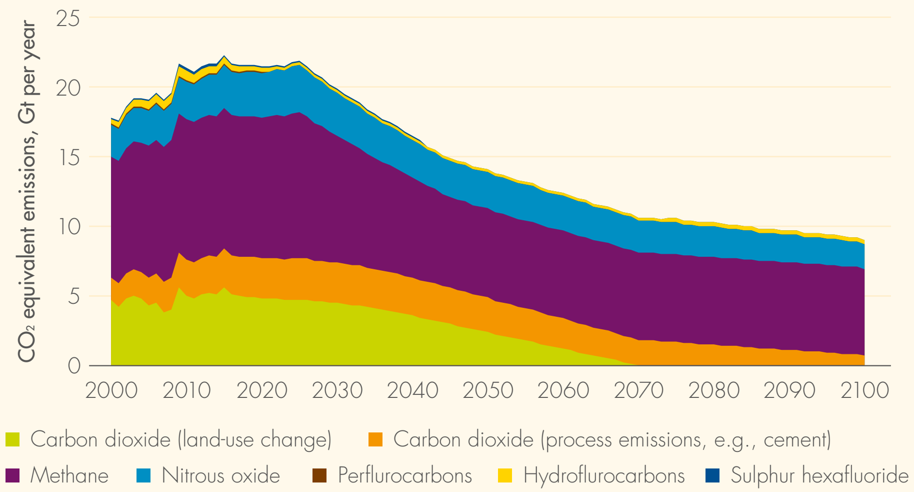
But numerous other human activities have changed the trace gas composition of the atmosphere, which have also contributed to warming the climate system. Cement manufacture is one example, where the calcination of limestone releases CO_2.

The agricultural system has added to the methane in the atmosphere due primarily to bovine livestock and rice growing. Land-use change over the course of several centuries, such as deforestation and agricultural degradation of soil, has also lowered the carbon-carrying capacity of the land-based biosphere, which, in turn, has added to atmospheric CO_2.

In the modern era, all these activities have accelerated, and new long-lived trace gases have appeared, some with extraordinary warming potentials. Sulphur hexafluoride, common in gas-insulated transformers, is one example, with a warming potential 24,000 times that of CO_2.

In the **Sky** scenario, significant changes are made in all the greenhouse-gas producing sectors. While all the items in the accompanying table represent best practice currently in some locations, the **Sky** pathway dictates universal uptake by about 2030, but with some recognised slippage in the least developed economies. For short-lived gases such as methane, the requirement is significantly reduced emissions, rather than net-zero, as these gases break down in the atmosphere over a few years.

NON-ENERGY SYSTEM GREENHOUSE GASES ALSO DECLINE SHARPLY IN **SKY**

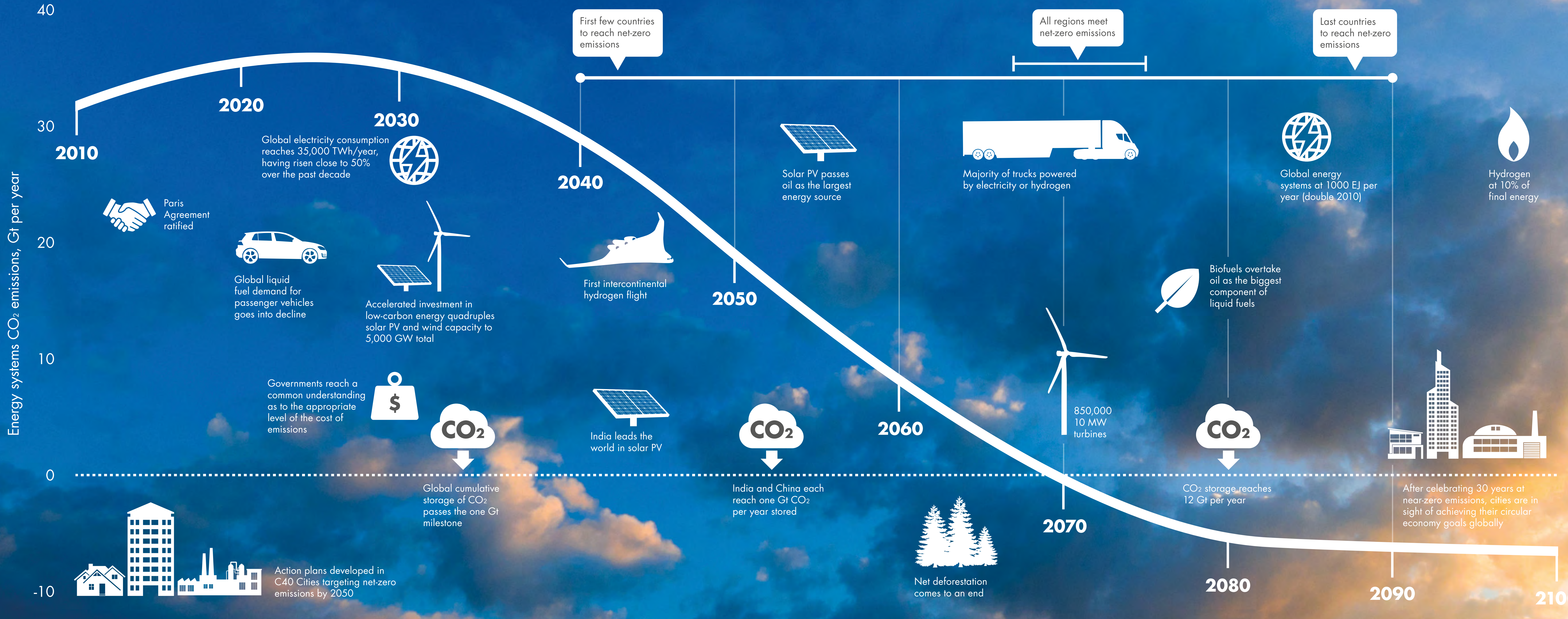


Source: Shell analysis, MIT

Although the emphasis in **Sky** has been on energy system CO_2 emissions, a view on all aspects of greenhouse gas emissions is needed to complete the scenario and understand the potential rise in surface temperature. That view has been developed based on full implementation of all the steps in the table.

GAS	SECTOR	ACTION REQUIRED BY **SKY**
Carbon dioxide	Cement	■ Progressive substitution away from cement in buildings ■ Some substitution away from limestone as a feedstock, e.g., using fly-ash ■ Using carbon capture and storage (CCS)
	Industrial (process emissions)	■ Using CCS
	Agriculture	■ Eliminating deforestation for land gain ■ Implementing soil carbon programmes, e.g., no-till farming, land-use rotation
	Urbanisation and development	■ Creating green cities through extensive tree planting ■ Maintaining green belts within and around cities ■ Avoiding city spread through higher density living ■ Addressing traditional biomass usage through modern access to energy programmes
Methane	Coal mining	■ Reducing coal consumption ■ Implementing best practice for methane drainage and use in coal mines (e.g., UNECE Guidance) ■ Managing abandoned mines
	Oil and gas industry	■ Reducing oil and gas consumption ■ Oil and gas industry leaders implementing best-practice from the 2020s, and all world production meeting best-practice by 2050
	Cattle farming	■ Offering alternative products to consumers ■ Changing cattle diets to minimise methane
	Rice growing	■ Reducing forced flooding in rice paddies
	Urbanisation and development	■ Capturing methane from landfill
Nitrous oxide	Agriculture	■ Implementing nitrogen fertiliser management, i.e., application rate, formulation (fertiliser type), timing of application, placement
	Industrial processes	■ Implementing catalytic decomposition and thermal destruction techniques
Fluorinated gases	Various (e.g., IT industry, refrigeration, transformers)	■ Progressive substitution away from PFC, HFC, and SF_6 ■ Using best practice management ■ Introducing recovery programmes for retired equipment (e.g., refrigerators, transformers)

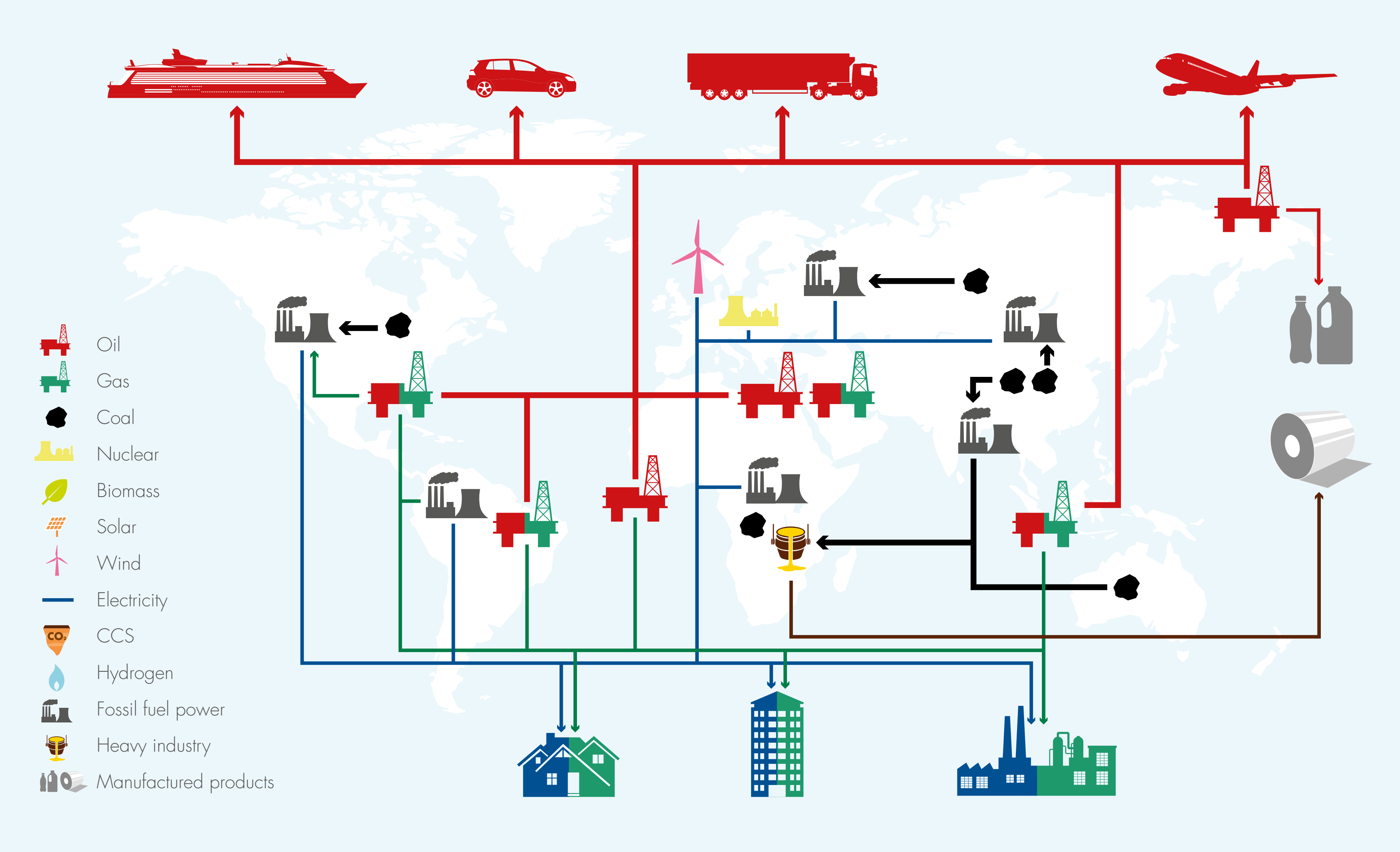
THE SCALE OF GLOBAL CHANGE IN **SKY** IS UNPRECEDENTED



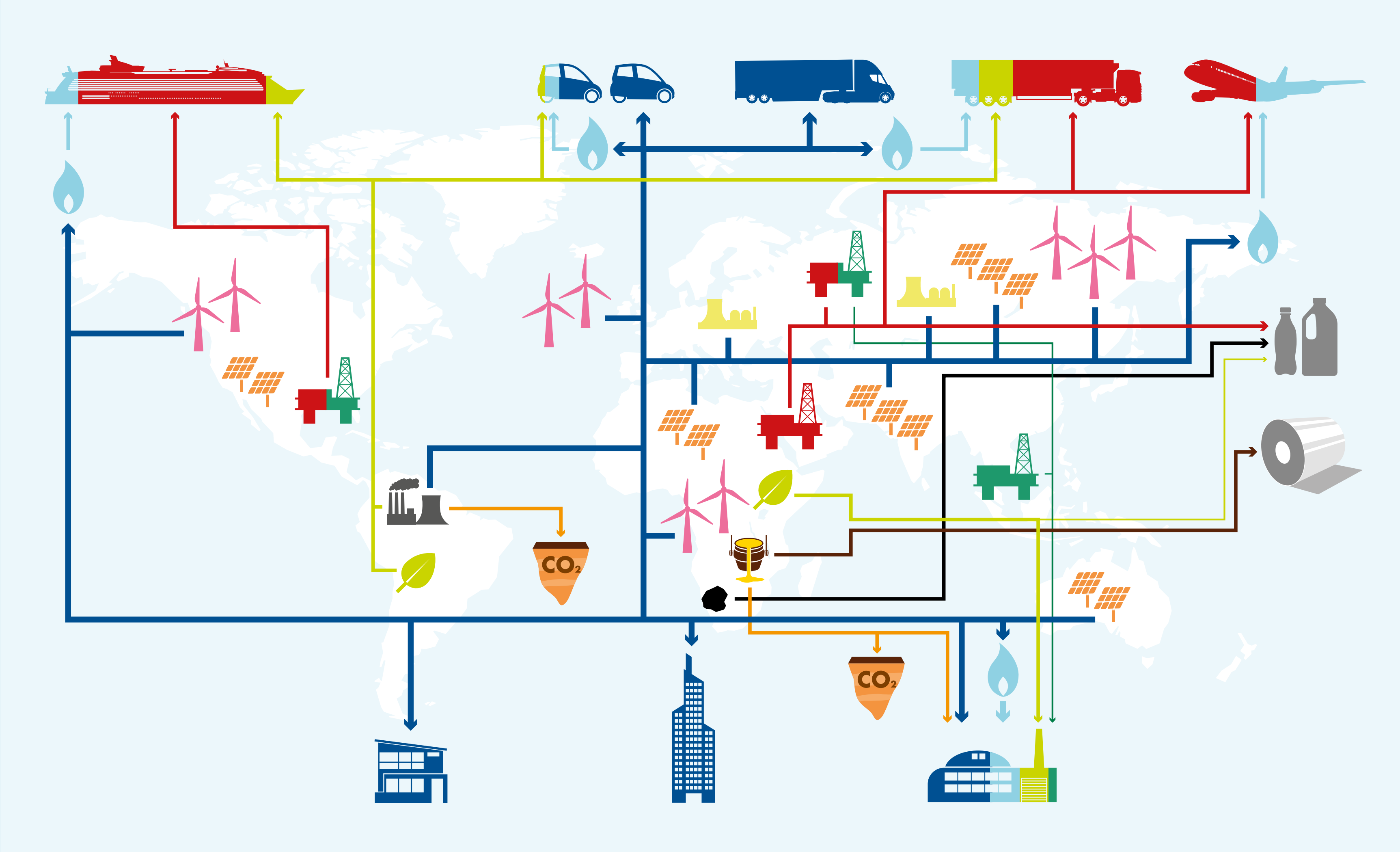
A NEW ENERGY SYSTEM

Over the past 200 years, our contact with energy has changed radically. For most of the global population in the early years of the 19th century, energy needs were met individually by collecting and burning wood, although coal deliveries in towns and cities were just commencing. Candles for domestic lighting were either made at home or purchased from a local chandler, who used various animal fats. One hundred years later, but primarily in wealthier countries, lighting was supplied by town gas, kerosene lamps, and for a rapidly increasing number of people, electricity. While there remain a disturbing number of people with little to no energy access today, much of the global population make regular use of petroleum products, natural gas, and electricity. But what could that look like in the latter part of this century as we reach for net-zero emissions? In **Sky**, an electricity-based energy system supplants the largely fossil fuel-based system of today.

TODAY – AN ENERGY SYSTEM BASED ON FOSSIL FUELS



SKY IN 2070 – AN ELECTRICITY-BASED ENERGY SYSTEM



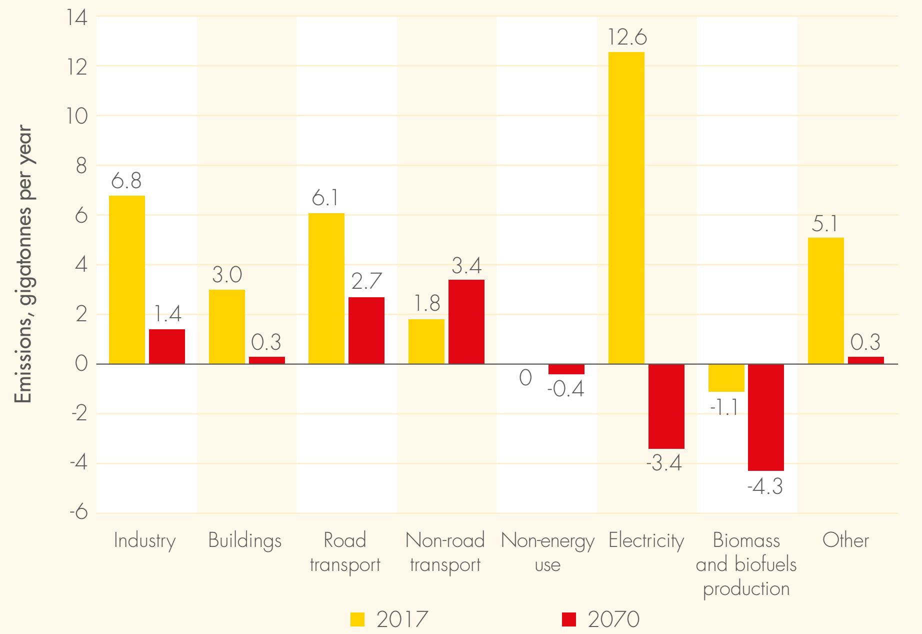
CHAPTER 6
ACHIEVING THE BALANCE

6. ACHIEVING THE BALANCE

Remaining emissions

In **Sky**, fossil fuel use declines sharply after 2030 – but it cannot be eliminated in all sectors to the extent that warming is limited to well below 2°C. Even with a broad suite of technologies available and a 50-year timeframe for deployment, not all technologies and energy services can be swapped out for non-emitting alternatives at the necessary pace. Indeed, in so-called "hard-to-abate" sectors, practical alternatives have yet to be developed, and innovation rather than deployment is still the current order of the day.

HOW THE ENERGY SYSTEM CO_2 EMISSIONS IN **SKY** TRANSFORM TO NET-ZERO BY 2070



Note: "Other" represents other energy-sector activities, such as the transport and refining of fossil energy, centralised heat generation, and in the future, hydrogen production.

Source: Shell analysis

REMOVING CARBON THROUGH USE

Carbon capture and use (CCU) operates very differently from CCS (permanent geological storage). There are examples of capture and use in practice today, such as the conversion of CO_2 to certain chemicals (for example, urea, the basis for fertilisers) and the production of plastics such as polycarbonates. These processes all require CO_2 as a feedstock, but are not necessarily designed to store it permanently. If the carbon is returned to the atmosphere, such as through the degradation or incineration of the product that is made, then the net impact of the process may be zero in terms of atmospheric CO_2 levels.

In a future energy system, there are two ways in which CCU could become effective:

- CCU might be focused on manufacturing synthetic hydrocarbon fuels, which could displace the need for fossil hydrocarbons. However, the synthetic fuels industry would need substantial technological innovation and then would need to scale very significantly before it could have a material impact, so this route is unlikely to be a significant contributor over the timescale addressed in **Sky**. Synthetic fuels are not a sink in themselves, since once they are made and used, the CO_2 is returned to the atmosphere.
- CCU could be applied to the manufacture of certain goods – for example, building materials or plastics. But to act as a mitigation mechanism akin to CCS, CCU must lead to more-or-less permanent storage. The total stock of the product must be maintained for a very long time (at least a century or more) for CCU to approach CCS equivalence. In **Sky**, fossil fuels and bio-feedstocks are used to make such products, acting as an effective carbon sink.

This situation means that assigning a mitigation value to CCU plays a critical role. Doing so for CCS is a relatively simple task – each tonne stored can be counted as permanent mitigation and will contribute to the overall task of reaching net-zero emissions. The same cannot be said for CCU. While carbon can be embedded in urea or polycarbonates, there is no established protocol to define this as permanent mitigation. Work remains to be done in this field.

Although every facet of the current energy system has either changed or is in transition in 2070, remaining fossil fuel use leads to emissions of some 15 Gt CO_2 per year, reducing to 11 Gt by 2100. This is about one third of today. For this reason, emission sinks (i.e., removing CO_2 from the atmosphere) feature in most long-term, low-emission energy scenarios, including **Sky**.

The Paris Agreement recognises this reality when it calls for a balance between emissions by sources and removals by sinks of greenhouse gases. Importantly, the Agreement recognises that even after significant mitigation efforts through substitution, greenhouse gas emissions will continue, meaning that sinks will be essential at some level.

Balancing mechanisms in the energy system

Within the energy sector, **Sky** utilises three mechanisms that either prevent the release of CO_2 or remove CO_2 from the atmosphere. In total, the mechanisms handle one trillion tonnes of CO_2 over the course of the century.

1. Conventional CCS applied in large point-source emitting facilities such as cement plants or iron ore smelters. The CO_2 is geologically stored, typically two to three kilometres below the surface. CCS technology is applied at scale in several facilities around the world today.
2. Conventional CCS applied in power plants operating with a sustainably produced biomass feedstock. In totality, this mechanism results in net removal of CO_2 from the atmosphere.
3. The production of various products, such as plastics, from fossil fuels or a biomass feedstock. These materials are then used by society and can deliver effective storage of carbon rather than releasing it to the atmosphere as CO_2. When the carbon is derived from biomass, this mechanism also results in net removal of CO_2 from the atmosphere.

The issue of greenhouse gas emissions extends beyond energy use, and there is also interplay between the energy system and natural systems, for example, when using bioenergy. **Sky** recognises this and the scope that exists for actions in one system to help the other and vice versa.

“In Sky, changes in land-use and an end to deforestation are critical to the overall outcome. But large-scale reforestation can be a game changer, with the potential to push even further to the ambitious 1.5°C goal of the Paris Agreement.

Nature-based solutions: Reforestation, restoration, and avoided deforestation

Land-use change throughout the world over the last century (but extending back hundreds of years) has contributed to the rise in atmospheric CO_2 and continues to do so. The Global Carbon Project has estimated that land-use changes have resulted in five Gt CO_2 per year being emitted for each of the last 20 years. If these changes can be stopped, many degraded ecosystems can be restored. The Nature Conservancy has estimated that around 500 Gt CO_2 in total can be drawn down from the atmosphere at costs today below US$100/tonne CO_2 and sustainably stored by improved soils and extended forest cover.

The fourth mechanism introduced into the scenario is one that is widely understood and much used today – reforestation, restoration of degraded land, and avoided deforestation. Without tackling these areas alongside the energy system, overall net-zero emissions cannot be achieved. **Sky** assumes significant land-related actions to bring the land-use and agricultural systems back into balance and ensure that by 2070 net deforestation has reached zero.

Further, very large-scale reforestation could accompany this, offering the opportunity to remove additional carbon from the atmosphere and thereby approaching the stretch goal of the Paris Agreement – to limit the rise of the global average surface temperature to just 1.5°C.

The scale of change required in the land-use sector will require action by governments, both domestically and through international cooperative mechanisms, such as those included within the Paris Agreement.

The design, implementation, and use of these mechanisms can trigger private sector involvement, which in turn could accelerate the necessary activities.

Early action is important in this area given the decadal process of restoration and reforestation. Therefore, in **Sky**, these nature-focused practices play an important role alongside the transformation of energy use across the economy. Indeed, in the coming decades, some of the initial impetus for these developments can come through industry support and utilisation of certified activities and traded certificates to compensate for hard-to-mitigate energy-related emissions. CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), the system agreed by the aviation industry in 2016 to counter the rising emissions in that sector, is a good example – nature-based solutions feature within their proposed offset categories. Over time, however, in **Sky**, systems such as CORSIA shift towards one of the three carbon-capture categories above for offset purposes.

By 2070 the goal of net-zero emissions is achieved within the energy system, and the interplay between energy and natural systems continues. As illustrated, the energy system balance is reached through combining CO_2 use and geological CO_2 storage with biomass feedstocks to balance remaining fossil fuel emissions still going to the atmosphere.

Through a broader swathe of actions across all sectors, including steps taken to bring net deforestation to zero and to begin the process of land restoration, the overall Paris Agreement goal of balancing remaining anthropogenic greenhouse gas emissions with sinks in the second half of the century is achieved.

NATURE-BASED SOLUTIONS: EXTENDING AMBITION THROUGH RESTORATION OF NATURE

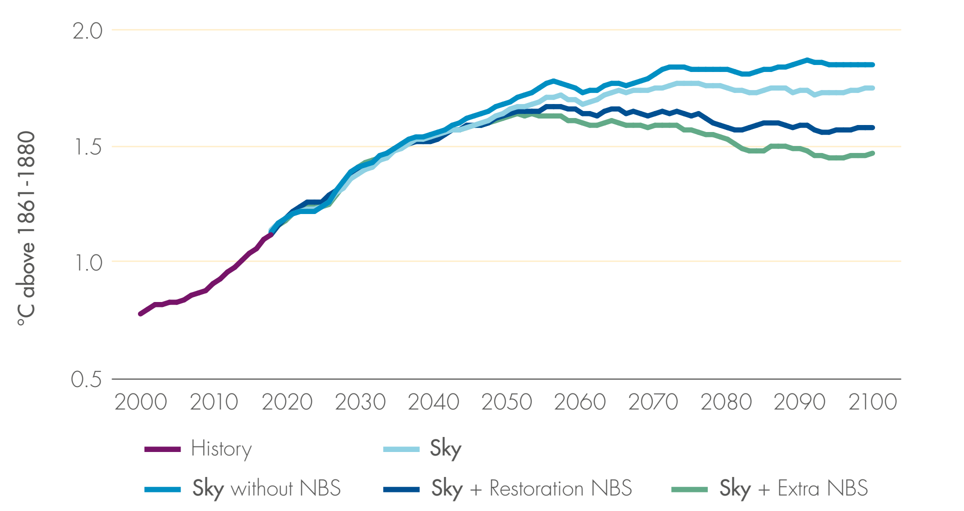
Our base case for **Sky** assumes that CO_2 emissions from land-use change fall to zero by 2070, in line with the energy system reaching net-zero emissions at the same time. But the restoration of ecosystems, including large-scale reforestation, can play a critical additional role, producing a net draw-down of CO_2 from the atmosphere and therefore offering a pathway to the ambitious 1.5°C outcome.

If social barriers can be overcome, such as the impact on agricultural communities, these nature-based solutions (NBS) can help to limit peak warming because scale-up can be considerably faster than transformation of energy technologies.

Research from institutions such as MIT, the Ecosystems Center at Woods Hole, and The Nature Conservancy has indicated that an additional drawdown beyond **Sky** of 10 Gt CO_2 per year is feasible through reforestation, although the scale of the task is very large. Some 700 million hectares of land would be required over the century, an area approaching that of Brazil.

We have run two sensitivities on the **Sky** scenario, in consultation with The Nature Conservancy (TNC) and MIT. The first sensitivity involves accelerated avoidance of deforestation and the introduction of a similar scale of restoration. We have called this "**Sky** + Restoration NBS". This adds five Gt CO_2 per year drawdown to **Sky**. The second sensitivity, "**Sky** + Extra NBS", is required to limit warming to 1.5°C and assumes many cost and social barriers can be overcome more successfully so that an additional drawdown rate of 10 Gt CO_2 per year (i.e., 15 Gt per year in total) can be reached.

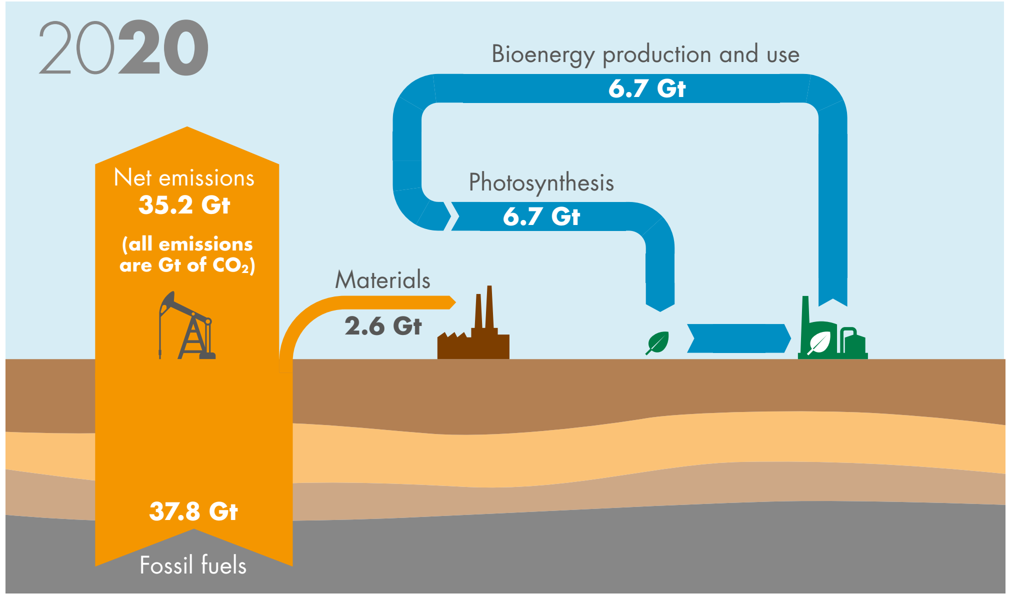
EXTENDING AMBITION IN **SKY**



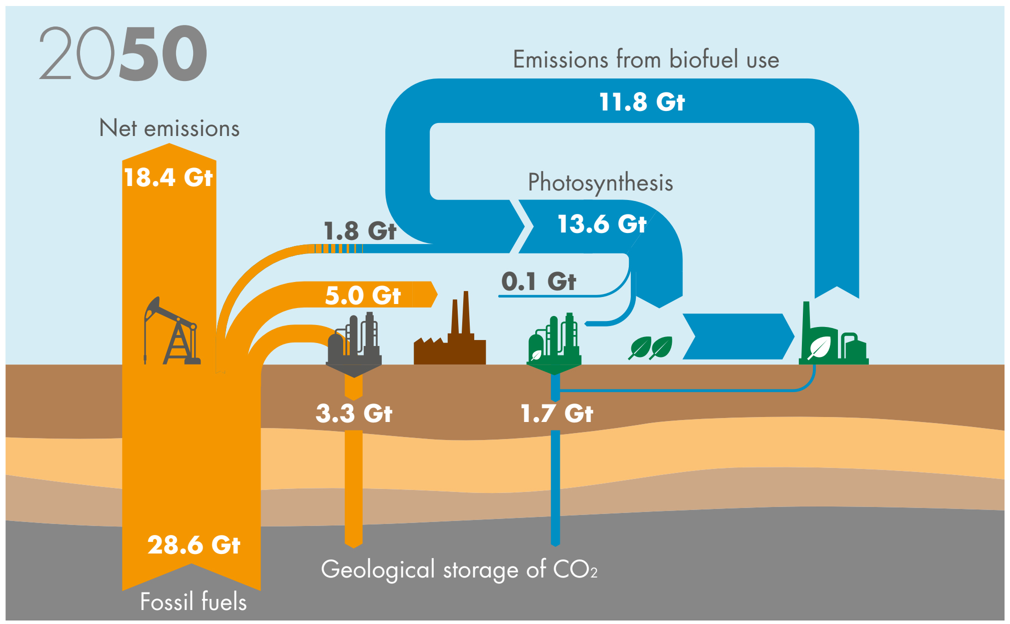
Source: Shell analysis, MIT

THE EVOLVING ENERGY SYSTEM CO_2 BALANCE SHEET IN **SKY**

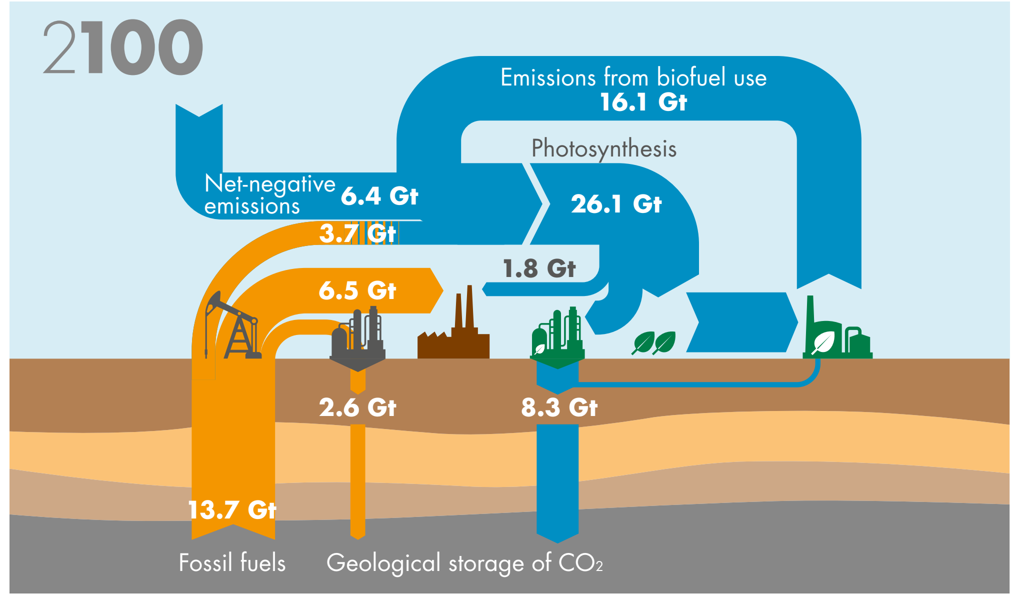
Fossil fuel production | CCS | Biofuel production | Bioenergy with CCS | Carbon in products | Growing biomass



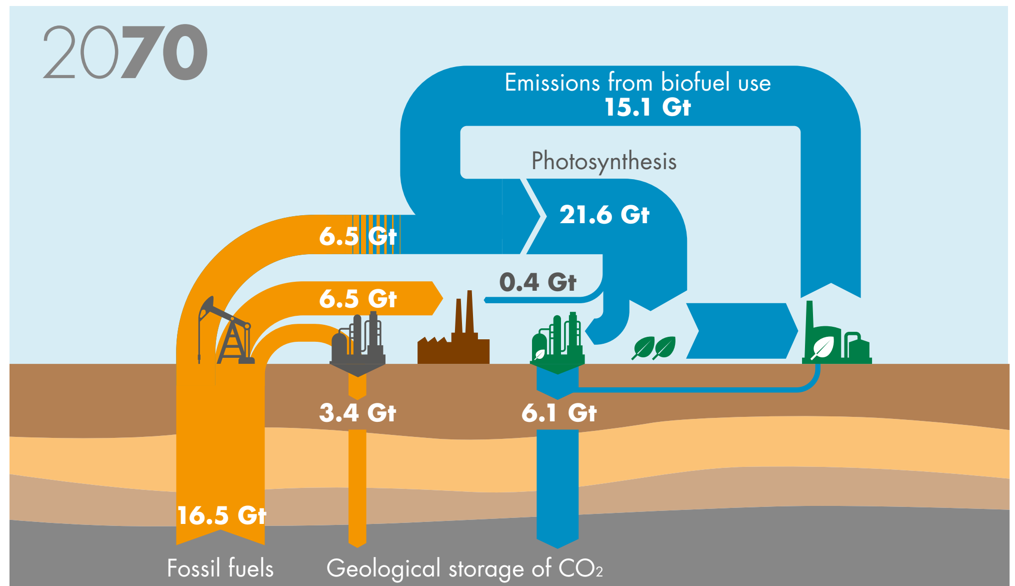
Today, most carbon in fossil energy production is burned and emitted to the atmosphere, while the CO_2 absorbed by wood and other plants used for energy is also returned to the atmosphere.



In **Sky**, in 2050, the storage of CO_2 is rapidly scaling up. There are equal contributions from the embedded carbon in materials production and CCS. Fossil energy CCS leads the way, but bioenergy CCS (BECCS) is close behind.

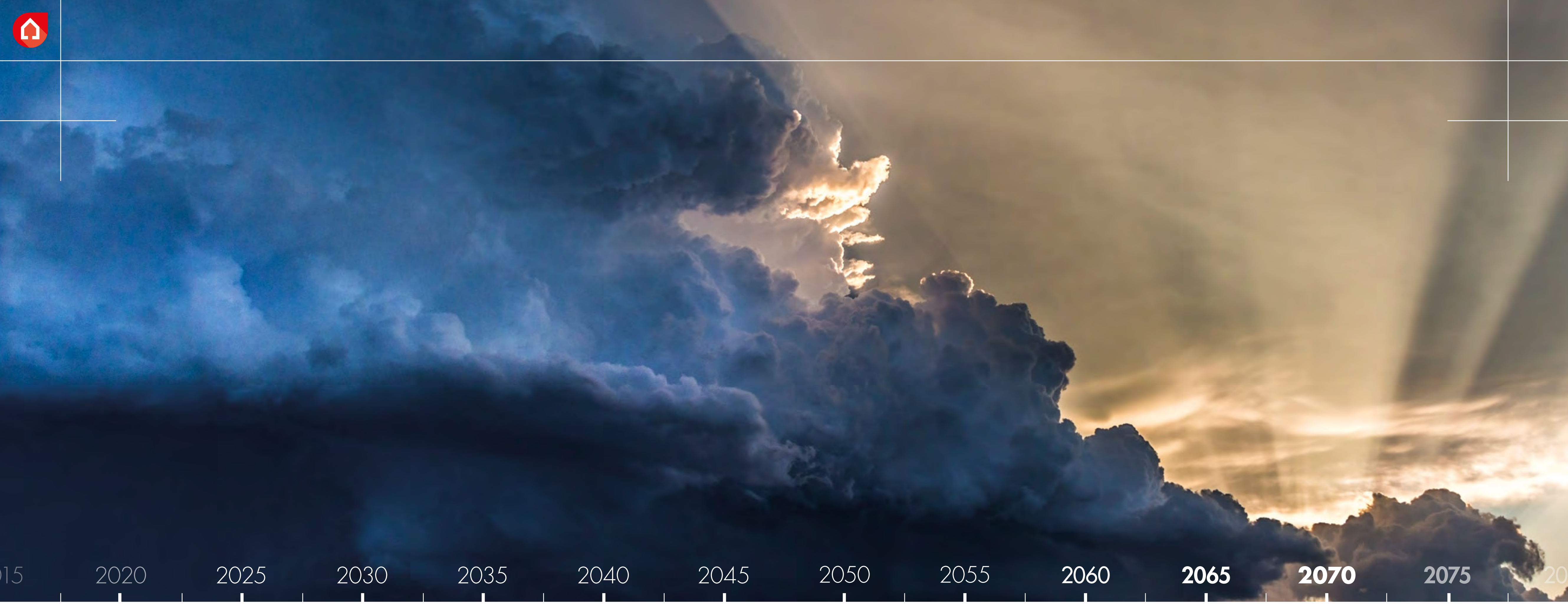


In **Sky**, at 2100, the bioenergy system has reached its resource base limit and is twice the size of the fossil energy system in CO_2 terms. The active management of CO_2 means that the total energy system is providing a drawdown of CO_2 from the atmosphere.



Note: The numbers do not add up exactly in 2070 owing to rounding up of data.

In **Sky**, in 2070, the energy system has achieved net-zero emissions. Fossil energy production is less than half today's level. Alongside direct CCS and the use of carbon for materials, the remaining fossil energy emissions are fully offset by captured CO_2 from an expanded bioenergy system.



CHAPTER 7

THE PARIS AMBITION REALISED

7. THE PARIS AMBITION REALISED

In **Sky**, beyond 2070, carbon capture levels off at around 12 Gt per year, but fossil fuel use continues to decline. This takes the overall energy system into negative emission territory, which draws down on accumulated carbon within the biosphere. As a result, warming peaks during the 2070s and levels out through the balance of the century.

By 2100, warming of the climate system is held to around 1.75°C according to independent expert analysis of the energy-system emissions trajectory described by **Sky**. In addition, a meaningful legacy carbon removal industry offers the 22nd-century society the opportunity for further climate restoration.

In addition to the actions covering the energy system outlined in **Sky**, significant reforestation action and restoration of natural ecosystems, such as wetlands, offer the possibility of limiting warming to 1.5°C, the ultimate ambition of the Paris Agreement.

Of course, the big challenge is whether there is the political will and, underlying this, the societal will to put in place and maintain the frameworks that are necessary to address this awe-inspiring task – re-wiring the whole global economy in just the next 50 years.

The Sky scenario outlines what we believe to be a technologically, industrially, and economically possible route forward. This should give us all some hope – and perhaps some inspiration. In more practical terms, perhaps this analysis can provide useful pointers to areas where focused attention could produce the best results.

> “The **future** depends on what we do in the **present.**
>
> Mahatma Gandhi

Acknowledgements

We wish to thank the many people consulted externally in the development of **Sky**.

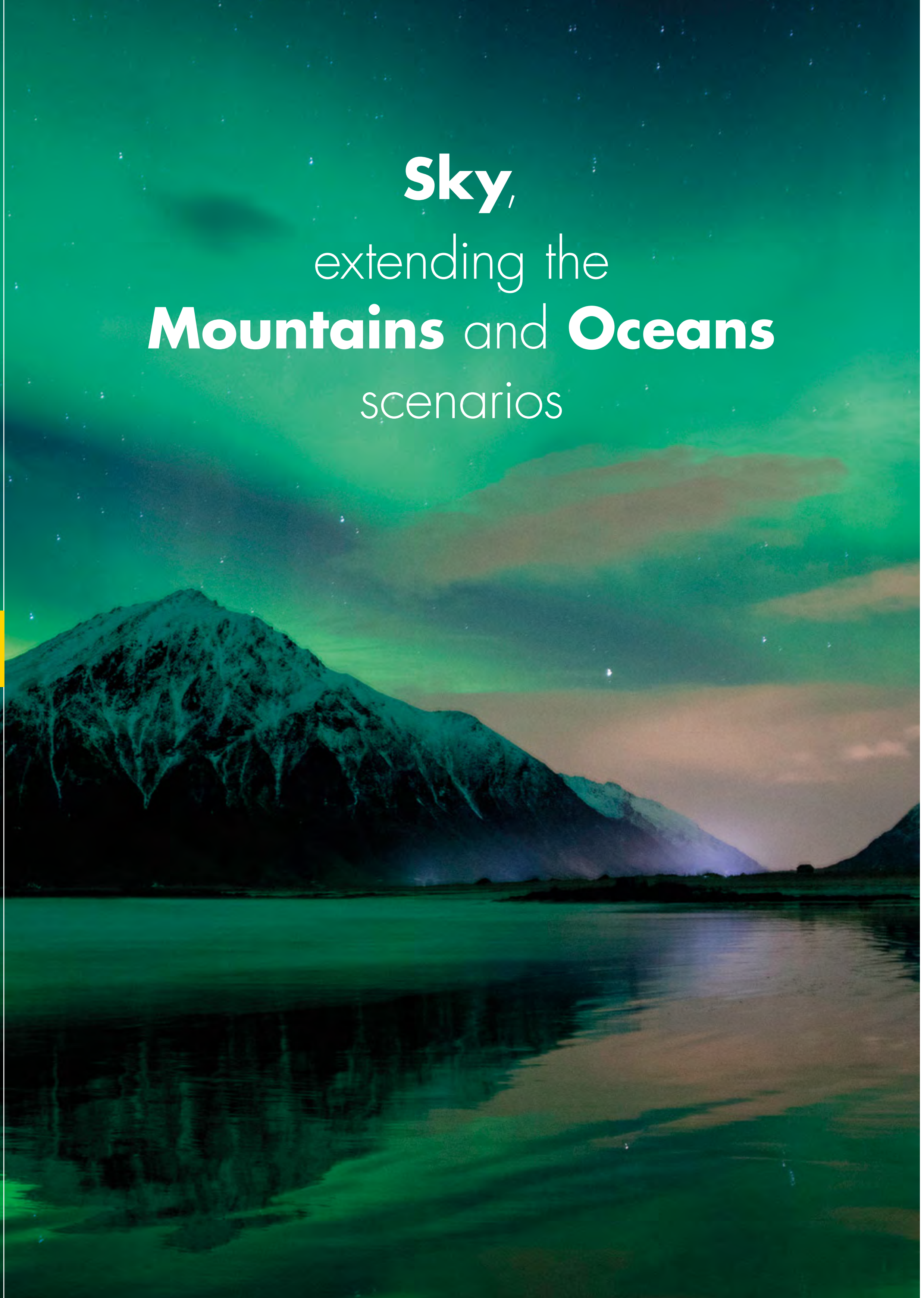
Particular thanks go to The Nature Conservancy.

We would like to recognise the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change for assessing the climate impacts of **Sky** and contrasting it with **Mountains** and **Oceans**.

For the **Sky** scenario, MIT modelled the impact using their Integrated Global System Modelling (IGSM) framework. Shell has donated US$100,000 to the Joint Program in recognition of the effort. MIT will publish a Joint Programme Report on the work it has done.

This work is partially based on historical data from the International Energy Agency's (IEA) World Extended Energy Balances © OECD/IEA 2017. The work has been prepared by Shell International B.V. and does not necessarily reflect the views of the IEA.

Please visit www.shell.com/skyscenario for additional data tables and further background information.



GLOSSARY

Energy Units

bcma	billion cubic metre per year
GJ	gigajoule (10^9 joule). The joule, J, is a unit of energy; 4.2 J are needed to heat one gram of water by 1°C.
EJ	exajoule (10^{18} joule)
kWh	kilowatt-hour (There are 3600 J per Wh). The unit Wh is commonly used for electricity generation, and J for energy more broadly.
TWh	terawatt-hour (10^{12} watt-hour, or one trillion watt-hours). A one GW power station operating for 300 days per year will produce about seven TWh.
GW	gigawatt (10^9 watt, one billion watts). A one GW power station is the typical size for a modern coal, gas, or nuclear installation.
Gt	gigatonne (10^9 tonne)

Other Terms

BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CCU	carbon capture and use
EV	electric vehicle, defined as either a battery electric vehicle or a plug-in hybrid electric vehicle
FCEV	fuel-cell electric vehicle
LPG	liquefied petroleum gas
NBS	nature-based solutions; the use of avoided deforestation, reforestation, and other restoration of natural ecosystems
NDC	nationally determined contribution; the actions countries take to reduce greenhouse gas emissions under the Paris Agreement
NZE	net-zero emissions, i.e., a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases
primary energy	the supply of energy sources including oil, natural gas, coal, bioenergy, nuclear energy, and renewables. Primary energy is energy drawn from nature, in its first usable form.
final energy	the demand for energy carriers, such as electricity or liquid fuels, by final consumers, such as industry, households and transport, for all their energy uses. When natural gas is used for home heating, it is counted as final energy; when it is used to generate electricity in a power station it is counted as primary energy.
solar PV	solar photovoltaic panels used for electricity generation

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This booklet contains data from Shell's new **Sky** Scenario. Unlike Shell's previously published **Mountains** and **Oceans** exploratory scenarios, the **Sky** Scenario is targeted through the assumption that society reaches the Paris Agreement's goal of holding global average temperatures to well below 2°C. Unlike Shell's **Mountains** and **Oceans** scenarios which unfolded in an open-ended way based upon plausible assumptions and quantifications, the **Sky** Scenario was specifically designed to reach the Paris Agreement's goal in a technically possible manner. These scenarios are a part of an ongoing process used in Shell for over 40 years to challenge executives' perspectives on the future business environment. They are designed to stretch management to consider even events that may only be remotely possible. Scenarios, therefore, are not intended to be predictions of likely future events or outcomes and investors should not rely on them when making an investment decision with regard to Royal Dutch Shell plc securities.

Additionally, it is important to note that Shell's existing portfolio has been decades in development. While we believe our portfolio is resilient under a wide range of outlooks, including the IEA's 450 scenario (World Energy Outlook 2016), it includes assets across a spectrum of energy intensities including some with above-average intensity. While we seek to enhance our operations' average energy intensity through both the development of new projects and divestments, we have no immediate plans to move to a net-zero emissions portfolio over our investment horizon of 10-20 years. Although, we have no immediate plans to move to a net-zero emissions portfolio, in November of 2017, we announced our ambition to reduce our net carbon footprint in accordance with society's implementation of the Paris Agreement's goal of holding global average temperature to well below 2°C above pre-industrial levels. Accordingly, assuming society aligns itself with the Paris Agreement's goals, we aim to reduce our net carbon footprint, which includes not only our direct and indirect carbon emissions, associated with producing the energy products which we sell, but also our customers' emissions from their use of the energy products that we sell, by 20% in 2035 and by 50% in 2050.

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