Shell scenarios

The Energy Security Scenarios

Full report

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Contents

A word on scenarios

What we present here are scenarios. To get the most from them, it is important to know what these are and what they are not. They are an exploration of how the world could possibly evolve under different sets of assumptions. They are informed by data, constructed using models and contain insights from leading experts in the relevant fields.

The process of creating scenarios involves considering different versions of possible futures. Some of these may seem unlikely or even surprising, yet they could still be possible. Other scenarios explore the possible outcomes of choices the world already appears to be making. This perspective offers the reader the chance to evaluate those choices. It is by exploring the assumptions behind such possible futures that readers can expand their world view and consider the options for significant change. An example of one such assumption, which comes from the **Sky 2050** scenario detailed in these pages, is that all sales worldwide of passenger vehicles with an internal combustion engine end by 2040. The biggest assumption in **Sky 2050** is that multiple changes of this scale and speed occur simultaneously across the energy system.

The value to Shell of producing scenarios is to help senior management think about the long-term challenges that Shell could face. In this way, the thinking in Shell's scenarios may influence the company's strategy – as one of many inputs – but that is as far as it goes: scenarios are not expressions of Shell's strategy, they are not Shell's business plan and they do not necessarily reflect the thinking or behaviour of the business.

Shell also publishes some of its scenario thinking to help governments, academia and business to think about the long-term challenges that they, and the world at large, could face.

As useful as scenarios are, however, they are not created by using a crystal ball. So, while scenarios may contain a great deal of valuable information and insight, they are absolutely not predictions or expectations of what will happen, or even what will probably happen. Nor are they statements of what should happen. In short, scenarios are possible worlds built from incomplete and uncertain information. That is true of all scenarios, not just those created by Shell. All scenarios probably hold truth, but all of them are likely to be wrong in one way or another.

Ultimately, for all readers, scenarios are intended as an aid to making better decisions. They stretch minds, broaden horizons and explore assumptions.

Introduction

Net zero: reset and go again

As recently as 2021, at COP26 in Glasgow, world leaders gathered and collectively promised to deliver on the stretch goal of the Paris Agreement and limit global warming to 1.5 degrees Celsius (1.5°C). Yet, within months, the Russian invasion of Ukraine had caused political upheaval and pointed society in a different direction. In the wake of COP27 in Sharm el-Sheikh, this publication seeks to explore the landscape global society now inhabits and what the trends visible in 2022 could mean for the future. There is a particular focus on the potential climate outcomes for the planet. In one scenario, we look at how things could evolve if current trends continue and, in another, we look at a possible optimistic future. Finally, we discuss how the world could switch from where it appears to be headed, towards a lower-carbon future.

The background

In early 2021, Shell released three new scenarios: **Waves, Islands** and **Sky 1.5**. Each of these was built around possible approaches to climate change action as the world emerged from the COVID-19 pandemic.

Waves assumed that society would prioritise repairing the economy. In **Waves** this focus on wealth pushes other societal and environmental pressures into the background, until their relative neglect provokes backlash reactions. This prompts rapid action to address global emissions but, even though the world achieves net-zero emissions, it comes too late to meet the stretch goal of the Paris Agreement – to limit global average warming to 1.5°C above pre-industrial levels by the end of this century. This scenario shows late, but fast decarbonisation.

Islands assumed that security becomes the priority after COVID-19. In **Islands** a new emphasis on nationalism threatens to dismantle the post-war geopolitical order and co-operation is limited. Competition between nations, however, means technology advances. Innovations are adopted, infrastructure is renewed and eventually the world does still reach net-zero emissions. The goal of the Paris Agreement is missed. This is late and slow decarbonisation.

Sky 1.5 set a fixed goal of achieving the Paris Agreement and worked backwards from that point to explore how that could happen, taking into account the global situation in the early 2020s. Using this normative approach, in **Sky 1.5** there is a post-pandemic focus on health and public well-being that results in high levels of co-operation towards mutually beneficial aims. This is accelerated decarbonisation.

The shift to a security mindset

In February 2022, however, the fragile post-Cold War global order cracked apart when Russia invaded Ukraine. There had already been worries about the supply of fossil-fuel energy, but the invasion made it clear how dependent society is, collectively, on traditional fuels like oil and gas. As nations respond, the world is collectively plunging into the security mindset that dominates **Islands**.

As the security mindset begins to take hold and national interests take precedence within political agendas, a tension emerges between what was promised to the world at COP26 in Glasgow and what nations must do to address immediate energy concerns.

Four different responses to the situation are beginning to be visible. These involve countries behaving in similar ways when they share similar vulnerabilities to energy supply failures and energy price volatility. This publication explores the possible results as these four responses – which we call "archetypes" – interact. Two scenarios emerge, both starting with the security mindset we see today.

One potential future is painted in the **Archipelagos** scenario, so named because it is rooted in our earlier **Islands** scenario and an archipelago is a cluster of islands. Another, more optimistic, potential future is set out in the **Sky 2050** scenario. The **Archipelagos** scenario seeks to follow a possible path from where the world was in 2022, while **Sky 2050** takes a normative approach that starts with a desired outcome and works backwards to explore how that outcome could be achieved. In the case of **Sky 2050**, the future it is aimed at is a world that achieves two key things: net-zero emissions by 2050 and global warming limited to 1.5°C by the end of the century. Working backwards to the realities of 2022 means that, while **Sky 2050** does make many stretching assumptions, there is no expectation of halving emissions by 2030 as required by the Glasgow Climate Pact from COP26.

In addition to the **Archipelagos** and **Sky 2050** scenarios, we also explore how the world could seek to bridge the gap between these two possible futures. It is worth noting that, even in **Sky 2050**, global warming does exceed 1.5°C before it drops back down because of net removal of CO_2 from the atmosphere.

The overshoot is an outcome some will consider unacceptable but, as our modelling implies, any discussion on how to prevent a breach of 1.5°C would need to include action greater than the already substantial measures laid out in **Sky 2050**, which may not be technically feasible.

Global tension translates into four behaviour archetypes

The starting point for both the scenarios we explore is the way countries are reacting to their circumstances. We have identified four different archetypes, with nations behaving in roughly similar ways when they share similar vulnerabilities to energy supply disruption and energy price volatility. In both scenarios, the security mindset leads to aggressively competitive, rather than co-operative, decarbonisation.

The first archetype is called **Green Dream** and can be observed in the European Union. The EU's wealth enables it to deal with energy price volatility, but its advanced economies and depleted oil and gas resources make it highly vulnerable to energy supply failures. These countries seek security by driving hard towards energy efficiency and renewable generation.

The second archetype is called **Innovation Wins** and can be seen in countries like the USA and major energy resource holders like the United Arab Emirates. These countries are often self-sufficient in energy so are not vulnerable to supply failures, but their political systems are exposed to swings in the energy price. These countries do not feel so threatened in the short term, but invest heavily in innovation and infrastructure as longer-term solutions to their energy needs and the needs of their energy customers.

The third archetype is **Great Wall of Change**, which is mainly relevant to China. China is insulated from both supply and price concerns by several factors: the size of its economy, its large coal reserves and the scale of the investments it is making in its own energy supply and infrastructure. China takes a cautious approach, aware of the need to move away from coal – by far the most emissions-intensive fossil fuel – and carefully monitoring global energy market developments. It looks to use its manufacturing strength to grow its position as a global low-carbon energy powerhouse.

The final archetype is **Surfers**, which subdivides into **Emergent Surfers**, like India, and **Rising Surfers**. **Rising Surfers** include the world's least developed economies, and they are more focused on establishing the basic foundations for development, such as infrastructure. **Surfers** countries do not produce significant amounts of energy and so they are vulnerable to both energy supply disruption and price swings. **Emergent Surfers** quickly adopt new technologies while **Rising Surfers** keep a closer focus on spreading access to energy. **Surfers** of all types seek out partnerships and try to ride the opportunities created by other archetype countries.

The Energy Security Scenarios in summary

In **Archipelagos**, the security mindset emerging in 2022 takes hold worldwide. Global sentiment shifts away from managing emissions towards energy security. Despite this, the drive for energy security still involves significant use of low-carbon technologies. These dynamics translate into global emissions stabilising in the 2020s, and falling from the mid-2030s. This makes for a faster energy transition compared to the 2021 **Islands** scenario.

Nationalism underpinned by renewed militarism grows, especially in those regions straddling two spheres of influence. The war over whether Ukraine belongs with Europe or with Russia turns out to be a template for any number of other disputed countries and territories. In many ways, the geopolitical order of the 2030s resembles the 19th century world of power alliances more than the globalised post-Cold War order.

Competition between nations spreads into many aspects of life, and results in multiple technology races – including in relation to low-carbon technologies. Rather than acting together to save the planet, groups of nations now scramble to secure energy supplies and focus on building energy resilience to withstand future shocks. Emissions fall through the century, with net zero in sight, but still not achieved, by 2100.

The global average surface temperature is still rising in 2100 but begins to stabilise shortly afterwards at around 2.2°C as emissions close in on net zero.

In **Sky 2050**, the war in Ukraine translates into an uneven start as short-term energy security concerns dominate. Over time, however, a longer-term perspective on security emerges which includes the need to meet the threat of climate change. Momentum towards emissions reductions then gathers pace as the need to deliver low-carbon energy infrastructure grows, driven largely by concerns over security and price. While progress does not meet the most optimistic expectations, emissions start to fall from 2025. By 2040, the goal of net-zero emissions is clearly in sight.

At the outset, international institutions appear ineffectual in supporting the Paris Agreement, and nations cling to archetype behaviours which are focused on their vulnerability to energy supply failure or energy price volatility. Soon, however, citizens themselves start to push for change. Politicians adopt climate-friendly policies to secure support, especially among the young. Quickly these policies become national priorities, and success in fulfilling their aims becomes a measure of national power.

What might have taken decades to negotiate now takes much less time as individual nations, cities and companies "just go for it", with the world reaching net-zero emissions in 2050.

By 2100, despite overshooting 1.5°C earlier in the century, the rise in global average surface temperature is back below 1.5°C in 2075 and then falls back to around 1.2°C by 2100.

About this PDF document

This publication was designed to be read as an interactive experience, but we have also published it as a PDF for those who prefer to read it in this format. The original text includes a degree of repetition to allow for the interactivity – we hope it does not interfere with your reading experience of the PDF.

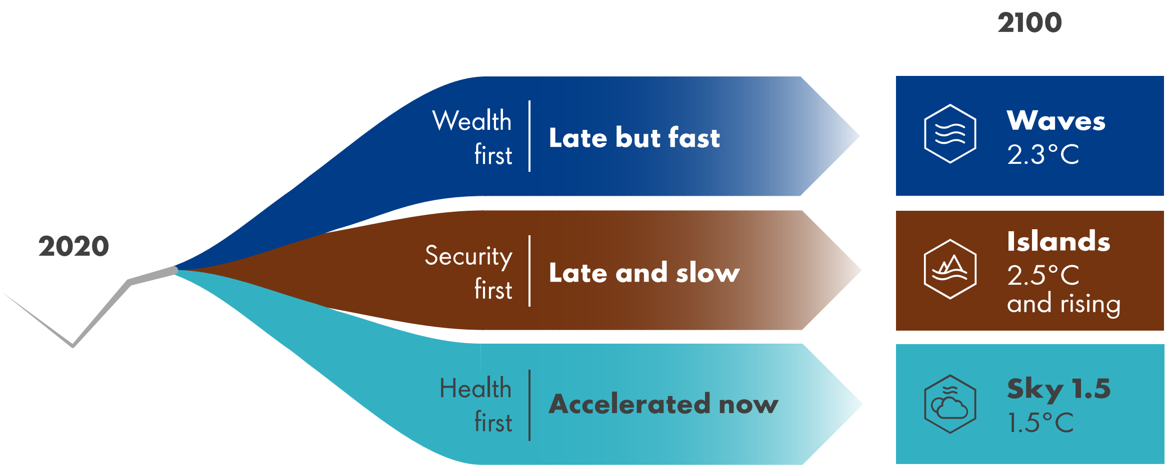
The evolving energy security challenge

Backdrop: the Energy Transformation Scenarios

The Shell Energy Transformation Scenarios form the backdrop to this publication. Released in 2021 before the Russian invasion of Ukraine, they explore three potential responses to the COVID-19 crisis and the climate change challenge.

- **Waves** assumes that society prioritises repairing the economy. This focus on wealth pushes other societal and environmental pressures into the background, until their relative neglect provokes backlash reactions. This prompts rapid action to address global emissions but, even though the world achieves net-zero emissions, it comes too late to meet the stretch goal of the Paris Agreement – to limit global average warming to 1.5°C above pre-industrial levels by the end of this century. This scenario shows late, but fast decarbonisation.
- **Islands** assumes that security becomes the priority. In **Islands**, a new emphasis on nationalism threatens to dismantle the post-war geopolitical order and co-operation is limited. Competition between nations, however, means technology advances. Innovations are adopted, infrastructure is renewed and eventually the world does reach net-zero emissions. The goal of the Paris Agreement is missed. This is late and slow decarbonisation.
- **Sky 1.5** assumes that health and public well-being become society's goals. In **Sky 1.5**, lessons learned from the COVID-19 pandemic result in high levels of co-operation towards mutually beneficial aims. This helps create a pathway to better health for both the planet's people and the planet itself. This enlightened approach succeeds in meeting the 1.5°C stretch goal of the Paris Agreement, which is to limit global average warming to 1.5°C above pre-industrial levels by the end of this century. This is accelerated decarbonisation.

Waves and **Islands** are traditional exploratory scenarios. They explore possible future worlds where a shift to net-zero emissions is desired, but geopolitical and societal headwinds present challenges. Both these scenarios result in temperatures above those called for by the Paris Agreement. **Sky 1.5**, on the other hand, is normative. This means it sets a fixed future of achieving the Paris Agreement and then works backwards from that point to the realities of 2019. In this way, **Sky 1.5** explores how the world might meet the stretch goal of the Paris Agreement.



The shift to a security mindset

This scenario publication exists because the Russian invasion of Ukraine radically realigned global thinking.

Since the end of the Soviet Union, many had assumed that, despite inevitable geopolitical frictions, the forces of globalisation and liberalisation would prevail.

Multiple developments seemed to support this view, including interconnected supply chains, international travel and global cultural events. Other sources of optimism included the spread of social media, the unifying effects of digitalisation and a shared concern over climate change. Beneath all of this, however, huge cracks had opened up in the global order with growing doubts about the future of globalisation itself. When Russia launched its full-scale invasion of Ukraine in February 2022, these cracks were exposed for all to see.

The signs pointing to trouble ahead have been present for some time. There has been a rise in nationalism, populism and growing inequality within and between states, as well as a failure to deliver significant climate finance. An example is US-China relations. What was initially seen as a politically motivated, short-term trade war between the USA and China became a widening rift, enlarging to include security concerns, such as the status of Taiwan. Other examples include Brexit (the decision by the UK to leave the European Union), increasingly difficult trading relations between Australia and China and the brief mob rule of January 6, 2021, in Washington D.C. With the war in Ukraine, the world has seen the threat to use nuclear weapons, the undercutting of international institutions such as the UN and interruptions in the supply of energy and food that are affecting the whole world. In the coming years, there appears to be little prospect of any return to the former world order.

Even though global volatility has been a near constant of the 21st century so far, the situation in Ukraine is proving to be a turning point. The stress it placed on the global supply of energy, food and other critical materials was only the start. Almost no aspect of the world order has remained untouched, including national security, technology, finance, refugees, commodity markets, global inflation and humanitarian aid.

How security fears have changed the world

As the direct impacts of the COVID-19 pandemic began to ease in late 2021 and global leaders gathered in Glasgow for COP26, there were signs the world might follow the pathway set out in our **Waves** scenario – a delayed but fast path to global decarbonisation emerging through a global focus on economic issues. It even looked possible that the world could follow the **Sky 1.5** pathway, in which it meets the stretch goal of the Paris Agreement through a focus on health and well-being. The situation in 2022 suggests a significantly different future is coming, particularly in relation to meeting the goal of the Paris Agreement. Instead of **Waves** or **Sky 1.5**, society appears to be plunging into an **Islands** world, with a focus on security potentially leading to late and slow decarbonisation. Driving us in this direction, in addition to the war in Ukraine, is the increasingly emotive nature of the global conversation in a world awash with information and misinformation.

In the **Islands** world, co-operation fades and post-war multilateral institutions falter. Given the distrust that prevails in **Islands**, the UN becomes less relevant, even as it attempts to press forward with its broad agenda, including the Paris Agreement. Instead, regionalisation emerges. This involves a further strengthening of regional organisations and alliances according to single-issue interests.

These alliances become more transactional, changing and shifting according to the issue at hand. In **Islands**, domestic security issues threaten to slow the energy transition, especially when governments choose to rearm their militaries and strengthen their own borders.

But the **Islands** future is not set and, even as the world adopts its security-first mindset, other variations on the future are possible. The **Archipelagos** and **Sky 2050** scenarios explore two pathways forward, dealing with the tension that emerges between what was promised to the world at COP26 in Glasgow and what nations must do to address immediate energy security concerns.

In imagining the **Archipelagos** scenario, basing it in the realities of 2022, we were mindful that the pressures to act on climate change will not go away. In fact, those pressures grow as the carbon budget is consumed and the world experiences a first year with temperatures 1.5°C higher than the pre-industrial average. This moment, and the climate-related events society is likely to see as the planet warms further, potentially leads to increasing societal activism that forces change irrespective of the security agenda. Another possible future takes us towards **Sky 2050**, where a mindset around environmental security dominates.

The fact that the war in Ukraine is a geopolitical shock with fossil fuels at its heart is important. It has reminded everybody of the importance of fossil fuels and their reliance on them. This realisation has already added to the belief of many that the global dependency on fossil fuels must end quickly. In **Archipelagos,** the focus on security also includes a focus on energy security. So, while the prospect of CO_2 emissions may not be enough to provoke movement, there is a different spur to action: the threat of a new Cold War-style stand-off with energy supply used as a weapon. It leaves governments throughout the world seeking security of energy supply as a national priority. In some cases, governments deliberately attempt to reduce domestic energy demand.

Responses to a security-focused world

Four different responses to the emerging landscape of 2022 are beginning to be visible, with countries acting in similar ways when they share similar vulnerabilities to energy supply failures and energy price volatility. This publication explores the possible results as these four responses – which we call "archetypes" – interact and move towards a low-carbon energy world.

The security-first mindset results in aggressive competitive, rather than co-operative, decarbonisation. The four behaviour archetypes are called **Green Dream**, **Innovation Wins**, **Great Wall of Change** and **Surfers**.

From the potential interaction between these behaviour archetypes, two revised energy security scenarios emerge.

One possible future is painted in the **Archipelagos** scenario. Another, more optimistic, potential future is set out in the **Sky 2050** scenario. The **Archipelagos** scenario seeks to follow a possible path from where the world was in 2022, while **Sky 2050** takes a normative approach – starting with a desired outcome and working backwards to the reality of 2022 to explore how that outcome could be achieved. In the case of **Sky 2050**, the future it is aimed at is a world that achieves two key things: net-zero emissions by 2050 and global warming below 1.5°C by the end of the century.

Green Dream

Four behaviour archetypes form the foundations of the scenarios in this publication. This is a description of the first of those: **Green Dream**. This archetype can be observed in the European Union. The EU's wealth enables it to deal with energy price volatility, but its advanced economies and depleted oil and gas reserves make it highly vulnerable to energy supply failures. **Green Dream** countries seek security by driving hard towards energy efficiency and renewable generation.

The pressures on **Green Dream** countries come from a lack of domestic energy supply combined with climate-related societal pressures not to submit, even in the short term, to the attraction of available fuels such as coal. An example is Germany. Germany wants to end coal power generation, but also feels a need to limit the shift to natural gas because of concerns about price and security of supply. To solve this challenge, Germany could choose to accelerate its push towards wind and solar, while encouraging the consumer trend towards energy efficiency. In addition, it could implement a radical efficiency programme for buildings, to improve energy use within homes and businesses.

The urgent challenge for Europe is how to rapidly halt its use of Russian oil and gas. Many Europeans were already protesting about high energy prices before Russia invaded Ukraine. The invasion has led to further price rises, while disruption to the supply of energy and products has added to the economic challenges.

The **Green Dream** countries' immediate demand for fossil energy, and their ability to pay, draws in supplies from other markets and forces some tough choices, both within and beyond their own borders. This dilemma plays out for liquefied natural gas (LNG), where new import infrastructure is built in **Green Dream** countries, even as they work to phase out fossil fuels. The USA responds best to this demand with its ability to increase supply incrementally. But the scramble for supply raises prices and undermines the economic case for LNG in countries just beginning to import it, or seeking to expand their existing import capacity, such as those included in the **Surfers** archetype.

Reductions in overall energy demand in **Green Dream** countries are driven by efficiency measures and price. Energy effectively becomes rationed because of the high price, caused by either the unspoken short-term policy of governments, or their inability to effectively manage the situation. As household fuel bills rise, policies are introduced to relieve some pain, particularly for the lowest-income households, but implementing these policies adds to the economic burden caused by COVID-19. Political issues related to a fair and equitable transition rise in importance. In addition, the difficult economic circumstances limit society's ability to afford the energy-efficient refitting of industrial facilities or the purchase of new high-efficiency domestic goods.

Overall, **Green Dream** countries that want to stay on their stated route to net-zero emissions will have to balance competing priorities in the next decade. They may need to revise their climate targets if they temporarily turn to coal to meet short-term energy security needs. If they stick to their climate targets, they are likely to find there is not enough low-carbon energy available to satisfy demand and will have to find long-term routes to reducing overall energy use.

Green Dream ultimately finds a way forward when the combination of new energy technologies and high oil and gas prices makes renewable energy solutions very attractive. Even so, the rate of deployment runs into headwinds in central Europe as local populations refuse to host substantial wind and solar sites. Such headwinds prevent **Green Dream** countries from stepping away from oil and gas as quickly as they would like. With economic pressures significant, there is also a reluctance to abandon functioning, but inefficient or carbon-intensive, assets.

Nevertheless, a mood of fossil fuel rejection emerges, which in turn influences climate policy. Importantly, green electricity and green hydrogen begin to dominate the agenda in the 2020s, with technologies related to fossil fuels, such as carbon capture and storage (CCS), seen by many as unhelpful.

Wealthier governments that are determined to move beyond fossil fuels are happy to fund emerging solutions, such as hydrogen in industrial processes and other hard-to-abate areas. But this results in a higher-cost industrial base that struggles to compete in the global market. This, combined with the gas supply shock, leads to a real risk of declining industrial capacity and deindustrialisation. To the extent this happens, it causes other countries to supply the industrial needs of **Green Dream** countries. This has the effect of causing other nations to emit greenhouse gases on behalf of **Green Dream** countries – the effect known as “carbon leakage”. In response, efforts are made to shore up domestic industry through carbon border adjustment mechanisms, which apply financial penalties to high-carbon imports. These mechanisms have a side-effect of encouraging some nations that sit in the **Surfers** archetype to adopt emerging energy technologies so they can secure penalty-free access to the European market.

To maintain their progress on the route to net zero, many **Green Dream** countries place even more emphasis on energy-saving measures, such as energy-efficient buildings. They also further increase investments in wind and solar and begin to develop highly effective public policies to regulate energy through the market. They incentivise products and services that have a low-carbon footprint through public procurement, carbon transparency and carbon pricing. Many cities establish smart grids. Other nations begin to look to Europe for energy policy leadership in their own attempts to manage price and supply dilemmas, and to avoid EU carbon border adjustments.

Innovation Wins

Four behaviour archetypes form the foundations of the scenarios in this publication. This is a description of the second of those: **Innovation Wins**. This archetype can be observed in countries like the USA and major natural resource holders like the United Arab Emirates. These countries are often self-sufficient in energy so are not vulnerable to supply failures, but their political systems are exposed to swings in the energy price. These countries do not feel so threatened in the short term, but invest heavily in innovation and infrastructure as longer-term solutions to their energy needs and the needs of their energy customers.

For countries that fit in the **Innovation Wins** archetype, after more than a decade of relatively cheap energy, the rising price of oil and gas becomes a political touchpoint. This is either for purely domestic reasons or because high prices result in political pressure from countries that import their energy. With price as the immediate concern in the energy system, emissions management fades as a short-term priority.

The USA is one major economy in the **Innovation Wins** category. So too are partners such as Australia, Canada and, to some extent, the UK. In the USA, energy prices dominate the electoral cycle, requiring action by both incumbents and newly elected policymakers.

This archetype also contains several of the major oil and gas producing countries in the Middle East. While these countries are immediate beneficiaries of higher prices, they come under significant political pressure to raise production, particularly those countries that export liquefied natural gas (LNG).

A key characteristic of **Innovation Wins** is the strong belief that, while domestic short-term action can address energy system disruptions, technological change and the pull of the market are the longer-term answers to reaching net-zero emissions. High energy prices drive innovation and the rapid commercialisation of low-carbon energy supply and technologies. A wide range of technologies benefit, with advances in renewables, battery storage, nuclear, hydrogen and carbon capture and storage (CCS). This dynamic is particularly visible in countries with abundant low-carbon energy resources. In addition, incentives for research, development and early deployment are widespread.

Innovation Wins countries look for immediate measures to reduce the pressures that come when energy prices are high. The USA, for example, places a focus on increasing the domestic production of oil and gas. A rising US rig count is one sign of this change. Suddenly, US shale gas in the form of liquefied natural gas (LNG) looks very attractive to importers, especially when additional supply can be delivered at scale within two or three years. Such a rapid response allows US LNG to be marketed as an answer to energy supply security while the new low-carbon energy system grows. But new drilling also faces headwinds, with climate change activists and investment groups both cautioning against a renewed oil and gas production push. The deployment of carbon capture and storage offers one way forward, particularly in the USA where the infrastructure is well developed and the technical capacity for deployment is very high.

In these countries, dealing with geopolitical and economic challenges takes priority over establishing public policy designed to manage emissions. Despite this dynamic, increases in extreme weather events, electricity outages, floods and wildfires keep climate change on the public agenda. In the case of the USA, federal green infrastructure initiatives emerge, but still do not deliver on the scale required to hit the 1.5 °C stretch goal of the Paris Agreement. As a result of this shortfall, many US states and cities further develop their own low-carbon initiatives. They build the infrastructure for public transport and bicycle lanes and incentivise home energy self-sufficiency, including rooftop solar, home energy audits and retrofits.

Within this **Innovation Wins** archetype more rapid electrification emerges, but not in a uniform way. There is a lot of change in some sectors, and considerably less in others. Direct pricing of carbon emissions continues to be rejected due to its impact on consumer energy prices.

Infrastructure investment is an important feature of **Innovation Wins** countries as they seek to use electricity interconnections, LNG export facilities and oil and gas pipelines to ensure availability of domestic supply and to improve regional cross-border transfers. In some countries, the high price of energy encourages the private sector to develop large-scale wind, solar and green hydrogen projects. These are delivered on the back of excellent solar and wind conditions and a proactive planning permission system.

Over time, government funding for changes to the energy system becomes more freely available. This funding is to encourage both innovation and the more rapid adoption of existing solutions, such as solar and battery technology. But in return, governments expect the private sector to respond, taking on risk through novel energy projects, new energy business models and the rapid scaling of technologies. This is an opportunity for the bold.

Great Wall of Change

Four behaviour archetypes form the foundations of the scenarios in this publication. This is a description of the third of those: **Great Wall of Change**. This archetype is mainly relevant to China. Several factors insulate China from both supply and price concerns: the size of its economy, its large coal reserves and the scale of the investments it is making in its own energy supply and infrastructure. China takes a cautious approach, aware of the need to move away from coal – by far the most emissions-intensive fossil fuel – and carefully monitoring global energy market developments. It looks to use its manufacturing strength to further grow its position as a global low-carbon energy powerhouse.

The **Great Wall of Change** archetype recognises China's enormous potential to reshape its own energy system and those of its immediate neighbours and distant partners.

China, which continues to experience slow population growth, is willing to make large investments and take big risks to create its own renewable energy path. It sees this as a way for its advanced green manufacturing industries to become leading suppliers of low-carbon goods, services and technologies to the rest of the world. The government is also very aware of the potential damage that carbon border adjustment mechanisms, in regions such as Europe, might do to Chinese exports if it does not act.

Competition from **Innovation Wins** countries also creates renewed pressure for innovation. China may initially benefit from Russian oil and gas, but China adopts a cautious approach, recognising that its longer-term interests are best met by expanding its domestic energy infrastructure. This, in turn, increases its focus on nuclear, hydroelectric, wind and solar generation technologies. China also invests heavily in grid storage solutions to deal with intermittency.

As coal use declines, carbon capture and storage (CCS) plays a growing role in emissions management. Local air pollution initiatives also help accelerate change, in combination with a trend towards a service-based economy that is less energy-intensive than one based on industry.

The shift aligns with the plans that President Xi set out ahead of COP26 and in the 14th Five-Year Plan for 2021-25. Emissions peak before 2030 and then start to fall as China moves towards an electricity-based economy, powered by nuclear, hydroelectricity, wind and solar. The shift includes further agreement with neighbouring countries to build a regional electricity network using Chinese grid technologies. This regional network also includes hydroelectricity along the Mekong River in Myanmar, Laos, Thailand and Cambodia. The network offers intermittency management, allowing much broader penetration of renewables in the region than would otherwise be possible. At the same time, the network does not leave individual countries with a critical energy dependency on others. The Belt and Road Initiative supports the growth of this network into an integrated green electricity grid across Southeast Asia

China sets the manufacturing agenda for new energy technologies in much of the world. It excels in large-scale solar photovoltaic production capacity, long-distance power transmission and hydroelectricity, as well as battery storage solutions and green hydrogen for industrial applications like iron ore smelting. In a renewed trading partnership with China, Australia pushes solar even further, reducing domestic coal use. China also uses its expanding capability in digital technology to create more integrated grid offerings, which improve efficiency and help address issues such as the intermittency of renewables. To achieve this, China uses innovations such as smart grids and virtual power plants.

As part of its global quest to acquire minerals, China builds power grids and microgrids across Africa and expands its infrastructure investment in Latin America. This helps to establish its dominance in parts of the world that are developing rapidly. China builds large hydroelectricity plants in developing economies. This provides impetus for the energy transition in those countries.

To meet the competition from **Innovation Wins** countries, the Chinese government imposes tough regulations designed to support its new manufacturing initiatives and it puts these industries at the forefront of the global green industrial revolution. Chinese industry shifts even more towards green solutions in response to demand from Western consumers. This shift is further encouraged as China's emissions trading system expands beyond power generation to industry.

A rapidly growing market for electric car batteries and grid storage to help manage renewable intermittency produces a further rapid expansion in Chinese battery production capacity. By the 2030s, China has become an electric vehicle production super-hub for the global economy, with Japanese companies struggling to regain their pre-electric market share.

By 2030, China's annual battery and solar photovoltaic production capacity still comfortably exceeds that of the rest of the world combined. But energy security concerns continue, and these worries impact decisions and policies. For example, the expectation that China can be a substantial source of bio-feedstocks (such as used cooking oil) for the region is tempered by these concerns.

Surfers

Four behaviour archetypes form the foundations of the scenarios in this publication. This is a description of the fourth of those: **Surfers**. This archetype subdivides into **Emergent Surfers**, like India, and **Rising Surfers**. **Rising Surfers** include the world's least developed economies, which are more focused on establishing the basic foundations for development, such as infrastructure. These countries do not produce significant amounts of energy and so are vulnerable to both energy supply disruption and to price swings. **Emergent Surfers** quickly adopt new technologies, while **Rising Surfers** keep a closer focus on spreading access to energy. **Surfers** of all types seek out partnerships and try to ride the opportunities created by other archetype countries.

The **Surfers** archetype features a variety of countries, but most are emerging (**Emergent Surfers**) and developing economies (**Rising Surfers**). The **Emergent Surfers** are mostly concerned with catching up in terms of economic development and creating new markets for their economic growth. The **Rising Surfers** are more focused on basic development needs and access to energy. In the least developed of these economies, the cost of energy supply dominates.

Countries that are neither technology developers nor energy suppliers are largely market-driven and opportunistic. **Surfers** are chiefly concerned with their own development, using the most economic energy sources available. This includes buying discounted Russian oil and gas to meet immediate needs. Most maintain their existing energy systems for some time, but shift when the market does – moving to electric vehicles, for example, only when the cost of ownership drops below that for internal combustion engine vehicles and production of the latter declines.

In response to energy security challenges, many regions establish alliances with countries that are energy or technology exporters. India and the Arabian Gulf states, for example, might consider working together to give India greater access to oil and gas resources, and to deploy large-scale renewables for hydrogen exports from the Gulf to India. Under the same arrangement, and in the longer term, Middle East countries could deploy carbon capture and storage for India, allowing it to stick to its climate goal.

The potential exists for **Surfers** to move straight to new technologies, at least in electricity generation. **Emergent Surfers** countries adept at seizing opportunities, like India, quickly adopt energy technologies that become available in the global market. In some cases, they build domestic manufacturing capacity for the technology itself. But they do not give up on what they have, so there is no early retirement of coal-fired power plants. Electric vehicles are less likely to be adopted by **Surfers** at the expense of internal combustion engines in the short term – in 2022, they are a more expensive option and these countries lack the infrastructure to support them.

The primary focus of **Rising Surfers** countries is energy access. They want to ensure all their people benefit from electricity, as well as having modern cooking methods which do not pollute inside the home and damage health. Even so, there is a real potential for these countries to leapfrog the oil and gas era almost completely. They can do this by adopting cheaper new energy technologies whenever possible and gaining infrastructure investment from sources such as major mineral extraction companies. Some of these countries benefit from partnerships with richer nations that help with technology. Some benefit from finance through multilateral development banks in return for low-carbon products. In many places, the construction of large hydroelectricity plants and the broad use of new transport options, such as electric scooters and electric three-wheelers, set the agenda for the energy transition.

Despite such potential, many **Surfers** have a very significant gap to bridge when it comes to deploying new energy technology. This gap may well widen before it begins to close. Energy access remains a key challenge for many countries in sub-Saharan Africa and developing Asia. Nearly a tenth of the world's population lacks access to electricity and almost a third lacks access to clean cooking facilities. On top of this, higher energy prices are also affecting food security.

The production pathway for ammonia, one of the chemical building blocks of the fertiliser industry, is a case in point. Ammonia is produced in a chemical process that starts with natural gas as a source of hydrogen, so higher energy prices also lead to price rises for fertilisers. This, in turn, affects food production and food prices. There is little immediate respite from these cost increases, although many countries accelerate their use of electrolysis to create hydrogen by splitting water molecules. This hydrogen can then be used to manufacture synthetic ammonia. This is especially an option where abundant renewable energy is available. By 2030, for example, a synthetic ammonia industry is established in South America.

Many **Surfers** countries have rich biomass resources available in the form of living vegetation and waste products. This is an area where they attract preferential investment and build significant momentum. They become the largest suppliers of sustainable aviation fuels to developed countries.

Huge voluntary carbon market funds – which emerge in the USA, Europe and many advanced developing economies – allow South American countries, Congo Basin countries and Indonesia to take advantage of carbon credits to make significant investments in their rainforests. But even with technology development and carbon market funds, climate continues to be a secondary priority for most **Surfers** governments.

Securing a stable climate

The goal of the Paris Agreement

There are multiple elements that make up the Paris Agreement, but collectively they target one clear goal as set out in Articles 2.1 (a) and 4.1:

- **Article 2.1 (a):** "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change."
- **Article 4.1:** "In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognising that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."

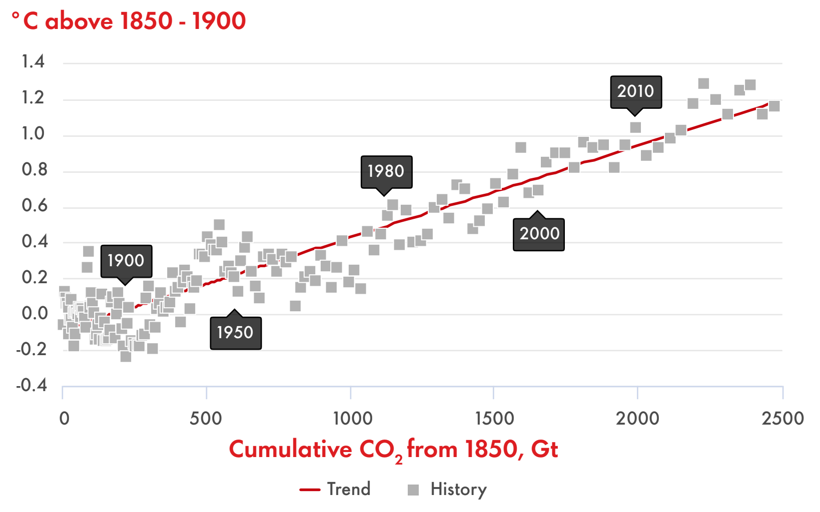
Warming to date is already estimated at 1.1-1.2°C above pre-industrial levels,[1] and rising by 0.2°C per decade. This means that 1.5°C could be passed by the mid-2030s.

In May 2022, the World Meteorological Organization (WMO) announced that there is a 50:50 chance of the annual average global temperature temporarily reaching 1.5°C above pre-industrial levels in at least one of the years to 2027. This finding is based on the variability caused by shifts in the El Niño-Southern Oscillation (ENSO).

Within ENSO, some years – known as El Niño years – are abnormally warm and lead to a temporarily elevated global temperature. In previous very strong El Niño years, the last one being in 2016, temperature rises of 0.2°C or more, compared to the years before and after, are typical. The 50:50 uncertainty in the WMO announcement is more linked to uncertainty about when the next very strong El Niño year will happen, and less to the expected impact on temperatures in the year it occurs.

[1] On the basis of a 10-year moving average temperature anomaly.

The link between surface temperature and cumulative CO_2 emissions is linear (1850-2022)



The carbon budget

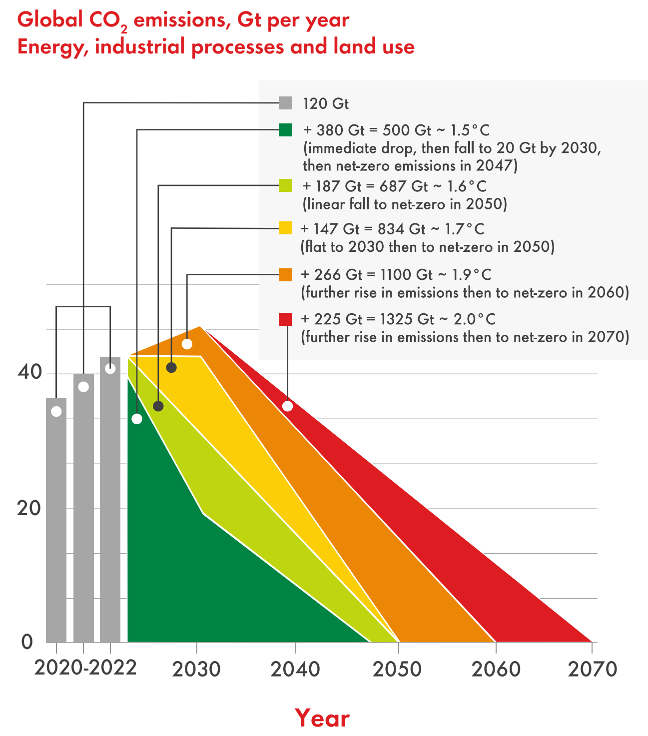
How close the world is to reaching 1.5°C of warming is best described in terms of what is known as the carbon budget. The ongoing rise in global temperatures has a roughly linear relationship to the amount of CO_2 emissions built up in the atmosphere over time. This means it is possible to estimate what sort of temperature rise is likely from a given amount of CO_2 emissions in the atmosphere. Knowing how much CO_2 results in a given temperature rise means society can estimate how much CO_2 can be emitted before the world hits 1.5°C of warming. This is the carbon budget.

In 2021, the Intergovernmental Panel on Climate Change (IPCC) reported that the remaining carbon budget for 1.5°C was 500 gigatonnes (Gt). This 500 Gt budget is based on a 50% likelihood of limiting global warming to 1.5°C with a starting point of January 1, 2020. By the end of 2022, 120 Gt of this budget had been used, leaving about 380 Gt.

Keeping overall emissions within a 380 Gt budget is now a near-impossible task given that global emissions are currently running at more than 40 Gt per year. The chart "Carbon budgets" shows that, from a 2023 starting point, remaining within that budget would need the world to cut its annual CO_2 emissions by half, to 20 Gt, over the seven years to 2030. After achieving that, the world would then need to reach net-zero emissions in the following 17 years to 2047.[2]

[2] Alternatively, but not shown in the chart, a linear reduction in emissions from 2023 would mean net-zero emissions before 2040.

Carbon budgets



The policy mechanisms required to reduce emissions on this timeline are not in place, nor is society ready to accept what would be needed to achieve that pace of change. While some governments have set ambitious timetables for reductions, almost none is delivering the necessary amount of change across their energy systems. The fact that emissions are not yet falling means the pace of change needed for a 1.5°C outcome is rising as time passes. For each year that emissions remain at 2022 levels, the date by which society must reach net-zero emissions also comes forward by a year.

Overshoot pathways

These dynamics around the carbon budget leave the world with only one option if it is to achieve 1.5°C. If society exceeds its budget, then it must make up the difference later. It can do so by removing CO_2 from the atmosphere to balance the excess.

For example, if society were to be on track for 1.9°C of warming it would achieve net-zero emissions in 2060 and reach that point having emitted 1,100 Gt of CO_2. This adds up to an overspend of 600 Gt compared to the 500 Gt 1.5°C carbon budget. To bring the global average temperature rise back down to 1.5°C, society would have to remove 600 Gt of CO_2 from the atmosphere after 2060. This assumes perfect elastic behaviour by the climate system – that a specific reduction in the carbon stock in the atmosphere exactly reverses the temperature rise caused by emitting it in the first place. This relationship is unproven, apart from through computer simulation and the analysis of periods before formal records were kept when the CO_2 level in the atmosphere did fall. This most recently happened during the glacial period between 20,000 and 130,000 years ago.

Pathways which exceed the carbon budget but then make up the difference in subsequent years, by removing CO_2 from the atmosphere, are referred to as overshoot pathways. In these pathways the global average surface temperature overshoots the desired goal, but eventually returns to that level. **Sky 2050** is an overshoot pathway.

The overshoot is an outcome some will consider unacceptable but, as our modelling implies, any discussion on how to prevent a breach of 1.5°C would need to include bigger and faster action than the already substantial measures laid out in **Sky 2050**, which may not be technically feasible.

The importance of carbon removal

If we accept that an overshoot scenario is more likely than immediate and drastic emission cuts, this leads to an inevitable conclusion: that carbon capture, carbon removal and carbon storage will have to play important roles. This set of technologies comes in many shapes and forms.

But how the world chooses to remove CO_2 from the atmosphere is less important than its critical need to develop large-scale capacity to do so.

This is firstly because the size of the carbon budget overshoot is likely to be very significant, and the world needs to mitigate that overshoot as quickly as it can to achieve the best possible climate outcome.

Secondly, it may take a century, or more, to completely remove fossil fuels from the global energy system. It will require entirely new technologies to replace fossil fuels for some uses and it will take time to bring the full range of technologies that the world needs to full maturity. For those uses that will continue to involve carbon emissions for many decades, the only way to mitigate their impact is by removing the CO_2 that they produce.

Finally, building large-scale capacity for removing CO_2 from the atmosphere offers a longer-term opportunity. With large-scale removal and storage comes the potential to continue bringing atmospheric CO_2 levels back down to pre-industrial levels of around 300 parts per million. But this is a project for the 22nd century.

Approaches to CO_2 removal

- Industrial CO_2 capture at a facility such as a chemical plant. This involves passing a stream of waste gases over a material which binds to the CO_2 and prevents it from reaching the atmosphere.
- Direct capture of CO_2 from the atmosphere (DAC). This involves sucking air over a material which binds to the CO_2 and removes it from the atmosphere. Very large quantities of air must be processed for this technology to deliver a meaningful result.
- Geological storage takes the CO_2 captured at an industrial facility, or through DAC, and places it in a geological formation some 2-3 km below the surface. This is permanent storage away from the atmosphere and so removes the CO_2 from the natural carbon cycle. In this way it either compensates for, or prevents, CO_2 from being added to the atmosphere by the combustion of fossil fuels or chemical processes.
- Increasing the carbon held in the land system through activities such as reforestation and soil restoration. This removes CO_2 from the atmosphere.
- Capturing CO_2 from power plants fuelled by biomass and permanently storing the CO_2. This is known as bioenergy with carbon capture and storage (BECCS). It indirectly removes CO_2 from the atmosphere.

Background considerations

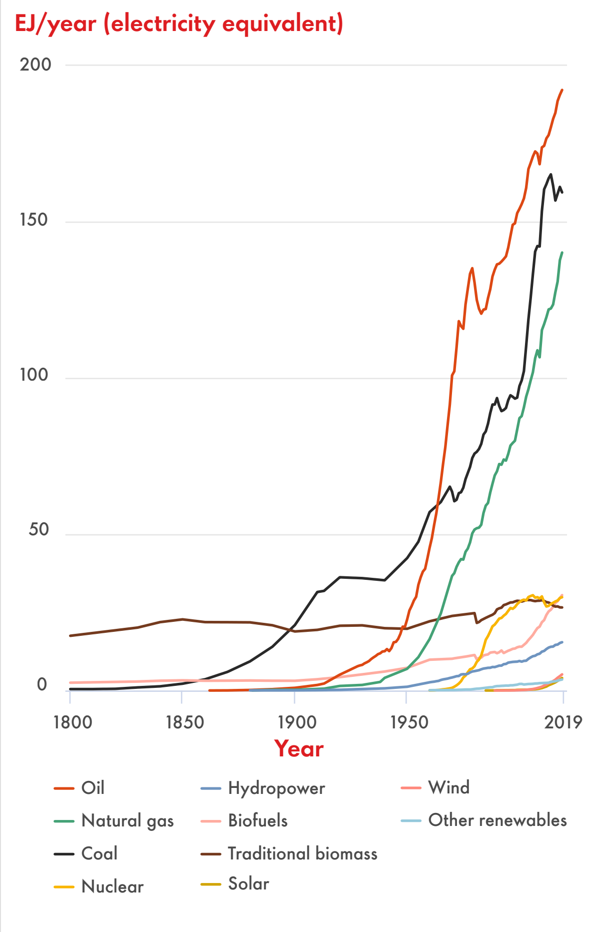
The carbon legacy

The backstory for the scenarios explored in this publication is 200 years of industrialisation and development powered by fossil fuels. The result is an energy system that is well entrenched and patterns of energy use that are hard to shift.

The evolution of the world's energy system

Today's fossil fuel-based energy system has been developing since the 19th century when the latent energy stored in coal was unleashed to power the Industrial Revolution. Oil emerged as another fuel in the latter part of that century. Initially, oil was used for kerosene lamps but then quickly became the fuel of choice for transport, radically changing how people and goods could be moved during the 20th century. The use of natural gas as a fuel has largely been a 20th century development, initially replacing coal-sourced "town gas" (hydrogen and carbon monoxide) in many cities. Subsequently, natural gas became a major fuel for electricity generation and heating. Large-scale hydropower and nuclear power are mainly a development of the latter half of the 20th century, with the first two decades of the 21st century seeing rapid growth in renewables.

Two centuries of energy system development and the growth of fossil fuels



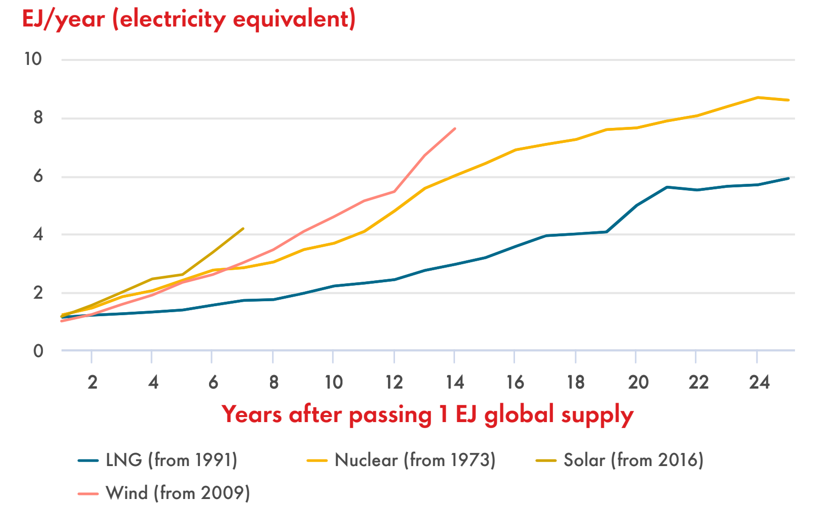
The speed of energy system change – renewables versus established technologies

Every significant change in the world's energy system so far – from the adoption of coal to the use of nuclear power – has taken many decades to become established. A major question around the future of the world's energy system is how quickly the new energy technologies can overtake the established energy system. The early indications, as shown in the figure "How quickly the world adopts new energy technologies", suggest solar and wind power are indeed being adopted much faster than previous technologies, including nuclear in the 1970s to 1990s and liquefied natural gas (LNG) from the 1990s.[3]

But, even so, new technologies can still be expected to take 20-30 years to establish themselves in the global energy mix. In terms of solar power, the first commercial solar array was built in the early 1980s, but solar power did not supply the landmark amount of 1 exajoule (EJ) of energy until the 2010s.

[3] Liquefied natural gas (LNG) is shown on the figure as notional electricity generated from the natural gas.

How quickly the world adopts new energy technologies



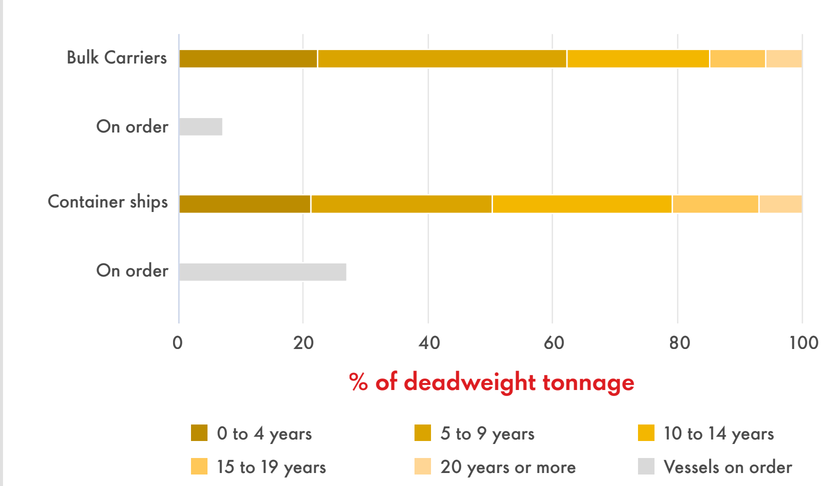
The challenge of long-lived energy system assets

Many parts of today's global energy system are designed to operate for decades. These are constantly being renewed, but their long life results in a slow turnover. This means it takes decades to replace the world's stock of such assets.

As an example, shipping accounts for around 3% of global final energy consumption. International bulk and container ships account for two-thirds of global tonne-miles across some 20,000 large vessels. Ships typically have a lifespan of 25+ years, so ships built today, powered by marine fuel oil, are likely to still be on the water by the middle of the century.

Despite this, no clear direction has emerged for the decarbonisation of this sector, so construction of conventional vessels continues. Several major shipowners and shipbuilders are working together with fuel suppliers to find agreement on which direction the industry should take. But even if agreement is reached today, recently built ships and ships already on order are likely to extend the transition of the shipping industry.

Fleet age distribution per shipping segment



Source: UNCTAD Review of Marine Transport

The carbon cost of human development

Of the four country archetypes explored in this publication, the population of one substantially exceeds the rest combined: **Surfers**.

In 2022, the population of the **Surfers** countries was more than 4.5 billion. **Rising Surfers** has the only significant population growth across all the archetypes to 2100. Their population is expected to double. **Surfers** currently have the lowest annual CO_2 emissions per capita at 3.1 gigatonnes (Gt) per billion people. Yet, even if the **Surfers** maintain their current CO_2 footprint, their population growth alone could take the world beyond 1.5°C by 2050 and to 2°C warming by 2100. If, as these nations develop, their per capita carbon footprint becomes similar to **Green Dream** or **Innovation Wins** countries in 2022, then the world could see warming of around 3°C by 2100.

There is, of course, no question that countries in the **Surfers** archetype should be free to develop to improve the quality of life for their people and reduce poverty. The challenge, in any future that seeks to limit surface temperature warming, is finding a way to enable that development while bringing down their carbon emissions per capita. Achieving decarbonisation while leaving room for development is at the heart of the debate around how to ensure a just transition.

Progress in delivering energy access globally

"Energy is the golden thread that connects economic growth, social equity, and environmental sustainability."

UN Secretary-General
Ban Ki-moon, 2012

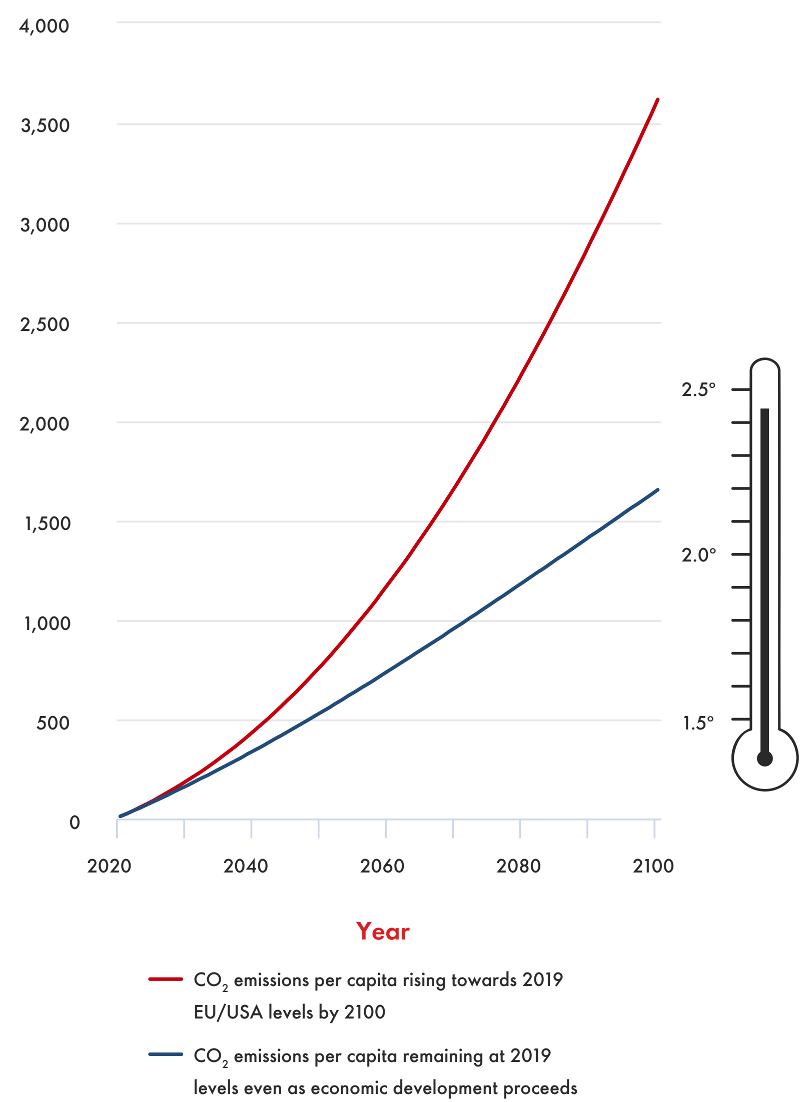
Gaining access to modern energy was not recognised as a Millennium Development Goal. The United Nations later addressed this gap by enshrining energy access in the Sustainable Development Goals in 2015, notably Goal 7 to "ensure access to affordable, reliable, sustainable and modern energy for all". SDG 7's targets for 2030 include:

- ensure universal access to affordable, reliable and modern energy services;
- increase substantially the share of renewable energy in the global energy mix; and
- double the global rate of improvement in energy efficiency.

The International Energy Agency (IEA) has defined modern energy services as: "A household having reliable and affordable access to clean cooking facilities, a first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average."

The need for Surfers to decarbonise

Potential Surfers cumulative emissions, Gt



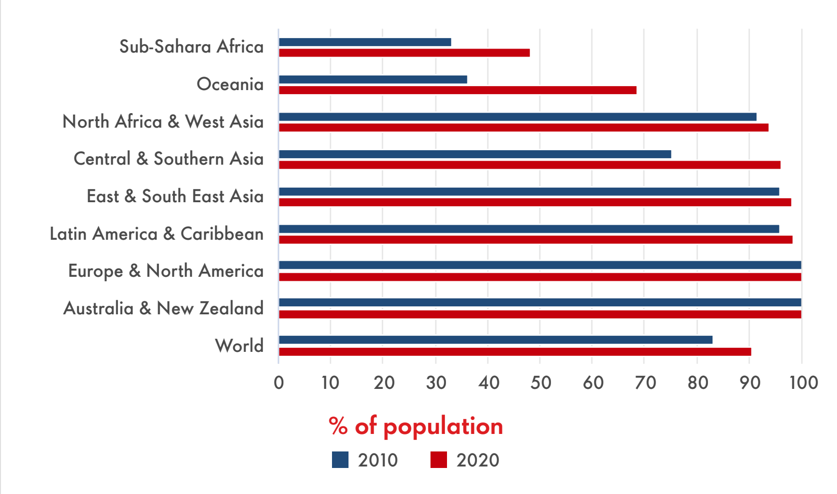
The World Bank's 2022 assessment from tracking the Sustainable Development Goals is that: "At today's rate of progress, the world is still not on track to achieve the SDG 7 goals by 2030." Nonetheless, progress has been made, even if much more needs to be done. In 2010, 1.2 billion people did not have access to electricity, but in 2020 that figure was 733 million. In 2010, three billion people did not have access to a clean method of cooking, but in 2020 that number was 2.4 billion.

To meet the goal of universal access by 2030 the connection rate to modern energy services must increase to 100 million people a year. At the current rate, a modern connection would only reach 92% of the global population by 2030. The connection rate has slowed, in part, because the people that are still to be connected are the very hardest to reach. In addition, marked progress on access to clean cooking has been made in Asia, but the situation in sub-Saharan Africa remains very challenging.

Both the COVID-19 pandemic and the consequences of the war in Ukraine are clearly holding back progress and have even set it back in some parts of the world. Analysis by the IEA found: "The number of people without access to electricity changed little between 2019 and 2021, after falling an average of 9% a year between 2015 and 2019. In sub-Saharan Africa, the number of people without access increased in 2020 for the first time since 2013. Sub-Saharan Africa's share of the global population without access to electricity rose to 77% from 74% before the pandemic."

Most recently, in advance of COP27 in 2022, the IEA produced a special report on Africa. One of its key findings is that: "Russia's invasion of Ukraine has sent food, energy and other commodity prices soaring, increasing the strains on African economies already hard hit by the COVID-19 pandemic. The overlapping crises are affecting many parts of Africa's energy systems, including reversing positive trends in improving access to modern energy, with 4% more people living without electricity in 2021 than in 2019. They are also deepening financial difficulties of utilities, increasing risks of blackouts and rationing."

Access to electricity



Securing minerals in a world of tension and supply concerns

The decarbonisation of the energy system will involve a major increase in demand for the minerals used to make critical components for low-carbon technologies. This could place significant pressure on the mining industry, where the current pace of development would need at least to double in the next 20 years to fulfil future demand. This need to increase the supply of essential minerals is an often-overlooked aspect of the energy transition.

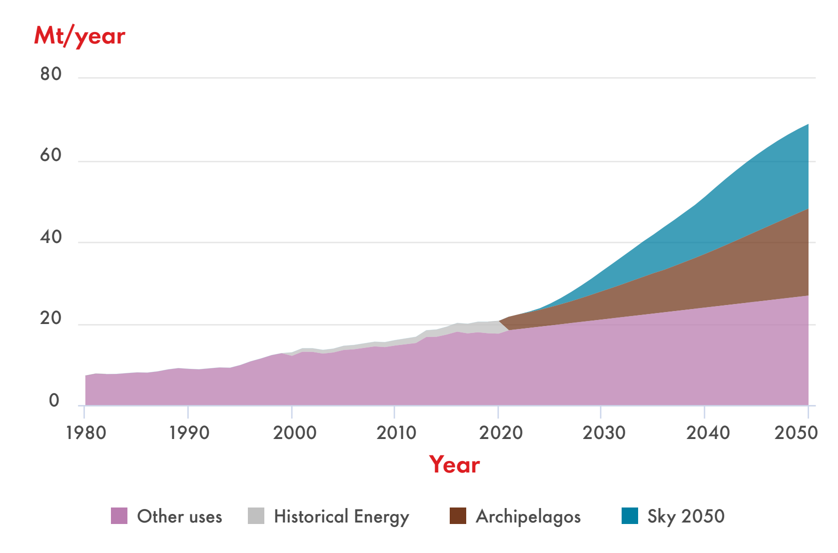
The more the world relies on electricity, as it will have to do to decarbonise, the more it will need to expand the electricity transmission network, and this alone will require an enormous increase in the amount of copper that is mined and processed. Expanding the transmission network will also mean huge investment in other civil infrastructure – including pylons and substations. This investment will increase demand for basic materials like steel, aluminium and concrete, all of which require mining and processing of one sort or another.

In addition to this, the rapid expansion of the global fleet of electric vehicles will unleash demand for lithium, cobalt, nickel and other minerals, which are all needed for vehicle batteries. Building and installing low-carbon power generation technologies, such as wind and solar, also require significant amounts of raw materials. A particular pinch point is likely to be rare earth elements – minerals which are currently produced in very few locations around the world – which are critical to components like the magnets in wind turbines. There is likely to be a scramble to find and produce enough rare earth elements to ensure a reliable supply.

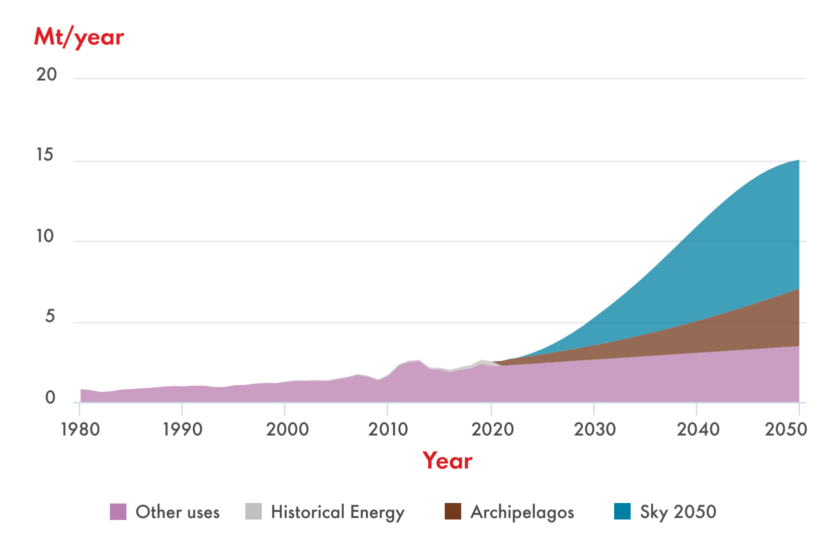
Further demand is expected from other, more traditional, uses for these materials as progress in human development lifts economic growth, reduces poverty and creates new generations of consumers.

As the graph shows, by 2040 copper demand is expected to increase by around 75% in **Archipelagos** and more than double in **Sky 2050**. Besides transmission lines, copper is also used in electric vehicle motors, wind turbines and extensively in wiring across many different applications. By 2040, uses of copper that are directly related to the energy transition account for a third of total demand in **Archipelagos** and half in **Sky 2050**.

World copper demand to 2050



World nickel demand to 2050



Another important mineral is nickel. The lithium-ion car batteries that evolved in the 2010s use materials such as nickel, cobalt and manganese or aluminium. But cobalt supply is dominated by the Democratic Republic of the Congo, which maintains around 70% of global production. Further, the total global resource appears limited. This combination is forcing battery producers to target high-nickel, low-cobalt formulations. As a result, by 2040 nickel demand is expected to double in **Archipelagos** and to grow more than 2.5 times in **Sky 2050**. Energy transition applications for nickel are expected to account for a third of demand in **Archipelagos** and half of demand in **Sky 2050**.

Ultimately, there is no concern about having enough of both copper and nickel to complete the energy transition. Both metals are naturally abundant, with global resources well in excess of future demand, according to the U.S. Geological Survey. Nevertheless, there are concerns about the ability of the mining industry to ensure sufficient production capacity. This is, in large part, because of how long it takes to get a mine into operation – the International Energy Agency (IEA) estimates it takes an average of more than 16 years to open a new mine. This dynamic could result in supply shortages as mining companies struggle to open new mines in time to meet booming demand. As such, the supply of minerals could act as a brake on the pace of the energy transition.

Careful consideration needs to be given to the political, economic and technical measures that could ensure a reliable and sustainable supply of essential mineral resources. To this backdrop, it is clear that recycling, as part of a circular economic approach, will be important in reducing the pressure on supply. It is worth noting that, although demand for minerals is lower in **Archipelagos**, the security situation that dominates geopolitics in that scenario could create more serious supply challenges than those already included in the modelling.

Are key mineral supplies under threat as the transition gathers pace?

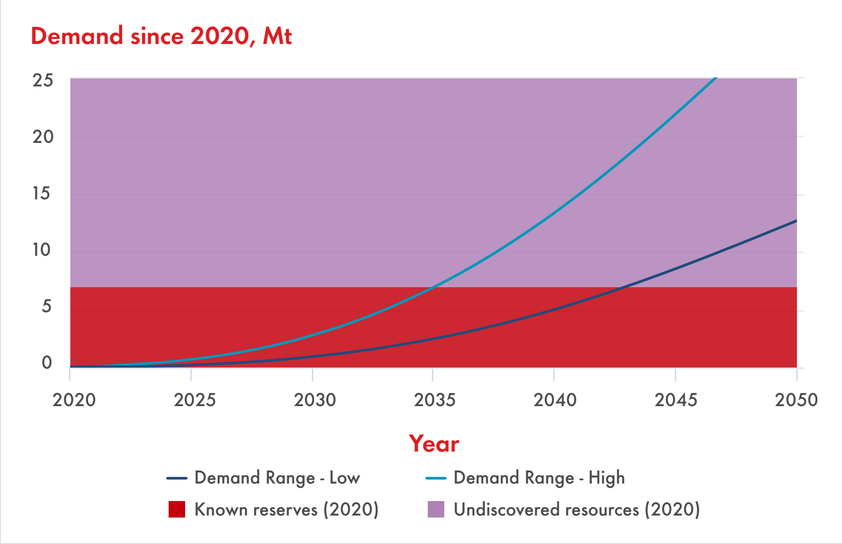
There are many minerals required for the energy transition – some are relatively new to the global economy, like lithium, and some have been in use for thousands of years, like copper. The challenges of meeting demand are different for each mineral. In most cases the Earth's geology has ensured there is more than enough of each mineral available to meet the needs of the energy transition. Some minerals, however, may hit short-term supply constraints as demand accelerates and new mining activity lags. Price increases, while perhaps not welcome, will help address this issue by giving mining companies clear signals to act.

In the case of some other minerals, there may be sufficient quantities available, but supply could be artificially constrained by politics, trade and geography. In a world where a security mindset dominates, this could become problematic. The supply of rare earth elements is currently largely controlled by China, with the ores being sourced from within China and, more recently, Myanmar. These elements, like neodymium, praseodymium, dysprosium and terbium, are used in a variety of renewable energy applications. An example is in the manufacture of neodymium–iron–boron (NdFeB) permanent magnets. NdFeB permanent magnets are used as components in generators for wind turbines, as well as in motors for electric vehicles.

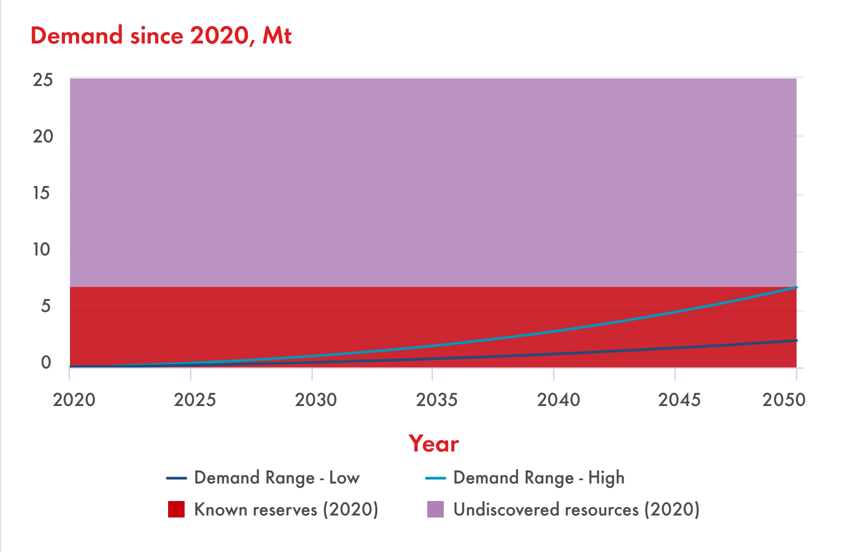
Most of the global ore processing and refining capacity for rare earth elements is also in China. In 2021, the U.S. Department of Energy noted that the USA currently imports 80% of its rare earth elements directly from China, with the rest indirectly sourced from China through other countries. It concluded that the USA is completely dependent on imports for 14 of 35 critical minerals. Finding and exploiting new deposits in other parts of the world is now a US priority, but this will take time to deliver.

Finally, there may be some minerals where real geological limits exist: there is simply not enough in the ground to meet expected future demand. Cobalt, which is used extensively in batteries, is one such example. Global resources of cobalt – the amount of a mineral that exists in both discovered and undiscovered deposits – may well be exhausted based on current trends. In 2022, cobalt reserves – the amount of a resource that has been discovered, has a known size and can be extracted on a commercial basis – were estimated by the U.S. Geological Survey to be around 7 million tonnes. Even with each car battery needing just a few kilogrammes of cobalt, the potential for more than one billion electric vehicles on the road, as well as much larger truck batteries, means the cobalt reserves quickly run short in **Sky 2050**, and a bit later in **Archipelagos**. This dynamic leads manufacturers to innovate more rapidly and find battery formulations that either use less cobalt, or none at all. This innovation process is already well under way.

Global cobalt demand and potential resources - Sky 2050



Global cobalt demand and potential resources - Archipelagos



The importance of the land

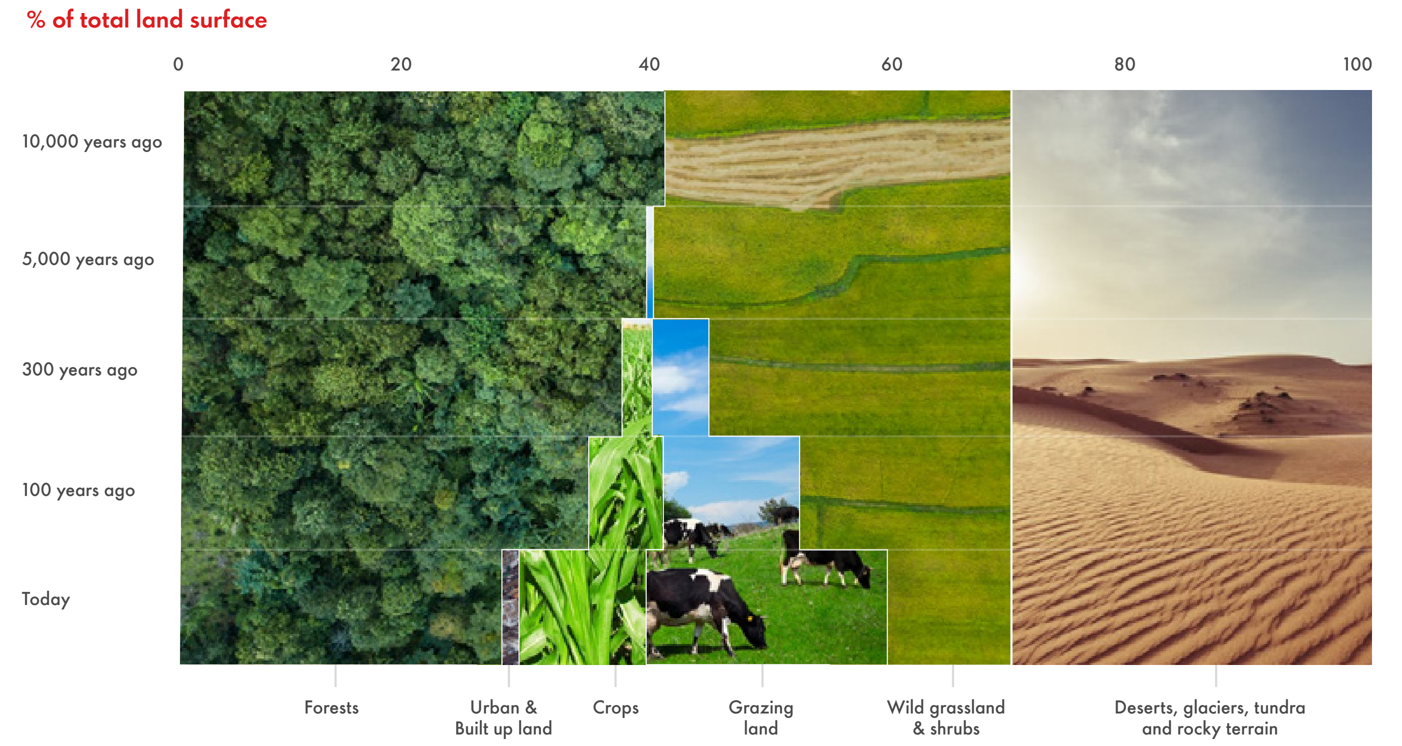
The way society currently uses land is not compatible with a 1.5 °C world. Present behaviours make significant contributions to greenhouse gas emissions and play a critical role in biodiversity decline and soil loss. Without an urgent reversal of current land-use trends the situation will get even worse.

Over the past 10,000 years, society has greatly changed its relationship with the land. Over that time, the world has progressed in one direction only, with forest cover, grasslands and shrubs cleared to expand the space available for crops and the grazing of farmed animals.

As humanity has cleared the land of vegetation, we have lowered its ability to store carbon. In turn, this has contributed to rising levels of CO_2 in the atmosphere and oceans. Just as concerning is the loss of biodiversity associated with land-use change, which may ultimately threaten humanity's food supply.

According to the Global Carbon Project, land-use CO_2 emissions have been relentless at 4-6 gigatonnes (Gt) per year for the past 60 years. Most of these emissions are the result of deforestation to clear land for agriculture. On average around the world, cropland soil is eroding at 13.5-21 tonnes per hectare per year.

Land use



The pressure is rising for change, however, and action is building. Advances include political commitments, such as the Glasgow Leaders' Declaration on Forests and Land Use, and the Bonn Challenge for reforestation. There are also changes under way in the support mechanisms for farming. In addition, the efforts of the conservation community, net-zero commitments from countries and organisations and the growth of the voluntary carbon market, are all positive. Country, as well as most company, net-zero targets incorporate land-use emissions. Also positive is the widespread public support for the protection and restoration of land. The challenge is finding the right mechanism.

This progress is essential, not least because the way society uses the land offers the one scalable way to take carbon out of the atmosphere – creating negative emissions – that does not rely on early stage or expensive technologies. The barriers to progress are largely social and political. It is probably the easiest solution from a technical standpoint, but the most difficult from a social and political standpoint.

Aggressively protecting the land through wilderness preservation, ecosystem restoration (including reforestation) and more sustainable farming practices can help to restore the amount of carbon the land can store. Increasing the land-based carbon stock is an important part of any strategy for stabilising the level of CO_2 in the atmosphere. Early action at scale would also help prevent irreversible biodiversity loss.

A new approach to land use is an important element of both the **Sky 2050** and **Archipelagos** scenarios.

Land carbon flux changes

The global carbon cycle governs the natural exchange of carbon between Earth's atmosphere, land, oceans and geosphere. Humans have disrupted this cycle by burning fossil fuels and clearing forests at progressively increasing rates since the Industrial Revolution. Natural processes on land and in the ocean act as a buffer to CO_2 emissions caused by humans and, between them, remove around half of these CO_2 emissions from the atmosphere. An example is the way that increased levels of CO_2 in the atmosphere increase the amount of photosynthesis in plants, thereby taking additional CO_2 from the atmosphere – a process known as CO_2 fertilisation of photosynthesis. Such natural carbon regulators have operated consistently over the last century and are expected to continue to operate in the future as atmospheric CO_2 concentrations increase. The ability of these processes to mitigate the emissions created by humans, however, may diminish over time and could, in some future emissions scenarios, flip to become net sources of CO_2.

There is large variability in the emissions the land takes up year-to-year and this is roughly equivalent to the net emissions from land-use change. Notably, the land presently acts as a net sink for CO_2, but is a net source of the powerful greenhouse gases methane and nitrous oxide.

Future changes in total land carbon stocks are dependent on a combination of how humans use the land and natural effects: the balance between CO_2 fertilisation, sustained warming and changes in water and nutrient availability. According to the Intergovernmental Panel on Climate Change (IPCC), impacts from climate change alone are expected to increase land carbon stocks in the higher latitudes (excluding permafrost thaw) because of warming and lengthening of the growing season. At the same time, the impacts from climate change will lead to a counteracting loss of land carbon in the tropics as droughts become more frequent.

Societal pressures to protect land-based ecosystems are rising from both a biodiversity and a carbon perspective. A combination of emissions reductions and nature-based solutions – such as planting forests – are needed to effectively protect and restore land carbon stocks.

A note on methods and approach: analysing nature

In putting together this publication, the Shell Scenarios team has drawn on the latest academic research and databases of different types of nature-based solutions (NBS) – such as reforestation or the protection of wetlands – and their potential scope and scale (in hectares and millions of tonnes of CO_2). In addition, we have drawn on internal expert advice on how quickly action can scale up to manage land for nature, recognising that this depends on the type of actions involved.

We differentiate scenarios by their ability to overcome two types of barrier: sociopolitical and economic. We overlay scenario views about how phased or co-ordinated action is around the world. Drawing on research on six institutional barriers to land-use protection, we go on to assume slower scale up in countries with greater barriers, and we assume that the time it takes to overcome these is twice as long in **Archipelagos** as in **Sky 2050**. Further, the NBS datasets come with cost estimates (US dollars per tonne of CO_2) which we also use as a proxy for societal willingness to overcome economic barriers in the two scenarios.

We find that the total technical potentials – that is, if we ignore cost restrictions – for the eight avoidance types match very closely with the Global Carbon Project 2021 estimate of total current land-use emissions. That is, taking up all avoidance actions to their maximum extent will eliminate all current land-use emissions. We reflect this in **Sky 2050**. The $100 per tonne of CO_2 ceiling in **Archipelagos** means that land-use emissions only fall to 1.3 gigatonnes (Gt) per year, although other land restoration giving rise to carbon sequestration means that the net result for land is still net negative from 2041.

For each different method of carbon sequestration, we apply research on carbon uptake by ecosystem to work out the subsequent profile (approximately a normal distribution) of CO_2 that each method takes from the atmosphere over time. Reforestation tends to be the slowest method: it typically takes seven years after planting a tree for it to absorb CO_2 from the atmosphere at a significant rate, and it will typically take decades to grow to maturity.

We apply the potential of all the avoidance types to apportion the estimates of 3.7 Gt per year across types and across countries for 2022. To classify as avoidance, there must be a real threat of loss, so the assumption is that avoidance potentials are greatest where land-use change has been and is the greatest.

Three important assumptions must also be recognised:

- We assume that once protected, land remains protected.
- For CO_2, we need to convert the databases of potentials for emissions reduction credits into net changes from the current ongoing rate of emissions. First, we assume a constant baseline, calculated as the average of the land-use emissions in 2016-20, at 3.7 Gt per year. The interpretation of a constant baseline is that after protecting one year's worth of land under threat, the threat is displaced onto the equivalent of another 3.7 Gt per year that then needs protection in the following year. In reality, the threat may recede, and so the potential for avoidance would fall, which would be reflected in a reduced baseline in reality. We assume a constant baseline for simplicity and consistency, and so we apply a rule that when emissions fall to zero (for an NBS type in a country) they remain at zero to represent all land of that type in that country, from that point on, being protected. In net-CO_2 terms, this is equivalent to resetting the baseline to zero from that point for that NBS type in that country.
- For the number we publish as hectares of land in a given scenario, we use the areas as given by our analysis for CO_2, described above, directly. This means that, for each year in each scenario, we have an area of land in hectares and a CO_2 sink related to it. Annual land enrolment – the process by which land is brought under management – continues until all the potential land that could be under threat – as measured by the total area potential in the avoidance datasets – is protected.

There are relatively large uncertainties around the capacity of land ecosystems to keep storing excess carbon in the future, particularly in response to sustained warming. This is an active area of scientific research. In this context, we have sought to develop a better understanding of the spatial allocation of anthropogenic and natural land CO_2 fluxes in our scenarios. Good representations of both fluxes are key for the evaluation of country progress towards net-zero emissions climate targets. However, countries report both anthropogenic and natural land CO_2 fluxes in their estimated land-use emissions as part of national greenhouse gas inventories, whereas natural land sinks remain difficult to resolve at country and regional scales with Earth system models (ESMs).

Hence, we have developed a simplified methodology to allocate the global natural land sink, as modelled by the Massachusetts Institute of Technology in its climate evaluation of our scenarios, to the country level based on present-day forest cover data. This approach allows for a direct comparison of land-use emissions (including NBS) and natural land sinks for all countries included in our scenarios. Although this approach may not be accurate for all regions given the uncertainties involved, it appears to be consistent with inferences from the Intergovernmental Panel on Climate Change (IPCC) that future land carbon sinks are expected to occur primarily in regions with present-day forests.

Finally, we take a cautious view of the potential in **Sky 2050** (equivalent to reforesting an area the size of Mexico by 2100), even though the potential for reforestation is more than three times as large. We took this position to minimise land competition and changes of existing use. We use a cost limit as a proxy for land competition.

NBS	Sky 1.5 (2021)	Technical maximum	Sky 2050	Archipelagos
Reforestation	678	673	202	201
Other Restore	76	109	46	17
Manage	5,063	6,536	3,451	2,952
Protect	895	1,092	1,092	838
Total	**6,712**	**8,410**	**4,791**	**4,008**

The energy transition: competing towards growth

There has been a lot of focus on the financial costs of the energy transition, but the opportunities are also significant. As government policies increasingly embed a carbon cost within goods and services, this progressively directs financial flows worth trillions of dollars towards low-carbon choices. As a result, a huge new market is created for low-carbon technologies, fuels, industries, industrial processes, goods and services – in short, in almost every part of the economy. Some examples include:

- new industries – solar panels, wind turbines, batteries, hydrogen electrolysers;
- new industrial processes – "green steel" produced using hydrogen, cement production facilities with carbon capture and storage (CCS), chemicals produced from bioenergy; and
- new supplies and supply chains – hydrogen, bioenergy.

Enterprising business leaders are already taking advantage of these new opportunities at every level of the economy, and some argue that the heavy industry sector is reaching a tipping point. This occurs when business leaders investing in low-carbon technologies start a process that rapidly decarbonises heavy industry through three reinforcing mechanisms:

- Governments perceive industrial policy advantages of new low-carbon technology, increase support for innovation and commercialisation and regulate laggard businesses to force the adoption of new technology.
- Businesses commission new low-carbon capacity to compete in new market conditions, which drives down costs.
- The number of green consumers grows as prices fall below the level at which people are willing to pay.

Progress in the energy transition in hard-to-abate industrial sectors has already exceeded expectations, and international competitiveness concerns have not been as much of a barrier to action as previously anticipated. Signs that a tipping point may be approaching are to be found throughout the world. For example, steel producers like SSAB in Europe and Baosteel in China are investing in low-carbon steel production using hydrogen. Another example is vehicle manufacturers like BMW, Mercedes-Benz and Volvo, which are securing green steel supply. Companies like Snam are upgrading and investing in new infrastructure to transport decarbonised gases like hydrogen, while countries like Germany and Sweden are setting the steel industry targets to hit net-zero emissions by 2050. Swedish steelmaker H2 Green Steel is contracted to deliver 2.5 million tonnes of green steel by 2025 – equal to 50% of Sweden's total 2020 steel production. This will be produced using a method called direct-reduced iron (DRI) running on 100% green hydrogen.

Progress is increasingly business-led, with policy in support. This is the opposite of the expectation from just a few years ago, when it was assumed that industrial decarbonisation would require strong policy interventions. It had been felt that policy would be necessary to address international competitiveness concerns – with low-carbon products costing more – and to incentivise business investment. While policy continues to have an important role to play, the world is seeing more proactive actions and investments by business. For example, the prospect of higher prices in the EU Emissions Trading System (ETS) is accelerating the decarbonisation of European heavy industry, driving the uptake of green hydrogen and carbon capture and storage (CCS). A specific instance is the first commercial deal for the cross-border transport and storage of CO_2, which was recently signed between Yara's fertiliser plant in the Netherlands and the Northern Lights carbon capture and storage project in Norway. European governments are following up with aggressive policy announcements to support the next stage of growth.

As business and policy interests align around economic opportunities created by the green industrial revolution a wave of innovation is spreading. The potentially large global market for low-carbon industrial products is, for example, also starting to drive interest and action in emerging economies like India and China.

An important role is emerging for industrial strategy in relation to these new opportunities. For example, China's industrial policy is designed to foster the deployment, use and scale-up of hydrogen. In China's 14th Five Year Plan for 2021-25, hydrogen is one of the six key future growth industries. This status marks hydrogen out as a government priority and directs public and private resources towards it. In parallel, Sinopec (a state-owned enterprise) has announced a target of net-zero emissions by 2050 (NZE 2050), largely on the back of transforming its portfolio from natural gas to hydrogen. Baosteel, the biggest steel manufacturer in China, has also announced an NZE 2050 target based on transforming its steel production to use hydrogen instead of coal.

By seizing the opportunities offered by the energy transition, early movers will reap the competitive rewards in an increasingly carbon-constrained world. In addition, pioneering businesses can make a significant contribution to transforming the industrial sector and getting the world onto a pathway compatible with the Paris Agreement.

Earlier decarbonisation of the industrial sector through the actions of pioneering businesses could reduce cumulative emissions by around 25 gigatonnes (Gt) of CO_2 between 2023 and 2050:

- Around 10 Gt in the steel sector, with hydrogen providing 55% of energy needs in 2050. With 71% of global coal-based steel plants requiring reinvestment in the 2020s, there is an opportunity to build green hydrogen production capacity.
- Around 10 Gt in cement, with 79% of energy needs covered by fossil fuels mitigated by CCS. Proactive business action, supported by policy actions such as a carbon price, could mean 88% of cement production is abated by CCS by 2050.
- Around 5 Gt in chemicals, through a combination of hydrogen and CCS. The uptake of hydrogen initially occurs in advanced economies, but is then adopted and grows strongly in China. The USA and the Middle East lead the uptake of uptake of CCS-abated energy in chemicals.[4]

The biggest impact on end-use sectors for industrial products is in the construction sector, with around 9 Gt in emissions saved between 2022 and 2050.

[4] Vivid Economics, Pathways to Accelerated Transitions, report prepared for Shell, 2022.

Two scenarios emerge

Following the Russian invasion of Ukraine, and the energy crisis that has followed, four different responses to the situation are beginning to be visible, with countries showing similar behaviours when they share similar vulnerabilities to energy supply failures and energy price volatility. The four behaviour archetypes are called Green Dream, Innovation Wins, Great Wall of Change and Surfers. Together they interact to produce aggressive competitive, rather than co-operative, decarbonisation.

From studying these behaviour archetypes, we have produced two potential scenarios.

One possible future is painted in the **Archipelagos** scenario. Another, more optimistic, potential future is set out in the **Sky 2050** scenario. The **Archipelagos** scenario seeks to follow a possible path from where the world was in 2022, while **Sky 2050** takes a normative approach. This approach starts with a desired outcome and works backwards to explore how that outcome could be achieved. In the case of **Sky 2050**, the future it is aimed at is a world that achieves two key things: net-zero emissions by 2050 and global warming below 1.5°C by the end of the century. Working backwards to the realities of 2022 means that, while **Sky 2050** does make many stretching assumptions, there is no expectation of an almost instant collapse in emissions.

In **Archipelagos**, the security mindset emerging in 2022 takes hold worldwide. Global sentiment shifts away from managing emissions towards energy security. Despite this, the drive for energy security includes the greater use of low-carbon technologies. These dynamics translate into global emissions stabilising in the 2020s, and falling from the mid-2030s.

Nationalism underpinned by renewed militarism grows, especially in those regions straddling two spheres of influence. The war over whether Ukraine belongs with Europe or with Russia turns out to be a template for any number of other disputed countries and territories. In many ways, the geopolitical order of the 2030s resembles the 19th century world of power alliances more than the globalised post-Cold War order.

Competition between nations spreads into many aspects of life, and results in multiple technology races – including in relation to low-carbon technologies. Rather than working together to save the planet, groups of nations now scramble to secure energy supply and focus on building energy resilience to withstand future shocks. Emissions fall through the century, with net zero in sight, but still not achieved, by 2100.

The global average surface temperature is still rising in 2100, but is beginning to plateau around 2.2°C as emissions close in on net zero.

In **Sky 2050**, the war in Ukraine translates into an uneven start, but momentum towards emissions reductions then gathers pace. Emissions start to fall from 2025 and, by 2040, the goal of net-zero emissions is clearly in sight.

At the outset, international institutions appear ineffectual in supporting the Paris Agreement and nations cling to archetype behaviours which are focused on their vulnerability to energy supply failure or energy price volatility. Soon, however, citizens themselves start to push for change. Politicians adopt climate-friendly policies to secure support, especially among the young. Quickly these policies become national priorities and, reinforced by economic opportunities that emerge as a result, success in fulfilling their aims becomes a measure of national power.

What might have taken decades to negotiate now takes much less time when individual nations, cities and companies "just go for it", with the world reaching net-zero emissions in 2050.

Despite overshooting earlier in the century, the world goes on to bring the rise in global average surface temperatures back below 1.5°C by 2075 and then to around 1.2°C by the end of the century.

Sky 2050: security through mutual interest

One of the two scenarios explored in this publication is **Sky 2050**. This scenario takes a normative approach, in that it starts with a desired outcome and works backwards to explore how that outcome could be achieved. In the case of **Sky 2050**, the future it is aimed at is a world that achieves two key things: net-zero emissions by 2050 and global warming below 1.5°C by the end of the century. Working backwards to the realities of 2022 means that, while **Sky 2050** does make many stretching assumptions, there is no expectation of an almost instant collapse in emissions.

An uneven start

Limiting warming to below 1.5°C was a formidable challenge even before the global pandemic and war in Ukraine. Dealing with the consequences of these events – whether through measures to control inflation, government action to mitigate the worst impacts on households and businesses, or budgetary reallocation to defence spending – has distracted leaders, delayed policy formation and reduced the government resources available to address climate change. By the end of 2022, many observers feared that the gap between the goal of the Paris Agreement and the current conditions was too wide to bridge.

Despite this poor starting point, however, in **Sky 2050** during the following three decades, several key geopolitical forces have their effect and eventually offer the possibility of success in 2050. Each of these forces serves to speed up the energy transition. After an uneven start, momentum gathers, meaning that while progress is initially difficult to see, by the 2040s net-zero emissions is in sight.

The people demand action

With the breakdown of the post-Cold War global order, structures of international co-operation weaken. Nations organise into clusters of mutual interest and values, leaving a world largely split between free market democracies, led by the USA and the EU, and state-managed economies like China. Climate change seems far down the list of priorities.

But while international institutions initially appear ineffectual in supporting the Paris Agreement, citizens and businesses push for change. Businesses recognise the economic opportunities of the energy transition and invest accordingly. They develop profitable new business models while also meeting societal aspirations. Politicians adopt climate-friendly policies that soon become national priorities, and success in fulfilling their aims becomes a measure of national power. By 2030, both oil and gas are in decline globally.

In China, for example, environmental policy reform and reductions in air pollution become core factors determining the government's political legitimacy. Brazil and Indonesia assume a leadership role in forest and marine ecosystem protection. In American cities, ambitious retrofitting of buildings to radically improve energy efficiency takes hold. What might have taken decades to negotiate now takes much less time when individual nations, cities, and companies "just go for it".

Competition drives a race to the top

Low-carbon and environmentally sustainable goods and services are booming industries, at the forefront of the green industrial revolution. Companies and nations vie with each other to create competitive advantage and capture market share. In advanced economies, business-led innovation creates a race to the top in new energy technologies and innovation. Businesses compete to bring the most innovative low-carbon products and services to market, and governments compete to provide the most attractive environment for business investment. China's experience of establishing itself as a market leader in solar panel manufacture and electric vehicle technology is seen as a template for developing and emerging economies in Asia, Africa and Latin America. Industrial policy is used to support the development of domestic low-carbon industries.

Policy support for measurement and innovation

As a result of the Ukraine war, energy security rises to the top of the political and economic agendas in many countries. Governments pour significant resources into technology development to reduce reliance on energy imports. Funds flow towards transformative small nuclear reactors, hydrogen and innovative battery technology. Climate change becomes an increasingly visible phenomenon due to the first year with global temperatures 1.5°C above the pre-industrial average, and some extreme effects caused by the warming climate. As a result, there is increasing urgency to support new low-carbon technologies, including among financial institutions and investors.

Environmental policies and regulations become more common, and innovations in labelling lead to increasing transparency about the carbon footprint of goods and services – this helps drive consumer choices. Policy mandates and government incentives are put in place to create demand for, and encourage uptake of, low-carbon goods, services and solutions.

Governments adopt regulations and create incentives for businesses to take responsibility for the ecological costs of their actions. They do this by bringing in pricing and taxing structures that ensure businesses accurately record, publish and pay for the environmental impact involved in the supply of their goods and services. Technology and innovation policies support businesses to make low-carbon alternatives commercially viable. At the same time, the price put on carbon increases and becomes more widespread, pushing businesses and consumers towards low-carbon choices.

Business opportunities and social responses

While globalisation and the rules of trade are fractured, new businesses spring up around green goods and services. Carbon clubs (groups of countries with mutually agreed rules on carbon accounting and trading) and carbon border adjustment mechanisms that penalise high-carbon imports are formed to bolster the decarbonisation progress. These are designed to support the growth of domestic low-carbon industries, protect them from being undercut on price by high-carbon imports and incentivise low-carbon imports. They also discourage carbon leakage – in which countries outsource carbon-intensive production elsewhere, reducing their emissions but with no overall effect on global emissions.

Methods of reporting the carbon embedded in goods and services become highly sophisticated, with a degree of transparency that allows individuals to track their personal carbon footprint. These global measurements allow even highly monitored citizens in authoritarian states to use imported goods (sometimes under local brands) with low environmental impact. Young people report their carbon use on social media, competing for the lowest scores and trading advice on how to make their scores even lower. 3D printed goods, including buildings, have remarkably low carbon scores, so this industry expands rapidly. The energy transition creates new business opportunities in almost every aspect of economic life.

Green investment and finance

As the energy transition proceeds, most countries restructure their tax systems away from the traditional energy, transport and industrial structures they currently rely on. Instead, they adopt a new focus on more sustainable sources of revenue that favour low-carbon options.

While individual investments in low-carbon technology may succeed or fail, the market and investors see where the future lies. Private finance reallocates significantly towards low-carbon energy supply, demand and infrastructure.

Public finances are prioritised for growth-enhancing green infrastructure investments and are used creatively to encourage private finance into other areas. Climate finance pledges are de-politicised, and lending by global and regional multilateral institutions consistently and systematically prioritises climate mitigation and adaptation.

Meanwhile, businesses seeking the approval of young people drive investment and operating decisions in a low-carbon direction. They do this not only as a way of making their goods and services more popular, but also to attract dedicated employees. Stakeholder capitalism becomes more than just a slogan. Many businesses redesign their office buildings to be energy neutral. Given incentives and numerous technological developments, the use of electric vehicles grows exponentially.

Towards a new global order of mutual interests

Even as distrust continues between different regional and geopolitical groupings, individual citizens reach across divides. The spirit of co-operation helps bring energy access to less developed areas of the world and fulfil the UN's Sustainable Development Goals at last. Innovative forms of citizen diplomacy spread ideas and encourage collaboration, especially in an era in which much education and work take place online.

Throughout the 2030s, coalitions of trading partners come together to establish common standards for carbon measurement. Rather than a new World Trade Organization or other global institutions being established, greater alignment begins to emerge in the objectives, priorities and standards between different groups of countries. This is not a top-down world order based on liberal values and principles, but a new bottom-up world order created around common priorities and objectives. The emerging rules of this new world order take embedded carbon into account and correct many of the flaws that had plagued earlier trading agreements. Observers remark that in some ways, starting afresh with your friends is easier than trying to negotiate with those who do not share your values or objectives. People conclude that tying a limited number of countries together in areas of common agreement, and then tying that network to another network, is faster than trying to get every nation to conform to a single document or plan.

By the 2040s, with a new generation of leaders in countries throughout the world, planetary politics forms the foundation for an emerging global order based on pragmatic agreements to reach common goals. This order crosses different ideologies and is focused on measuring progress and ensuring that challenges and opportunities are shared equitably. In earlier eras, nations clashed over forms of government. Now nations are aligned around a single ideal – the health of the planet and the diverse ecosystems within it.

Archipelagos: security through self-interest

One of the two scenarios explored in this publication is **Archipelagos**. Its name comes from the fact it is rooted in our earlier **Islands** scenario and an archipelago is a cluster of **islands**. The **Archipelagos** scenario seeks to follow a path from where the world was in 2022 to explore the possible outcomes of choices the world already appears to be making. This perspective offers the chance to evaluate those choices and consider if they are truly the right ones to make.

The USA retreats

Unused to a rival for economic supremacy, the US economy suffers from uncharacteristic economic volatility in the face of competition from China. In addition, a new generation of Americans, who do not feel the relevance of World War 2 and the Cold War to their lives, feels the costs but not the benefits of global engagement. Consequently, voters are no longer willing to support and fund the country's role as the global order's police force. The overall effect leads the USA into a new era of isolationism. The military budget is strictly focused on defence and the security of critical supply and trade routes.

The global financial system is also fragmented. In part this is because climate finance and development finance through multi-lateral development banks have become more politicised. Sanctions and wider geopolitical uncertainty prompt suspicion of western financial institutions and stock exchanges. This, in turn, creates barriers to the free flow of capital, leading to a greater focus on regional capital flows and institutions rather than global equivalents. While the US dollar remains the global currency of trade and finance, its supremacy is challenged as country-to-country and regional agreements are crafted to avoid sanctions and geopolitical risk.

The global free trade consensus shatters

A lesson is learned from COVID-19 and the war in Ukraine about the need for multiple secure sources of supply for critical goods and services. This leads democratic nations to form their own dependable trading bloc based on original World Trade Organization (WTO) rules. Meanwhile, the countries under the influence of the **Great Wall of Change** archetype form another trading bloc. This grants favoured trading status to those neighbours who go along with the growing Chinese dominance in the South China Sea, Hong Kong, Taiwan and beyond.

Australia is torn between China – its near neighbour and former main trading partner – and its geographically distant, but democratic, allies in the **Innovation Wins** archetype. Many emerging economies resist picking sides and enter into transactional agreements, especially for technology sharing, industry partnerships and the guaranteed supply of goods and services.

Even with these trends in play, by 2040 a multipolar trading world has developed with fierce competition for trade with India and some African and Latin American nations. These coveted countries trade with some sets of nations for key goods under one set of rules and with others using a different set of rules. Intermediary services, such as selling the same-sourced goods to different country groupings under different rules, form a new key business opportunity.

In addition, in an effort to protect domestic industries, some countries come together to form carbon clubs (groups of countries with mutually agreed rules on carbon accounting and trading) and then implement carbon border adjustment mechanisms. This involves penalising and excluding other nations and groupings which do not share the same approach on carbon emissions. These groups drive pockets of climate action, but a vicious cycle of protectionism plays out.

International institutions fade

By the 2030s, the World Trade Organization rules have been chipped away. Each group of nations establishes its own rules and enforcement mechanisms. The UN has become more of a humanitarian institution than a global authority and, without its influence, many of the ongoing disputes around the world threaten to destabilise. Short-term security assumes greater urgency than the long-term health of populations and the planet. As a result, global agreements, including pledges to support the UN Sustainable Development Goals and the Paris Agreement on climate change, fade in prominence.

Common international aspirations disintegrate into power struggles in almost every domain, including world health management and the environment. Rather than working together to save the planet, groups of nations now scramble to secure energy supplies and focus on building energy resilience to withstand future shocks. There are pockets of climate action in and across archetypes, driven by top-down government action to reduce reliance on energy imports. There is also bottom-up innovation to develop cleaner and more cost-effective energy technologies and solutions. These technologies and solutions become more widely adopted as they become commercially viable.

In the **Great Wall of Change** archetype, top-down state control creates short-term efficiencies, bringing down prices. Some **Emergent Surfers** countries, such as India, find these threatening, while other cash-strapped **Rising Surfers** countries view them as attractive economic opportunities. Meanwhile, economic insecurity and inequality leads voters in a number of democracies to elect populists who promise to fix problems and to keep out refugees and other immigrants.

Distrust and tension

Distrust of rich countries rises in the global south, which blames them for both economic inequality and climate change. The ill will increases as shifting climate patterns disrupt population centres and increase the number and desperation of refugees.

For some countries, including a number in the **Innovation Wins** archetype, autocratic regimes seem to offer clear solutions, even if those solutions limit individual freedoms. In these countries, more empowered and vocal younger voters seek justice, accountability and the redress of systemic inequalities that they argue have been caused by capitalism.

Military proliferation and border disputes

With a shift in US military focus now clear for all to see, nationalism and renewed militarism grow, especially in regions which straddle two spheres of influence. The war over whether Ukraine belongs with Europe or with Russia turns out to be a template for any number of other disputed countries and territories.

In many ways, the geopolitical order of the 2030s resembles the 19th century world of power alliances more than the globalised post-Cold War order. Climate impacts reinforce this trend, creating climate refugees and putting stress on shared resources such as water. These developments feed polarisation, increase border tensions and heighten the risk of military conflict.

A broader competitive landscape

Competition between nations spreads into many aspects of life that had previously appeared well regulated at a global level. The Internet splits into two main orders, one governed by the **Great Wall of Change** archetype and the other by the **Innovation Wins** archetype. Many nations have accepted Chinese infrastructure spending, so are almost automatically part of the Chinese information system, with long-term implications for political alignments. Meanwhile, the different archetypes cannot seem to come together for international regulations on key issues as diverse as nuclear proliferation safeguards and key learning points from the COVID-19 pandemic.

A new set of technology-oriented races emerge, but all with their roots in national security and each also linked to the digitalisation of society. Military, cyber security, blockchain and space races all get going, and have impacts on the energy industry.

Within the energy sector, the oil and gas industry shifts and realigns to accommodate the political schisms that emerge and deepen. They also move and remodel to compete with the broadening range of applications for, and deeper use of, battery-based energy storage and hydrogen as a green source of energy. The growth of renewables for electricity also features in this world, as countries seek to secure their energy supply and build energy independence. Demand for natural gas as a global electricity source peaks in the 2020s and declines from that point on. Demand for natural gas from industry, however, continues to grow. In part this is driven by the growth in the refining of minerals which are needed for the expansion of renewables. Even so, overall demand for natural gas starts to fall in the 2040s, as industry progressively electrifies and begins the shift to hydrogen.

Features of Sky 2050 and Archipelagos

Exploring oil and gas supply in the Energy Security Scenarios

The Energy Security Scenarios seek to follow a possible path from where the world was in 2022. Here we compare and contrast how the landscape for oil and gas changes in **Sky 2050** and **Archipelagos**.

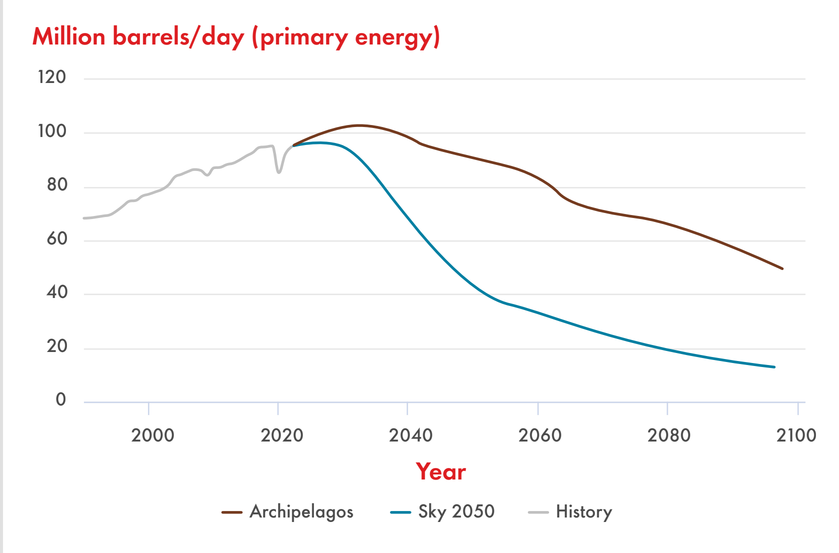
Demand diverges

Archipelagos sees oil demand continue to grow into the 2030s, while gas demand remains flat. Once demand does start to fall, it is a relatively slow process.

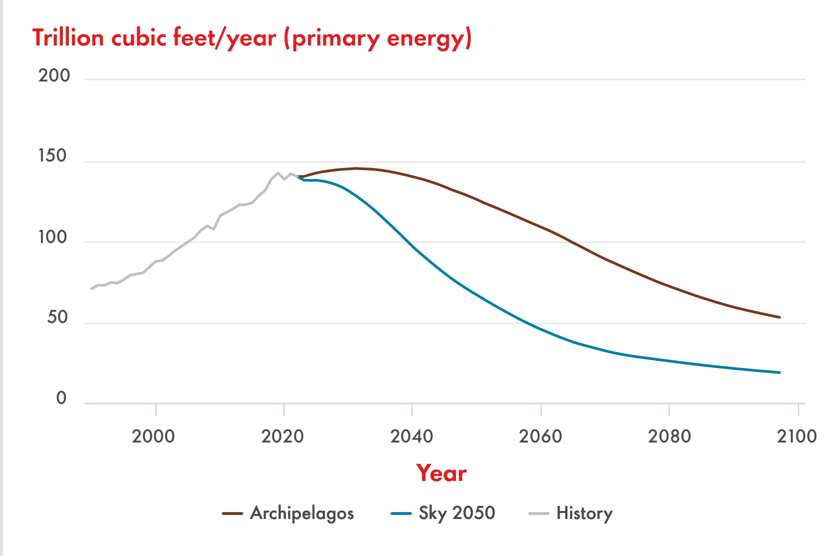
The rapid decarbonisation in **Sky 2050** results in global demand for both oil and gas peaking towards the end of the decade. Demand then remains level until 2030 when a more rapid decline begins. By 2050, demand stands at less than half that of 2022.

For both oil and gas demand, decline is hastened by the persistence of generally high and volatile prices. High prices incentivise demand reduction. An example is the rapid adoption of battery electric vehicles which, in **Sky 2050**, sees the use of oil in road passenger transport fall to just 10% of its 2022 level by 2050.

World oil demand



World natural gas demand

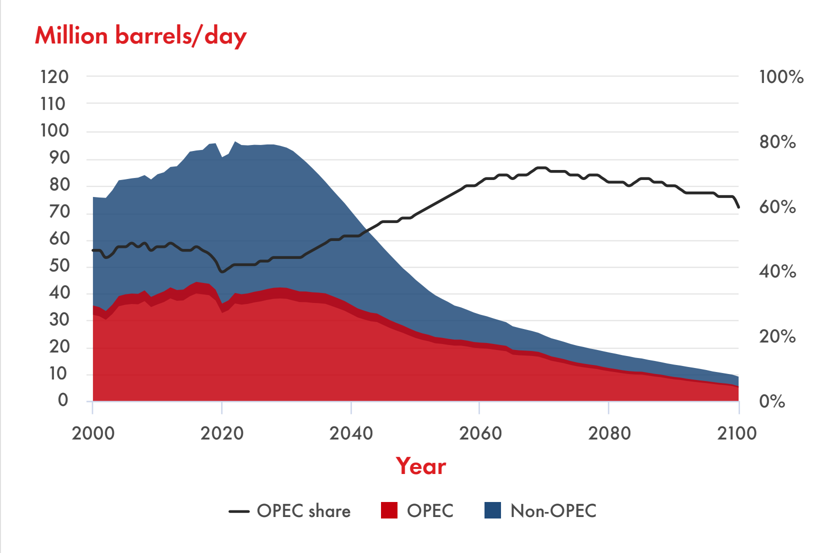


The role of OPEC

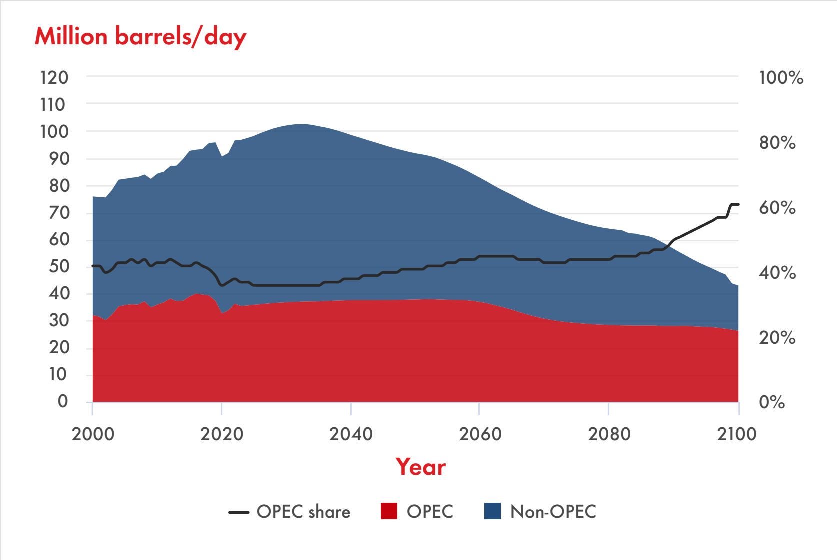
In **Archipelagos**, the Organization of the Petroleum Exporting Countries (OPEC) holds production flat, maintaining market share. The core OPEC countries – such as Saudi Arabia and the United Arab Emirates – take advantage of the generally high oil and gas price to diversify their economies. Later on in the century there is a shift in the balance within OPEC, with non-core OPEC countries (specifically, **Rising Surfers** countries like Iran and Iraq) having a greater share of the bloc's production. This allows the non-core countries to grow their share of the market while generating cashflow from their underdeveloped resources. Reintegration of Iran into the global system unlocks its potential as a new supplier with significant reserves, as well as paving the way for Iraq to develop its own resources and increase its production level.

In **Sky 2050**, the core OPEC countries also enjoy additional revenues from the generally high prices and choose to use the money to diversify their economies. On occasion, they use their ability to increase production volumes to balance the market and manage prices. Even by keeping production flat they increase their market share as overall global supply declines. For the countries where production is dominated by independent rather than national oil companies, particularly in North America, the industry takes a cautious approach. Having been burnt in the past by over-investing, only to lose out when prices fall, companies prefer to generate cash for their investors rather than invest in additional production capacity. In addition, inflation means that the money that companies have to invest in additional oil and gas does not stretch as far as it once did. The overall result is that oil and gas supply peaks during the second half of the 2020s.

Oil production in Sky 2050



Oil production in Archipelagos

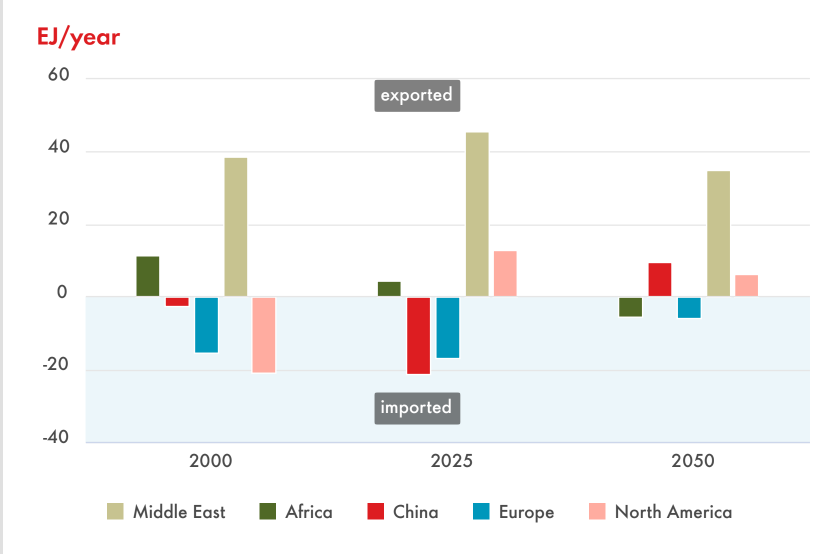


Regional oil trade balances show a profound shift

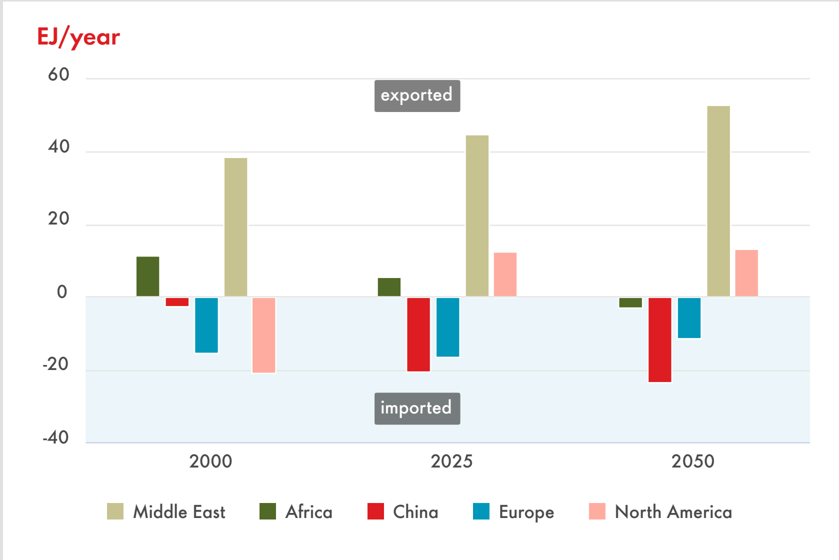
While the Middle East remains the most significant net exporter in both scenarios, other regions see a major shift in the first half of the century. North America remains a net exporter, even though it still imports significant volumes as well. The need for imports is due to the fact that many of its refineries are designed to process heavier grades of crude oil than are produced domestically. North America as a net exporter is a marked shift from the start of the millennium, when the continent was the world's largest net importer of liquid hydrocarbons. In 2022, China is the largest net importer, ahead of Europe.

In both scenarios, as Europe attempts to accelerate decarbonisation it falls further behind China as a destination for imports. Africa, for so long a net exporter of raw materials, becomes a net importer. This happens as soon as the early 2030s in **Sky 2050**, as growing demand cannot be met by domestic supply, where a lack of investment capital holds back new production.

Net regional crude movements in Sky 2050



Net regional crude movements in Archipelagos



LNG grows even as global gas demand plateaus/falls

The global gas system is dominated by regional supply and demand networks. Only around 15% of global gas supplies are made up of liquefied natural gas (LNG), which can be shipped anywhere in the world. But, as natural gas continues to displace coal, demand for gas expands beyond established regions and existing pipeline networks. A reluctance to invest in new pipeline projects, which are expensive and typically take a decade to build, means that additional demand for natural gas is mainly met by LNG.

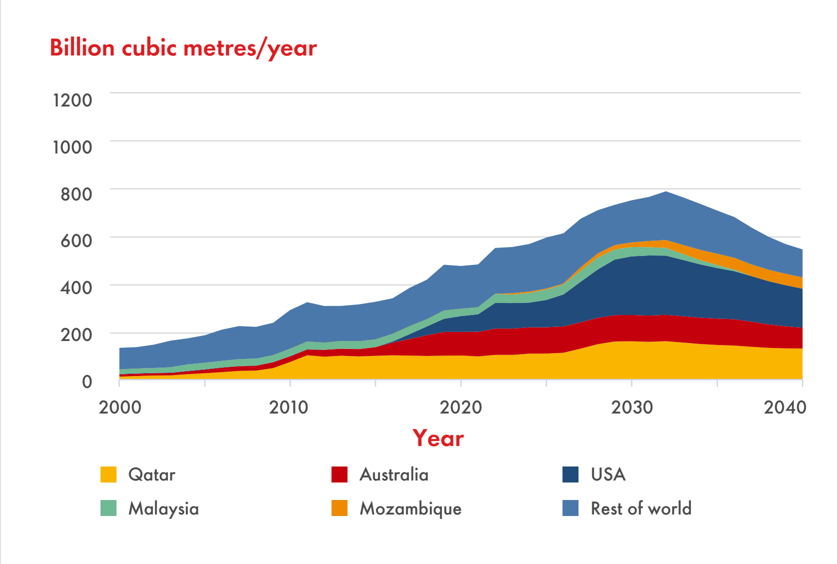
In both scenarios, in the near term, **Green Dream** countries move away from Russian pipeline gas. These nations meet their needs partly by increasing domestic production, partly by using pipeline imports from North Africa and Azerbaijan and partly through LNG imports.

In **Archipelagos**, **Green Dream's** LNG imports are sourced from **Innovation Wins** countries, such as established exporters Australia and Qatar. In the USA, LNG exports continue to grow up to the end of the 2020s. After that point, rising domestic demand and restricted investment in additional capacity limit further growth in exports. Some **Emergent Surfers** countries, such as Mozambique, also join the global LNG trade.

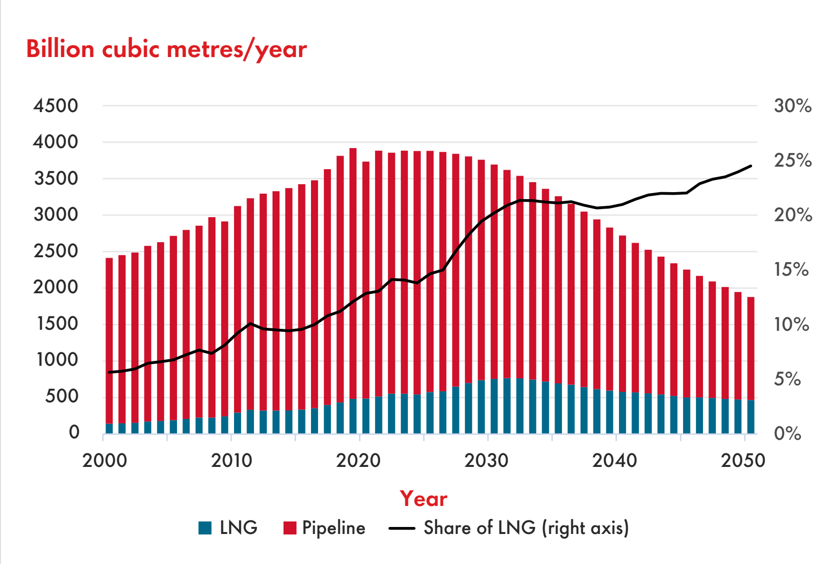
In China, a three-way balance develops between domestic supply, pipeline imports from Russia and Central Asia and LNG imports. Strong domestic supply and significant LNG capacity ensure China is not dependent on a single supplier to meet its gas needs.

A key characteristic of the **Sky 2050** scenario is that the "golden age of gas" comes to an end. The increased demand for LNG is short-lived. Demand peaks in the 2030s and falls off from that point as the world rapidly moves away from using natural gas for electricity generation, residential cooking and heating. By 2027, Europe's gross demand for natural gas is 150 billion cubic metres lower than 2022. The scale of this reduction in demand is equivalent to the amount of natural gas imported into Europe through Russian pipelines before the invasion of Ukraine. Meanwhile, China's focus on domestic supply to shield itself from external price shocks, alongside declining domestic use, results in reduced demand for both pipeline imports from Central Asia and LNG shipments.

World LNG supply in Sky 2050

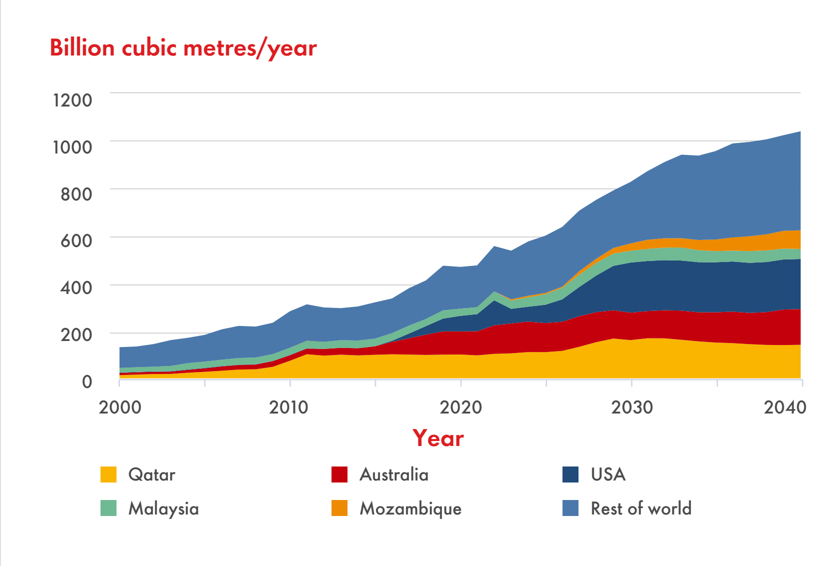


World natural gas production in Sky 2050

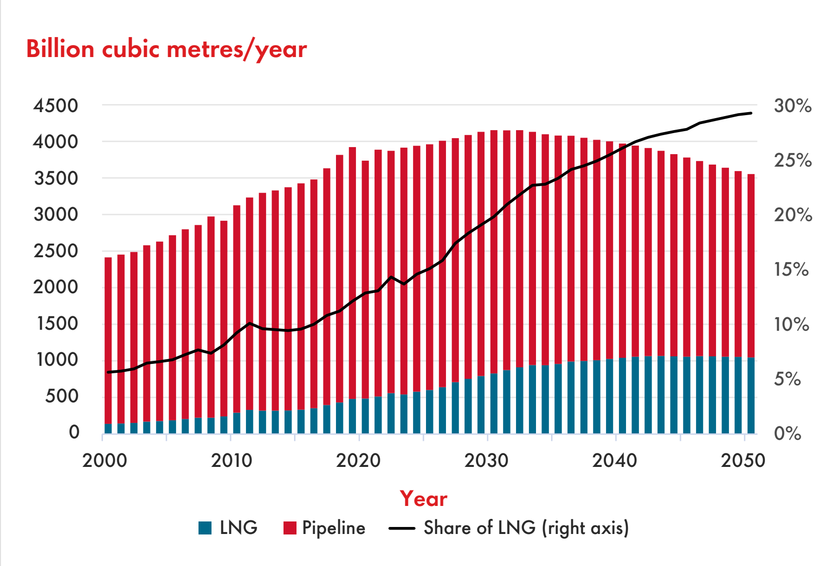


Although global demand for natural gas peaks by the middle of the 2020s and more than halves by 2050, LNG continues to see growth in the short term. As in **Archipelagos**, increased demand from Europe for LNG, caused by the end of Russian pipeline imports, is met largely by the big three of LNG: Australia, Qatar and the USA. These three countries continue to dominate the market longer term, joined by some emerging new players such as Mozambique.

World LNG supply in Archipelagos



World natural gas production in Archipelagos



Technology is key

In **Archipelagos**, countries in the **Innovation Wins** archetype make use of technological developments to continue oil production in a more sustainable manner. Canada, for example, successfully pursues the development and deployment of carbon capture and storage (CCS) technologies to allow it to continue production from its oil-sands resource base. In the USA, growth in shale production is moderate, with better understanding of this unconventional resource base combining with a period of financial discipline. Overall production in the USA peaks in the early 2030s.

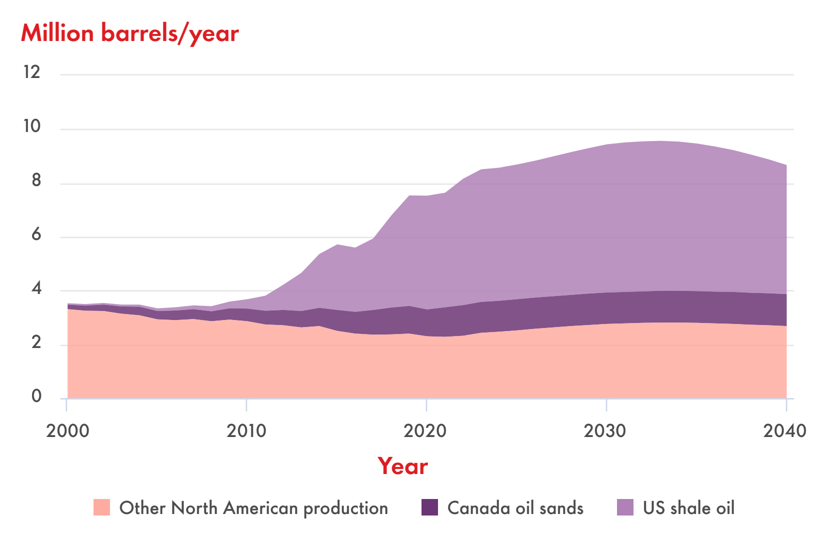
Higher cost of supply

Decline in oil demand in **Archipelagos** is slow. In fact, it takes until the late 2070s (oil) and early 2080s (gas) for demand to fall to the levels seen in 1990. Meeting such persistent demand requires continued investment in the development of new reservoirs of oil and gas.

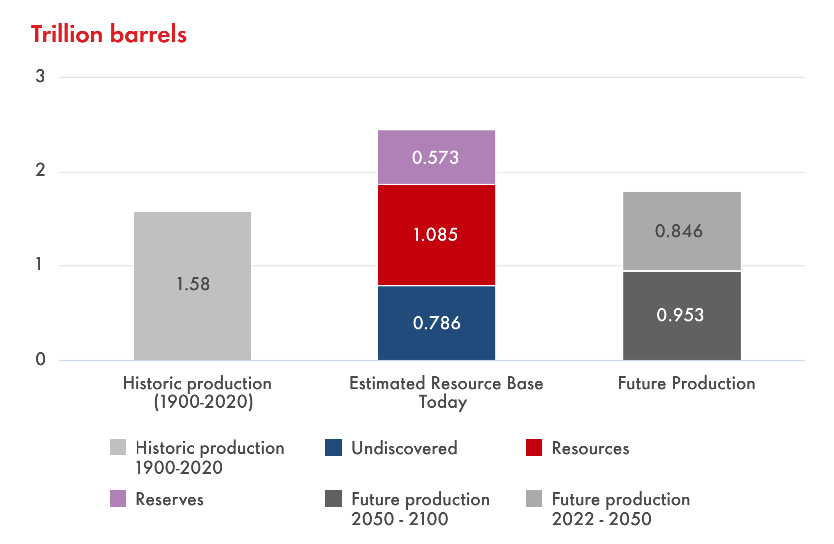
Producing nearly 1,800 billion barrels of oil equivalent by the end of the century exhausts virtually the entire discovered resource base in the world. The fact that the cheapest-to-exploit reservoirs have already been tapped means that meeting demand becomes ever-more expensive. Some of the more costly resources are displaced by new finds but, overall, the higher cost of developing new reserves helps create a long-term trend of rising oil and gas prices.

Not all resource bases are exploited equally, however. **Emergent Surfers** countries with abundant undeveloped resources, such as Brazil with its pre-salt reservoirs and Argentina with its Vaca Muerta shale province, see production growth. Russia's oil production, meanwhile, sees further decline from the peak production levels achieved in the late 2010s. The decrease is partly due to the natural decline in Russia's oil and gas fields and partly because of a significant reduction in access to foreign investment. The lack of investment limits Russia's ability to fully offset falling production by either reinvigorating existing fields or developing new resources. Production from **Green Dream** countries continues to decline, with most of their resource base depleted.

North America's oil production in Archipelagos



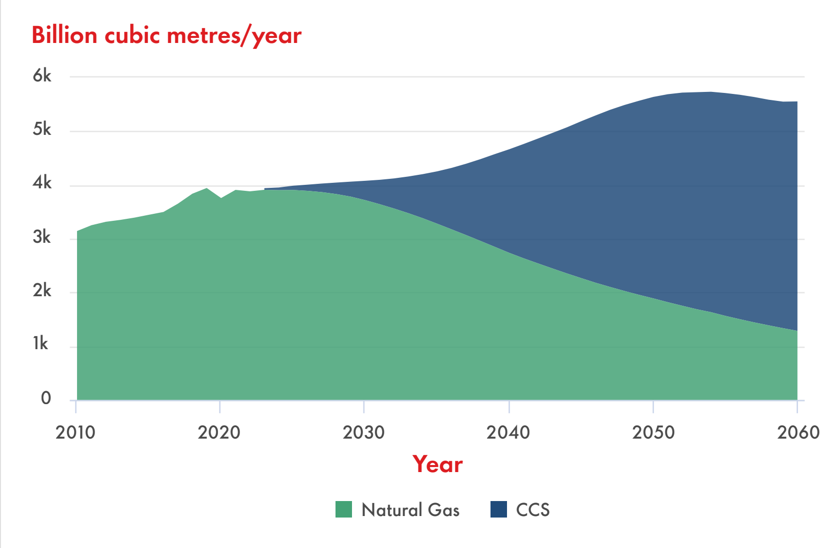
World oil resources and future production in Archipelagos



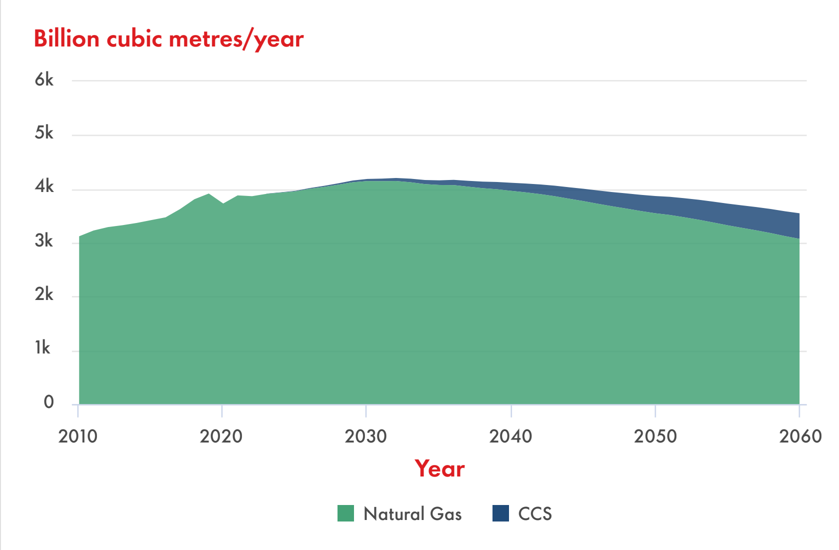
Large-scale carbon capture and storage: a transition opportunity

Achieving net-zero emissions by mid-century requires an enormous increase in society's ability to extract and safely store CO_2 away from the atmosphere. Carbon capture and storage (CCS) at sites producing a concentrated stream of CO_2 – such as power plants – as well as the emergence of direct air capture, play a critical role. The CCS challenge is well suited to the exploration and production arm of the oil and gas industry which has a unique skillset in engineering and geology. In **Sky 2050**, the CCS industry handles more CO_2 by volume in 2050 than the total volume of natural gas produced in the world in 2022.

Volumes of gas handled by the CCS and natural gas sectors in Sky 2050



Volumes of gas handled by the CCS and natural gas sectors in Archipelagos



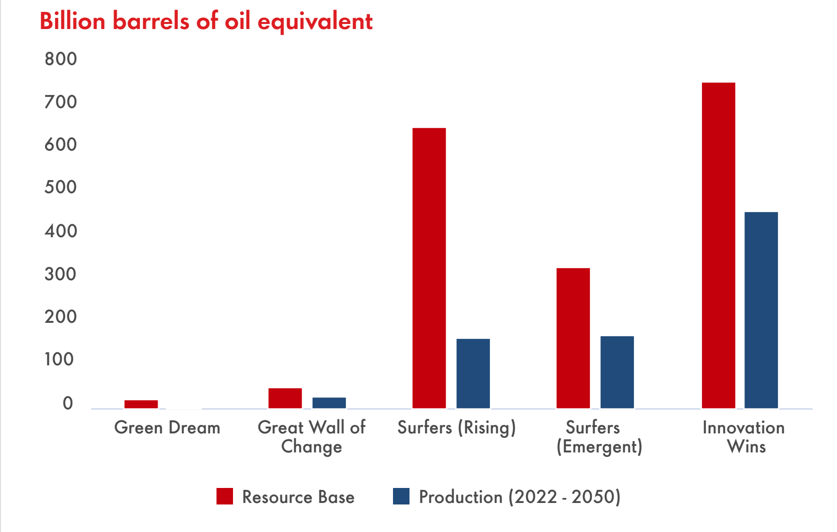
Despite high prices, lack of investment stifles new supply in Sky 2050

For **Green Dream** nations – which include countries in the European Union – investment in domestic hydrocarbons is not seen as a solution. Although production in Europe makes up a minor component of global supply, the effects of this stance are wider ranging than might be expected. This is because the environmental concerns that enjoy a broad political consensus across the EU strongly influence key players in the financial and energy industries. Consequently, the shift away from oil and gas is not only felt in domestic production but in the financing and development of projects elsewhere in the world. Companies with share listings on EU stock exchanges scale back their involvement in oil production globally.

The situation leaves most of the nations with oil and gas reserves from the **Surfers** archetype in a predicament. Operators leave, taking with them technical expertise, and financial institutions refuse to invest in new production projects, removing a source of finance. As a result, many of these countries are unable to fully develop their existing resource base. In fact, without investment, even maintaining existing production levels is a challenge too far for many national oil companies. In some cases, such as Guyana and Brazil, opportunities align with willing investors and growth remains possible, but these are exceptions rather than the rule.

For the **Great Wall of Change** archetype – which primarily means China – energy security remains a priority. This manifests itself as an increased focus on domestic production, but it does not extend to China becoming the financier or technician to cash-starved resource holders elsewhere. This is especially the case once Chinese domestic demand starts to fall in line with the rest of the world.

How effectively each archetype develops and produces their oil resources in Sky 2050



A turning point for fossil fuels?

The world is living with the legacy of a fossil fuel-based global energy system, built up over the past 200 years. But it is now on a new course.

The development of the global power generation system in recent decades has largely relied on coal – by far the most emissions-intensive fossil fuel – and natural gas. In the past 10 years, however, that entrenched dynamic has started to change, with wind and solar taking an increasing share of new generation. With fewer new coal plants entering into the mix, the main area of fossil-fuel growth in electricity generation is likely to be natural gas. Even natural gas, however, is being rapidly eclipsed by renewable energy.

Over the period 2005 to 2020, the global increase in demand for electricity generated from natural gas averaged around 160 terawatt hours (TWh) per year. This rate of increase changed very little over that period. Although the demand for coal-fired power has grown year-on-year, the pace of this growth is in decline. This downward trend for coal growth means that there was around 150-200 TWh less demand growth in 2020 compared to 2005. By 2020, the amount of additional coal-fired power generation was trending below the amount of extra capacity fuelled by natural gas. At the same time, the amount of additional power generation capacity that comes from renewables has been increasing sharply.

In both our scenarios, by the early 2020s a turning point has been reached. For solar photovoltaic alone, the amount of additional power generation capacity being added each year is around 200-250 gigawatts (GW), delivering around 250-300 TWh of electricity. In the **Archipelagos** scenario, this grows to around 400 TWh by the early 2030s. This rate of addition is greater than that seen for both coal and gas combined in the early 2020s. With the addition of wind, both coal and natural gas are in decline and, from the mid-2030s, neither fuel is adding capacity, on a net basis, into the global energy system.

Leapfrog development: a competitive advantage

There is, of course, no question that countries in the **Surfers** archetype should be free to develop to improve the quality of life for their people and reduce poverty. But if their development led to a per capita carbon footprint similar to **Green Dream** or **Innovation Wins** countries today, then global warming of around 3°C would result by 2100. So, the challenge, in any future that seeks to limit global temperature warming, is finding a way to enable that development while bringing down the carbon emissions per capita in **Surfers** nations.

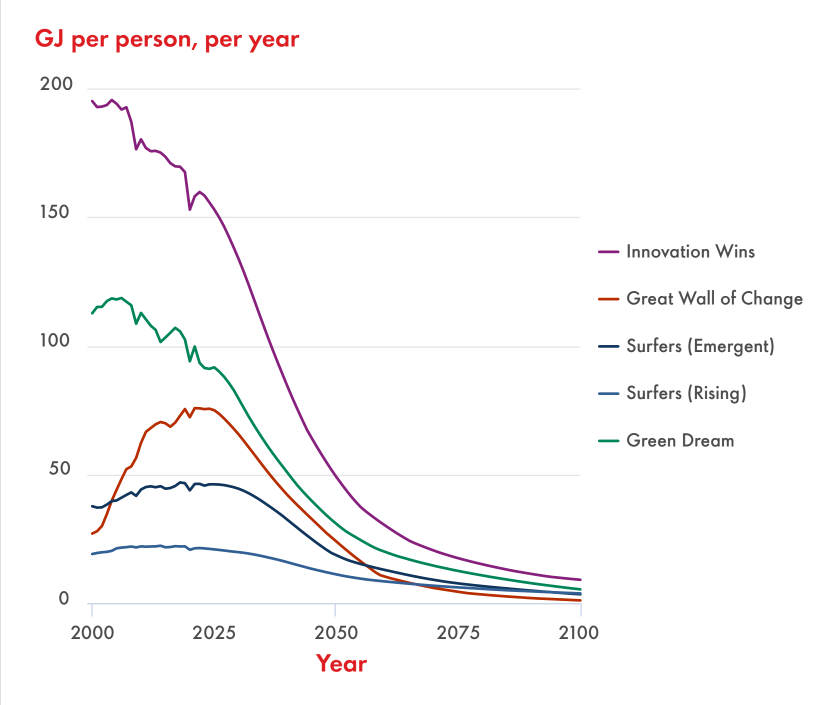
A new way to develop

An important element of securing the goal of the Paris Agreement is an effective leapfrog over the fossil fuel era – more or less cutting out the use of fossil fuels entirely – by countries in the **Surfers** archetype. Specifically, this applies to **Rising Surfers**.

These nations have the potential to leapfrog because they start from such an energy-poor position. Rather than fuelling their countries' development by burning fossil fuels – as nations from all other archetypes have already done – they move directly into widespread electrification and low-carbon sources of electricity generation. Apart from global climate benefits, bringing forward electrification with renewables has significant domestic advantages. These benefits include improving local environmental quality, increasing energy access and reducing import dependence.

In **Sky 2050**, and to a large extent in **Archipelagos**, the **Rising Surfers** countries do not enter the fossil fuel era to the extent that others have (although many still consume biomass, such as wood) and instead move straight to electricity-based energy technologies such as wind and solar. They adopt these technologies at only a slightly slower rate than nations of other archetypes.

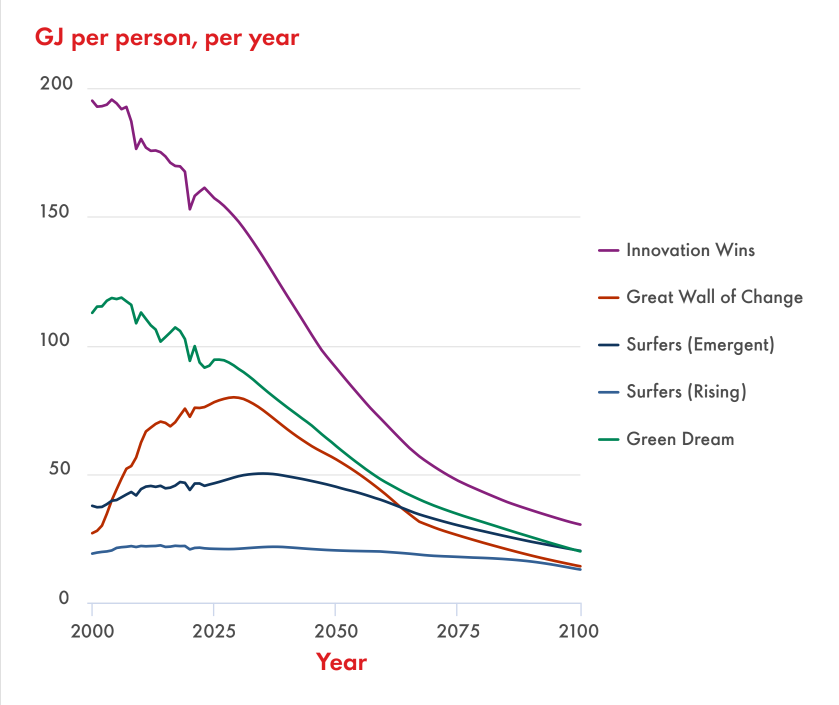
Fossil fuel use per person in Sky 2050 by archetype



In **Archipelagos**, however, the fossil-fuel consumption already in place has a long tail of extended use in **Rising Surfers** nations. This adds pressure on the world's carbon budget and ultimately feeds through into higher global temperatures.

A successful leapfrog – which involves electrifying the economy, accelerating the adoption of renewables and investing to integrate these new energy sources into each nation's energy system – requires three things.

Fossil fuel use per person in Archipelagos by archetype



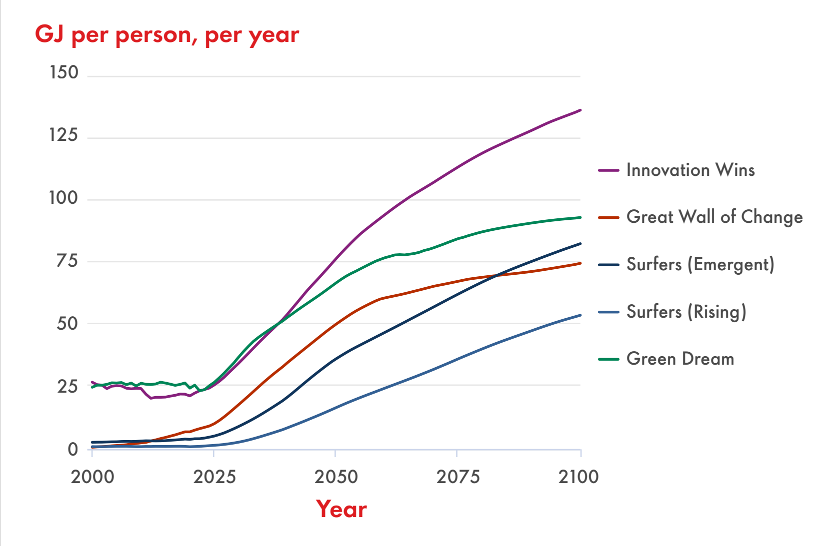
The first is for the governments of **Rising Surfers** countries to establish powerfully effective policies. These policies incentivise electricity use sector-by-sector (such as transport, buildings and industry). The policies also work to decarbonise the power sector and include both targets for the uptake of renewables and subsidies to support their adoption. The world is already seeing action of this nature starting in countries like South Africa and Indonesia.

In addition, government policies remove institutional and regulatory barriers to renewable deployment. One example would be to ensure that the low cost of renewable electricity is reflected in the prices that customers pay. Another example would be to speed up planning processes and regulation reforms.

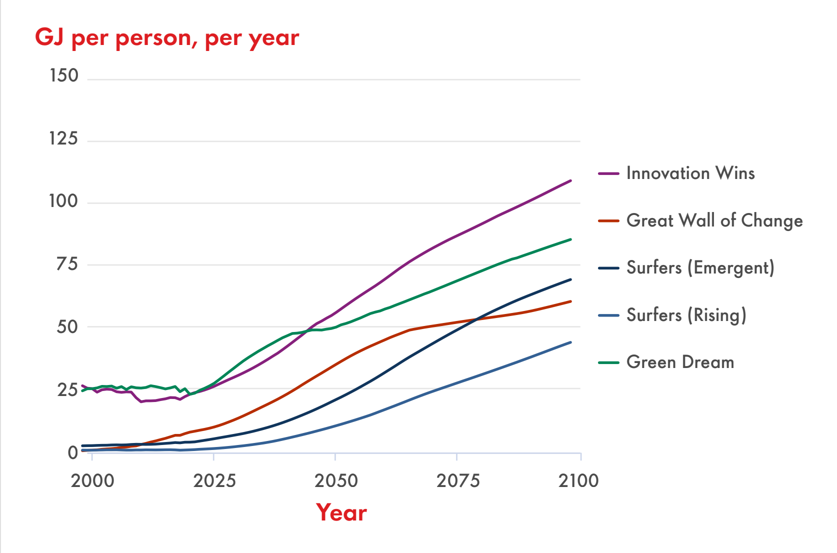
The second thing necessary for success is beyond the control of **Rising Surfers** governments. They need the rise of renewables to continue to accelerate worldwide. Critically, the cost of renewables must fall, alongside the cost of technologies that integrate intermittent renewable generation into the power grid. Falling costs can drive further deployment and improve confidence in renewables-based systems.

Finally, there needs to be sufficient finance. **Rising Surfers** governments do not have the means to directly meet the costs of leapfrog development. This means governments and international institutions, such as multilateral development banks, need to find innovative ways of working with private sources of capital to provide adequate funding streams.

Non-combustion energy use per person in Sky 2050 ~ by archetype



Non-combustion energy use per person in Archipelagos by archetype



The impact of leapfrog development

The potential power of the leapfrog phenomenon tends to be overlooked. In part this is because most forecasts have systematically failed to anticipate the declining cost of solar and wind generation. This failure means the speed of renewable deployment is also typically underestimated. In addition, not enough weight has been given to the cost reductions that are likely as more and more renewable systems are rolled out around the world: society will learn as it goes and find better and more efficient systems and techniques.

Meeting the 1.5°C goal is not possible without leapfrog development. Taking a subset of the fastest growing **Rising Surfers** economies – Mexico, Indonesia, Nigeria, Turkey and South Africa - it is easy to see the impact. Increasing the rate of electrification from 20% in 2022 to more than 50% in 2050 reduces cumulative emissions by more than three gigatonnes (Gt) of CO_2 by 2050. If that increased demand for electricity is met through renewables – at a rate of 81% by 2035 and 87% by 2050 – this electrification shift reduces cumulative global emissions by 12 Gt by 2050.

Another way of assessing the impact of leapfrog development is to look at the pace at which coal – by far the most emissions-intensive fossil fuel – is discarded from the energy systems in **Rising Surfers** countries. Phasing out coal in South Africa by 2035 and in Indonesia by 2045 could reduce cumulative global CO_2 emissions by more than 4 GT and 7 GT respectively, compared to the path both nations currently appear to be on.

The assumptions behind Sky 2050

Sky 2050 is the third generation of our Sky scenario series, designed to illustrate the steps required for society to align with the goal of the Paris Agreement. All three Sky worlds have followed some common scenario design principles and all have taken a normative approach: starting with a desired outcome and working backwards to explore how that outcome could be achieved. As they have evolved, each new version has reflected updated data and changing views on the prospects for different societal choices and technologies. In addition, the Sky scenarios have changed to recognise the climate community's tightening definition of what a Paris-aligned scenario should mean in practice.

We have published three Sky scenarios: **Sky (in 2018)**, **Sky 1.5** (in 2021) and now **Sky 2050**. **Sky (2018)** and **Sky 2050** were entirely new scenarios, while **Sky 1.5** was an update of **Sky (2018)** that kept common energy assumptions and data from 2030 onwards.

Sky (2018) was designed to achieve well below 2°C by 2100. To be consistent with this, total anthropogenic CO_2 emissions reached net zero in 2073, and energy-related CO_2 emissions reached net zero in 2070. **Sky 1.5** was designed to achieve the 1.5°C target, as mentioned in the Paris Agreement, by 2100 and a new narrative element on land use was introduced. Subsequently, the Glasgow Climate Pact clarified and strengthened the Paris Agreement's target to a new ambition of "net zero around mid-century". In line with that, **Sky 2050** is designed to meet a target where total anthropogenic CO_2 emissions reach net zero in 2050, while energy-related CO_2 emissions reach net zero in 2056.

This evolution substantially raised the ambition held within the scenarios. Whereas **Sky (2018)** and **Sky 1.5** reached net-zero emissions for energy CO_2 in 52 years (between 2018 and 2070), **Sky 2050** achieves the same end point in 33 years (between 2023 and 2056). This dynamic meant we had to reflect on almost all the key aspects of the energy system: the total demand for goods and activity in the economy (energy service), the efficiency of both the end use of energy (energy service efficiency) and the energy system (production efficiency), as well as the substitution of the energy forms consumed by end users (energy carriers) and the substitution of the primary energy forms in the energy industry (energy sources). For **Sky 2050**, we focused on what raised ambition means for the energy system. We also incorporated a full overhaul of the assessment of land-use change, although the overall impact is of a similar order to that found in **Sky 1.5** over the century: land-use emissions of -402 Gt of CO_2 in **Sky 1.5** compared to -308 Gt of CO_2 in **Sky 2050** between 2022-2100. In addition, agreed in consultation with the MIT Joint Program on the Science and Policy of Global Change, we included an update for other greenhouse gases that is still very similar to **Sky 1.5**.

All Sky scenarios include the principle that uncertainty becomes greater in the long term. As such, our narratives and modelling recognise the short-term implications of trends and momentum in the energy system today. For **Sky 2050**, that includes the changes of direction triggered by the COVID-19 pandemic and the Russia-Ukraine war. From around 2030, all Sky scenarios have blended into a target-driven normative modelling approach. All Sky scenarios are based on the idea that the barriers to action will fall away, that there is proportionate effort from all actors across the energy system, and that all recognised energy production and end-use technologies can be employed and successfully deployed.

Sky (2018) and **Sky 1.5** both used our base (empirical) assessments of the growth of energy services with GDP (energy ladders). In moving to **Sky 2050**, we updated the GDP outlooks and, more significantly, included narrative elements in the quantification concerning structural design efficiency (e.g. building materials, compact cities) and behavioural change (e.g. less flying, more public transport, less materials-intensive lifestyles). This has the effect of slowing the growth of energy services with GDP.

Each generation of Sky has incorporated our highest outlooks for efficiency at the time for every pathway. The most significant revision between **Sky (2018)** and **Sky 2050** is the refitting of buildings to very high energy efficiency standards over much shorter time frames: by 2050 instead of late-century. The combination of the lower energy ladders and higher buildings efficiency is largely responsible for the much-reduced energy demand growth to 2050 in **Sky 2050**, compared to **Sky (2018)** and **Sky 1.5**.

Alongside lower demand growth, the energy transition for energy carriers and sources is accelerated in **Sky 2050** compared to **Sky 1.5**. In particular, we raised the rates of electrification – from 43% of final energy demand in **Sky (2018)** and **Sky 1.5** by 2050, to 50% in **Sky 2050**. We also charted a much more successful development for hydrogen – from 9 exajoules (EJ) in **Sky (2018)** and **Sky 1.5** by 2050 to 28 EJ in **Sky 2050**. Beyond this, the need for carbon capture and storage (CCS) is also higher by 2050 – 5.3 Gt CO_2 in **Sky (2018)** and **Sky 1.5**, compared to 7.7 Gt CO_2 in **Sky 2050**. The changes are not, however, all in one direction. While bioenergy grows in all Sky scenarios, for **Sky 2050** we moderated this growth to recognise rising concerns about the availability of a large sustainable resource base. This translates into bioenergy growth in **Sky 2050** from 24 EJ in 2022 to 48 EJ in 2050, compared to **Sky (2018)** and **Sky 1.5**, which both included a rise to 92 EJ.

The role of negative emissions is critical across all Sky scenarios. For **Sky 2050**, we reflected rising hopes for engineered emissions removals by introducing a new technology option: the direct air capture of CO_2 (DAC). We combined this with a new pathway to convert captured CO_2, alongside green hydrogen, into synthetic hydrocarbon fuels – a technology known as power-to-liquids, or PTL. These technologies make very strong advances from infancy today to the point where they are capturing 0.5 Gt of CO_2 per year by 2050. The material impact on the global CO_2 balance, however, is in the second half of the century, when DAC direct air capture technologies remove 6.6 Gt of CO_2 from the atmosphere per year in 2100. Of this 6.6 Gt, 1.2 Gt goes to make synthetic hydrocarbons.

For energy supply in **Sky 2050**, solar photovoltaic and wind see upward revisions by 2050, compared to the earlier Sky scenarios: with solar photovoltaic rising from 110 EJ to 169 EJ, and wind increasing from 88 EJ to 96 EJ. As a result of all these changes, with less energy being used overall and other forms of energy being substituted, the fall in all three fossil energy sources – oil, natural gas and coal – is stronger in **Sky 2050** than in **Sky (2018)** and **Sky 1.5**.

The uncertainty of a warmer world

A comparison of Archipelagos and Sky 2050 with the IPCC's Sixth Assessment Report – SSP1-1.9 and SSP2-4.5

Sky 2050 and **Archipelagos** move along different energy pathways through the 21st century. For this reason, the two scenarios result in different levels of carbon emissions and warming. By 2035, both scenarios exceed 1.5°C of warming relative to pre-industrial times (defined as 1850-1900 in the IPCC Sixth Assessment Report). A **Sky 2050** world, however, develops a significant carbon removal industry which it uses to reverse the warming trend before 2055. By 2100, warming has been reduced to 1.2°C in **Sky 2050**. In **Archipelagos**, warming is stabilising at 2.2°C by the end of the century.

Sky 2050 and **Archipelagos** both fall within the range set out in the Intergovernmental Panel on Climate Change's (IPCC) SSP1-1.9 and IPCC SSP2-4.5 scenarios (see box). As such, the climate impact data found in the IPCC Sixth Assessment Report is relevant to both scenarios and can shed light on the differences between the two worlds.

Using data from the Sixth Assessment Report, for example, in **Sky 2050** the sea level rise in 2100, relative to 1995-2014, could be around 40 centimetres. Assuming that the same level of warming remains for an extended period of time, and that future actions to reduce warming do not materialise, after 2,000 years the rise could be between 2-3 metres, and in 10,000 years it could be 6-7 metres. By contrast, in **Archipelagos** the outcome could be 55 centimetres in 2100, but up to six metres in 2,000 years and 13 metres in 10,000 years.[5]

[5] IPCC, Sixth Assessment Report, Working Group I, Table 9.10.

A 13-metre sea level rise would mean very substantial changes for society. Most coastal cities, for example, would have to relocate. There would also be significant impacts on society from a 6-7 metre rise. Over a 10,000-year period, of course, human society is likely to change beyond recognition, but this is cold comfort for a low-lying island nation today. Through the eyes of such a country, an outcome in line with IPCC SSP1-1.9 might at least mean it could still exist several centuries from now. An outcome in line with IPCC SSP2-4.5 could mean its destruction.

What is clear is that, whether the sea level rises in line with a **Sky 2050** story or an **Archipelagos** version of the future, society will have to adapt. The question is about the pace and scale of the adaptation required and the ability of society and, critically, of nature to cope. The rate of change in global conditions is unprecedented in human history and, of course, the higher the world's peak temperature the more severe the impacts and the greater the adaptation needed.

There is not, however, any level of temperature rise that stands as a critical, well-established threshold. The IPCC Special Report on 1.5°C does not suggest that 1.5°C of warming is, in itself, special. Instead, it concludes that limiting warming to 1.5°C, if it could be achieved, would be better than limiting warming to 2°C. So, while 1.5°C has become a rallying point for climate and political action, the reality is that every 0.1°C of additional warming matters. An outcome of 1.4°C, or 1.3°C, would clearly be more desirable than 1.5°C, but such outcomes would still have negative effects in the world. Conversely, an outcome of 1.6°C is less desirable than a 1.5°C outcome, but it would not be likely to tip the world into a situation that is catastrophically different to a 1.5°C world. The fact that every 0.1°C of warming matters is reflected in the text of the Paris Agreement and its call to limit warming as much as possible.

Sky 2050 and **Archipelagos** both fall within the range encompassed by the IPCC SSP1-1.9 and IPCC SSP2-4.5 scenarios. **Sky 2050** is less aggressive in the short term than SSP1-1.9 in that it has a greater overshoot of 1.5°C before returning to around 1.2°C in 2100. **Archipelagos** is somewhat more aggressive than SSP2-4.5 in that the 2100 temperature is around 2.2°C.

SSP1-1.9: This is the IPCC's most optimistic scenario. It describes a world in which global CO_2 emissions are cut to net zero around 2055. Warming reaches 1.6°C, but then reverses and reaches around 1.4°C by the end of the century.

SSP2-4.5: CO_2 emissions remain around current levels before starting to fall mid-century, but do not reach net zero by 2100. In this scenario, temperatures rise 2.6-2.7°C by the end of the century.

So, the need to adapt is inevitable, but humans do have an extraordinary capacity for adaptation. This is in plain sight today: humans live in a wide variety of conditions across the planet, from the Arctic to central Saudi Arabia. But climate change may mean that society has to shift towards a state of continual adaptation, particularly for agriculture. This is likely to be magnified further by failures in the natural world to adapt to changing conditions. Combined, this could hinder prosperity, affect the security of resources and disturb the established order of society.

It is clear, as the IPCC Sixth Assessment Report has shown, that there are multiple and increasing ecosystem risks associated with warming around 2°C, when compared to warming below 1.5°C. There is little research work and quantitative assessment, however, on factors relating to overall economic growth within the temperature range that emerges between **Sky 2050** and **Archipelagos**. The uncertainty in the human economic outcome means both **Sky 2050** and **Archipelagos** share the same economic growth parameters.

One area in which uncertainty is, perhaps, decreasing, is in the likely overall temperature outcome for the world. In the IPCC's Fifth Assessment Report of 2014, there was a major effort to contrast 2°C and 4°C of warming, with 4°C appearing as a possible outcome. In 2023, 4°C no longer appears a likely outcome given the pace of the transition under way. The **Archipelagos** scenario now represents something of a bookend for the possible span of outcomes in 2100, with **Sky 2050** sitting at the other end of possible futures. With a further acceleration in the energy transition, we can hope that the **Archipelagos** outcome of 2.2°C will, in time, also appear unlikely. Today, however, it is still possible.

A tour through the scenarios in graphs and charts

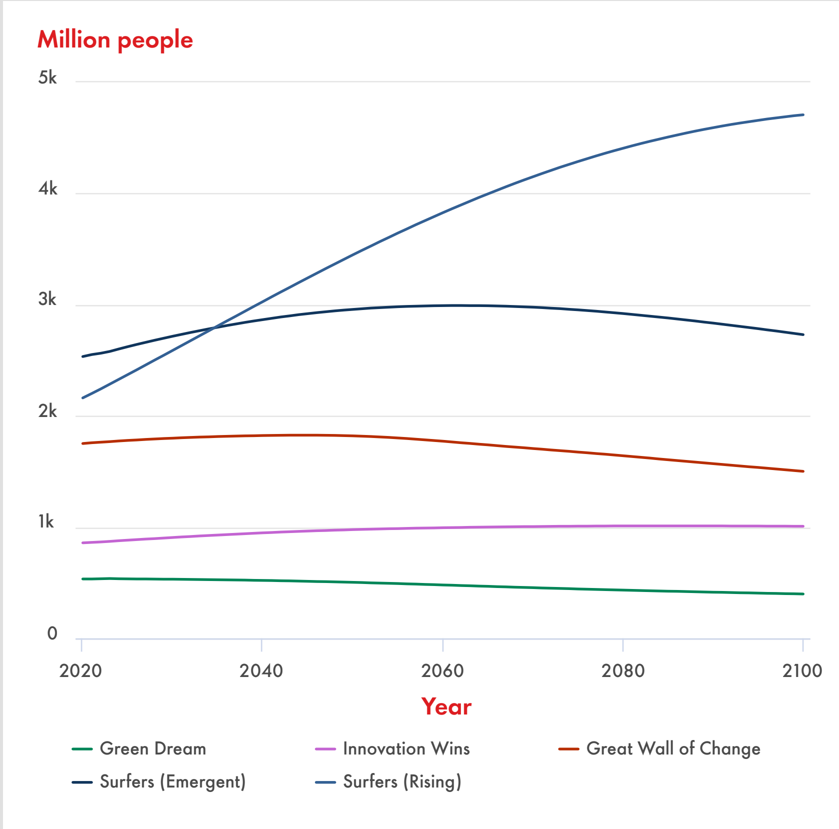
Primary energy demand rises through the century

Globally, primary energy use rises through the century, with only a modest and temporary levelling off in **Sky 2050**, as efficiency measures and early electrification take effect. By 2050, nearly half of global energy use takes place in **Surfers** countries, with little or no growth elsewhere. In 2100, **Surfers** dominate global energy needs, with all growth coming in that group of countries as they experience population rises and rapid economic development.

The dual causes of energy demand growth for Surfers

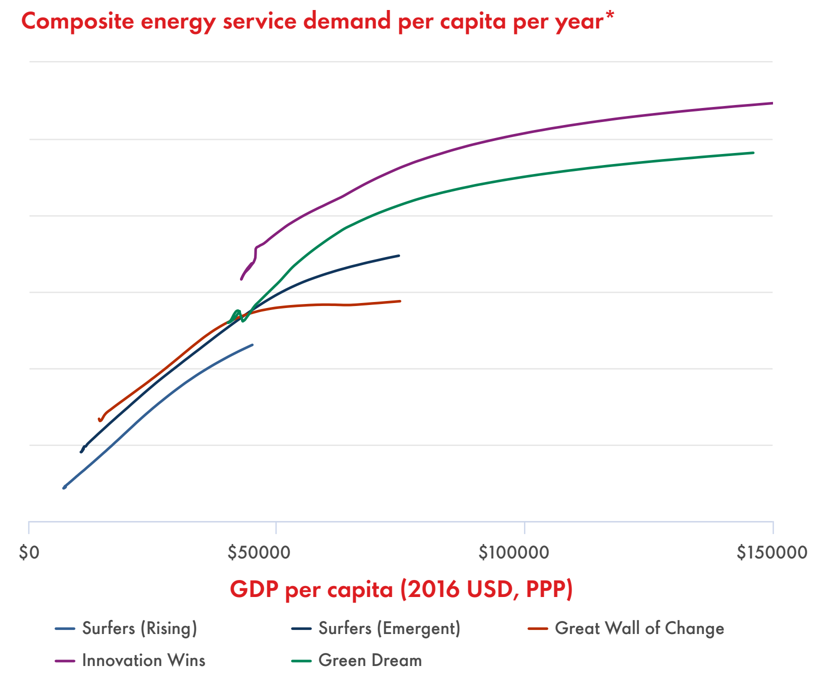
During the second half of the century, the only countries with growing populations come from the **Rising Surfers** archetype, with an increase of around 1.3 billion people between 2050 and 2100. During that period, all **Surfers** countries see rapid growth in the use of energy services as their economic situations improve. This happens as more and more people gain access to clean water, electric cooking, sanitation, lighting, refrigeration and personal and public transport.

Population projection by archetype



The overall result of a rising population that is increasingly using energy services is sharply rising energy demand throughout the century. Despite this dramatic increase in demand, additional fossil fuel use is limited, as the **Rising Surfers** largely skip fossil fuels and move directly to electricity for many energy services. The increasing demand for energy in the **Surfers** countries feeds through into rising global energy demand across both scenarios.

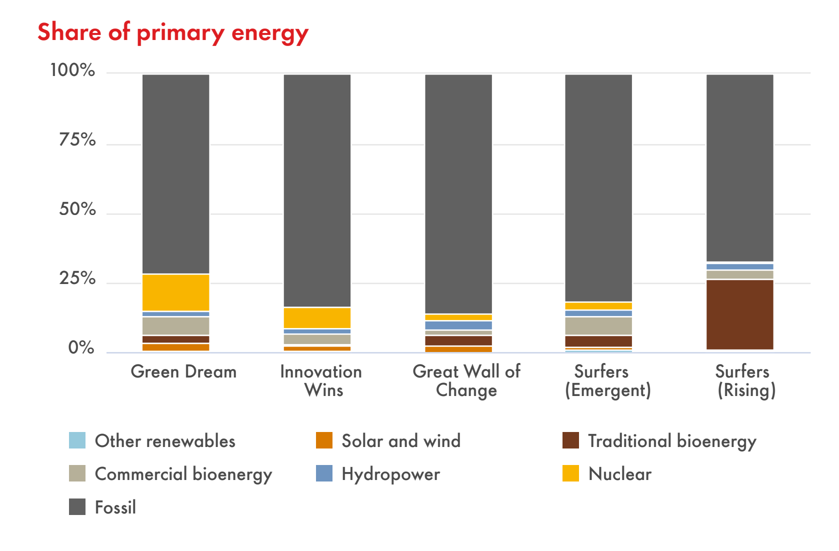
How increasing wealth translates into increased energy use in each archetype



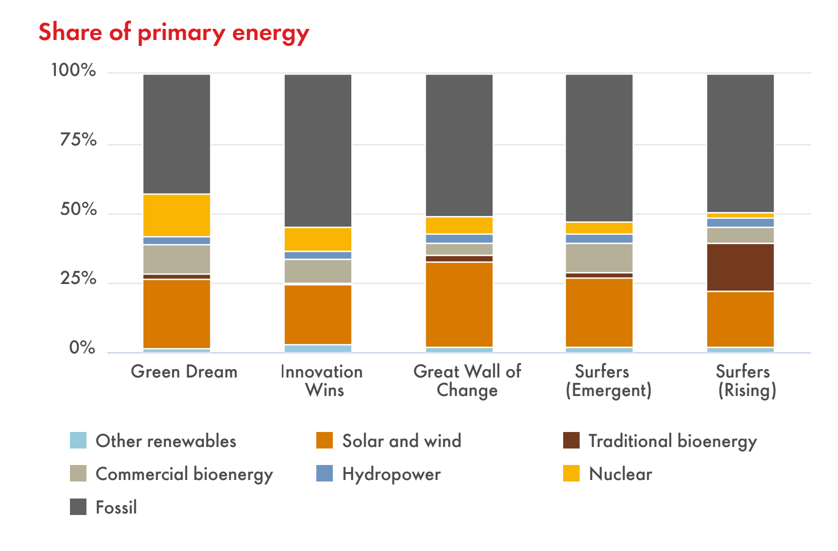
*The composite energy service is a weighted sum of energy service demand by sector. The weights are set by the respective sector total final energy consumption in 2019 with the dataset then rebased for ease of comparison over time.

Primary energy trends

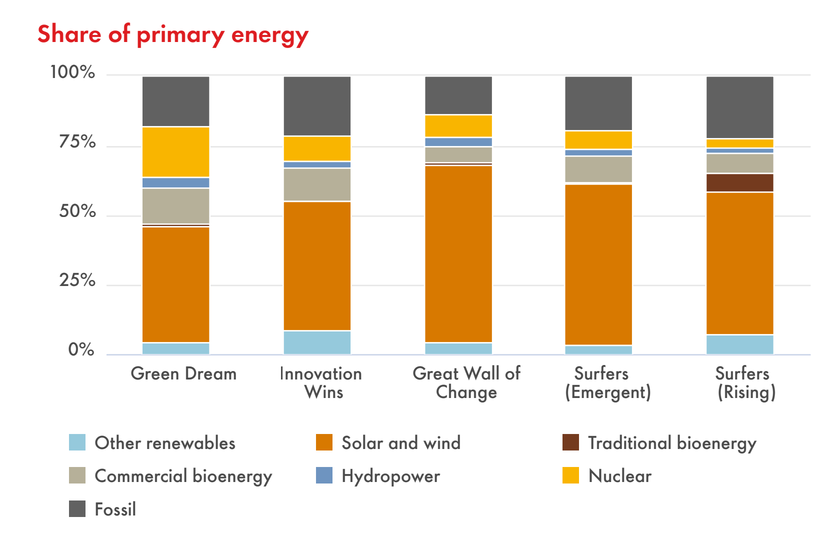
Global primary energy mix in Sky 2050 - 2020



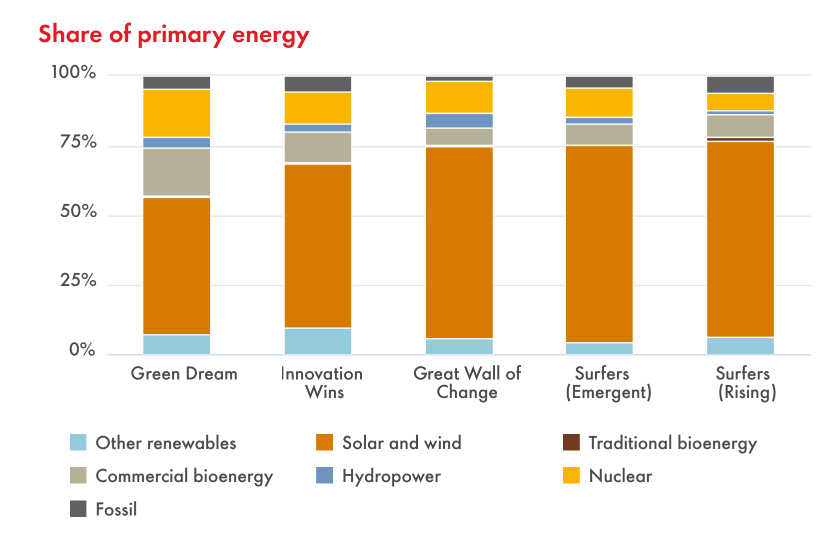
Global primary energy mix in Sky 2050 - 2040



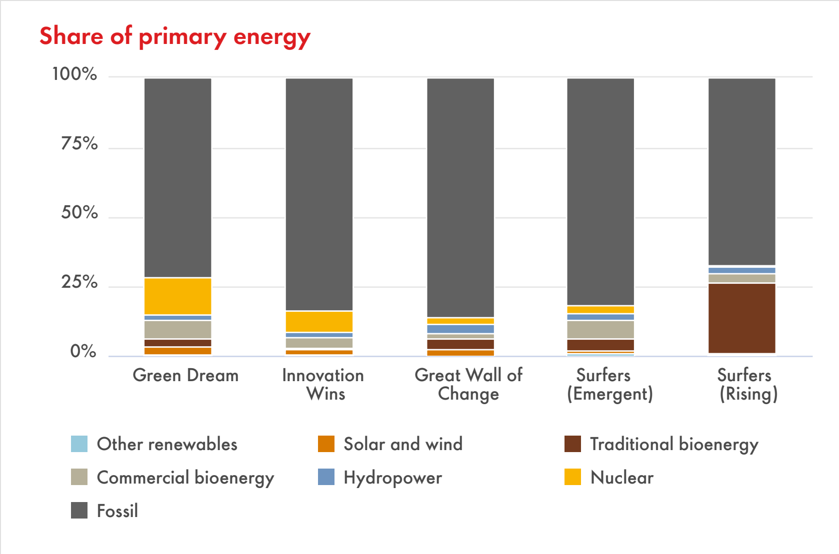
Global primary energy mix in Sky 2050 - 2060



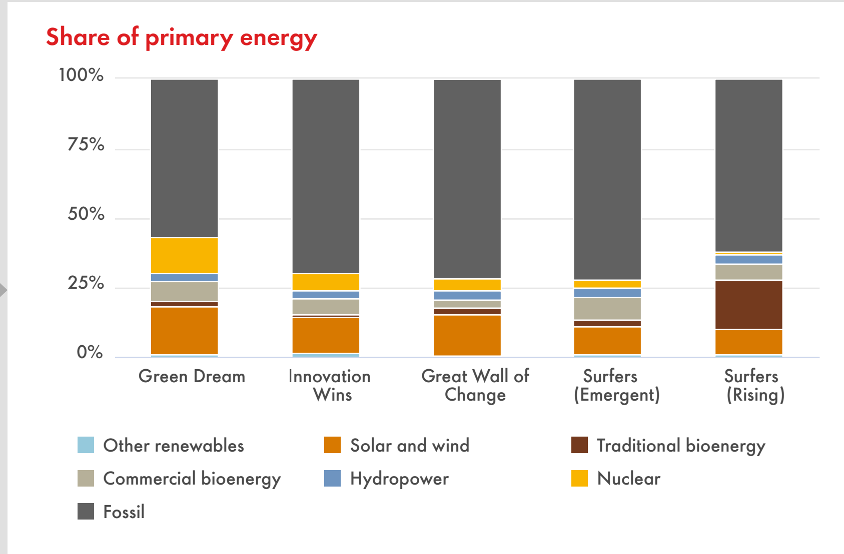
Global primary energy mix in Sky 2050 - 2100



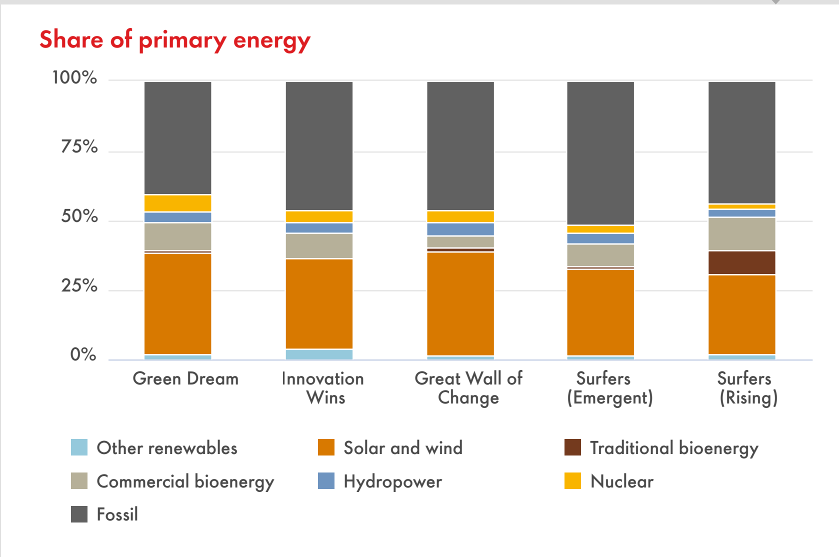
Global primary energy mix in Archipelagos - 2020



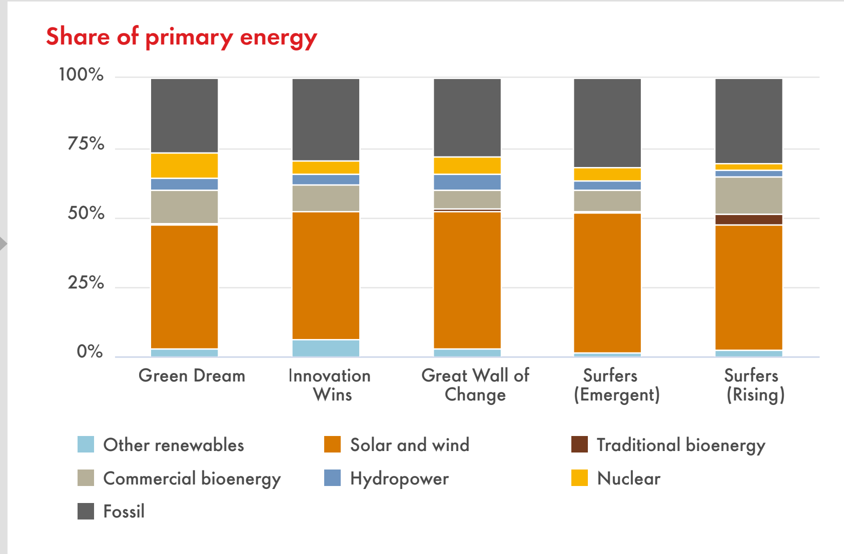
Global primary energy mix in Archipelagos - 2040



Global primary energy mix in Archipelagos - 2060



Global primary energy mix in Archipelagos - 2100



The coal era ends

Industrial economies have been built on the back of coal throughout the 19th, 20th and early 21st centuries. Countries such as the UK and USA did this in the 19th and early 20th centuries, only to progressively phase out using coal for energy between 1980 and 2020. By 2020, the UK had little reliance on coal, apart from in its iron ore smelters. China largely repeated the coal-led development trend between 1990 and 2020 and became the world's biggest coal user, but is now beginning to limit and reduce domestic coal use. India was on a similar pathway up until 2015, but its trend of rapidly growing coal use has since significantly moderated.

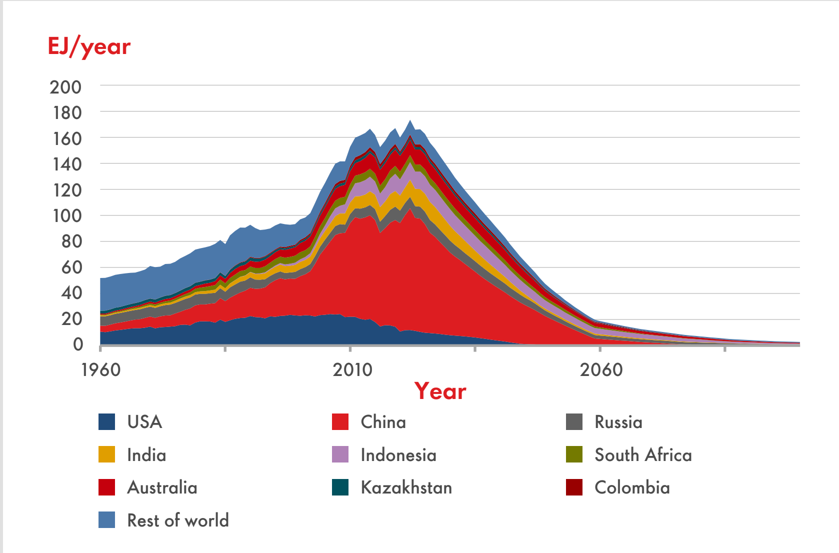
In **Sky 2050**, coal use is well into decline by the middle of the 2020s. In **Archipelagos**, the drop off is only visible in the early 2030s.

One feature common to both scenarios is **Green Dream** countries struggling to reduce coal use in the early 2020s, as they fight to meet their immediate energy needs.

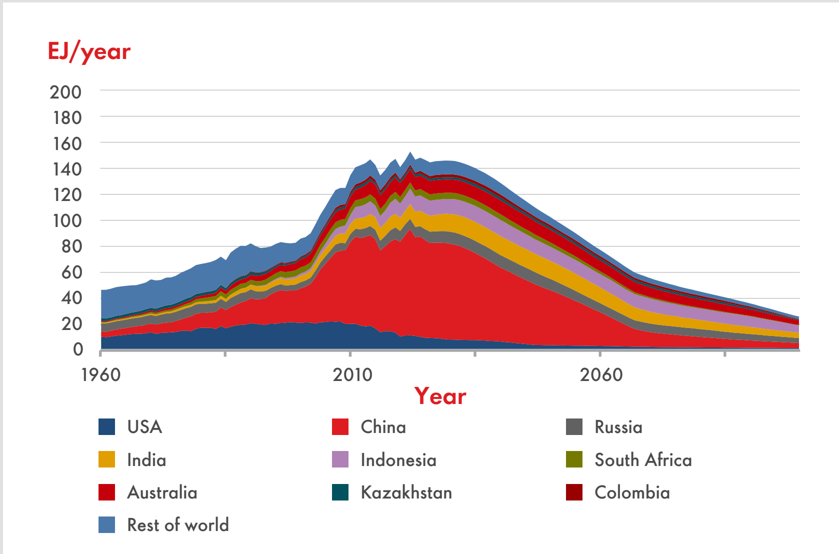
In both **Sky 2050** and **Archipelagos**, the 2 billion people in **Rising Surfers** countries develop largely without coal, even as their overall population doubles towards the end of the century.

In the period 2060-80, coal is starting its true exit from the energy system after nearly 300 years of use. **Archipelagos** lags **Sky 2050** in this trend by between 10 and 30 years.

Coal production in Sky 2050



Coal production in Archipelagos

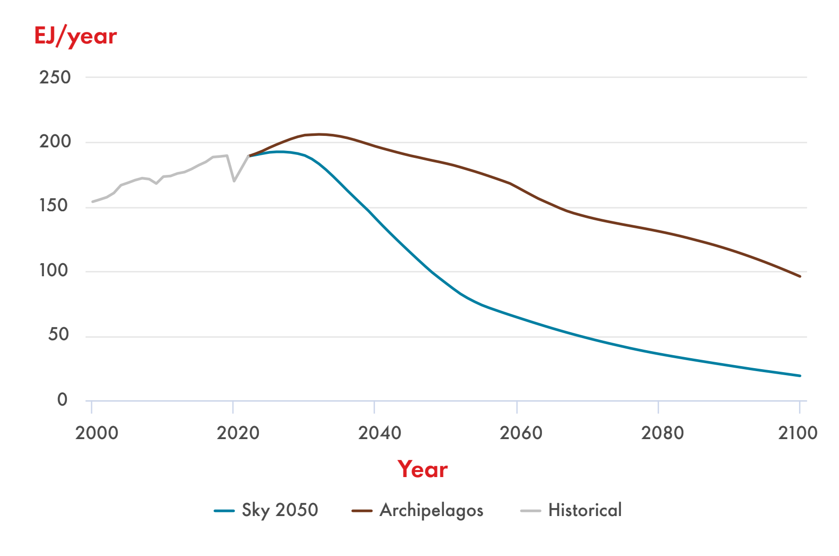


Oil largely vanishes in Sky 2050, but remains resilient in Archipelagos

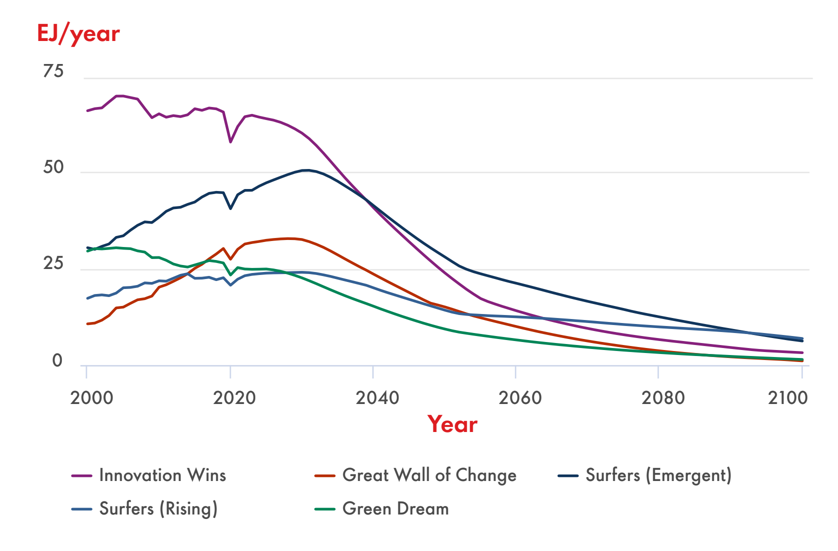
In **Sky 2050**, peak global oil demand is in the mid-to-late 2020s, and in **Archipelagos** it is only five years later. The main difference between the scenarios is the shape of demand after that peak. In **Sky 2050**, demand drops sharply, and oil is almost gone from the global energy system by the end of the century.

In **Archipelagos**, oil demand experiences a much slower decline, with the world still using about half the amount it used in 2022, even into the 22nd century. In **Archipelagos**, it is not until the mid-2080s that oil demand is falling in all parts of the globe. **Surfers** are the primary source of demand in the second half of the century, with use mainly driven by population growth rather than increasing individual needs.

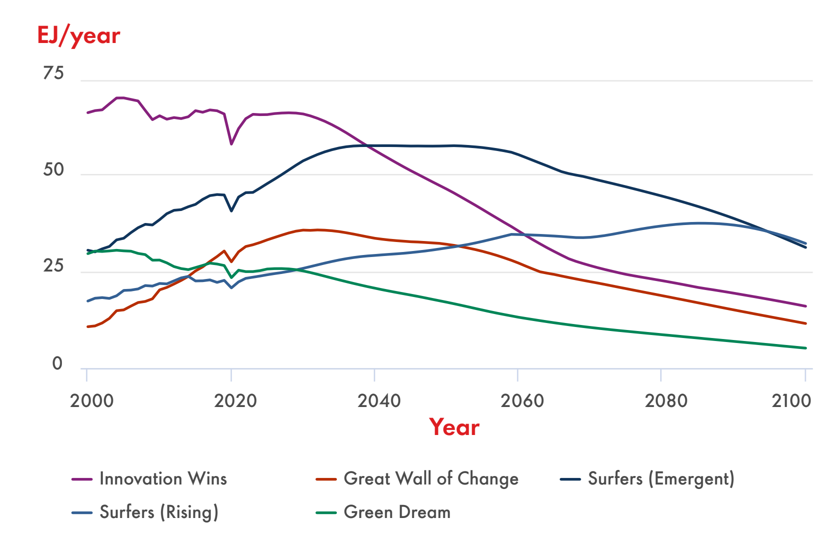
World demand for oil



Oil demand by archetype in Sky 2050



Oil demand by archetype in Archipelagos

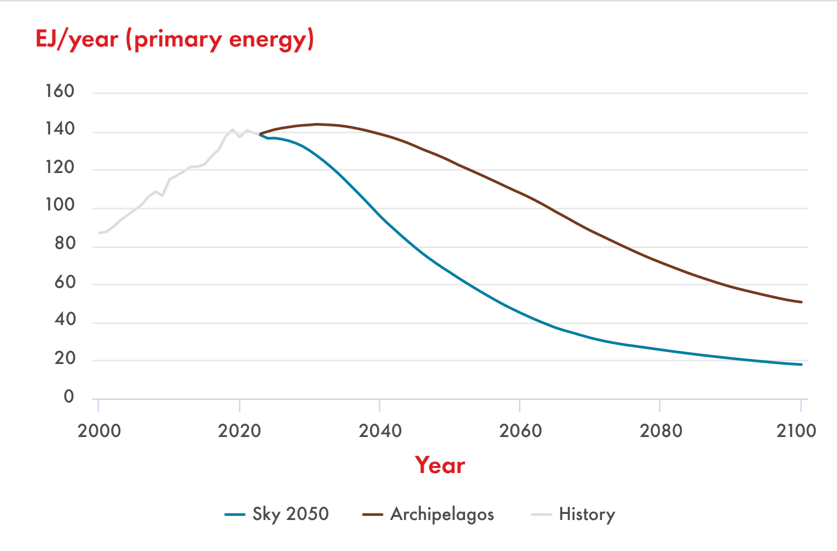


Natural gas plays an important role well into the century

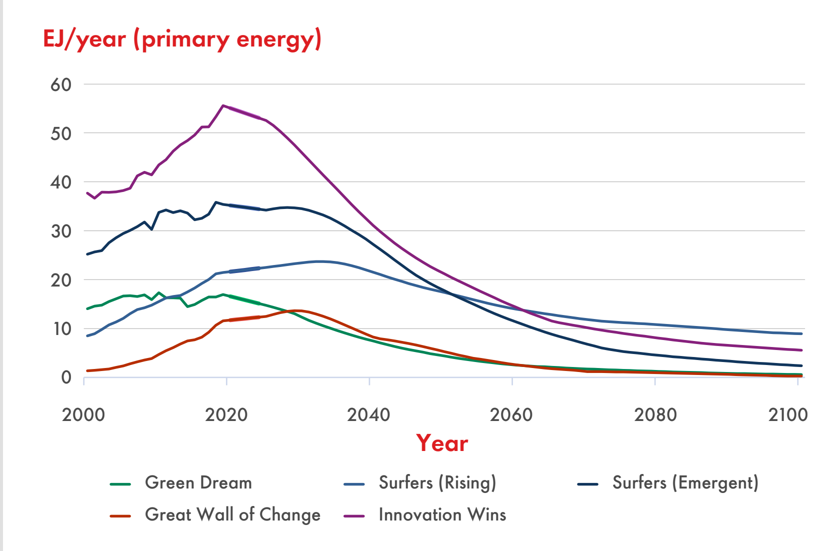
In both **Sky 2050** and **Archipelagos**, natural gas plays an important role throughout the century, even as its use declines. It continues to be used by industry as a fuel, by people to heat their homes and to support power generation networks as intermittent renewables take an ever-increasing share of the load.

In **Sky 2050**, peak gas demand is in the early 2020s, but it is not until after 2050 that use falls by 50%. In **Archipelagos**, peak gas demand comes in the 2040s, with use falling 50% by 2090. Late in the century, the most important use of natural gas is in the production of chemicals.

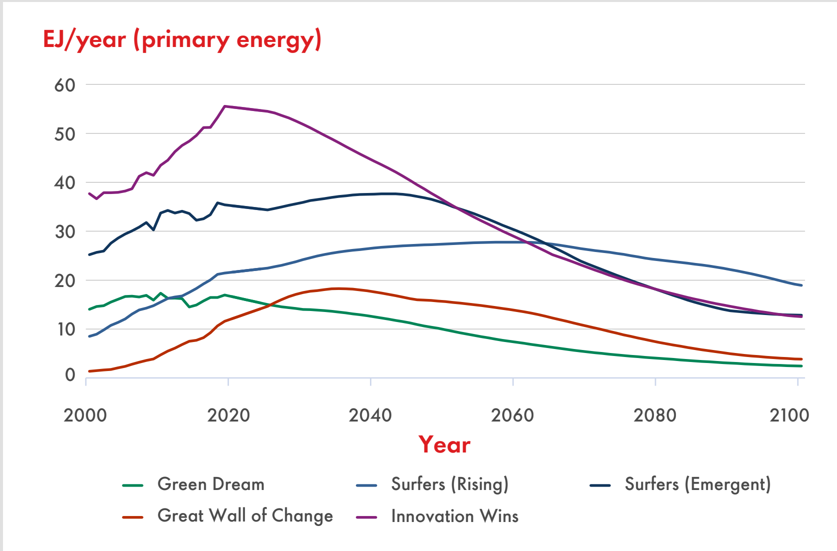
World demand for natural gas



Natural gas demand by archetype in Sky 2050

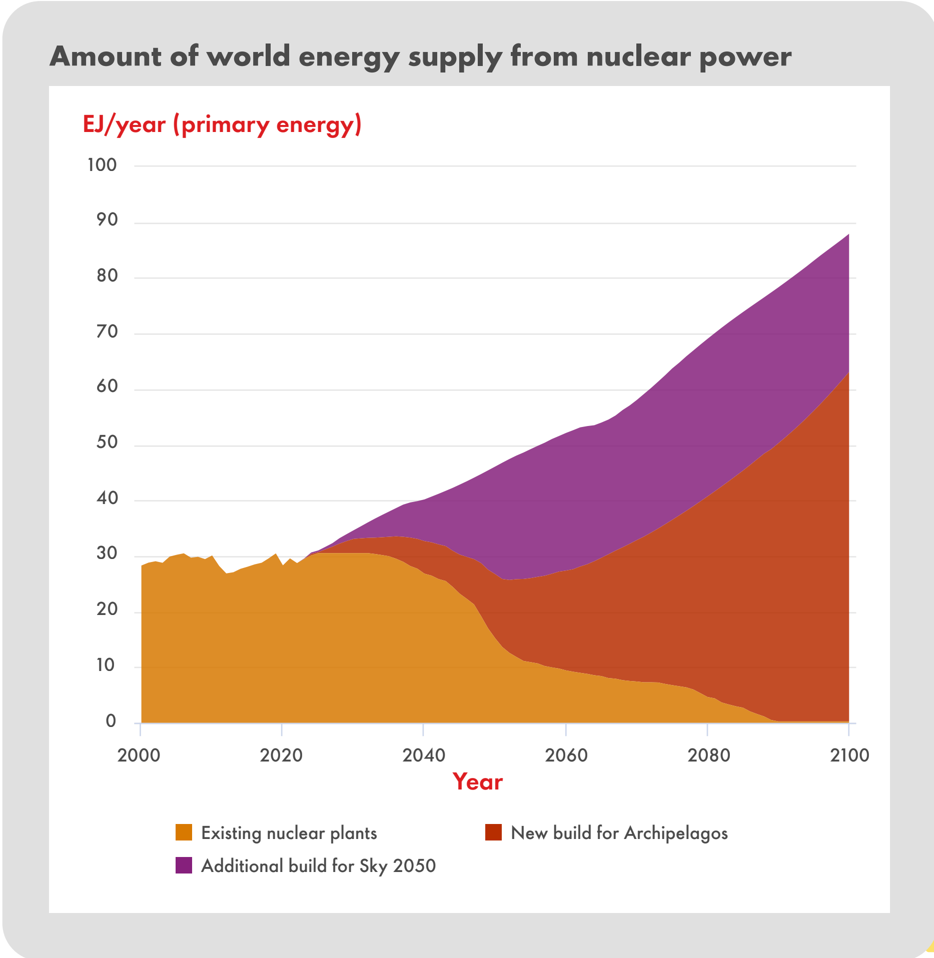


Natural gas demand by archetype in Archipelagos



Nuclear succeeds, 100 years on from its first attempt

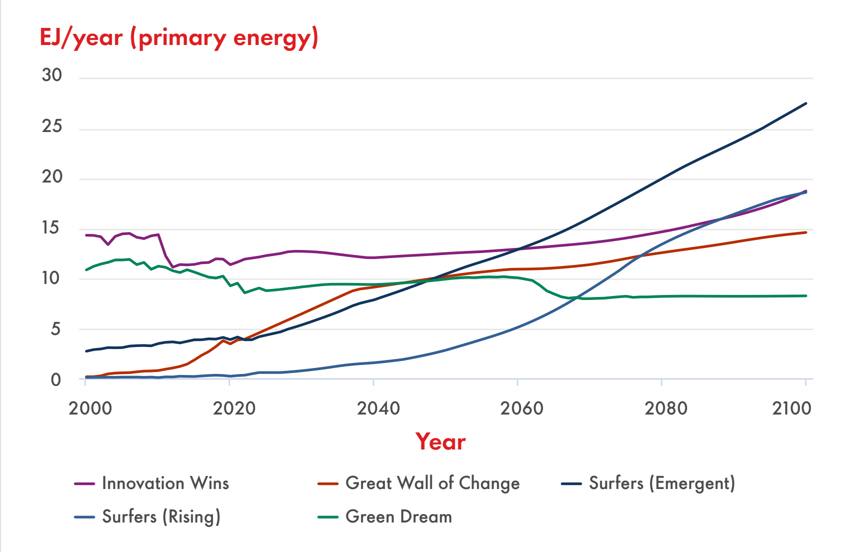
During the first two decades of the 21st century, nuclear has remained static in the energy mix. Some countries have begun to phase it out, others are replacing older facilities and still others are introducing nuclear for the first time. The net gain, globally, has been close to zero.



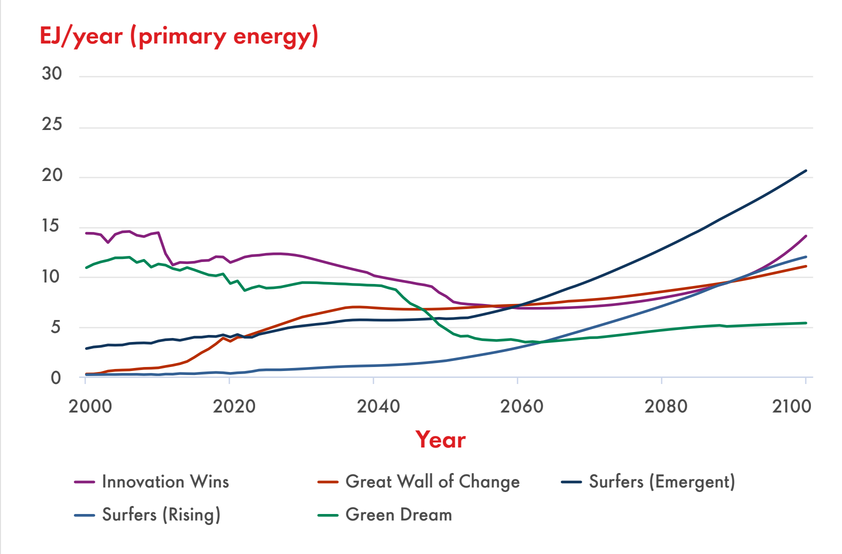
In **Sky 2050**, the world turns to nuclear power much more readily because of the rapid trend to electrification and the supply intermittency issues that emerge as renewables become dominant. Older nuclear facilities are replaced as they age and, beyond that, new power stations begin to be built from the late 2020s. In **Sky 2050**, in the second half of the century, more than 1,500 one-gigawatt facilities are constructed globally. **Surfers** countries take particular advantage of the resurgence in nuclear technology.

In **Archipelagos** this trend continues until mid-century, when new technologies emerge and an increased need for dependable base-load power prompts fresh nuclear investment. From 2050 to 2080, some 700 one-gigawatt facilities are built globally. This is in addition to the power stations needed to replace existing sites as they come to the end of their lives.

Use of nuclear power by archetype in Sky 2050



Use of nuclear power by archetype in Archipelagos

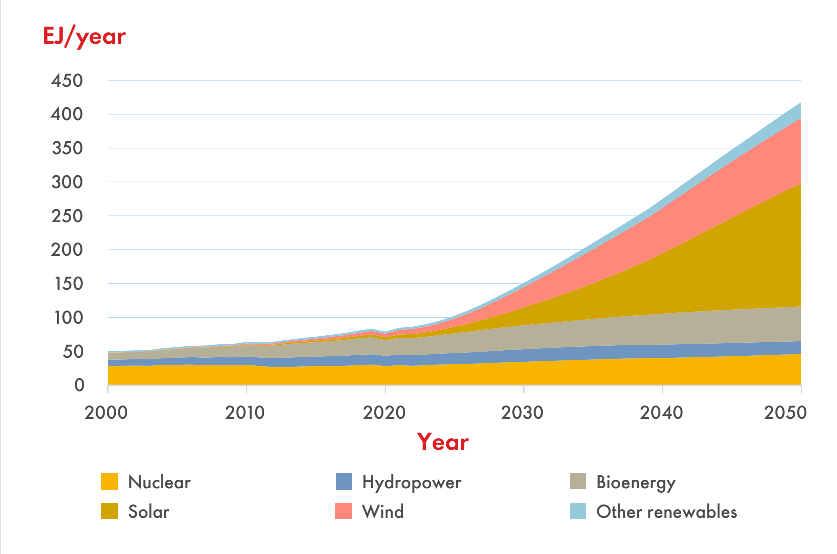


The rise of renewables

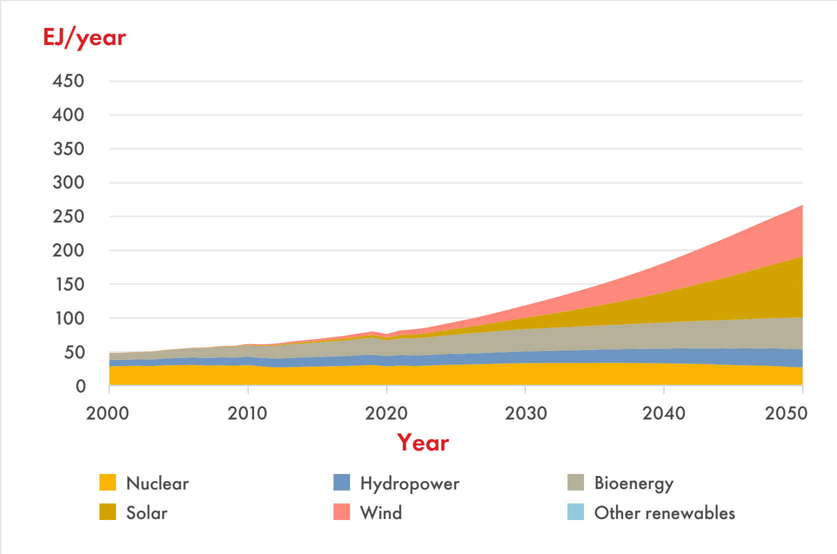
As the energy transition moves forward, wind and solar quickly become dominant. From 2020, when they contributed around 10 exajoules (EJ) to the global energy system, the acceleration in both scenarios is dramatic. The amount of primary energy generated by wind and solar grows by a factor of 17 in **Archipelagos** by 2050, and by a factor of almost 30 in **Sky 2050**.

The rise of solar is especially steep. Even in recent years, the world has been adding around 200-250 gigawatts (GW) of solar photovoltaic capacity each year, delivering some 250-300 terawatt-hours (TWh) of electricity. Even at the slower pace seen in **Archipelagos**, the capacity added each year grows to around 400 TWh in the early 2030s. This level of expansion outstrips the growth seen in the early 2020s for coal and natural gas combined. The rapid uptake of solar means both coal and natural gas stop growing as sources of electricity in the 2030s, with no further net addition of generation from these energy sources.

Non-fossil energy sources in Sky 2050

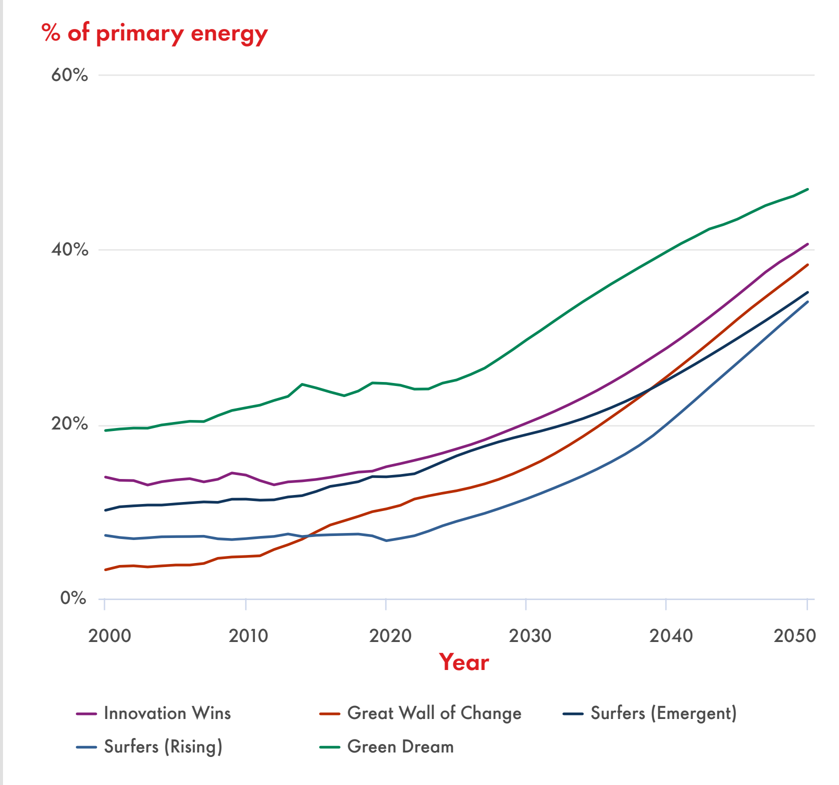


Non-fossil energy sources in Archipelagos



The advance of solar and wind pushes the market share of fossil fuels into retreat. Despite the fact that, for 60 years, the share of fossil fuels in primary energy has barely moved at around 80%, this changes in both scenarios. By 2040, coal, oil and natural gas have all seen their market share peak. The decline that follows, in **Sky 2050**, is very pronounced. The global primary energy mix shifts rapidly towards solar and wind, with nuclear also growing in the 2030s and 2040s. In **Archipelagos**, the early trends are similar, but then lag behind those seen in **Sky 2050** by 10-20 years.

Share of energy from non-fossil sources - Sky 2050



Integrating variable renewables into the electricity system

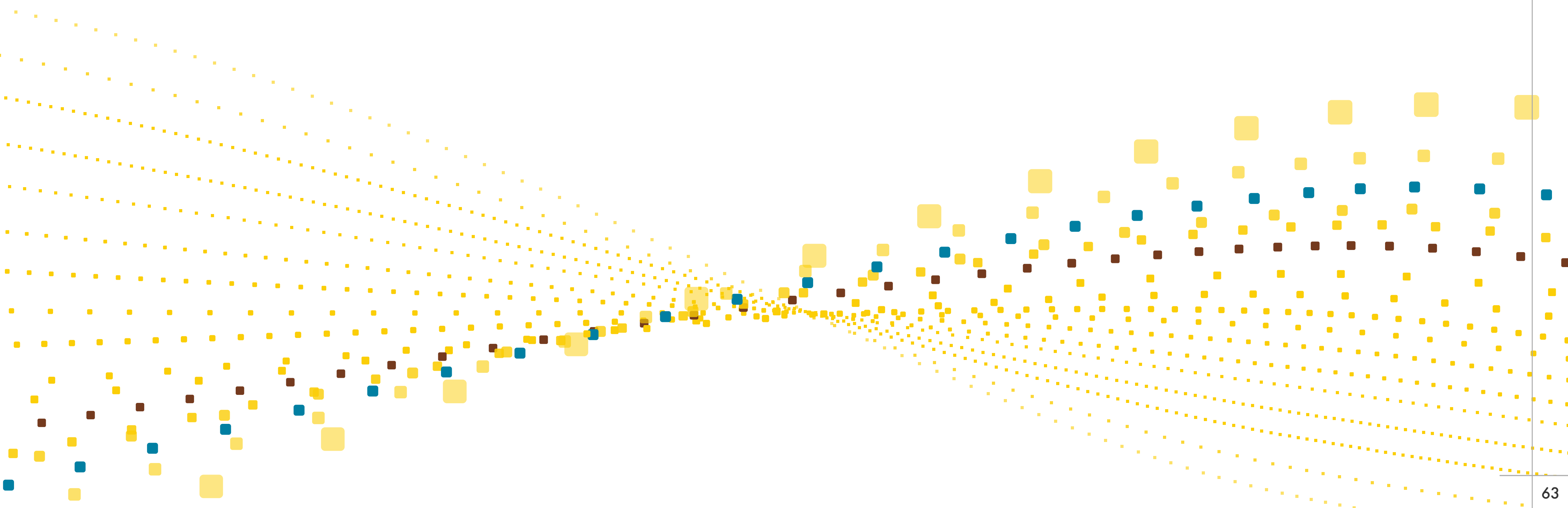
Integrating a high share of renewable power generation into the energy system is possible but it requires significant support. Systems that enable large-scale energy storage, interconnection and flexible demand management must all be developed rapidly together. The amount of electricity storage capacity, for example, will need to be of a similar order to the amount of energy generated by non-intermittent sources in 2022 (albeit in a larger electricity system).

Between 2011 and 2021, the share of total annual electricity demand worldwide from intermittent sources like wind and solar rose from 2% to 11%. In our scenarios, the momentum behind wind and solar means that this share rises rapidly and by 2035 has reached 35% in **Archipelagos** and 55% in **Sky 2050**. These figures, however, disguise the fact that, from hour-to-hour, the share contributed by intermittent sources will be very different.

To date, wind and solar generation has been backed up by a combination that includes hydroelectricity, natural gas and interconnection between grids, and this been enough to level out the variation in generation. As solar and wind increasingly dominate, however, additional technologies will need to rapidly come into play at scale. These include:

- lithium-ion battery storage at a massive scale, for balancing supply and demand for periods lasting from a few hours to a day;
- chemical storage, such as flow batteries and hydrogen, for balancing supply and demand for periods lasting from weeks to months and over seasons;
- flexible demand, in which demand can be increased or decreased remotely through things like smart devices, the heating of buildings and the charging of battery electric vehicles; and
- local or cross-border interconnections, to help balance supply and demand across a larger geographical area.

The indications are that the mix of solutions employed will be highly dependent on each country's circumstances, such as its energy resources, degree of interconnection, patterns of demand and the level of seasonal variation it experiences. A general principle, however, is that storage needs increase rapidly as the contribution from variable renewables rises.

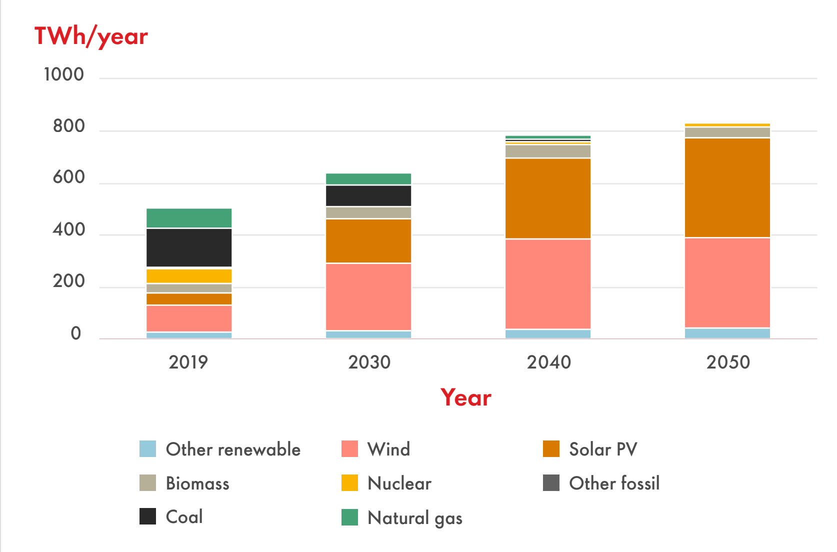


Both scenarios chart optimistic futures for technology rising to this challenge, and we assume that variable renewables will be able to meet up to 85-90% of final consumption eventually. In **Sky 2050**, some countries achieve this level early, with Germany reaching this point mid-century. The detailed electricity system modelling for such a Germany in 2050 indicates that much of the storage will not be needed for much of the time – either to store excess renewable energy or to keep the lights on when high demand coincides with low renewable generation.

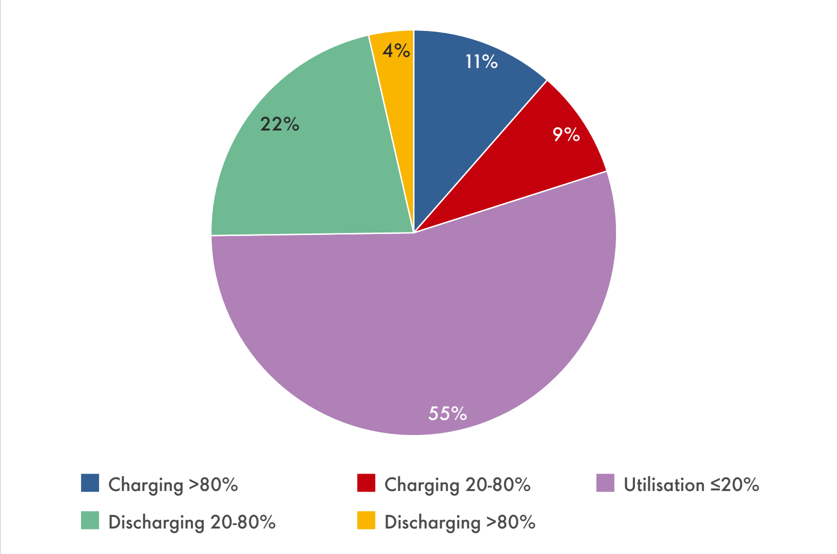
This analysis assumed:

- batteries capable of delivering 50 gigawatts (GW) per hour of power over six hours, in addition to the existing pumped-hydro capacity, which is capable of delivering 8 GW per hour over a 24-hour period;
- flexible demand – up to 10% of demand is flexible during daylight hours;
- interconnection – up to 20% of demand in peak periods can be met by imports;
- curtailment – up to 10% of total solar and wind capacity can be turned off during peak supply hours; and
- no seasonal variation.

Germany - Electricity - Sky 2050



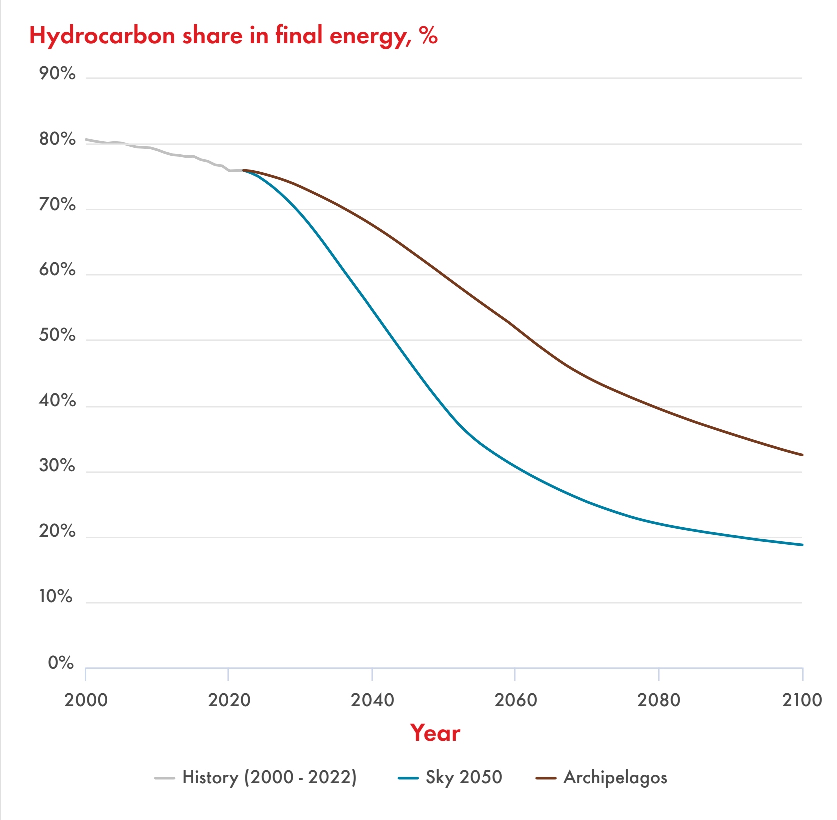
Battery usage across the year in a net-zero emissions Germany



The final energy mix accelerates away from hydrocarbon fuels

In both **Sky 2050** and **Archipelagos**, there is an immediate acceleration of the trend away from hydrocarbon fuels, such as petrol in cars and natural gas to heat homes.

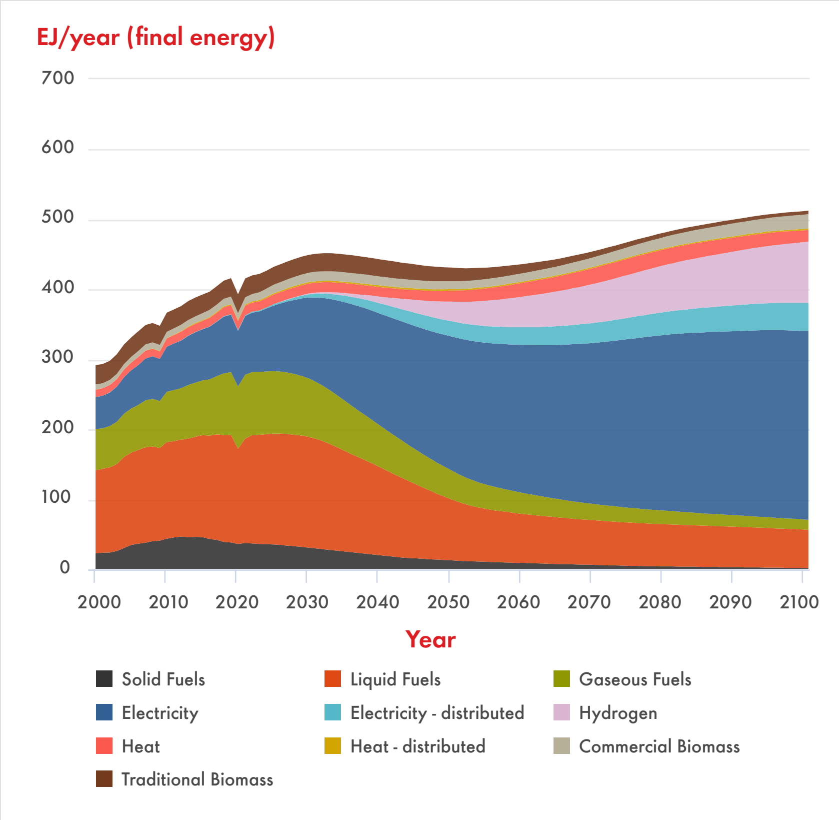
The role of hydrocarbons in the world's energy mix



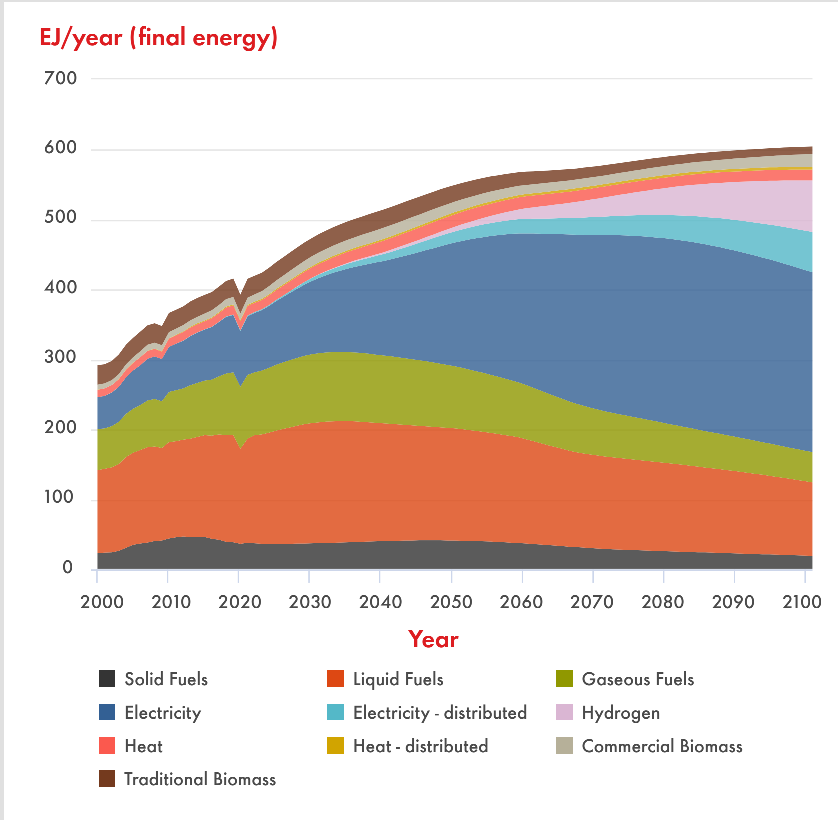
Electricity is the winner: cars shift to batteries, homes to electric cooking and heating, and industry increasingly relies on electricity for process heat. In **Sky 2050**, hydrogen starts to become a significant fuel in the 2030s, but it takes around a decade longer to establish itself in **Archipelagos**. In both scenarios, hydrogen is largely produced using renewable electricity to split water through electrolysis.

By late in the century, in **Sky 2050**, electricity and hydrogen account for nearly 80% of the final energy mix.

How the world gets its energy in Sky 2050



How the world gets its energy in Archipelagos

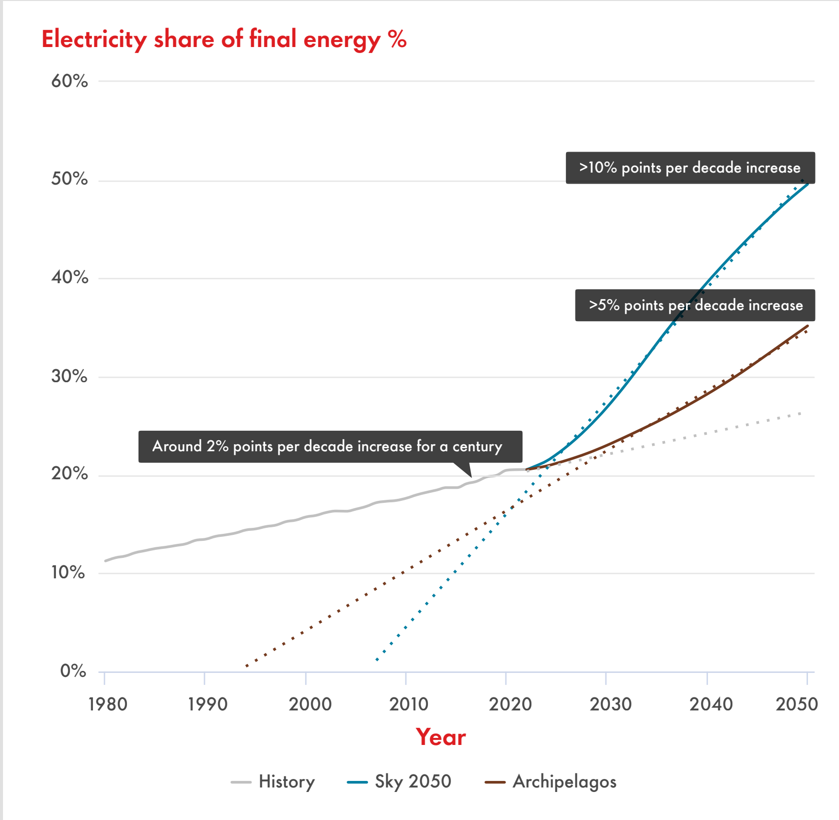


Electrification of the energy system

The major energy system shift in both scenarios is the rise of electricity in the final energy mix. In **Sky 2050**, this change starts early in the decade and, in **Archipelagos**, an acceleration is visible by 2030. Both scenarios suggest unprecedented change. In **Archipelagos**, electricity use grows at more than five percentage points per decade in the final energy mix. In **Sky 2050**, the growth runs at more than 10 percentage points per decade. This compares with a century-long historical trend closer to two percentage points per decade. The expansion of electricity into transport, through battery-electric passenger vehicles, provides the initial momentum for change.

Electrification on this scale requires considerable new grid infrastructure. This includes interconnections between existing standalone networks, such as between countries. This also includes much greater use of long-distance, ultrahigh-voltage direct current transmission, including some interconnections with undersea cables. Such connections can allow large-scale flows of renewable energy to balance regional supply and demand mismatches. They can also enable large-scale energy storage to manage the intermittency of renewable generation.

The electrification of final energy

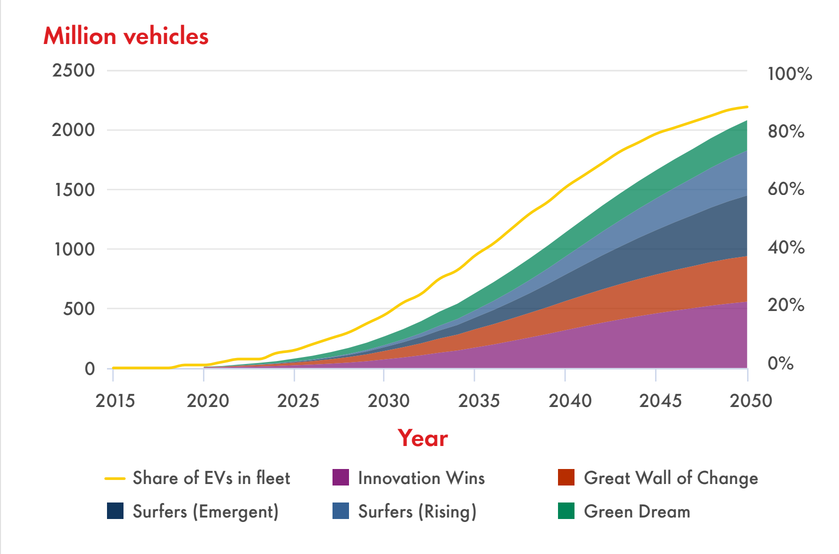


Electric passenger vehicles rapidly gain in popularity

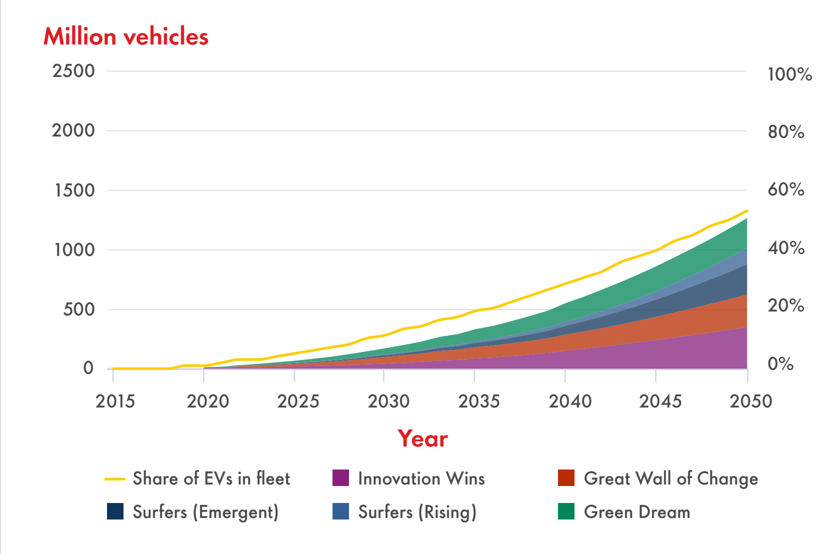
Electrically powered vehicles quickly become the dominant choice for consumers. In **Sky 2050**, the passenger vehicle market is completely transformed by 2040. This happens as mandates against selling new internal combustion engine vehicles take effect in a growing number of countries, states, cities and companies. All sales of passenger vehicles with an internal combustion engine have ended by 2040.

In **Archipelagos**, the switch to electric passenger vehicles is still fast, but it takes until 2040 to reach 50% of the market. After that point, the transition accelerates until all new vehicles sold are powered by electricity.

Electric vehicle penetration by archetype in Sky 2050



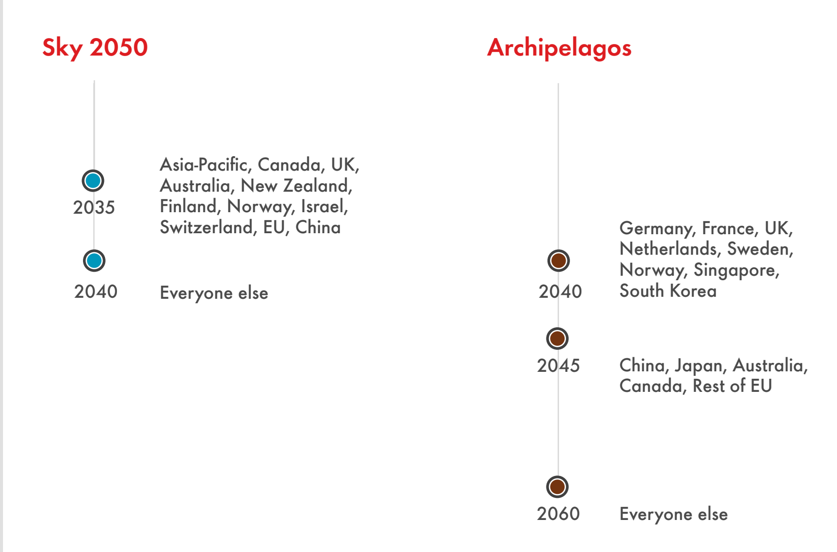
Electric vehicle penetration by archetype in Archipelagos



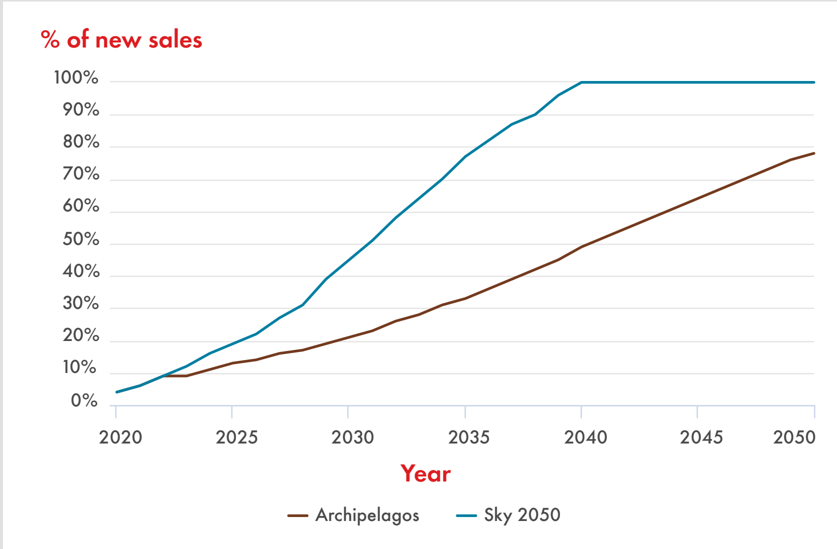
Factors contributing to the slower pace of change, compared to **Sky 2050**, are:

- limitations on the supply of key battery minerals, such as nickel, cobalt and lithium, with delays caused by the pace of new mine development and cross-border trade issues around important metals;
- reluctance in certain countries to accept investment in the mining and manufacturing sectors;
- continued domestic production of internal combustion engine vehicles in some countries for reasons of job security;
- the determination of oil-rich economies to make the most of their domestic resources; and
- slower consumer interest in some countries, with populist leaders responding to such sentiment.

When the world bans sales of internal combustion engine cars



The share of electric vehicles in new car sales

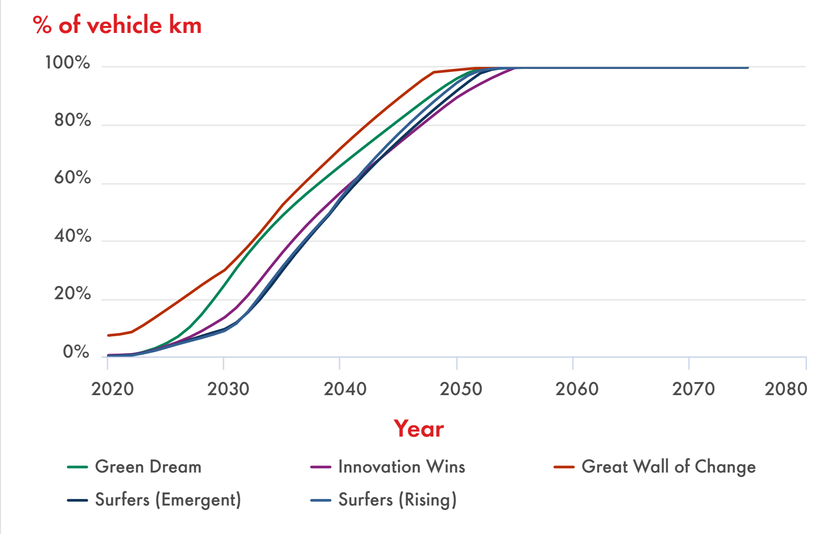


All passenger vehicles run on electricity by the 2070s

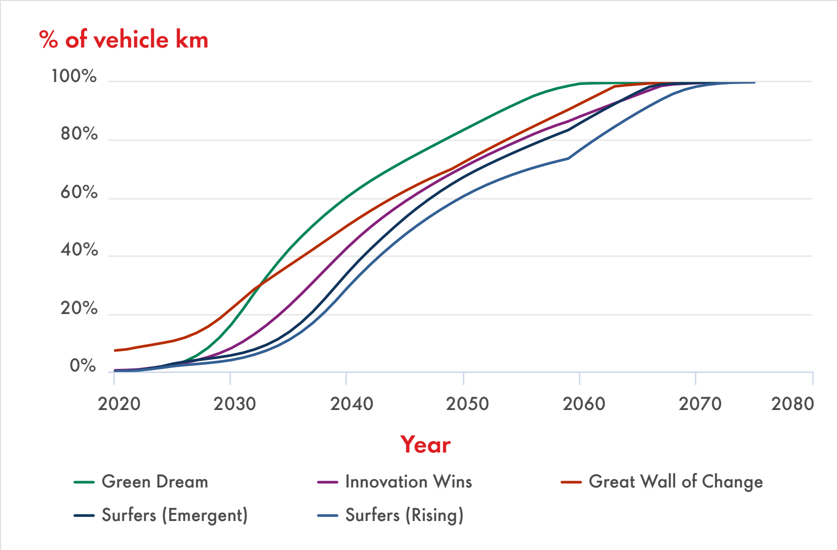
In both scenarios there is a rapid transition of passenger vehicles away from the internal combustion engine. The primary factor holding back change is the availability of materials, notably copper, nickel, lithium and cobalt. In **Sky 2050**, these issues are overcome more quickly through cross-border co-operation in the mining sector.

In **Sky 2050**, almost all passenger vehicles are electric by the early 2050s. **Archipelagos** lags behind by up to 20 years, with internal combustion engines still being used in the **Rising Surfers** countries.

Uptake of electric passenger vehicles in Sky 2050



Uptake of electric passenger vehicles in Archipelagos



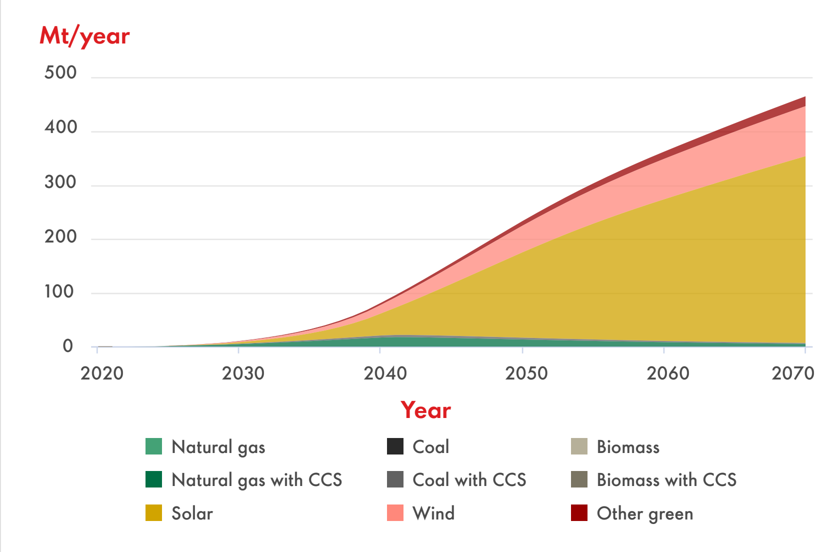
The growth of hydrogen

In **Sky 2050**, hydrogen use begins to gain a foothold in the mid-2020s, but in **Archipelagos** this does not happen until the early 2030s. The gap goes on to widen as the years pass and, by 2050, the world of **Sky 2050** is using twice as much hydrogen as the world of **Archipelagos**.

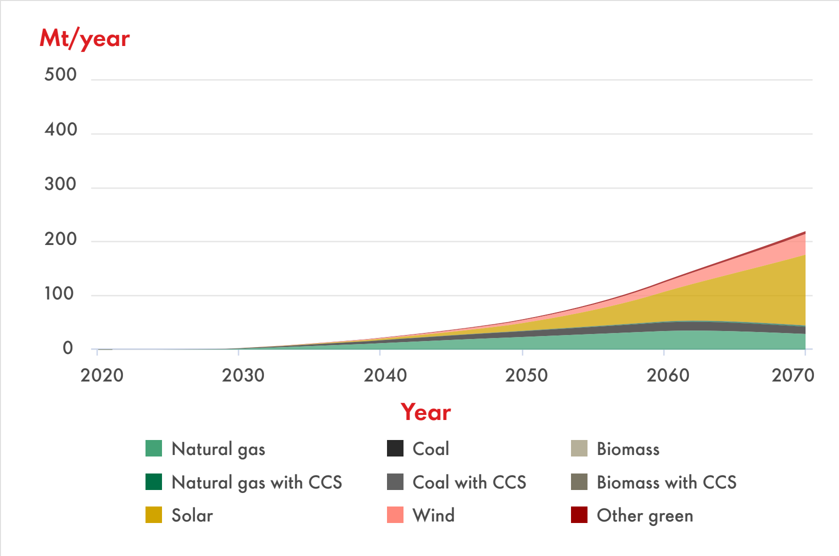
In **Sky 2050**, the dominant production process for hydrogen by 2035 is to use renewable electricity to split water using electrolysis.

In **Archipelagos**, this production process does not take the lead until 2055. Until then, most hydrogen is produced by breaking down natural gas, with this technique remaining important well into the second half of the century.

How the world produces hydrogen in Sky 2050



How the world produces hydrogen in Archipelagos



Hydrogen: the answer to many questions

Building on developments in the 2020s and 2030s, hydrogen becomes an important part of the energy system. In **Sky 2050,** hydrogen makes up 12% of final energy demand by 2070. In **Archipelagos**, by the same date, hydrogen makes up 4% of final energy demand.

In **Sky 2050**, the first passenger flights on a hydrogen-powered plane take place in 2040, bringing in a change in aviation not seen since the arrival of jets in the 1950s.

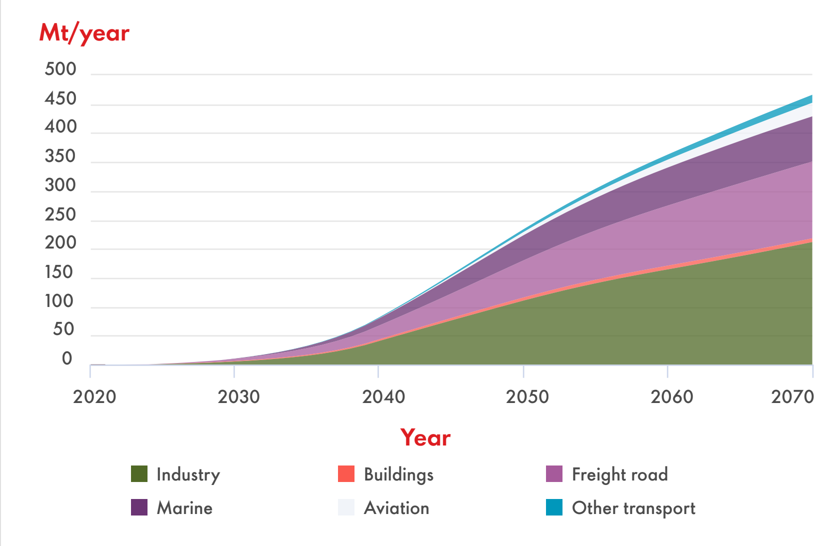
Heavy industry changes emerge in the early 2020s in **Sky 2050**, with green hydrogen – made by using renewable energy to split water by electrolysis – starting to be used in the ammonia industry and for iron ore smelting. By 2050, around a third of the smelters in the world run on hydrogen.

In both **Sky 2050** and **Archipelagos**, hydrogen becomes the alternative workhorse for heavy-freight road transport, with the first commercial appearance of hydrogen fuel-cell trucks on the road in the late 2020s.

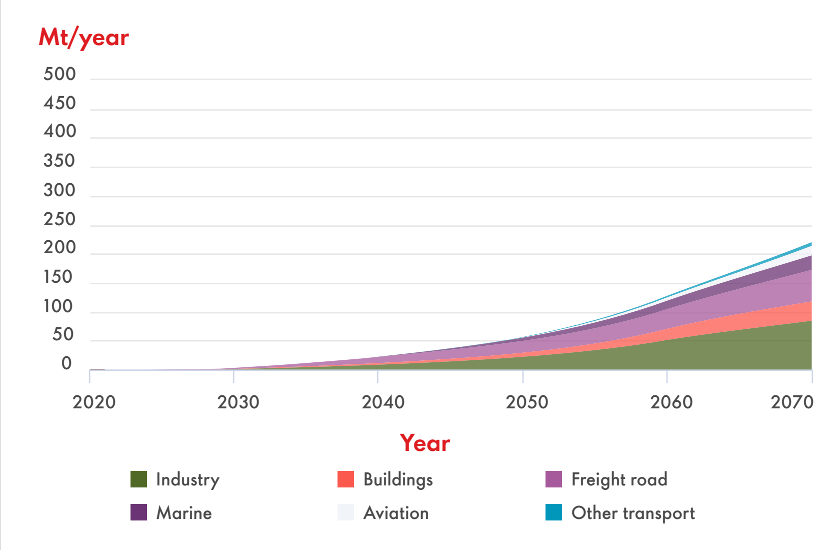
In **Sky 2050**, container ships fuelled directly by hydrogen, or indirectly using ammonia, take to the seas in the 2030s. In **Archipelagos**, this advance takes a decade longer to emerge.

Hydrogen demand growth in **Sky 2050** is 3 exajoules (EJ) per year in the 2040s, seven times the rate seen in **Archipelagos**. Rapid growth of hydrogen demand does not take place in **Archipelagos** until after mid-century.

The global use of hydrogen by sector in Sky 2050



The global use of hydrogen by sector in Archipelagos



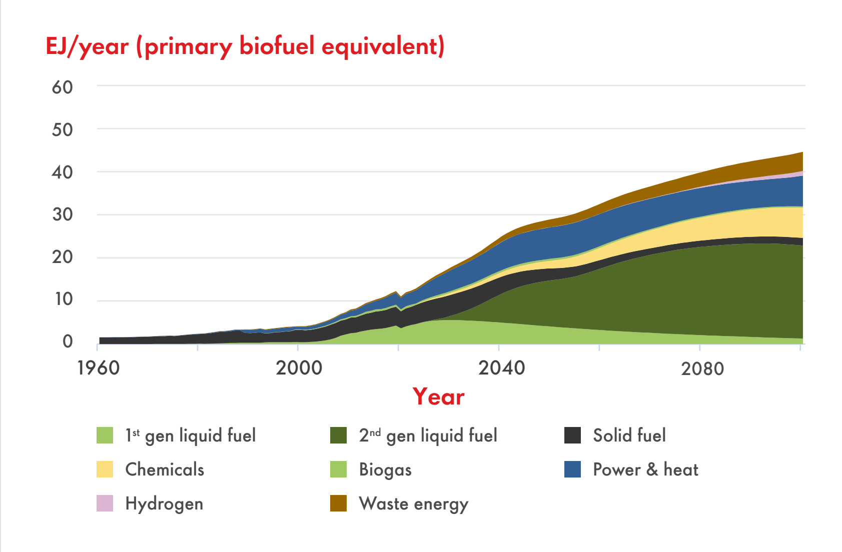
The important role of bioenergy

Bioenergy is considered CO_2-neutral in the energy system. Bioenergy is highly flexible and can be used to make any energy carrier – solid, liquid or gaseous fuels – as well as electricity and hydrogen. It can also replace fossil carbon in the production of chemicals. Finally, when burned to generate power and combined with carbon capture and storage (CCS), it is a way to remove CO_2 from the atmosphere (known as negative emissions).

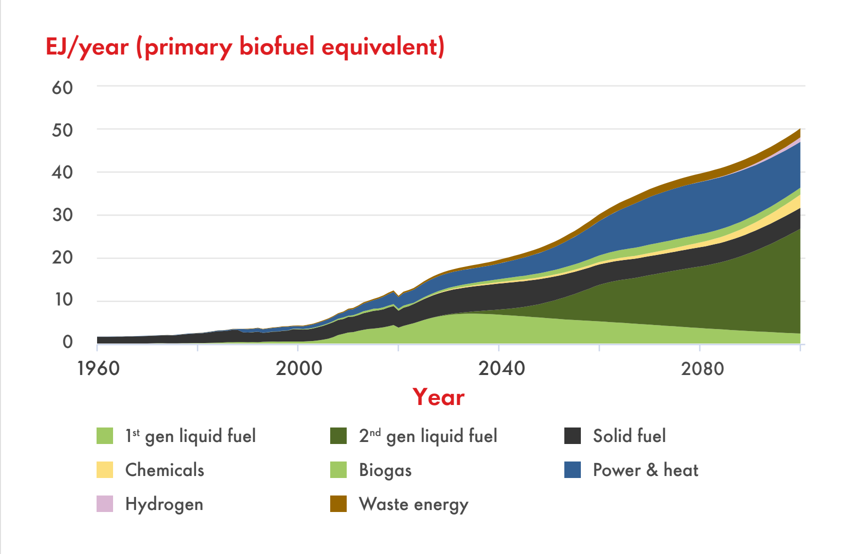
Both **Sky 2050** and **Archipelagos** rely on bioenergy. In **Archipelagos**, bioenergy use doubles by 2050. In **Sky 2050**, bioenergy use nearly triples by mid-century. By the end of the century, in both scenarios, bioenergy use is around four times the level seen in 2020. The underlying trends beneath this growth differ between the scenarios.

- In **Sky 2050**, the use of first-generation biofuels, such as corn ethanol, peaks by 2030, but not until 2035 in **Archipelagos**.
- In both scenarios, but aggressively so in **Sky 2050**, there is a switch to second-generation sources, such as non-edible cellulosic plant material. In **Sky 2050**, the use of second-generation biofuels in the late 2030s is equal to that of first-generation biofuels in 2022. **Archipelagos** reaches the same point in the early 2050s.
- In **Sky 2050**, there is dominant early growth in liquid fuels, mostly to replace oil in hard-to-decarbonise transport sectors – for example as sustainable aviation fuel (SAF) for planes.
- In **Archipelagos**, bioenergy gradually becomes more important over the century in replacing fossil fuels as a source of electricity generation. In **Sky 2050**, its use for electricity remains small as wind, solar and storage solutions are very successful.
- At the end of the century, in **Sky 2050**, the demand for bioenergy grows fast for non-energy purposes, such as manufacturing chemical products.
- Biogas, created by using microorganisms to break down organic matter, fills an important niche in **Archipelagos**. In **Sky 2050**, biogas is quickly displaced by solar and wind.
- In both scenarios, some countries, which lack solar and wind resources, find that importing biomass plays an important role in their energy mix.

Bioenergy uses in Sky 2050



Bioenergy uses in Archipelagos



Sectoral and societal trends

The chemical industry transforms

Since World War II, the demand for non-energy products made from oil – such as petrochemicals (including plastics), fertiliser and bitumen – has grown steadily. The world's use of chemicals is extremely diverse: they are used in many products that provide comfort and convenience, including packaging, clothing, home insulation and foams for furniture. Less obvious to many, they are also essential to products used for sanitation, preserving foods, treating diseases and increasing crop yields. Innovation into new advanced materials – and new ways of using them – is constantly increasing the usefulness of these products in our lives.

So central have non-energy oil products become that demand for them has grown at the same pace as the global economy (in terms of GDP). Demand growth in developing countries runs even faster than GDP, as lifestyles catch up. In rich countries, the evidence suggests that per capita demand is slowing down and may have reached a peak for some products. However, predictions of a shift to less material-intensive growth have not yet occurred at large scale. Attempts to move towards traditional materials like metal and glass often run into the challenge that they can come with higher carbon footprints.

With rising incomes in non-OECD countries, demand continues to grow in both **Archipelagos** and **Sky 2050**. Growth in richer countries starts to plateau in both scenarios, albeit at different rates. Plastic waste in nature, growing concerns on microplastics and the industry's increasing share of global CO_2 emissions lead to a wide range of environmental challenges. Addressing these is not easy for the industry: it is a highly complex sector due to its diversity across consumers, products, technology, by-products and international trade. The industry's production facilities can also last 60 years or more, often locking in old technology.

In **Archipelagos**, the industry focuses on two areas. The first is on finding the most cost-effective solutions to improve the collection of plastic waste. The second is dealing with the emissions linked to its processes and energy use (Scope 1 and 2 emissions). This second focus area leads to a need for carbon capture and storage (CCS) where there is enough support from governments. More wealthy consumers are willing to pay for more costly, but sustainable, offerings.

The **Green Dream** archetype, with a developed waste-sorting infrastructure, emphasises recycling. In other archetypes, like **Surfers**, burning waste plastics to produce energy makes sense for them until recycling becomes cheaper. The circularity of products – their capacity to be recycled – gradually increases and is mostly aimed at packaging material.

Alternative sources of carbon, such as biomass, cannot meet the need for some uses that cannot use recycled materials and must use freshly produced, or virgin, materials. As a result, the sector is one of the last industries using fossil oil and natural gas as its primary production inputs, or feedstocks. Where production processes can be easily electrified, they are, but high temperature process heat is still mostly provided by natural gas.

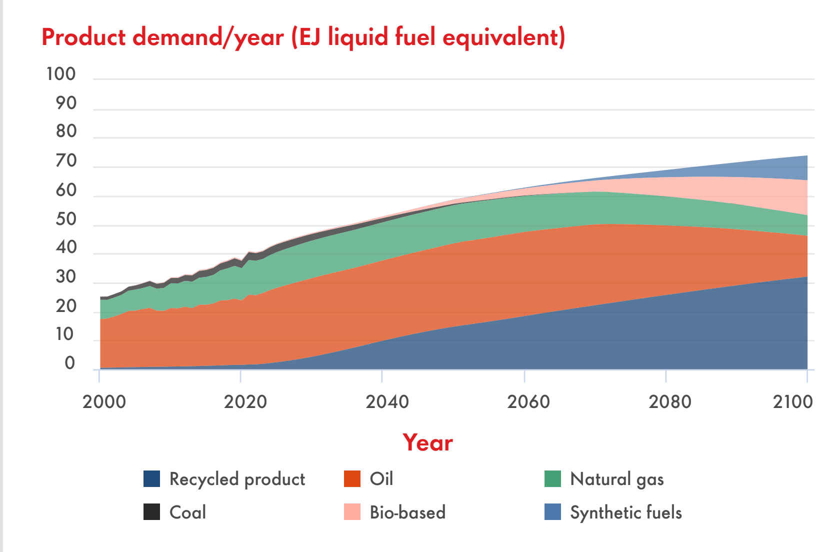
In **Sky 2050**, society sees a larger lifestyle change which, in richer countries, leads to a turning point and lower demand per capita for non-energy oil products. There is lower demand for packaging materials. This is, to a large extent, offset by increased demand for products to help society decarbonise, including plastics for lighter cars, building insulation and materials for batteries. The growth in fertiliser demand slows due to more precision farming and a slow shift to diets with less meat. There is a larger push for circularity in all applications where that is possible, including for durable chemical products, like bitumen and lubricants. The increasing ability to recycle products reduces the need for virgin materials but also causes additional energy use because of the extra energy it takes to recycle materials. In time, innovative recycling technologies use green electricity and hydrogen to minimise emissions. More products are shared, reused and designed to achieve longer lifetimes or be easier to repair. Many products are designed to make recycling easier. Society pursues a carbon-circular economy, which reduces the need for fossil fuels as feedstocks at the start of the production process.

A growing share of bio-based chemicals emerges through a mix of new policies and a higher willingness from consumers to pay a premium. Many such chemicals will be based on different molecules than those that emerged from the oil-based feedstocks that are common today. In addition to bio-based feedstocks, there is a move to bio-degradable products. These are focused on applications where the lack of recycling options means there is a high risk of these products remaining for a long time in nature, such as microplastics. The fertiliser industry is the first to move at large scale to products made from green hydrogen – made by using renewable energy to split water molecules. Renewable power is used to electrify the industry at a faster pace compared to **Archipelagos**, including to provide furnace heat.

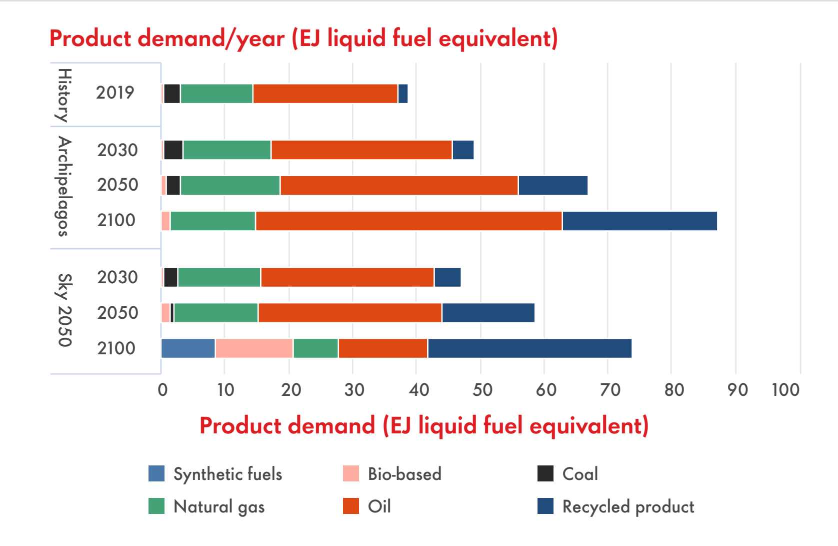
After 2050, a new form of chemical production achieves scale: e-chemicals. These products are made from CO_2 and green hydrogen. The CO_2 for this process is captured first from concentrated industry sources and later comes from the air once direct air capture (DAC) is available economically at scale. However, the combination of growth in demand, the need to scale up many new technologies, long-lived infrastructure and complex supply dynamics will mean that, even in **Sky 2050's** accelerated transition, fossil products are still being used in 2100.

Nevertheless, the need for fossil feedstocks is much lower than in **Archipelagos** and peaks in the 2030s before declining. The continued use of fossil fuels means **Sky 2050** requires deep circularity and CCS over the whole industry.

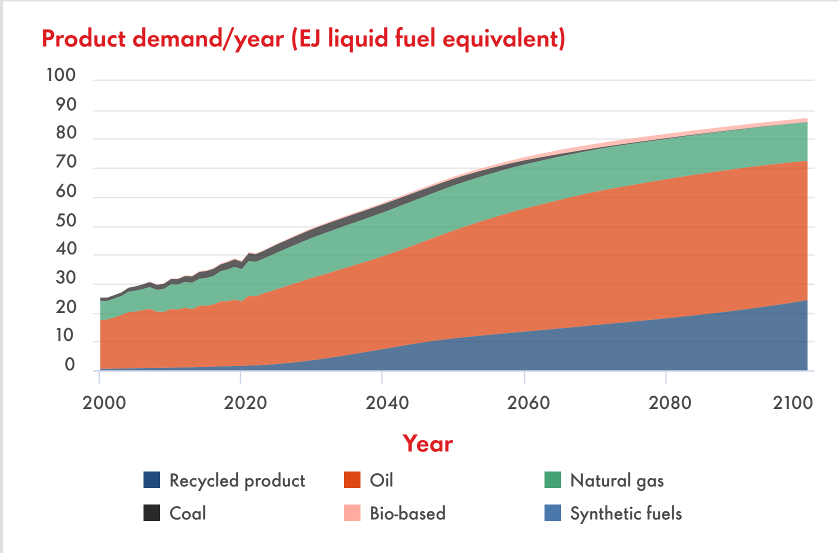
Inputs for the chemical industry in Sky 2050



Inputs for the chemical industry: comparing the scenarios



Inputs for the chemical industry in Archipelagos



Improving energy efficiency is a route to security in both scenarios

The security-first mindset that dominates following the Russian invasion of Ukraine, combined with the high price of energy, brings energy efficiency to the top of agendas. This is a factor across both scenarios.

When fossil fuels dominate the energy mix, energy use drives emissions. This means that limiting the use of energy can help limit emissions. In addition, by keeping overall energy use as low as possible the growth of new energy supplies can displace a greater proportion of the legacy fossil fuel-based energy system.

Energy use can be limited by two methods. Firstly, people can choose to use energy in more efficient ways – by driving smoothly and limiting speed, for example. Secondly, products and processes that use energy can be designed to use it more effectively – cars can be designed so that the amount of energy they need to drive 1 kilometre comes down.

This second path is known as energy service efficiency, and it can take two routes:

- Progressive change. This is where existing technologies, business models and supply chains are improved bit by bit, but there is no fundamental change. The modern passenger jet, for example, is little different to the 1958 Boeing 707. Even so, a 787-8 that is flying today is more than twice as efficient as a 707 in terms of how far it can carry each passenger.
- Step change. This is where a completely different technology is introduced to provide the same service. An example is the light emitting diode (LED) replacing the incandescent lightbulb. Another example is the electric car replacing vehicles powered by internal combustion engines.

Both types of change require a turnover of capital stock – the old things being replaced by new, more efficient equivalents as the old wear out or become uneconomic. The most profound difference, however, is made when a step change takes place, as this may only need a single turnover to deliver significant benefits. Progressive change, on the other hand, needs many turnover cycles to have a substantial effect. In addition, the allure of a new step change technology, and the significant savings that it can bring, may encourage early replacement, bringing the benefits forwards.

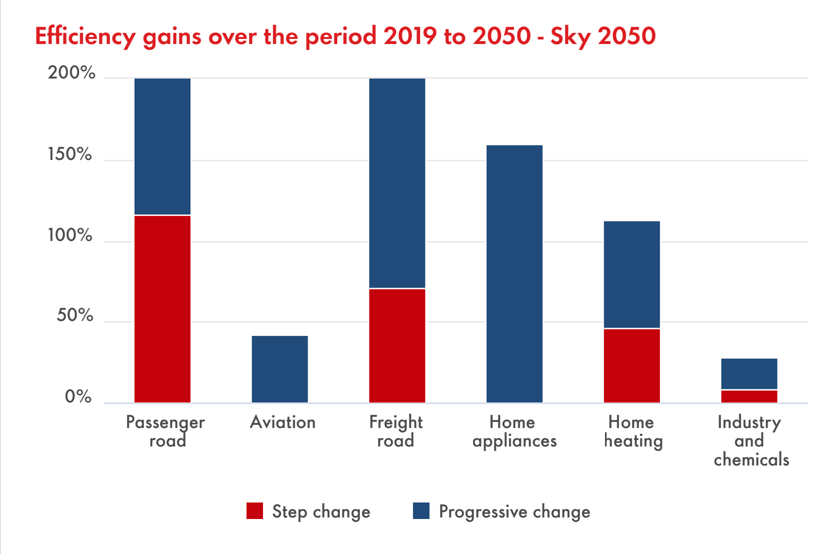
In **Sky 2050**, the most significant change for energy efficiency comes with the shift to electricity for road transport. This also has a significant impact in **Archipelagos** as well, although overall efficiency gains are around half as strong compared to **Sky 2050**.

Electric vehicles convert around 80% of the energy they take from the grid into power at the wheels. This means that if the electricity for an electric vehicle comes from a renewable energy installation, which generates electricity without losing energy through combustion, the overall efficiency of the system is around 80%. The exact figure depends on transmission losses, electricity storage and other factors. The picture is less good for electric vehicles if the electricity is produced by burning coal or natural gas. If fossil fuels are the source of the grid power going into an electric car, the overall efficiency is around 25-40%. Conventional internal combustion engine vehicles convert less than a third of the energy stored in petrol to power at the wheels.

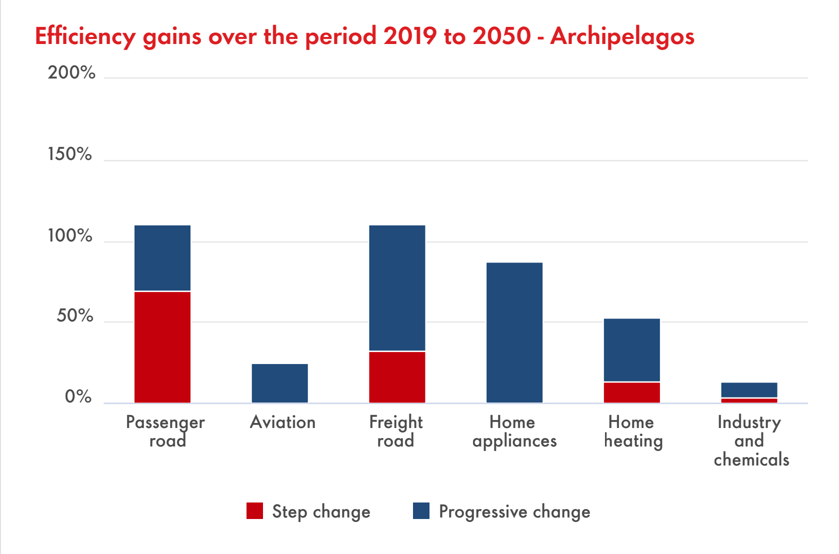
Beyond electric vehicles, other major step changes involve appliances and heating in homes and buildings. While most appliances are already electric, moving from cooking on flames to electric cooking significantly improves efficiency. Natural gas cooking hobs are about 40% efficient, whereas whole electric-coil and standard smooth-top electric hobs are around 70% efficient. The latest induction hobs are more than 80% efficient. Cooking with biomass, like wood, is likely to be less efficient than natural gas, although in certain circumstances where home heating is incorporated, this may not always be the case.

Finally, the efficient use of energy to heat or cool buildings can be improved both as a step change – by introducing technologies such as heat pumps – and progressively through an active insulation programme. Under ideal conditions, an electric heat pump can transfer 300% more energy than it consumes. In contrast, a high-efficiency gas furnace is about 95% efficient.

Efficiency gains over the period 2019 to 2050 - Sky 2050



Efficiency gains over the period 2019 to 2050 - Archipelagos



A transport revolution in Sky 2050

Road passenger

The future of road passenger vehicles shifts rapidly to a single solution: battery electric power. No space emerges for any other solution as manufacturers abandon the development, then production, of vehicles with an internal combustion engine. Business models throughout the passenger transport sector rapidly move towards electric vehicles. The energy efficiency of electric vehicles means that total energy demand in this sector falls even as vehicle numbers grow.

Road freight

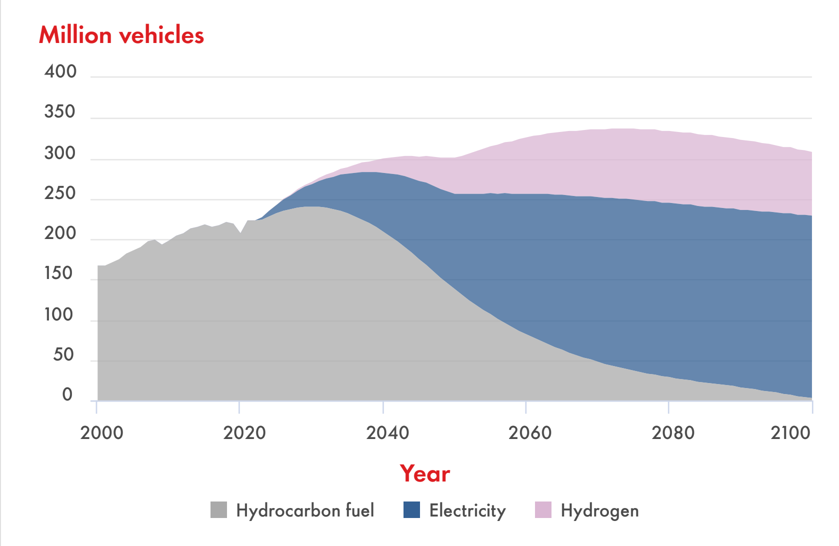
The road freight transition also includes a shift towards electricity. This starts with light vans, municipal trucks and service vehicles, before spreading into medium-haul trucks. But the high-energy density of molecular fuels remains critical for very heavy-duty applications and long-haul, high-capacity road freight. Biofuels and, much later on, synthetic fuels based on CO_2 directly captured from the air, contribute to a lower carbon footprint for the sector. From the late 2020s, hydrogen fuel-cell vehicles emerge as the preferred solution.

Aviation

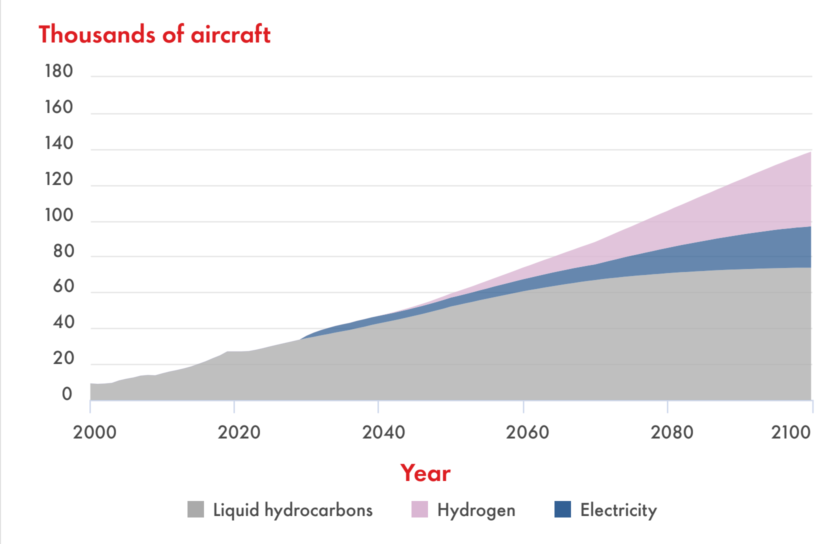
Aviation remains reliant on liquid hydrocarbon fuels, with no alternatives emerging at scale until the 2040s. Battery-electric planes – with the electricity used to turn propellers – make their first appearance in the 2030s on very short commuter routes. Jet turbine planes, burning hydrogen as a fuel, start to appear on medium-haul routes in the 2040s.

The major shift comes in the formulation of jet fuel, with sustainable aviation fuels taking market share from the 2020s onwards. This starts with biofuel being mixed with kerosene. In time, the cost of capturing CO_2 from the air using direct air capture (DAC) fall, and this allows for the cost-effective production of synthetic hydrocarbon fuels.

How the global truck fleet changes fuels in Sky 2050



How the global aircraft fleet changes fuels in Sky 2050

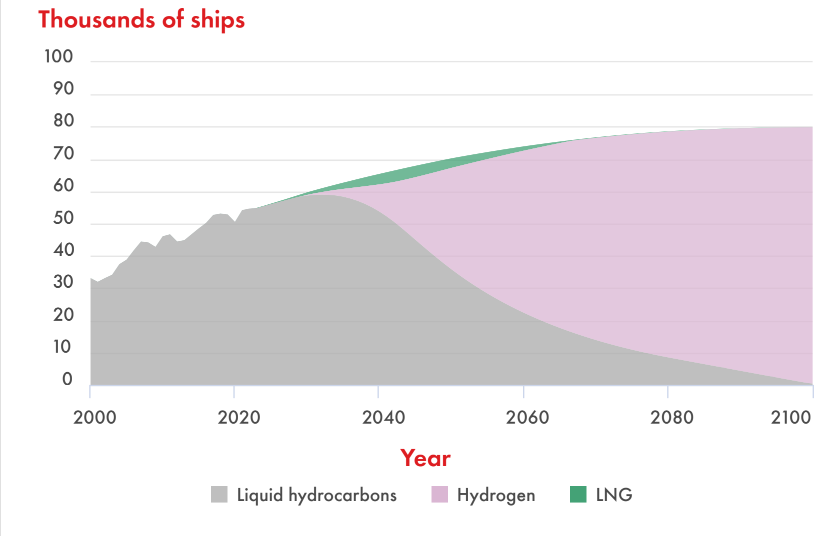


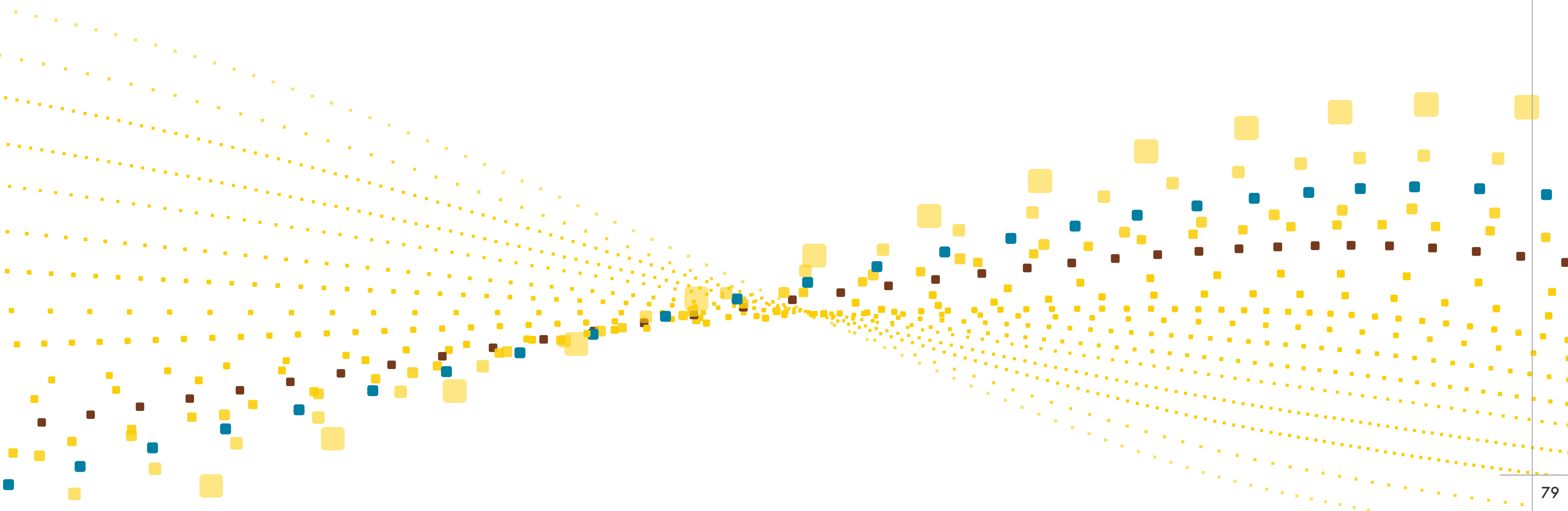
Shipping

In the 2020s and 2030s, the shipping industry experiments with a number of options to reduce its carbon footprint. These include biofuels such as bio-methanol, liquefied natural gas (LNG) and hydrogen (either directly using hydrogen as a fuel, or in the form of ammonia). In the mid-2030s, however, the industry settles firmly on the hydrogen-based solution, working in close co-operation with shipbuilders, fuel suppliers and key bunkering ports. Almost all ships constructed after this time have fuel systems that use either hydrogen or ammonia.

In **Archipelagos**, the trends are similar, but slower and less pronounced. One significant difference in **Sky 2050** is that synthetic fuels do not emerge at all, given the slow progress of direct air capture development. The electric passenger vehicle transition lags **Sky 2050** by some two decades and, while hydrogen and electricity both emerge as options for road freight, the uptake for hydrogen runs at almost a third of the pace seen in **Sky 2050**. Aviation remains largely reliant on liquid fuels, in part because of the slow emergence of hydrogen after mid-century. The same is true for the shipping industry, with the decision to switch to hydrogen only being implemented in part from the 2040s and progressing slowly from that point on.

How the global shipping fleet changes fuels in Sky 2050





The rise and rise of electrification in transport

Battery-powered cars have taken the world by storm... and by surprise. Twenty years ago, the future of passenger vehicles was supposed to be a mix of battery hybrid systems or hydrogen fuel cells. In this world, hydrogen filling stations were expected to gradually take over from pumps supplying petrol and diesel. The battery-electric passenger vehicle (BEV) was barely considered a possibility. Even as Tesla rose to prominence and other companies began introducing BEVs, the expectation was that the technology would not become dominant until well into the second half of the century. **Sky 2050** now includes a complete transition to BEVs, from Amsterdam to Zanzibar, only 30 years from now.

Today, the debate is about whether batteries can power heavier transport such as buses, municipal vehicles, vans and long-haul freight. Long-haul freight has long been considered a step too far for batteries: their size and weight reduce load capacity, while the recharging time for a 1 mega-watt hour (or more) battery brings logistical challenges. Overall, the case for batteries in long-haul trucks has not been convincing. Hydrogen is seen as one solution, particularly for vehicles that have to carry very heavy loads over long distances. Yet, the hydrogen fuel cell is already fading as an option in other areas.

Tests of hydrogen bus fleets through the 2010s have come and gone, with most cities now adopting battery-electric buses. Some Chinese cities are already well on their way to fully switching their bus fleets to batteries. A similar story is unfolding for municipal trucks, with the City of London Corporation becoming the first UK authority to run a full fleet of electric refuse collection vehicles in 2021. In late 2022, Tesla named PepsiCo as the first customer for its battery-powered semi long-haul truck.

In **Sky 2050**, part of the road freight fleet moves to hydrogen fuel-cell technology for long-distance haulage. Hydrogen takes a 25% share of this market by 2070 and is growing in absolute terms. Even so, it is battery power that wins overall.

Of course, scenarios can be wrong, so is it just a question of time before all forms of road transport use battery-electric power?

The carbon gap between the scenarios

Carbon sinks

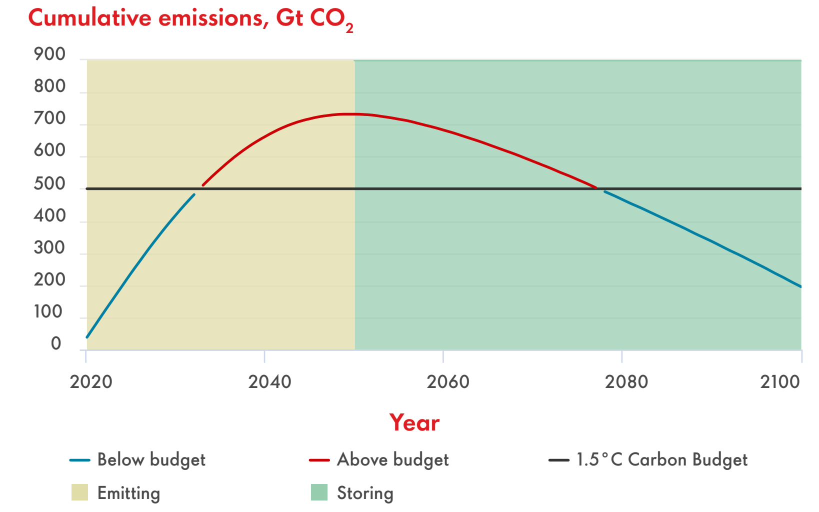
The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by maximising the amount of carbon that is stored permanently in carbon sinks.

In the early 2020s, only a handful of zero-carbon technologies exist that can replace some of the uses society has for fossil fuels. Nuclear, solar and wind can be used to generate electricity instead of coal and natural gas. Even so, their use still remains limited. Nuclear continues to suffer from public concerns over its safety. Solar and wind are intermittent – they generate electricity only when the sun is shining or the wind is blowing – and there is a lack of commercially viable options to store large amounts of electricity to compensate for cloudy, windless periods. In the transport sector, passenger electric vehicles are now a commercially viable substitute for the internal combustion engine, but this has taken several decades to reach its current level of maturity.

Other developments are coming to the fore, including electric freight transport, electrification of various light industry processes, hydrogen for shipping and heavy industry and sustainable fuels for aviation. But the full suite of technologies required to completely replace all uses of fossil fuels, at the scale they will be required, is still many decades away. This means that CO_2 emissions will remain a feature of the energy system well past mid-century and possibly into the 22nd century. However, the day when combustion of fossil fuels for energy use ends is drawing closer.

To stop adding CO_2 to the atmosphere by 2050, society must turn to technologies that can capture CO_2 at the point of emission or from the air itself and permanently store that CO_2 away from the atmosphere, several kilometres under the ground. At the same time, the land-based carbon stock – in trees, plants and ecosystems – must be increased. As the natural ecosystem takes CO_2 from the air and water, it lowers the levels in the atmosphere and dissolved in the oceans. These technologies and practices are collectively known as sinks.

The emissions overshoot in Sky 2050



Capturing CO_2 and combining this with geological storage is known as carbon capture and storage (CCS). This is already a commercially available and scalable technology, although direct air capture (DAC) – removing CO_2 from normal air – is still in the process of commercial development. The practices required to better manage land carbon are well established, but not widely used.

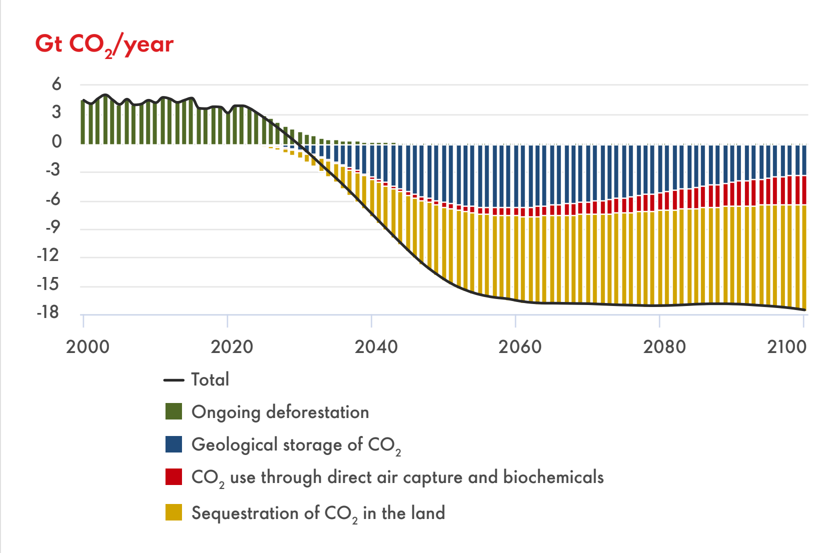
Sky 2050 makes much greater use of sinks than **Archipelagos**, which is a major reason why **Sky 2050** is able to restrict climate warming below 1.5°C by the end of the century. In the shorter term, neither scenario sees emissions fall fast enough to contain warming: both scenarios state the world exceeds the 500 gigatonne (Gt) carbon budget it was set by the Intergovernmental Panel on Climate Change (IPCC). The moment the carbon budget is breached is in the early 2030s in both scenarios, with **Archipelagos** on a slightly earlier timeline.

As emissions fall rapidly in **Sky 2050**, and both industrial and natural sink capacity grow to 12 Gt per year in the early 2050s, the scenario not only achieves net-zero emissions in 2050, but falls into negative territory after that point. This means that the combination of techniques delivers a significant and growing removal of CO_2 from the atmosphere. CCS prevents emissions from reaching the atmosphere in the first instance. Three other solutions combine to remove CO_2 from the atmosphere: bioenergy with carbon capture and storage (BECCS), direct air capture with carbon storage (DACCS) and land use practices that increase its land carbon stock. As the fall in atmospheric CO_2 gathers pace, the global average surface temperature begins to fall, crossing the important 1.5°C threshold before 2100.

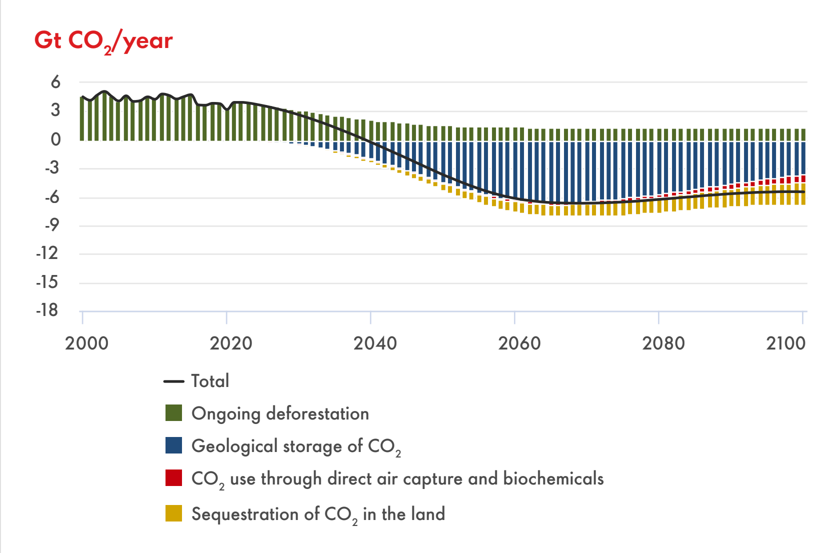
In **Archipelagos** there is also considerable sink capacity developed, but it is insufficient to counter the slower energy system transition so atmospheric CO_2 continues to rise throughout the century.

Natural and industrial sinks are not an alternative to emission reductions, but an essential way to manage emissions that cannot be avoided. This is necessary both to reach net zero as early as possible and to start addressing the elevated level of CO_2 in the atmosphere in the decades after net zero. Without the development of large-scale sinks, the early achievement of net-zero emissions is not possible and the long-term goal of climate restoration cannot happen.

Land use change and the development of sinks in Sky 2050



Land use change and the development of sinks in Archipelagos



The role of nature in the energy transition

Action to deal with climate change will obviously require a revolution in the global energy system, but that is not all it requires. In both the **Archipelagos** and **Sky 2050** scenarios, a very large area of land will need to be managed to reduce the amount of carbon in the atmosphere.

By 2070, almost all land that humans interact with is managed to maximise carbon storage, although only a fraction of this land changes from one type of use to another. The great majority of carbon management comes through improved farming practices and better management of forests, peatlands and wetlands.

Reforestation is the major change of land use in both **Archipelagos** and **Sky 2050**. Both scenarios include the potential to reforest an area up to the size of Mexico: about 200 million hectares. The journey starts with a strong push towards ending deforestation and includes increased reforestation through government intervention and action by businesses to create carbon credits.

In both **Sky 2050** and **Archipelagos**, nature-based carbon credits gain trust and acceptance through various initiatives such as the Taskforce on Scaling Voluntary Carbon Markets, which was started in 2020. As such, land carbon becomes a commercial proposition with voluntary carbon markets channelling funds towards preservation of existing forests, reforestation and soil carbon management in farming.

From a meagre start in the early 2000s, the voluntary carbon markets expand rapidly in the 2020s and 2030s. By 2030, these markets exceed $150 billion in trade for nature-based credits. These credits account for 1.5 gigatonnes (Gt) of CO_2 per year. This involves having around 20 million hectares under management, including grazing land associated with soil carbon credits. This is equivalent to the size of Cambodia. Overall, this represents more than 10 Gt of additional carbon stored in the land system by 2035. With further expansion of carbon markets, this extends to some 30 Gt by 2050. The market remains buoyant throughout and trades at around $100 per tonne of stored CO_2. Some 70 million hectares are reforested globally by 2050, nearly equivalent to the area of Chile.

By 2040 most businesses in the Fortune Global 500, and many state-owned energy companies, have a portfolio of nature-based projects. These deliver carbon removal credits to their businesses and on to their customers. Several companies are managing land portfolios in excess of two million hectares each.

In **Sky 2050**, governments take direct action in addition to the changes under way through commercial mechanisms. For example, the Glasgow Leaders' Declaration on Forests and Land Use is largely met through direct government action with net deforestation reduced by 70% by 2030 and 98% by 2035. In **Archipelagos**, where government action to manage land carbon is modest, it is not until the early 2040s that net deforestation has been reduced by 50%. Nevertheless, by the early 2050s, there is no longer further CO_2 being added to the atmosphere from forests on a net basis.

While **Archipelagos** sees a focus on land-based carbon storage, it proves insufficient for the aggressive changes required for net-zero emissions by 2050. There are also some parts of the world that act with greater urgency than others. This means that progress is not made early enough, even though substantial action is taken over the longer term. In addition, this delayed action also increases biodiversity loss.

In **Sky 2050**, action happens more broadly and on a faster time scale, with most countries acting early. Businesses act under the voluntary carbon market and trade stored CO_2 at around $100 per tonne. Governments act to offer oversight and give credibility to these actions. Governments also step in more broadly to take a range of direct actions: large areas of land are set aside for national forests, farmers are required to manage soil carbon with the same attention that they pay to crops, and money is spent on protecting and restoring coastal mangroves and wetlands in multiple countries. By 2050, an area of more than 100 million hectares has been reforested in **Sky 2050**.

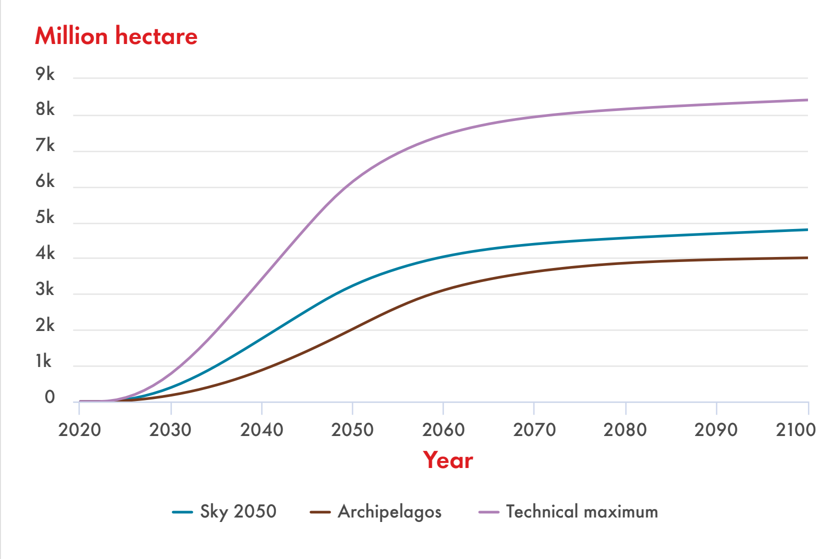
Land carbon: a system in flux throughout the century

In **Sky 2050**, the overall CO_2 emissions caused by human use of the land end by 2032. In **Archipelagos**, this takes longer – until 2041. The way this is achieved in each scenario is, however, significantly different because of the different concentrations of CO_2 in the atmosphere that each scenario creates. By 2050, atmospheric CO_2 concentrations are expected to reach 452 parts per million (ppm) in **Sky 2050**, and 493 ppm in **Archipelagos**. By the end of the century, the atmospheric CO_2 concentration in **Sky 2050** is 373 ppm, and 508 ppm in **Archipelagos**.

In **Sky 2050**, emissions linked to the use of land decrease rapidly. This happens through a combination of reforestation, preventing deforestation and other methods of drawing carbon into the land. Global total CO_2 emissions reach net zero and then become net negative. As atmospheric CO_2 growth slows and levels off, the natural land sink will reach a plateau and stop drawing CO_2 out of the atmosphere around 2030. At a global level, the natural land sink is expected to change to become a net source of CO_2 around 2070. This is a side effect of the world achieving net-negative emissions, which causes a reversal of the biosphere buffering capacity and rereleases CO_2 into the atmosphere. By 2100, human actions are removing 3.2 gigatonnes (Gt) of CO_2 per year through land use, but this is offset by 2.5 Gt per year released into the atmosphere from natural land ecosystem processes. The overall result is 0.7 Gt per year removed from the atmosphere.

Conversely, in **Archipelagos**, land-use emissions become negative at a slower pace, and total CO_2 emissions caused by humans do not reach net zero by the end of the century. As a result, the concentration of CO_2 in the atmosphere stays much higher than in **Sky 2050**, and the natural land sink effect is stronger until around 2040. In **Archipelagos**, natural land ecosystems are not expected to become a net source of CO_2 by 2100 at the global level.

The area of land managed to remove carbon



How land use evolves through the century in Sky 2050

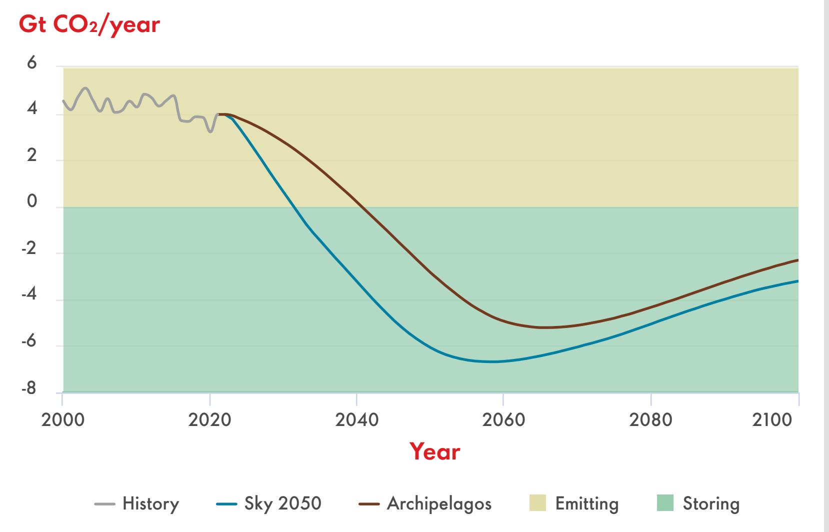
The land plays an important role in **Sky 2050**. Plant life, forests and other ecosystems are essential in removing CO_2 from the atmosphere and restoring the overall carbon balance. The land also plays a critical role in providing energy crops for biofuels and biomass combustion, as well as providing the physical space for solar arrays and wind turbines.

By the end of the century, more than 5 billion hectares of land are managed in ways to store carbon. Around 700 million hectares are devoted to growing crops to turn into sustainable energy. These crops deliver 65 exajoules of energy into the global energy mix, or about 7.5% of primary energy demand.

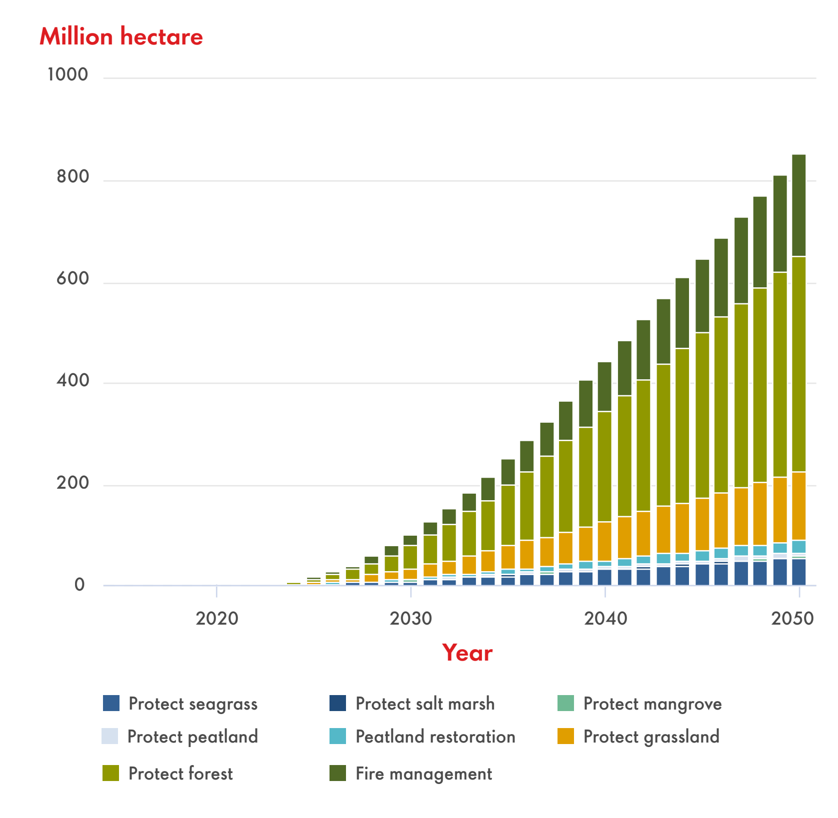
Almost all of this land under management, representing just under 5 billion hectares, is existing agricultural and grazing land. This is managed both to produce food and also grow the carbon stock in the soil. This is an approach known as carbon farming. Carbon farming involves employing land management practices that are known to store carbon and/or reduce greenhouse gas emissions. Examples include managed grazing practices, multi-species cover cropping and no-till planting.

About 200 million hectares of reforestation takes place by 2100 and, in addition to this, there is active forest management of some 1.5 billion hectares to ensure they are protected from land-use change and fire.

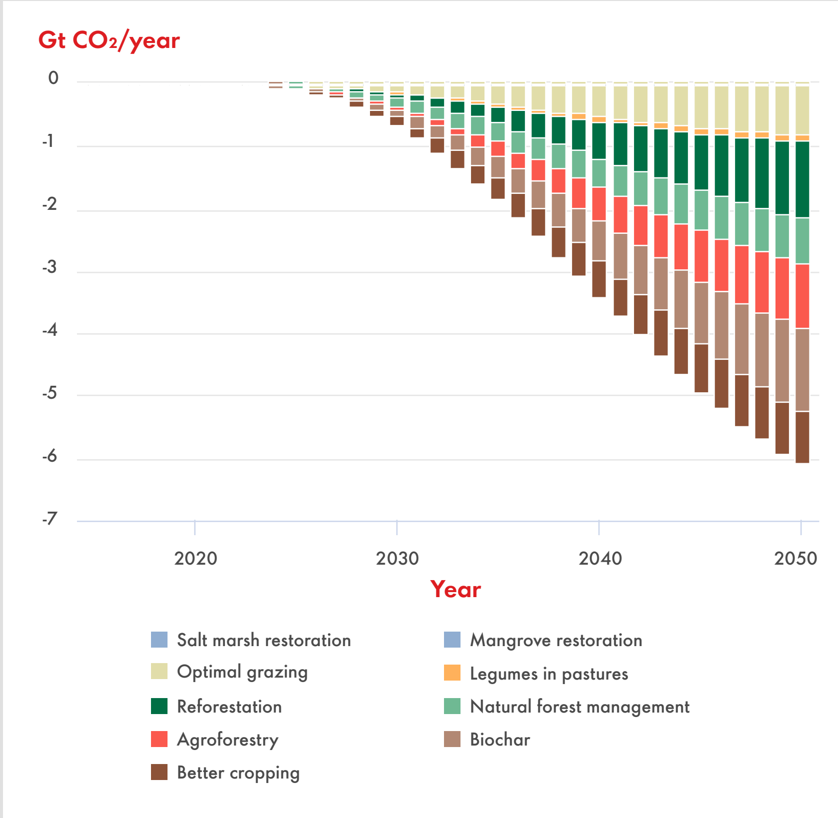
Land-use related emissions



Area of land managed to avoid carbon emissions - Sky 2050



Amount of CO_2 emissions stored through land management - Sky 2050



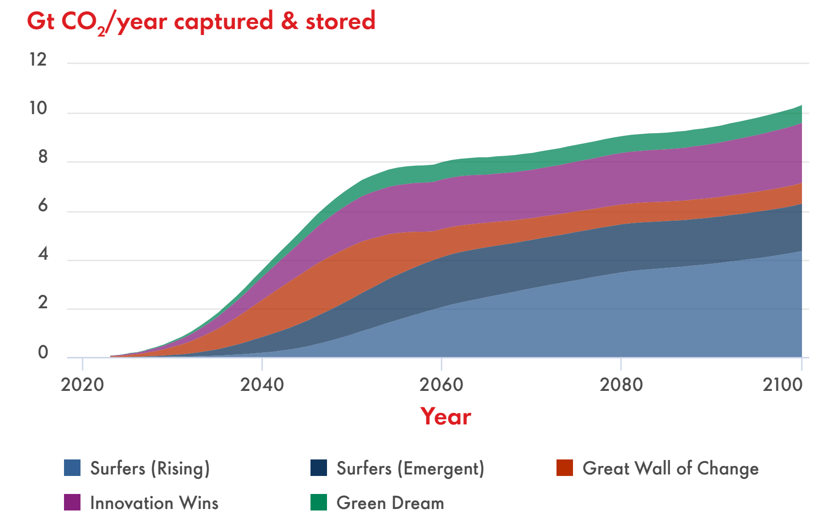
Geological storage of carbon dioxide

To stop adding CO_2 to the atmosphere by 2050, society must turn to technologies that can capture CO_2 at the point it is emitted, or from the air itself. These technologies need to be combined with facilities that can permanently store CO_2 away from the atmosphere, several kilometres under the ground. There are three approaches to carbon capture used in the scenarios, each combined with geological storage:

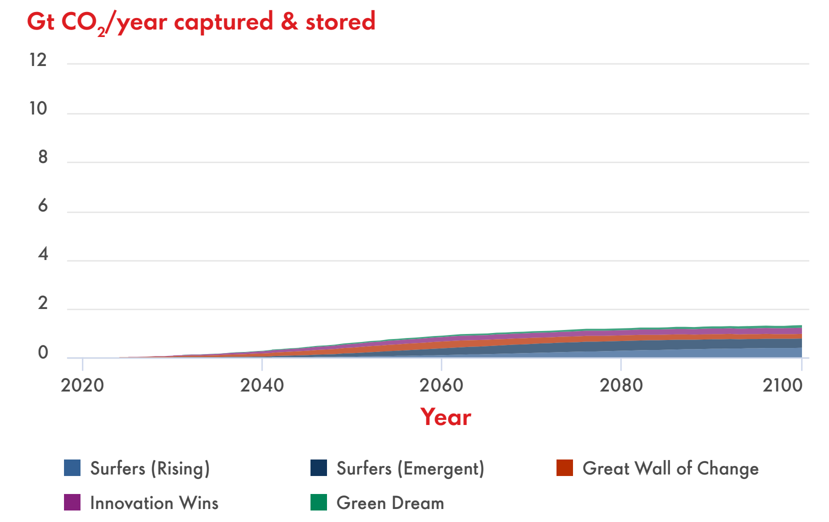
- industrial CO_2 capture at a facility such as a chemical plant (CCS);
- direct capture of CO_2 from the atmosphere (DACCS); and
- capturing CO_2 from bioenergy processes, which indirectly removes CO_2 from the atmosphere (BECCS).

In **Archipelagos** the world develops considerable geological storage capacity that is capable of dealing with 600 million tonnes of CO_2 per year by 2050. Even so, that fact that the energy transition moves much more slowly in **Archipelagos** compared to **Sky 2050** means this is insufficient and atmospheric CO_2 continues to rise throughout the century. **Sky 2050** makes much greater use of geological storage than **Archipelagos**, with capacity to store 7 billion tonnes of CO_2 per year by 2050. This far superior capacity is a major reason why **Sky 2050** is able to restrict climate warming below 1.5°C by the end of the century.

How the archetypes use carbon capture and storage in Sky 2050



How the archetypes use carbon capture and storage in Archipelagos



In the 2020s and 2030s, in both scenarios, direct air capture (DAC) technology is still in its infancy and in the process of commercialisation. By the early 2040s in **Sky 2050**, DAC facilities are capturing 20-30 million tonnes of CO_2 globally each year. By 2050, the amount of CO_2 being stored has jumped tenfold. In **Archipelagos**, direct air capture is virtually non-existent until the 2080s.

From the perspective of individual archetypes, the story varies.

- In the **Green Dream** countries, a mood of fossil fuel rejection emerges, which in turn influences climate policy. Importantly, green electricity and green hydrogen begin to dominate the agenda in the 2020s, with technologies related to fossil fuels, such as CCS, seen by many as unhelpful. While there is some uptake in **Sky 2050**, it levels off by mid-century. In **Archipelagos** the uptake of CCS is very limited.
- Within **Innovation Wins**, climate change activists and investment groups both caution against a renewed oil and gas production push. The deployment of CCS offers one way forward, particularly in the USA where the infrastructure is well developed and the technical capacity for deployment is very high. In these countries, **Sky 2050** sees a strong push to build CCS capacity, while relatively little is built in **Archipelagos**.
- In **Great Wall of Change**, initially CCS plays a growing role in emissions management. Existing coal-fuelled power plants and industrial facilities are retrofitted with carbon capture technology, while new facilities are built with it already in place. Over time, however, local air pollution initiatives cause the closure of coal-fired power plants. In addition, a move towards a service-based economy reduces the size of China's industrial footprint. These trends cause CCS to peak and then decline in both scenarios, although the deployment of CCS is far more widespread in **Sky 2050**.
- Within the **Surfers** countries, many regions establish alliances with countries that are energy or technology exporters. India and the Arabian Gulf states, for example, might consider working together to give India greater access to oil and gas resources. Under the same arrangement, and in the longer term, **Innovation Wins** countries could use their expertise in the technology and build CCS facilities for their energy partners among the **Surfers** nations. In both scenarios, **Surfers** countries are by far the biggest users of CCS by the end of the century, although uptake is initially slower compared to other archetypes. The scale of deployment is massively greater in **Sky 2050** compared to **Archipelagos**.

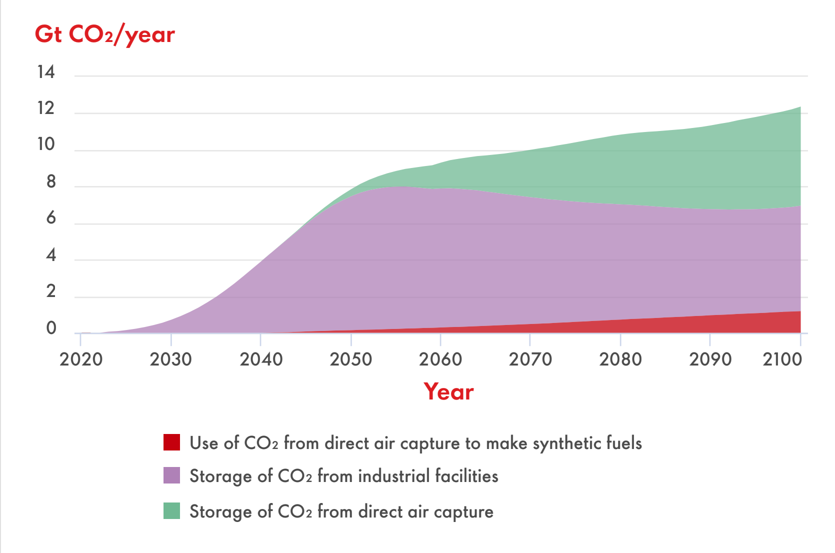
The dual role of direct air capture in **Sky 2050**

In **Sky 2050**, various forms of carbon capture and storage are widely used. One technology is direct air capture (DAC), in which air is drawn over a material which strips out carbon dioxide. When this technology is combined with permanent geological storage, it is known as direct air capture with carbon storage (DACCS). In the 2020s and 2030s, direct air capture technology is still in its infancy and in the process of commercialisation. In the early 2040s, facilities are capturing 20-30 million tonnes of CO_2 globally each year.

By 2050, the amount of CO_2 being stored has jumped tenfold. In addition, DAC is providing CO_2 to a growing synthetic hydrocarbon industry – turning streams of CO_2 and hydrogen into artificial fuels. Such synthetic hydrocarbon fuels are seen as a long-term solution for the aviation industry. By the end of the century DAC is contributing to the production of seven million barrels a day of synthetic hydrocarbon products. This scale of production is equivalent to meeting the demand for global aviation in 2019. In addition, DAC is removing five billion tonnes of CO_2 from the atmosphere each year for geological storage.

In **Archipelagos**, direct air capture is virtually non-existent until the 2080s.

How CO_2 is captured in **Sky 2050**



Limiting the surface temperature rise

All greenhouse gas emissions must fall

CO_2 is not the only greenhouse gas that needs to be addressed. In **Sky 2050**, the world achieves the Paris Agreement objective of balancing out all greenhouse gas emissions in the early 2060s. In **Archipelagos**, overall greenhouse gas emissions decline from a peak in 2030, but the rate of decline is similar to the growth rate in emissions before that date. This puts the world on a course for net-zero emissions, in terms of CO_2-equivalent (CO_2e), in the 2100s.

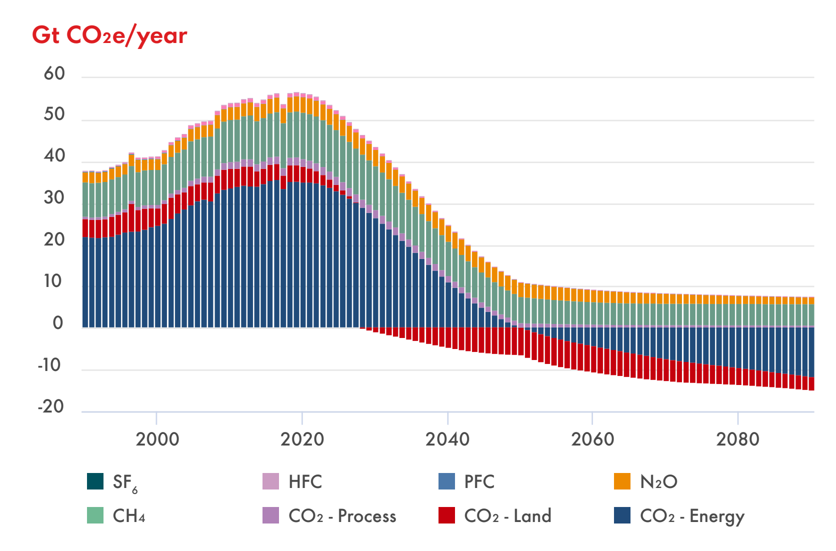
In **Sky 2050**, methane (CH_4) emissions peak by the mid-2020s, before falling by a third by 2050. In **Archipelagos**, however, methane emissions do not reach their highest point until 2040, a decade after the peak for CO_2 emissions.

In **Sky 2050**, urgent efforts are made to reduce the 30% of methane emissions linked to fossil energy, and these emissions also fall as the use of fossil fuels declines. These factors account for almost all the reduction in methane emissions by 2050. The methane emissions that remain, which come from agriculture, are a greater challenge. **Sky 2050** assumes that reductions in agricultural methane emissions only contribute around 20% to the long-term overall reductions, and over a longer timescale.

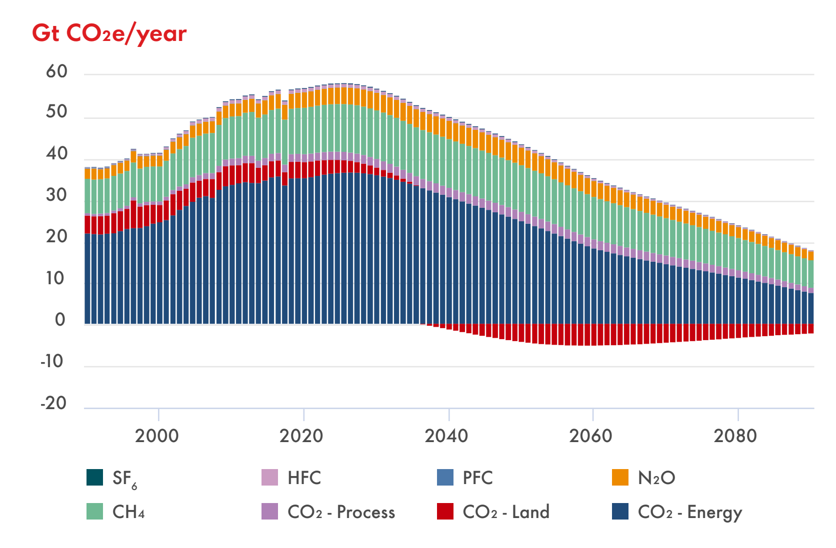
Achieving the stretch target of the Global Methane Pledge – an initiative launched in 2021, to reduce global methane emissions 30% by 2030 from 2020 levels – would represent a notable gain on the reductions assumed in **Sky 2050**.

Nitrous oxide (N_2O) is another greenhouse gas. Emissions are largely caused through the use of fertiliser, for which there is no simple alternative in farming. Reducing these emissions relies on farmers being more efficient with their use of fertilisers. In **Sky 2050**, N_2O emissions peak in the late 2030s, while in **Archipelagos**, they peak in the late 2040s. After peaking, both scenarios show cautious rates of decline.

Greenhouse gas emissions in Sky 2050



Greenhouse gas emissions in Archipelagos



Fluorine gases – perfluorochemicals (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6) – also have a greenhouse effect in the atmosphere. PFCs are typically used in electronics, HFCs in air conditioning and SF_6 as an insulator in electricity transformers. PFC emissions have been falling rapidly, and this trend continues in both scenarios. HFCs are now subject to the Kigali Amendment to the Montreal Protocol and, with substitutes available, growth in HFC emissions stops this decade. HFC emissions subsequently fall rapidly to 15% of that of 2022 by 2050 in **Sky 2050**, or by the end of the century in **Archipelagos**. SF_6 is an extremely potent greenhouse gas, so both scenarios impose high incentives to prevent emissions, with action especially strong in **Sky 2050**. The historically rising trend in SF_6 emissions turns around in the mid-2020s in **Sky 2050**, and by 2030 in **Archipelagos**. By 2100, SF_6 emissions fall to 3% of that of 2022 in **Sky 2050**, or 33% in **Archipelagos**.

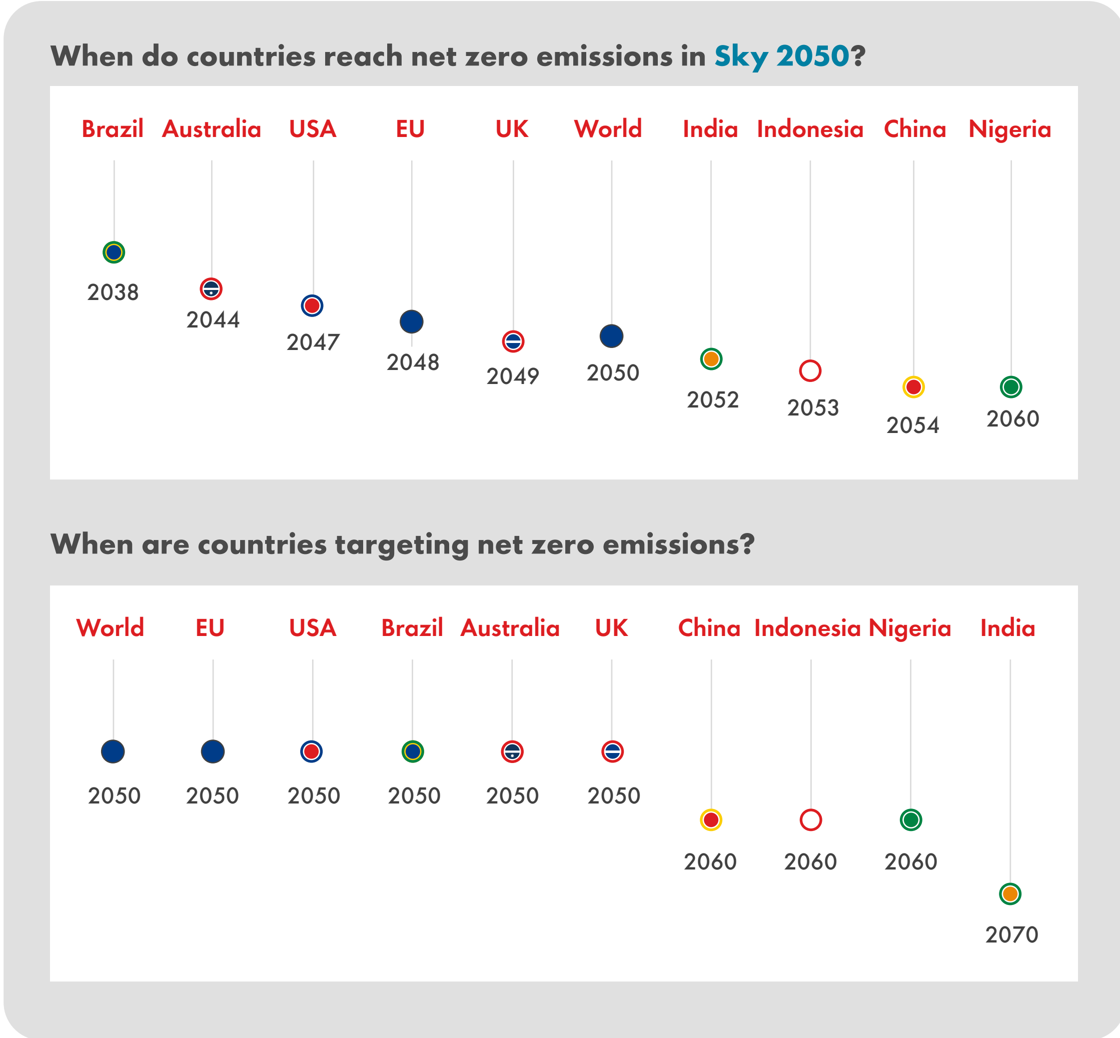
Methodological note: in our scenarios, we have consciously taken profiles for the principal non-CO_2 greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), that are less stringent than for CO_2. This is to reflect the findings of the Intergovernmental Panel on Climate Change that these two gases are typically more difficult to abate than CO_2.

Net-zero emissions globally and national goals

Currently announced national net-zero emission targets are not compatible with reaching net-zero emissions globally in 2050. This is because leading countries are only targeting net-zero emissions by 2050, and many other countries are planning to reach the same point significantly later than that.

For example, China has announced a target of reaching net-zero emissions in 2060, and India is aiming for 2070. If these two countries alone stick to these targets the world could see an additional 2.5 gigatonnes of CO_2 emissions in 2050. A global net-zero emissions target for 2050 that makes space for these targets for China and India would require all other countries (many of which are developing) to achieve net-zero emissions by 2045.

This dynamic means that, to achieve net-zero emissions globally by 2050, in **Sky 2050** we had to assume countries will do better than the ambitions they have stated in 2022.



Sky 2050 – meeting the Paris goal

With a goal to limit warming to 1.5°C by 2100, the Sky 2050 scenario offers a pathway towards net-zero emissions by 2050. But net-zero emissions does not mark the end of the transition.

Fossil-fuel use continues to decline, and major industries emerge based around the removal of CO_2 from the atmosphere. One involves direct air capture with carbon storage (DACCS). This strips CO_2 from the air and stores it permanently in geological formations. Another industry – bioenergy with carbon capture and storage (BECCS) – captures the CO_2 produced during bioenergy processes, also storing it underground.

In **Sky 2050**, by 2100, DACCS has eclipsed other CO_2 capture and storage mechanisms within the economy. DACCS may even offer the world of the 22nd century the means to restore the global ecological balance to pre-industrial times and regain the environmental security that could come with it.

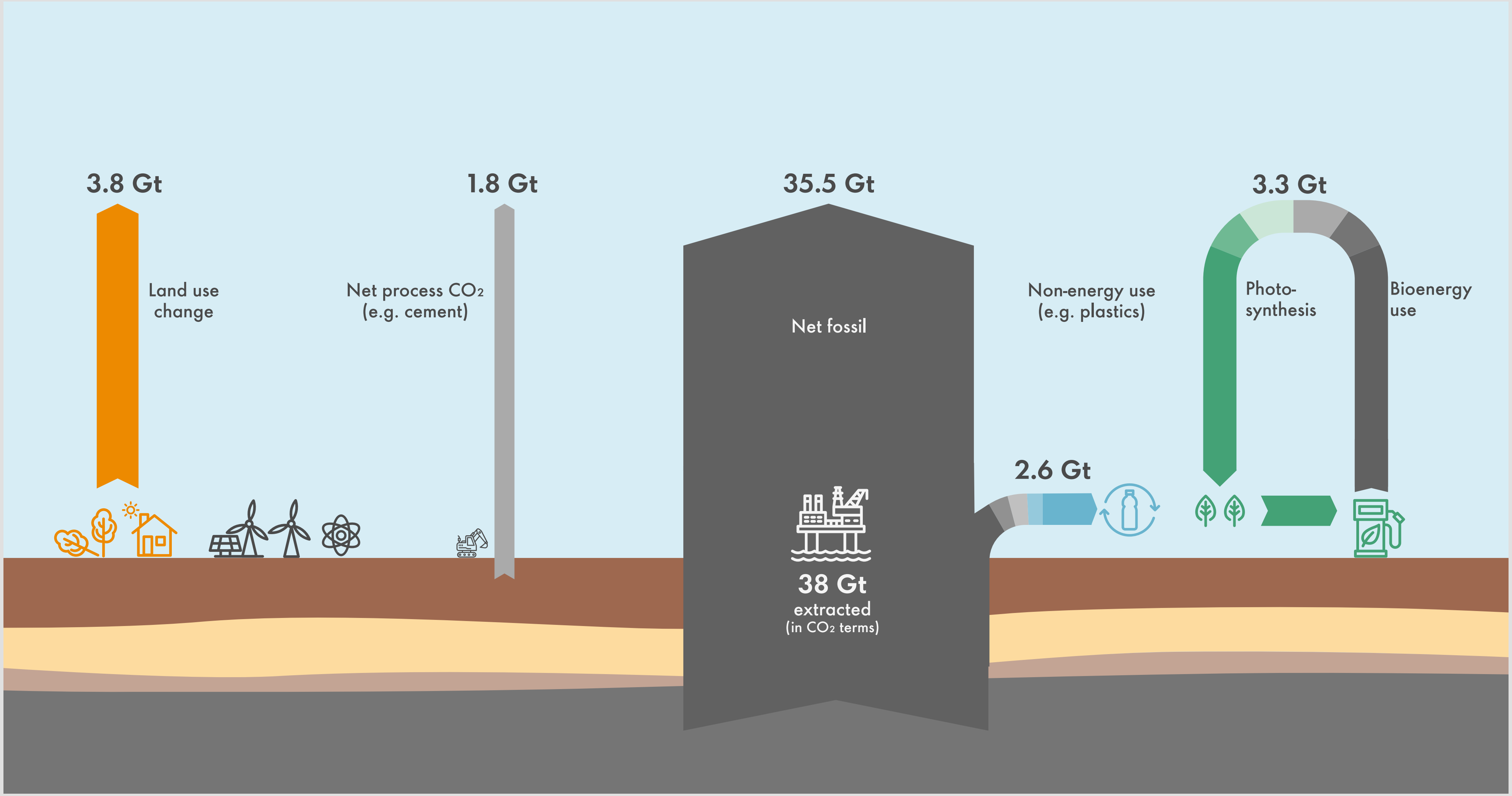
Methodological note: in our scenarios, we have consciously taken profiles for the principal non-CO_2 greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), that are less stringent than for CO_2. This is to reflect the findings of the Intergovernmental Panel on Climate Change that these two gases are typically more difficult to abate than CO_2.

Sky 2050 – meeting the Paris goal

Sources and sinks of anthropogenic carbon (as CO_2) in 2019

Positive emissions of 41 Gt CO_2 per year

2019

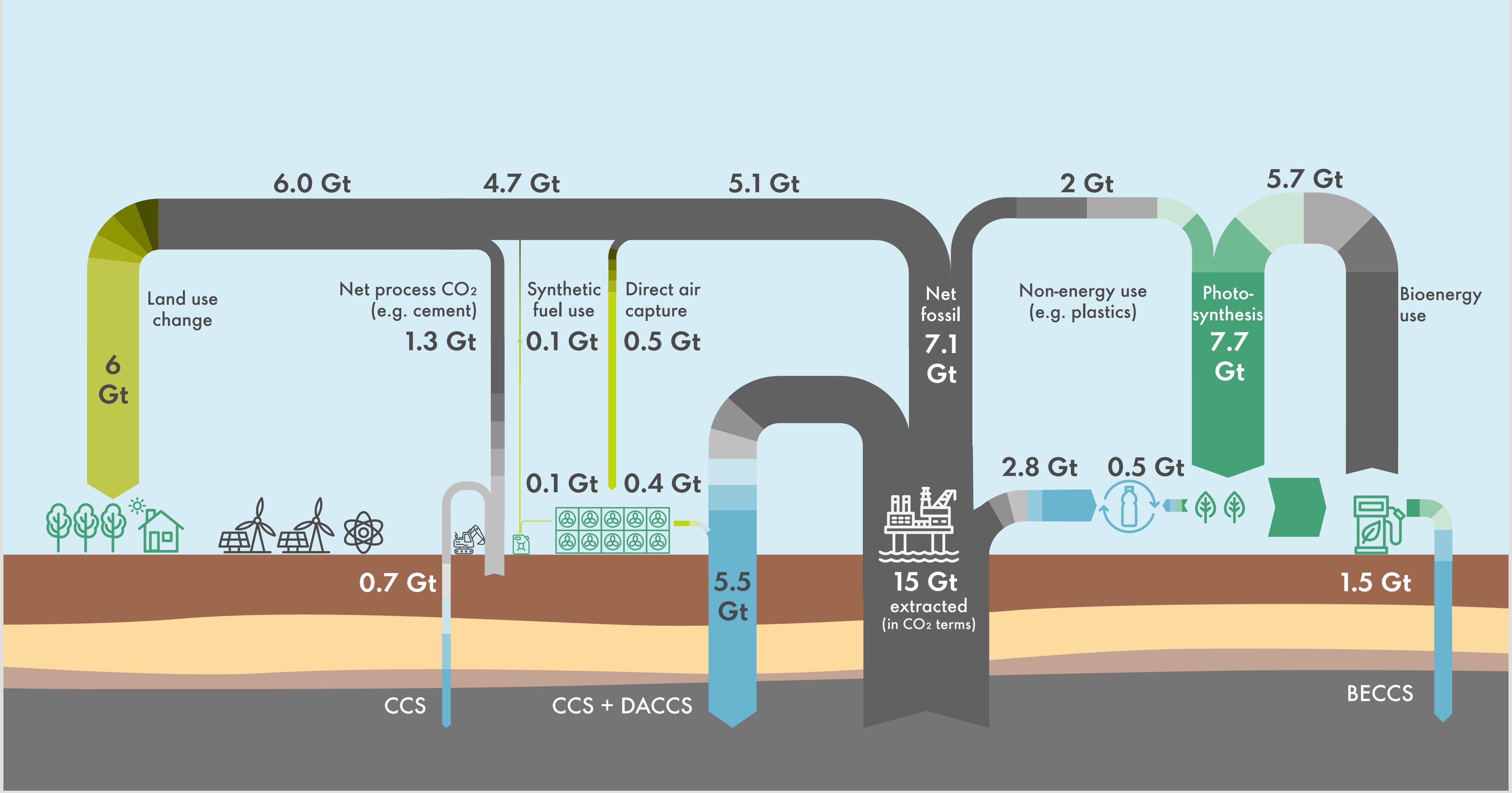


Sky 2050 – meeting the Paris goal

Sources and sinks of anthropogenic carbon (as CO_2) in Sky 2050

Net-zero emissions in 2050

2050

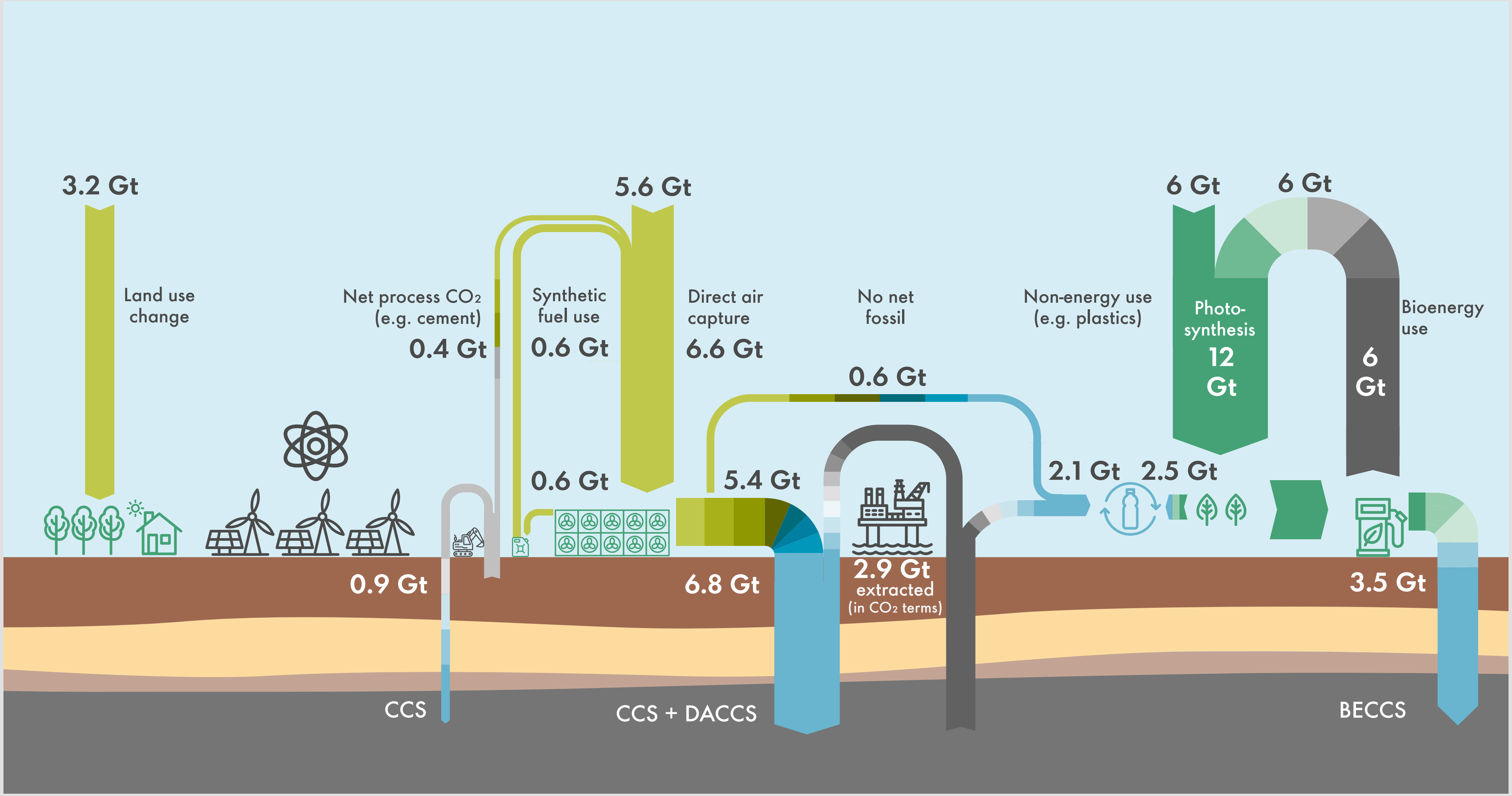


Sky 2050 – meeting the Paris goal

Sources and sinks of anthropogenic carbon (as CO_2) in Sky 2050

Net-negative CO_2 emissions of 14.8 Gt CO_2 per year in 2100

2100



Climate outcomes for Sky 2050 and Archipelagos

Climate scientists at the MIT Joint Program[6] assessed the **Sky 2050** and **Archipelagos** scenarios on their likely climate outcomes. They found that, in **Sky 2050**, the global surface temperature rise – compared to 1850-1900 – was 1.24°C[7] in 2100 (with a range of very likely outcomes from 0.97-1.56°C).[8] They also found that the global surface temperature rise at 2100 in **Archipelagos** was 2.22°C (with a range of 1.73-2.72°C).

[6] Sokolov, A., S. Paltsev, A. Gurgel, M. Haigh, D. Hone, J. Morris (2023). Temperature Implications of the 2023 Shell Energy Security Scenarios: Sky 2050 and Archipelagos. MIT Joint Program on the Science and Policy of Global Change, Report 364. (http://globalchange.mit.edu/publication/17980)

[7] All temperatures quoted in this publication from MIT's model-runs are global mean surface temperatures (ensemble medians), as recommended by MIT (see MIT's report in note 1 for the methodology).

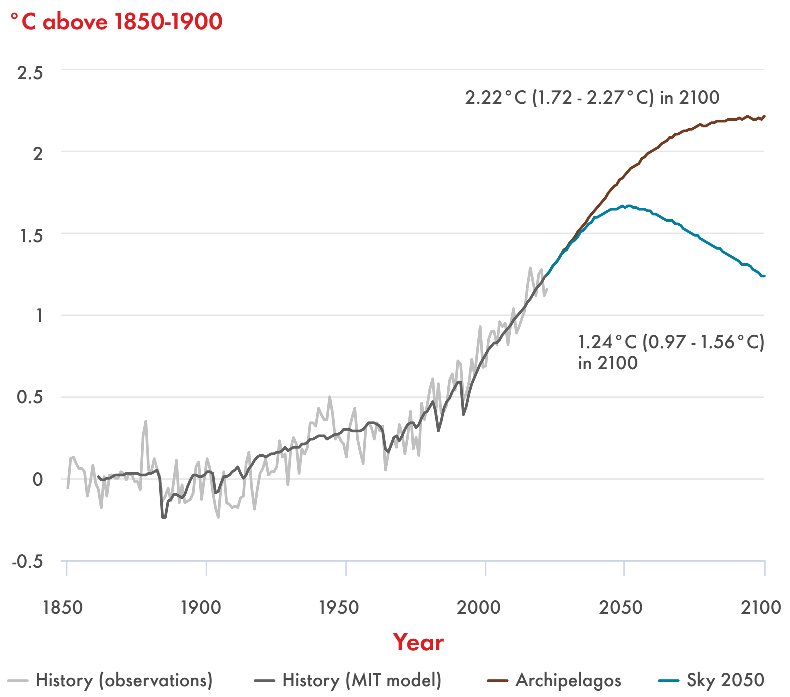
[8] The "very likely" range (90% interval) follows that of the 2021 Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), in square brackets.

Sky 2050 meets the Glasgow Climate Pact commitment for global net zero by 2050 – interpreted as net-zero total anthropogenic CO_2. Given the extremely limited remaining carbon budget, however, and the momentum in both the energy and climate systems, **Sky 2050** is an overshoot 1.5°C scenario. In MIT's assessment, **Sky 2050** hits its peak temperature in 2051 at 1.67°C (with a range of 1.37-2.01°C). The temperature rise remains more than 1.5°C for 40 years (2034-73). **Sky 2050** meets the IPCC AR6 definition[9] for a 1.5°C scenario with high overshoot.

MIT's model calibrates well with historical observations (See Global mean surface temperature above 1850-1900 baseline: Sky 2050 and Archipelagos"). The model provides an estimate that the trend temperature rise in 2023 stands at 1.27°C, and that it is currently rising at around 0.23°C per decade. As such, in little more than 10 years, 1.5°C is due to be passed. In **Archipelagos**, this point is passed in 2033. In **Sky 2050**, it is passed in 2034. The first year exceeding 1.5°C may occur even sooner, depending on the next El Niño cycle.

[9] IPCC, AR6, Working Group III, Table SPM2, 2022.

Global mean surface temperature above 1850-1900 baseline: Sky 2050 and Archipelagos



Historical temperature data are taken from HadCRUT5 (November 2022). In these scenarios, we use global mean surface temperatures (ensemble medians) as modelled by the MIT Joint Program (December 2022). The figures inbrackets refer to the 'very likely' range, defined as the 90% interval.

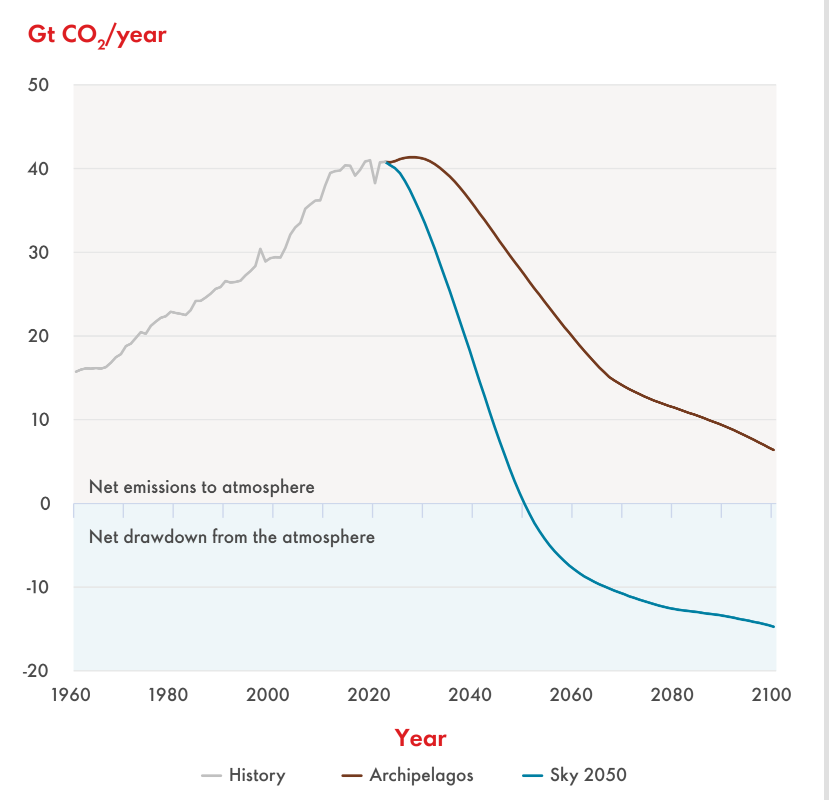
In **Archipelagos**, the ongoing energy transition does slow the temperature rise as the century progresses. Even so, the rise in the global temperature is only on course to reach a peak at the end of the century. As such, societies have to adjust to a higher temperature. By contrast, **Sky 2050** offers the prospect of climate restoration with sustained net-negative emissions from 2050 of 10-15 gigatonnes of CO_2 per year (Gt CO_2/yr). If these levels of net-negative emissions were to continue, the **Sky 2050** scenario would be on course to return temperatures to pre-industrial levels towards the end of the 22nd century.

While energy use dominates total CO_2 emissions, the single largest opportunity to reduce emissions by 2030 is by meeting the Glasgow deforestation pledge: to stop net deforestation worldwide by 2030. Meeting the pledge is consistent with **Sky 2050** and amounts to a reduction of nearly 4 Gt CO_2/yr by 2030. In terms of the land's impact on the climate, we looked at what might happen if the action to halt land-use emissions included in **Sky 2050** was delayed by 20 years – stopping deforestation by 2050, and with carbon sequestration at scale only from the 2040s. In those circumstances, the peak temperature would be 0.07°C higher, at 1.73°C, in 2055.

In addition, such a delay would mean the temperature in 2100 was nearly 0.1°C higher than in **Sky 2050**. Beyond this effect on temperatures, such a delay could also have other significant consequences due to biodiversity loss. Scientists estimate that, on current trends in land use, a million species are at risk of extinction within decades.[10]

In **Sky 2050**, the temperature in 2100 is almost the same as in the early 2020s. In broad terms, this is because the cumulative CO_2 emissions (2023-2100) are relatively low at around 75 gigatonnes (Gt). In this scenario, in the second half of the century the world removes nearly as much CO_2 (538 Gt CO_2) as it emitted between 2023 and reaching net zero in 2050 (612 Gt CO_2). While the temperature may be returned to today's level, other impacts would depend on global environmental changes over the century and the fact that the temperature is falling in 2100 (by around 0.1°C per decade) rather than rising (by around 0.2°C per decade) today.

Global anthropogenic CO_2 emissions from energy use, industrial processes and land use



Exploring the gap to Sky 2050

Understanding the gap by sector

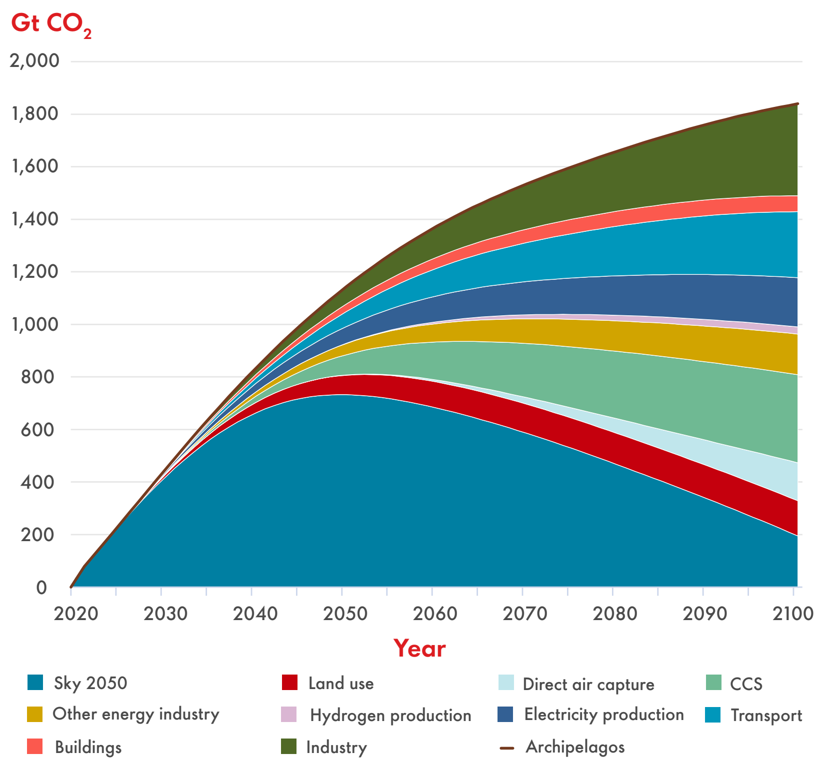
By 2100, a world that has followed the **Archipelagos** pathway has emitted some 1.5 trillion tonnes of CO_2 more than a world that has followed the route outlined in **Sky 2050**. This emissions gap is equivalent to around 1°C of warming.

Although the gap is caused in many ways, the lack of facilities to store carbon in sinks in **Archipelagos** contributes to more than a third of the difference. In **Sky 2050**, land management, direct air capture and carbon capture and storage remove 600 billion tonnes more CO_2 by 2100.

The overall gap continues to widen until at least 2100, as a result of industry and transport emissions. Together the industry and transport sectors contribute 500 billion tonnes of additional emissions by the end of the century compared to **Sky 2050**. Within transport, in **Archipelagos**, aviation, shipping and road freight are still decarbonising late in the century, but emissions in all three are falling.

Industry needs to take decisive steps to reduce the emissions gap. For example, hydrogen reaches 1% of industrial final energy use in 2044 in **Archipelagos**, but **Sky 2050** gets to the same landmark 10 years earlier.

Cumulative emissions - The Gap to Sky 2050



Note: CCS = carbon capture and storage.

Accelerating the energy transition through sectoral coalitions: aviation

Historically, new technologies have been developed and deployed one after the other and bit by bit, but greater urgency is needed to achieve an effective energy transition. One way of accelerating progress is by using coalitions within specific sectors to co-ordinate simultaneous investment towards an agreed decarbonisation solution. By working together such coalitions can quickly develop supply of a new energy technology, create the new markets that support that supply and provide enabling infrastructure. These coalitions can speed up commercialisation, making low-carbon technologies cost-effective, compared to fossil alternatives, much faster than would otherwise happen.

An example is the Clean Skies for Tomorrow Coalition. This is an initiative of high-ambition companies and organisations working to decarbonise global aviation through sustainable aviation fuel (SAF) – initially by blending it with kerosene – and other next-generation technologies. At the same time:

- fuel suppliers are investing in developing adequate quantities of SAF;
- aircraft manufacturers are developing planes that fly on SAF, batteries and hydrogen;
- airlines are shifting their fleets to fly on SAF;
- airports are investing in SAF refuelling and bunkering facilities;
- air freight consumers are demanding that their products have a low-carbon footprint;
- air passengers are moving away from offsets, demanding SAF; and
- governments are enacting policies like the proposed EU SAF blending mandate of 2% by 2025, rising to 5% by 2030.

Business-led activity is accelerating. As of late 2020, United Airlines has made the industry's single largest investment in SAF, Delta has announced a 10-year contract worth up to $1 billion for SAF, and JetBlue has committed to 10% SAF blending by 2030. Leading airports in Europe have committed to 10% SAF blending by 2030. And aircraft and aero engine manufacturers like Airbus, Boeing and Rolls-Royce have committed to ambitious SAF targets this decade.

Overall, SAF production currently accounts for less than 0.5% of global jet fuel demand. Offtake agreements – commitments to buy an agreed amount of fuel – have reached 15 billion litres, representing around 5% of projected SAF demand in 2050 in a 1.5°C scenario. With existing capacity able to produce 1 billion litres, these offtake agreements are a clear sign of future demand that should incentivise significant additional investment to supply customers.

Establishing a coherent policy framework

The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. To bridge this gap, it is critical society establishes a coherent policy framework.

An energy transition consistent with the Paris Agreement requires governments, businesses and consumers to work together to produce a virtuous cycle of change.

In this context, the role of policy in bridging the gap to **Sky 2050** is extremely important. Government policies, for example, can correct a basic failure of the market. Today almost all products and services have an impact on the environment because of the greenhouse gases emitted as they are produced and consumed. Currently, the market fails to price in the cost of this damage and pass it on to consumers. In this way, consumers are insulated from the damage they cause, directly or indirectly, and are not motivated by price to change their behaviours or choices. Government policy that corrects for this market failure can help level the economic playing field to ensure high-carbon products cost more, making lower-carbon options more attractive. Such policies, in turn, incentivise business investment to develop low-carbon products, processes and solutions, as well as new business models to support them.

At the most basic level, setting net-zero targets – and intermediate milestone targets – provides an important signal to business and broader society. A set direction reduces uncertainty around policy, and less uncertainty feeds into greater confidence to invest. Government policies can also help protect citizens from the impacts of climate change while enabling low-carbon choices. When governments enable and amplify consumer action, a low-carbon society is delivered earlier.

At COP26 in Glasgow, the signatories to the Paris Agreement decided on the implementation of common time frames for the nationally determined contributions (NDCs) referred to in Article 4, paragraph 10, of the Paris Agreement. The first global stocktake – the process by which countries are held to account for their progress against their NDCs – takes place at COP28 in the United Arab Emirates in 2023. After that, at COP30 in 2025, countries are to submit new NDCs. Specifically, at COP26 in Glasgow it was agreed that, in 2025, countries should communicate NDCs with an end date of 2035. These NDCs will be an important starting point for policy development or may be an important affirmation of policies already coming into law.

The energy transition is a complex process – not just in terms of the required techno-economic change, but also in terms of the social process of change. No single policy can deliver a Paris-compliant energy transition. Instead, there must be a mutually reinforcing network of policies that all work to push society towards a low-carbon future. Such effective policy interventions and frameworks must be:

- integrated – looking beyond just transforming the energy supply;
- stable – to incentivise the necessary long-term investments;
- efficient – keeping costs down by harnessing market forces rather than fighting against, or trying to replace, them; and
- flexible – to allow evolution as countries go through different stages of the energy transition.

The promises needed in 2025 to achieve Sky 2050

At COP26 in Glasgow, it was agreed that the next round of nationally determined contributions (NDCs) should be announced in 2025. But what should they say?

NDCs can and do vary widely in content but, following COP24 in Katowice in 2018, they must follow a certain format and include a general description of the NDC target. NDCs must also now include a list of the sectors, gases and categories covered. Although there is no specific requirement in the Paris Agreement for types of targets, there is an expectation that wealthier countries should quickly embrace absolute reduction targets. Over the longer term this will become the case for all nations due to the necessity of achieving net-zero emissions.

Behind each NDC sits national policies designed to deliver on them, although these are not typically included in the NDC submission. While the contribution remains a matter for national decision-making, we can still make some observations from our scenario modelling. Significant action is needed in the next round of NDC submissions to gain traction and scale for the 2030s and 2040s.

Green Dream and Innovation Wins

These archetypes are mainly made up of relatively wealthy developed countries. The emphasis of their NDCs must continue to be ambitious absolute emission reduction targets leading to net-zero emissions by 2050 at the latest. However, with a global goal of net-zero emissions in 2050 and the high likelihood of a 1.5°C overshoot, these countries will need to be mindful of two future requirements:

- If the global goal of net-zero emissions in 2050 is achieved, it will not be because all countries are at net-zero emissions on January 1, 2050. With countries at different stages of development and at different points in the evolution of their energy systems, some will reach net-zero emissions much later than others. For some less developed economies, or countries making very heavy use of domestic fossil fuel resources, it may take until the 2060s to reach net zero. This means that, if the world is to reach net zero overall by 2050, other countries will need to reach net-zero emissions before 2050 in order to balance the outcome.
- After the global goal of net-zero emissions is achieved, the world will need to move into net-negative emissions: more CO_2 will need to be removed from the atmosphere than is being added. Net removal of CO_2 from the atmosphere will ultimately lower the global average surface temperature, which is likely to have exceeded 1.5°C before 2050. Some countries will need to reach negative emissions before 2050, both as a way to reduce average warming over the longer term and to ensure net-zero emissions is reached in 2050 on a global basis.

Reaching net-zero emissions in the 2040s and then becoming net negative is likely to require action beyond the borders of the countries that take this path. Land-use change is one example, with action needed early. Ambitious **Green Dream** and **Innovation Wins** countries can do this by buying nature-based carbon removal credits from the broader global carbon market. This will result in a flow of climate finance to land-based projects in many countries, improving the capacity of the land on a global basis to absorb carbon and act as a sink. These activities will require countries to make use of Article 6 of the Paris Agreement – which governs carbon trading – and create opportunities for companies to use the voluntary carbon markets.

Great Wall of Change

Great Wall of Change is dominated by China. With its substantial manufacturing capability providing essential goods for the global market and a population of 1.4 billion people, China has the world's highest emissions. China's 2025 NDC will need to build on its announced intention to peak emissions well before 2030. Ideally, its NDC would shift to a 40% absolute reduction from peak emissions by 2035. This would require substantial change in both land management practices and the energy system, making use of significant national production capacity for solar photovoltaic, wind turbines, electric vehicle batteries, electricity grid development and nuclear power plants.

Emergent Surfers

As **Emergent Surfers** countries look towards the 2030s, the larger and more economically developed of them will need to shift their NDCs towards absolute targets. For example, emissions in India should be 25-30% below their 2020s peak by 2035. In the same time frame, Brazil should be nearing net-zero emissions through a major transformation of its land-use practices. After the mid-2030s, Brazil could be a substantial supplier of carbon removal credits to the rest of the world. This would require emissions accounting transparency at a national level and clarity on Brazil's proposed carbon budget or net-zero goal. These elements could be established through Brazil's 2025 NDC.

Rising Surfers

For the less developed **Rising Surfers** countries, the 2030s offer a significant opportunity to access climate finance through carbon credit trading. Many countries will be looking for removal units to manage their own carbon budgets, and many **Rising Surfers** countries can supply them through improved land management practices and forestry projects. The precondition for any country to sell carbon credits, in order to manage the Article 6 accounting provisions, is a domestically established national carbon budget. This could be established through the 2025 NDCs, offering confidence to buyers for the years ahead. Establishing domestic carbon budgets will also bring clarity to each nation's energy system carbon goals – once they know how much carbon they can emit, they can take action to remain within that limit. This, in turn, can maximise the drive to leapfrog fossil fuel use.

The 2020s: policies to accelerate commercialisation

The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by establishing policies designed to accelerate business action.

The low-carbon technologies and fuels required for the energy transition are in various stages of commercialisation. Compared to the cost of a fossil-based electricity system, the cost of a renewables-based system is expected to be the same or lower in parts of the world most suited to such systems – but not until 2030. Similarly, electric vehicles are expected to get closer, in terms of the overall ownership cost, to internal combustion engine vehicles – but not until the second half of the 2020s. The gap to commercialisation is bigger in other sectors, such as low-carbon fuels in aviation, shipping and heavy-duty road transport. There is also a significant gap for heavy industrial products like green steel, zero-carbon cement, sustainable chemicals and technologies like heat pumps to decarbonise buildings.

There are three ways government policies can accelerate the commercialisation of low-carbon technologies and fuels: by incentivising low-carbon supply, creating markets for low-carbon energy and driving infrastructure investment.

Incentivise low-carbon supply

The USA's Inflation Reduction Act increases investment tax credits for wind, solar and energy storage to $128 billion, makes existing tax credits for carbon capture and storage more generous and introduces a tax credit of up to $3 per kilogram for green hydrogen. China has taken an industrial policy approach in its 14th Five Year Plan for 2021-25 – for example, designating green hydrogen as a focus for public and private resources and as one of six future growth industries. The European Union, in turn, has chosen a third, more regulatory pathway to accelerating clean energy. The EU is, for example, providing funding through the Recovery and Resilience Facility to support REPowerEU objectives – related to making the EU independent from Russian fossil fuels – and to drive clean energy commercialisation and deployment.

Create markets for low-carbon energy

Commercialising low-carbon energy technologies requires growing demand as well as supply. This simultaneous scale-up has already been undertaken in the power sector through feed-in tariffs, contracts for difference and renewables auctions that combine elements of both. In other sectors, like buildings and road transport, tightening technology and emissions performance standards over time has become a common policy lever used throughout the world. This approach supports lower-carbon product development and more efficient energy use. This policy lever is also starting to be used in harder-to-abate sectors, like aviation, where the EU plans to introduce a mandate for blending sustainable aviation fuel, starting with 2% in 2025 and increasing to 5% by 2030.

Drive infrastructure investment

The key role of infrastructure in unlocking the energy transition is increasingly being recognised by policymakers. An example is electricity transmission grids connecting renewables-rich regions to demand centres. Another example is pipelines for transporting hydrogen and CO_2. In these cases, and many others, infrastructure is essential for the deployment and use of low-carbon energy, but takes time to build. Policies to start driving these investments include co-ordination of strategic infrastructure. Examples include guiding the interconnection between fragmented regional electricity markets and changing the planning and permitting system to accelerate the approval of low-carbon infrastructure. Another example would be offering incentives to draw in private investment in areas such as electric vehicle charging. At the other end of the spectrum is direct government investment and the regulation of key electricity transmission and distribution infrastructure. China is leading in building ultrahigh-voltage grids and is considering reforms to link its six regional power markets. Planning reform is a key pillar of REPowerEU.

Simultaneous investment in developing new supply, creating new markets and investing in enabling infrastructure will accelerate the process of commercialisation, bringing forward the moment individual low-carbon technologies become cost-effective.

The 2030s: policies to drive low-carbon choices

The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by establishing policies designed to drive low-carbon choices.

The current suite of policies aimed at driving low-carbon choices has a limited shelf life. The current approach is to implicitly price in the cost of carbon by offering fiscal incentives – tax benefits – that help level the playing field between fossil fuels and low-carbon energy. This approach does not have a long-term future because, as the range of low-carbon alternatives expands and the number of actors providing low-carbon solutions increases, it will become increasingly expensive for governments to support. An explicit carbon price, whether through a carbon tax or an emissions trading scheme, provides a more economically efficient and cost-effective method of driving low-carbon choices.

In the early 2020s, introducing a high carbon price faces the significant political challenge of being viewed as an additional tax, or cost, placed on consumers and businesses. This perspective is given extra weight because low-carbon alternatives are not yet commercial. A carbon price can be an effective mechanism, however, when phased in gradually. Success depends on it being part of a comprehensive energy transition policy framework that incentivises innovation and encourages the commercialisation of clean technologies, fuels and products. Success also depends on sufficient investment in infrastructure to support the deployment and large-scale take-up of low-carbon options. As low-carbon choices expand, a robust carbon price can harness market forces to drive their uptake.

The evolving role of carbon pricing

Carbon pricing is an important part of both the **Sky 2050** and **Archipelagos** scenarios.

At lower levels, a carbon price has been shown to drive improvements in energy efficiency and to lower emissions in end-use sectors like transport, buildings and industry. It has also been effective in driving fuel switching. This has been seen in the EU with a combination of the EU Emissions Trading System (ETS) and the EU Industrial Emissions Directive pushing through a switch from coal to gas for power generation. A rising carbon price can then begin to drive resources, especially investment capital, towards lower-carbon technologies and infrastructure.

While the EU ETS is an example of a relatively mature carbon pricing scheme, other countries have also started implementing carbon pricing. For example, China launched its national ETS in July 2021. This is currently focused on the power sector, but it is expected to expand to other sectors of the economy and a wider range of participants. Singapore launched a $5 per tonne of CO_2-equivalent (tCO_2e) carbon tax in 2019, rising to $50-80/$tCO_2e$ by 2030. Indonesia is exploring a carbon tax, carbon trading and results-based payment as part of its carbon economic value framework to meet its 2060 net-zero emissions target.

As new low-carbon solutions develop, consumers and businesses will choose from a broader range of low-carbon options and providers. Once these low-carbon solutions get close to commercial viability and the infrastructure to facilitate their adoption at scale has been established, the carbon price has an important role to play. In these circumstances, it allows consumers and businesses to seek out the lowest cost alternatives best suited to their needs. In fact, the prospect of higher carbon prices is already starting to drive action. Steel producers in Europe are beginning to invest in hydrogen-based processes to produce green steel. In 2022, the first commercial deal for cross-border transport and storage of CO_2 was signed between Yara's fertiliser plant in the Netherlands and the Northern Lights carbon capture and storage project in Norway.

In addition, mechanisms that work alongside carbon pricing, like the EU's proposed Carbon Border Adjustment Mechanism, can have several positive effects. Firstly, they reduce carbon leakage – disincentivising producers from taking high-carbon facilities elsewhere and reimporting the products. Such behaviour lowers one country's carbon emissions while raising another's, creating no net benefit to the environment. Secondly, such mechanisms can protect domestic competitiveness for those countries inside them – preventing businesses from outside taking advantage and undercutting domestic production on price. Finally, and no less significantly, they incentivise climate action beyond the borders of the mechanism, as those wishing to export to member countries seek to avoid carbon-linked penalties.

In the longer term, cleaner alternatives are likely to become cost competitive with fossil fuels in sectors such as power and passenger road transport. However, other sectors, such as aviation, are likely to require a sustained and high carbon price to bridge the gap to clean technologies and fuels.

Carbon prices in Sky 2050 and Archipelagos

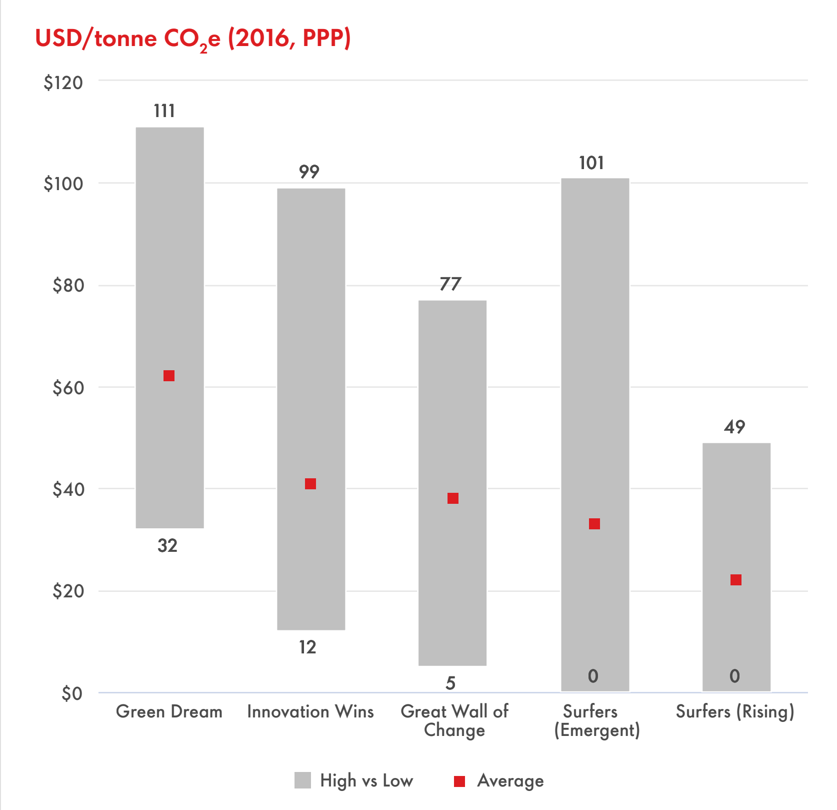
Archipelagos makes considerably less use of carbon pricing mechanisms, and at a lower level, than is seen in Sky 2050. A significant consequence is that, in **Archipelagos**, global emissions have only just peaked by 2030 and are still at 35 gigatonnes (Gt) in 2040.

Carbon pricing has long been called for by a broad range of energy system observers and, while some regions have introduced it to some extent, progress has been modest at best. Carbon pricing can emerge in many different forms. In the numerical modelling behind **Sky 2050**, we are neutral on the type of mechanism used, but instead have used the carbon price as a broad driver of change.

In both scenarios, in the 2020s the carbon price would be delivered largely through implicit approaches – such as tax credits for low-carbon products and services – but with some explicit systems operating. In **Sky 2050**, the application of carbon pricing becomes broader and reaches deeper within the global economy. The type of measures include:

- Indirect mechanisms, such as the tax credit system operating in the USA, where incentives are offered for certain technologies. The 45Q system offers tax credits to drive carbon capture and storage (CCS) deployment, acting as a form of carbon price – a government-funded discount – for the project developer. However, the 45Q system does not include penalties for continuing to emit CO_2, as it is focused on getting CCS projects started to establish a base of knowledge and expertise.
- Standards that impose specific carbon emission limits, such as the various vehicle CO_2 requirements operating throughout the EU.

Sky 2050 - Carbon price ranges 2020 - 2040



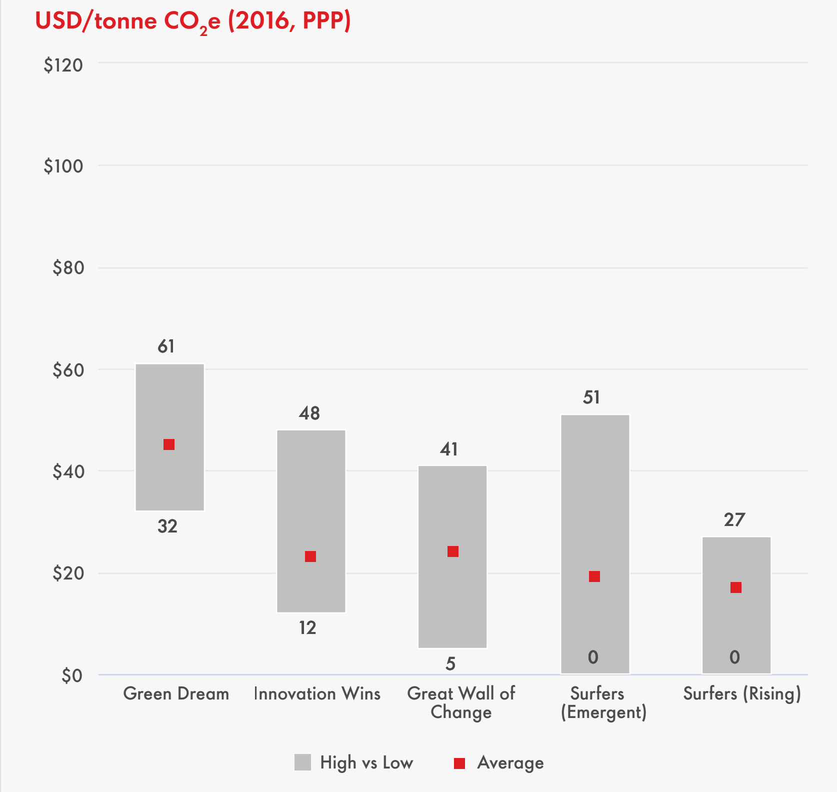
In the 2030s, more explicit mechanisms prevail:

- Direct taxation is widely regarded as the most efficient way forward. This can be on the basis of carbon emissions (such as in British Columbia and Singapore) or the implementation of a cap-and-trade system (such as in the EU).
- Other direct trading and offset requirement systems, such as the baseline and credit system in Alberta or the Emissions Reduction Fund in Australia.
- These systems would have an effect more widely through carbon border adjustment mechanisms. They impose a financial penalty on high-carbon imported goods, which may force manufacturers to reduce emissions in order to compete in markets protected by such mechanisms.

Further support of a carbon price will also be present and growing throughout the period from 2020 to 2050:

- Other cross-border trading mechanisms, such as carbon credits through Article 6 of the Paris Agreement. While not directly imposing a carbon price, these can offer carbon pricing incentives to various technologies in places where a direct mechanism is not functioning.
- Voluntary carbon reduction goals can translate into a carbon cost within an organisation. Once an organisation sets its goal, it may seek carbon credits as part of its reduction strategy. This then translates into a carbon cost set by the price of carbon credits in the voluntary carbon market.

Archipelagos - carbon price ranges 2020 - 2040



Protecting domestic industry: carbon border adjustment mechanisms

One of the most powerful levers in bridging the gap to **Sky 2050** is the carbon border adjustment mechanism (CBAM). Once domestic actions have been taken to adequately price carbon, these mechanisms act to reduce carbon leakage – essentially the exporting of emissions – while also protecting domestic competitiveness by preventing high-carbon imported products from undercutting domestic production on price. The EU already has plans to adopt an ambitious CBAM from 2026, covering imports of industrial products. This action, in turn, has the potential to incentivise increased carbon pricing beyond Europe.

A route from distrust to decarbonisations

In the development of **Sky 2050**, CBAMs create a cascade of change throughout the global economy. Firstly, responding to pressure from climate-ambitious businesses and key trading partners, the USA follows the EU's lead and adopts its own CBAM. This follows in the wake of federal carbon pricing to support domestic industries, many with ambitious net-zero emissions commitments. Secondly, trading partners of the EU and USA – such as Turkey, China, India, Mexico and Brazil, which are highly exposed to trade in industrial products – implement and reinforce their own carbon prices to avoid being penalised. This practice is also adopted in other parts of the world seeking to increase exports to Europe and the USA. Third, the global policymaking environment evolves as consumers adopt low-carbon technologies and costs fall. As low-carbon products get closer to the cost of traditional products, policymakers become less concerned that their carbon pricing puts domestic industry at a disadvantage.

In fact, climate policy (including carbon pricing) is increasingly viewed as an integral part of industrial policy to support domestic business as it pushes to the forefront of the global green industrial revolution.

The value of CBAMs

CBAMs are valuable not just because they reduce emissions in the countries implementing them – Europe and the USA, in this instance – but also because they incentivise climate action beyond their borders. CBAMs tip global exporting countries into self-reinforcing and substantially more aggressive carbon pricing regimes. For example, an EU-US CBAM is estimated to reduce emissions by 15 gigatonnes of CO_2. Yet, more than 60% of that estimated emissions reduction is made by trading partners in emerging and developing economies.

The 2040s: consolidate and amplify

The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by making sure the lessons learned by early movers are passed on to others.

The nature and pace of the energy transition is likely to be different in different parts of the world. Countries that move quickly in the early stages of the energy transition will gain important experience as they handle the risks associated with the new technologies, roll out low-carbon solutions and build their supporting infrastructure. This knowledge will be essential for speeding up the transition for those nations coming behind. It is know-how that will help evaluate and amplify the technologies most suited to different sectors and parts of the world, the most effective policy approaches and the best financing mechanisms for different types of energy transition investments.

Policies to support negative emissions

Actions that remove CO_2 from the atmosphere – creating negative emissions – will be essential both before 2050, and after. Before 2050, negative emissions are needed to balance emissions from high-growth sectors like aviation and industry to keep greenhouse gas emissions as close to the 1.5°C carbon budget as possible. After 2050, negative emissions are needed to remove the greenhouse gases emitted in excess of the 1.5°C carbon budget – the overshoot – and to bring the global temperature rise back down below 1.5°C by the end of the century.

Delivering negative emissions requires a systematic and robust policy framework for carbon removal. Options include direct air capture (DAC), bioenergy with carbon capture and storage, (BECCS) and creating natural carbon sinks, such as by planting forests, cultivating seagrass or developing mangrove biomass. Global consensus on Article 6 of the Paris Agreement – which governs the trading of carbon credits between nations – and its implementation is essential. COP26 in Glasgow agreed the rulebook for Article 6, but further work is still needed before it can be put into action. If this consensus can be achieved, it will mean that carbon credits generated by negative emission technologies could either be used towards domestic climate targets or be traded internationally for other countries to use against their targets.

Carbon trading could be a win-win for both global climate and economic development objectives. Countries like Indonesia host some of the world's most important terrestrial and marine ecosystems for storing carbon. For example, Indonesia contains 10% of the world's tropical forests, 36% of the world's tropical peatlands and 17% of the global blue carbon reservoir (a form of carbon sink that includes mangrove swamps, seagrasses and salt marshes). Protecting and restoring such ecosystems has a critical role to play, contributing to global efforts to combat climate change and preserve biodiversity. By protecting and restoring these ecosystems, Indonesia can generate carbon credits and use the carbon trading system to sell them and bring in funds. At the same time, Indonesia has the opportunity to make itself an attractive destination for international climate and biodiversity investment through enabling policies, robust institutions and transparent governance.

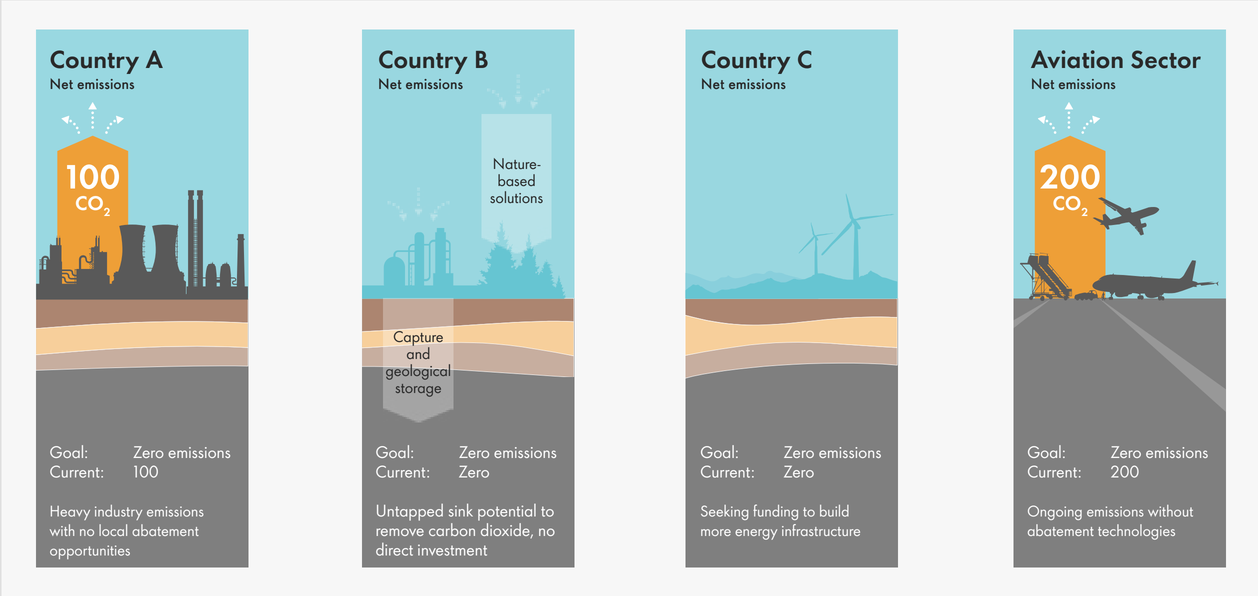
The role of Article 6 of the Paris Agreement

Article 6 of the Paris Agreement offers countries the opportunity to co-operate with each other and trade carbon credits as a route to achieving their respective nationally determined contributions (NDCs).

In Figure 1, we see three notional countries and a sector. All of them have goals to reach zero emissions but none of them, individually, are able to achieve that outcome at the same time as meeting their other goals, such as building energy infrastructure or achieving development goals. The architects of the Paris Agreement recognised that there will be pockets of emissions remaining for a long time after the point that the world needs to be at zero emissions. As a result, they constructed the balancing proposition of net-zero emissions: that emissions made in one place may be offset by action to avoid, or negate, emissions in another.

Article 6 is designed to deal with the fact that, while sources of emissions may remain in many places, natural and industrial sinks may only be economically available in some places. This means there needs to be a way of trading between those who emit and those who can provide mitigation for emissions. Article 6 is intended to be the underpinning mechanism for the long-term cross-border trade of carbon units. Ultimately, Article 6 can help deliver the goal of the Paris Agreement by channelling investment towards zero-emission energy systems and expanding the use of natural and artificial sinks.

Figure 1 - With countries and sectors isolated, net-zero emissions is unlikely to be achieved

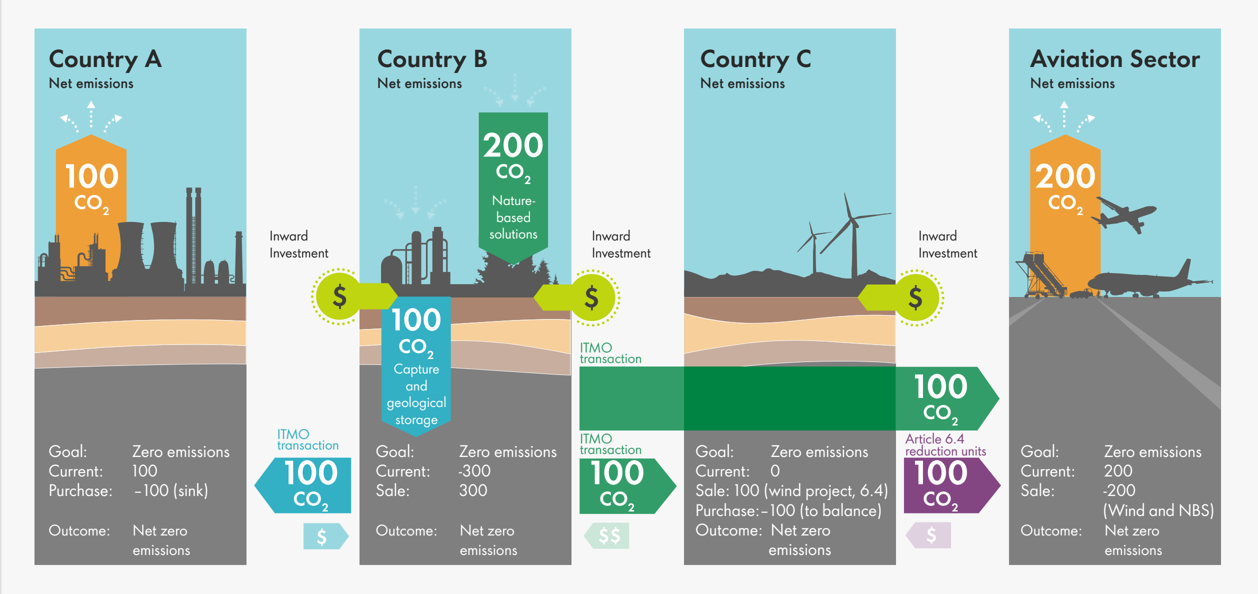


Progressing the example in Figure 1, we see in Figure 2 how cross-border co-operation through Article 6 and the use of trade can deliver the overall goal of net-zero emissions.

An essential component of Article 6 must be an emissions accounting methodology. This ensures the environmental integrity of trading and demonstrates that an overall reduction in global emissions is achieved. Given the need to rapidly reach a high volume of trading in carbon units, the accounting approach used needs to be numerically based around the carbon reduction goals of each country's respective NDC. The other main method proposed is a subjective assessment through baseline analysis and qualitative additionality tests for individual projects – but the bespoke nature of this technique means it is hard to scale up and the subjective element is likely to undermine market trust in the carbon credits it validates. If Article 6 provides a sound accounting basis to instil market confidence for large-scale investment, economic studies show that both buying and selling countries will benefit from such trade.

Numerical assessment starts with a process that quantifies carbon emissions through each country's NDC. This paves the way for a transparent adjustment of that quantification as a result of trade in carbon units. It also allows observers, including the markets, to see that the sought-after emissions reductions of the NDC are truly achieved.

Figure 2 – Article 6 opens the possibility of trade in carbon units, drawing investment into areas where it would otherwise not occur and delivering a net-zero emissions outcome



A just transition: fairness as a prerequisite of global security

The energy transition is more than a techno-economic process of transforming the energy system – it also involves social transformation. Energy affects every part of life, from work to home and leisure. So, to make progress at pace, action must have broad-based support, and this means the energy transition needs to be fair. Fairness covers energy affordability, energy availability and making sure people are shielded from climate impacts. Unjust outcomes increase the risk of conflict, mass migration, populism and many other forms of social change which lead to instability on a global scale.

In the long term, a net-zero emissions energy system will produce significant societal benefits, such as more efficient energy consumption and better environmental outcomes. Actions to transform energy supply, energy demand and land use in line with climate goals have strong synergies with delivering sustainable development.

Given the scale, scope and speed of change, however, the effects of this transition will not be equally felt across society. In short, some countries – and within countries, some people – are more able to afford new technology than others. Similarly, some are more able to afford to take actions to protect themselves from climate effects than others. Sharing fairly the economic, social and environmental benefits of the energy transition to all parts of society, while supporting those most negatively impacted by its effects, is a precondition for making progress at pace in the energy transition and, ultimately, ensuring global security.

How can government policies support a just energy transition?

Manage energy price volatility

While the effects of the war in Ukraine, including high energy prices and inflation, have focused minds on energy security and affordability, pressures had already been building for some time. There has been a systematic underestimation of the time and resources required to build a new low-carbon energy system. This underestimation has covered more than just investment in wind and solar deployment, but also investment in electricity grids, flexibility technologies to balance the intermittency of renewables, electric vehicle charging infrastructure and the transport and storage of hydrogen and CO_2. Coupled with declining investment in oil and gas for much of the past decade, this has created an increasingly inelastic energy supply – a situation where there is an inability to increase supply no matter what prices are offered. As a result, at least in the short term, even minor disruptions in the market – like pipeline shutdowns – are likely to be reflected in relatively large energy price swings throughout the 2020s.

Governments need to accelerate construction of the low-carbon energy system while, at the same time, ensuring adequate oil and gas investments to secure energy supplies through the transition. As they do this, they also need to develop policies to protect the most vulnerable from inevitable energy price volatility: consumers and businesses alike.

Ensure economic opportunities are widely shared

To sustain progress in reducing emissions, all parts of society must benefit from the government policies relating to the energy transition. Vulnerable communities, and those that lack sufficient access to energy, must get affordable and reliable supplies. They must also be made resilient to climate impacts, such as sea-level rises and extreme weather events. In addition, governments and society must ensure the most vulnerable benefit equally from climate mitigation and adaptation opportunities presented by the energy transition.

Plan for the transition out of coal

The transition away from coal – which is by far the most emissions-intensive fossil fuel – is a key condition for the world to achieve net-zero emissions by 2050. This is a particularly acute issue in developing and emerging economies that rely on domestically produced coal for power and industry. In these countries, the transition is not just about reducing coal in the energy system, but also about helping entire local economies, communities and livelihoods oriented around coal production. Early and systematic action to support them through this process is required to ensure a smooth transition.

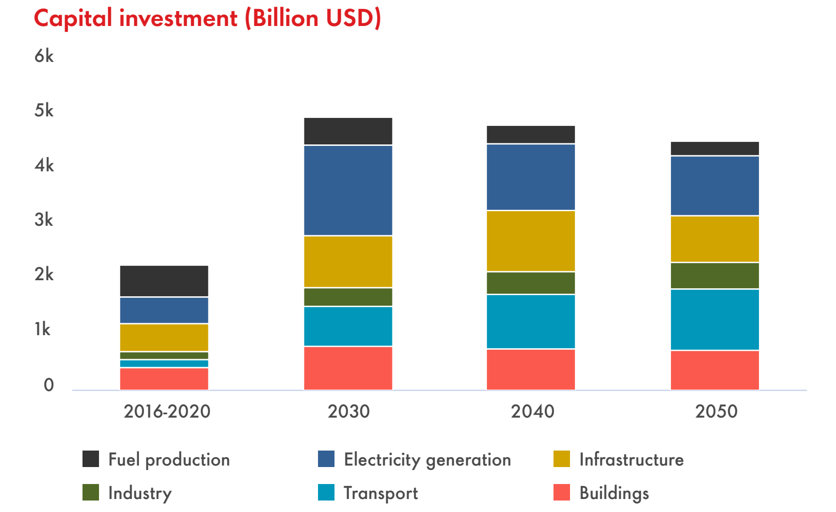
Some countries, such as Germany, Poland, the UK and the USA, have already grappled with the challenges around moving away from coal, with varying degrees of success. Based on their experience, successfully managing the coal transition will require:

- Building a social contract: the world needs a rapid energy transition to restrict the global temperature rise, but fast transitions threaten the capacity of local labour markets to replace jobs lost in coal. Trade unions have begun shifting from defensive support for coal towards a just transition approach, which secures workers' rights while transitioning to a green economy. It is important that this emerging consensus is treated with care: union support could still unravel once redundancies start to bite. Nevertheless, effective negotiations have been a powerful tool used by countries like Germany to manage industrial transitions in its western coal regions since the late 1960s.
- Planning early for closures: if transition planning is delayed until mass redundancies are on the horizon, labour markets will not be able to cope with the large volume of workers seeking jobs. Early planning for closures is starting to emerge at an industry and company level in some nations such as Australia, Germany and Italy. These plans include retraining, support for early retirement and the redeployment of workers. Site remediation – restoring the site of a mine to an acceptable state – is also an important way to improve the local environment, create community buy-in for the transition and generate semi-skilled and low-skilled jobs at the most critical time of the transition.
- Diversifying the regional economy: as coal-related jobs decline, some workers from the sector can be transferred to other industries, such as renewables and carbon capture and storage (CCS). Development of bio-resources could be another way of diversifying the regional economy. However, market restructuring alone will not deliver a just transition. Some coal regions see little prospect for developing large-scale renewables, CCS or bioenergy. This means workers will rarely transfer seamlessly to new jobs without having to move away from home. Moreover, as many of the new opportunities are likely to be in the construction phase of projects, existing employment will be replaced by a higher volume of temporary jobs.
- Establishing comprehensive policy frameworks and funds: it is essential that policies do not simply incentivise or support low-carbon energy, but also manage the socioeconomic impacts of the transition. Specialist funds are being established to oversee, develop and implement coal transition programmes. The European Commission, through its initiative for coal and carbon-intensive regions in transition, is investing funds in 13 coal regions. Germany has recommended a funding package of €40 billion to support coal regions, and Spain has established a €250 million fund, which includes support for workers, economic diversification and environmental restoration.

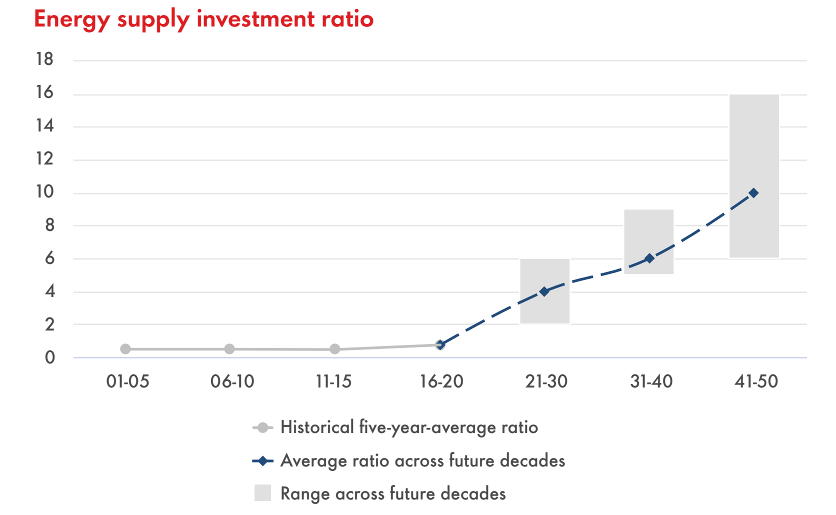
Financing the energy transition

The scale of the change necessary to reduce global emissions from the energy system is huge in both **Sky 2050** and **Archipelagos**. This scale of change also requires huge investment. Investment in the energy system will need to find a balance between ensuring energy security and building the new system.

Annual average capital investment in net zero emissions in Sky 2050



Range of decadal energy supply investment ratio 2001-2050 (all scenarios)



Financing needs

The financing needed to transform the energy system from fossil fuels to low carbon is substantial. The International Energy Agency (IEA) estimates that the annual average capital investment in the energy transition will need to be between $4-5 trillion in the 2030s and 2040s, compared to a little more than $2 trillion between 2016 and 2020.* Electrification is the backbone of most deep decarbonisation scenarios, including **Sky 2050**, and consequently investment in low-carbon electricity generation is around one-third of all energy investments in 2030. A substantial share of investment will also be needed to transform energy end-use sectors like transport, industry and buildings, rising from roughly a third in 2022 to more than half by 2050. Developing a new low-carbon energy system also requires substantial investment in infrastructure – from electricity transmission grids to connect renewables-rich regions and population centres, to pipelines for transporting and storing hydrogen and CO_2. Annual infrastructure investment will need to be maintained at almost double the level of 2022 over the next three decades.

Transforming the energy system requires investment in low-carbon technologies and fuels, such as renewables, hydrogen, advanced bioenergy and carbon capture and storage (CCS). At the same time, it requires ensuring adequate investment in traditional fossil fuels to provide secure and affordable energy to meet demand, even as the system transitions to net-zero emissions. Studies estimate that the ratio of low-carbon to fossil investment in energy supply is 4:1 this decade, rising to 6:1 in the 2030s and 10:1 in the 2040s. This ratio was 0.73:1 between 2016-20.

*International Energy Agency, Net Zero by 2050 – A Roadmap for the Global Energy Sector, 2021.

Macroeconomic context: opportunities and challenges

The world has seen more than a decade of generous monetary policy and a benign financing environment. This has meant a lower cost of capital and greater access to capital. This has, in turn, helped to fund low-carbon investments, particularly in renewables where deployment has soared over the past decade. As monetary policy normalises, the cost of capital is likely to rise (as interest rates are raised) and access to capital is likely to become more difficult (as quantitative easing is tapered and then withdrawn). However, the proliferation of ambitious government targets to decarbonise means that the energy transition is likely to remain an area of increasing interest for private finance. An example of this in action is the creation of the Glasgow Financial Alliance for Net Zero and other groups like it. Moreover, tightening monetary conditions could drive a flight to quality, focusing on investments that provoke wider system change and create further investible opportunities that have the potential to be adopted widely and replicated.

Governments have emerged from the COVID-19 pandemic with higher debt levels and more limited resources to put towards the energy transition. Russia's invasion of Ukraine has further strained government budgets, and the worsening global economic prospects will have knock-on effects on government finances. Resources are increasingly prioritised towards defence (particularly in Europe and other advanced economies) and mitigating the effects of high energy and food costs. Even so, using scarce public finance resources to invest in infrastructure, such as upgrading power grids and making them smarter, can provide multiple benefits: stimulating economic activity, enhancing the productive capacity of the economy and supporting progress in the energy transition. Governments can also use innovative policy mechanisms to attract private capital. Examples include fiscal measures – such as investment tax credits, subsidies and accelerated depreciation allowances – and financial measures, such as co-funding initiatives and public-private partnerships. In addition, governments can use their substantial balance sheets to have an effect. For example, through loan and credit guarantees to lower cost and increase access to capital.

Creating a virtuous cycle of policy and finance

In advanced economies, private finance will provide most of the funds required, as long as supporting policies and policy frameworks are in place. Policy has a critical role in reallocating capital towards low-carbon energy investments – such as through a carbon price – and creating the enabling conditions for low-carbon investments. The most effective policies are likely to be those that harness financial market resources and actions, rather than seek to replace, or even oppose, them.

Setting clear national targets for decarbonisation will begin to redirect private finance towards energy transition business opportunities. This is amplified by the anticipation of rising carbon prices, either directly through carbon taxes, emissions trading schemes and regulatory changes, or indirectly through carbon border adjustment mechanisms. Even businesses in hard-to-abate industrial and transport sectors start investing in low-carbon production processes and drive trains respectively.

Even with enabling policies in place, however, private finance alone is not likely to be adequate to meet the financing needs of developing and emerging economies. The Energy Transitions Commission – a global coalition of energy sector leaders committed to achieving net-zero emissions – estimates that emerging and developing economies (excluding China) will account for about one-third of energy transition financing needs this decade.[12] While this is a relatively modest share of overall financing needs, it is large in absolute terms and even more so when considered relative to the respective GDPs – and current investment levels – of these economies.

The challenge is made more acute by the constraints on public finance. Many developing and emerging economies are still struggling to return to pre-pandemic growth trends, with limited fiscal and monetary capacity to support the energy transition. Concessional finance (money loaned at below the market rate for development purposes) provided by multilateral development banks (MDBs) and finance institutions is critical to plugging the gap – increasing access and reducing the cost of capital faced by developing and emerging economies. These institutions can provide and/or bring in finance at a lower cost than the private sector because of the equity and guarantees provided by their government shareholders.

Currently, around one-quarter of MDB finance (deployed or mobilised) relates to energy transition and adaptation. Bridging the energy transition financing gap in developing and emerging economies will require:

- Raising the share of low-carbon finance. Many MDBs have already committed to raising this share to 35-50% by 2025. Moreover, targeting MDB finance on the substantial areas of overlap between climate change and sustainable development – such as on providing secure and affordable energy, clean and plentiful water, resilient food production and supply chains, and better local environmental outcomes – can help maximise its impact along both dimensions.
- Raising how much private capital is brought in through MDB financing and expanding the role of blended finance (in which development finance is used to attract private investment funding). For example, $1 of MDB capital currently brings in $0.4 of private capital. The Energy Transitions Commission estimates that this could be raised to $1 of MDB finance bringing in $2 of private capital. MDBs could potentially achieve this by absorbing some of the risks of investing, providing technical assistance and capacity development and using their reputation and expertise.

While a lot can be achieved by stretching MDB balance sheets in ways that do not affect their financial rating, it will require changing internal policies and practices and reforming the capital and guarantee commitments of the national shareholder governments.

Advanced economies, through their $100 billion annual commitment to climate finance, have an important role to play in developing and emerging economies, particularly to support the coal phase-down, avoid deforestation and develop natural carbon sinks and removals. With careful design and targeting, they could finance not just emissions reductions, but also support economies onto more sustainable economic development pathways.

A financing mix

The energy transition requires more than investing in new low-carbon energy supply. It also needs a range of investments to transform energy demand, build supporting infrastructure and develop carbon removals (natural and manmade). Each of these categories of investment tend to have a different risk-return profile, making them more or less suitable for different types of financing. Overall, a combination of finance types will be needed to achieve a Paris Agreement-aligned energy transition. These include finance that is private, public, concessional, climate and blended (when development or philanthropic funds are used to attract private investment).

Table 1 illustrates the different energy transition financing needs and potential sources of financing. The role of policy targets and initiatives remains a key enabler for all.

Table 1

Financing need	Potential sources
1. Driving technologies to commercialisation	
a. Mature (renewables, hydrogen, electricity storage, second generation or advanced biofuels)	Private finance (equity or debt), supported by time-limited policy incentives
b. Nascent (direct air capture, power-to-liquids)	Private finance (venture or equity), supported by R&D or innovation policies and public finance (demonstration projects, public-private partnerships)
2. Investing in carbon removals (natural, manmade)	Climate finance or concessional finance (particularly for natural carbon removals), private finance through voluntary carbon credit markets evolving (with changes to the policy framework) into mandatory compliance schemes
3. Building low-carbon enabling infrastructure (electricity transmission and distribution grids, hydrogen and CO_2 transport, electric vehicle charging)	Public, concessional or blended finance (e.g. in developing and emerging markets), innovative public-private finance approaches like the regulatory asset base model (e.g. in advanced economies), private finance (e.g. electric vehicle charging, hydrogen or CO_2 transport infrastructure)
4. Phasing down fossil fuels (especially in developing and emerging economies)	Climate finance, concessional finance or blended finance (to fund currently higher cost alternatives), public finance and incentives (for decommissioning or early retirement of existing capacity)
5. Transforming demand (including through energy efficiency)	Private finance, supported by credible policy targets and time-limited policy or regulatory initiatives to create demand or take-up

Consumer behavioural change

Vehicle ownership and shared mobility

The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by people choosing to travel in different ways.

Consumers are finding sharing, instead of owning, increasingly appealing as part of a wider trend towards a sharing economy. This is a major driver of shared transport innovation and, despite it being an industry in its infancy, more urban consumers are incorporating sharing in their daily commutes.

Sustainability has become a dominant topic, as consumers have embraced climate-conscious behaviour. Sharing vehicles can contribute to better sustainability by reducing private car use. It can assist cities to reduce traffic and curb air pollution. It can also help to improve urban layouts that make cities more friendly for people to navigate on foot or by bicycle.

More people than ever are living in cities. By 2040, 64% of the global population will be urban. Shared mobility is expected to play an active role in urban transportation as cities become more crowded. Private passenger car travel will become more challenging, with less space for parking and more restrictions placed on private car use. Younger populations are embracing sharing more than others. This is being influenced by different generational values and attitudes to ownership. For example, Generation Z and Millennials are much more likely to use shared mobility options than Generation X or baby boomers. Younger generations may be less interested in ownership and instead focus on experiences.

Urban areas have felt the greatest impact from shared transport options. Major cities have become key battlegrounds for shared transport companies like Uber and Lyft, and competition is expected to intensify as more personalised and efficient services appear. Technological progress is helping propel the industry. Internet access and smartphones have enabled consumers to access a huge range of services at the touch of a button, such as shared scooters, cars, bicycles, hail cars and carpool rides.

The value of shared mobility's bookings is expected to reach $500 billion by 2040. Growth will be driven by emerging market economies such as Indonesia, China and India. Four of the five largest shared mobility markets will be in emerging and developing nations by 2040. Asia-Pacific is the largest shared mobility market. By 2040, it will account for 51% of global bookings in the sector, with China cementing its position as the largest single market. By 2040, China will account for 28% of global shared transport bookings in terms of value. Ride hailing is the largest and most popular mode of shared transport. It controls more than 80% of bookings in terms of value. Uber and Didi Chuxing are the leading ride-hailing companies globally in terms of overall bookings.

Scooter and bicycle sharing are expected to be the fastest growing modes of shared mobility between 2021 and 2040. This comes as governments seek to reduce personal car travel in favour of micro-mobility, both electric and non-motorised modes. In 2021, scooter and bicycle sharing accounted for a relatively small proportion of the shared transport market, with just 5.1% of bookings by value. However, this is expected to grow to more than 8% by 2040 as consumers' appetite for small, nimble alternatives increases. China was the largest shared micro-mobility market globally in 2021, with bookings worth $6.3 billion or 14% of the country's shared mobility bookings in terms of value.

Due to the relatively limited wealth of the middle classes in Africa and the Middle East, car ownership rates in these areas remain the lowest in the world. This does, however, provide opportunities for ride-hailing companies offering personal transport services. For example, Uber already has 36,000 drivers in sub-Saharan Africa, and plans further expansion in West Africa. In 2019, Uber indicated it plans to expand its operations in Nigeria. The country remains an attractive market as its urban population is forecast to double by 2050.

South-east Asia, which was home to more than 670 million people in 2021, is primed to be the growth market for shared transport over the next two decades. Its key markets of Indonesia, Malaysia, Thailand and Vietnam are projected to be among the fastest growing countries for shared-mobility bookings over the period 2021-40.

So, sharing transport has a bright future. Its ultimate effect on global emissions, however, is worth examining. Compared to the status quo, ridesharing and micro-mobility alternatives clearly offer savings in terms of emissions per person-kilometre travelled. This is not, however, the only relevant metric. New transport options typically lead to increases in the overall amount people travel. Historically, this has been seen with the railways, the car and, in recent decades, aviation. These increases have been extraordinary when measured over longer periods of time: global and regional travel is now widely practiced compared to just two centuries ago when village or town life was largely static. Nevertheless, in urban environments in which people are already travelling almost as much as they can, analysis shows emissions are reduced when shared mobility is introduced. Compared to the status quo situation in a busy European capital, a study* has shown energy demand reductions of 35-47%, depending on the form of replacement, ranging from hybrid to electric vehicles.

*All data in this section are taken from Vivid Economics, Pathways to Accelerated Transitions, report prepared for Shell, 2022.

Using fewer resources

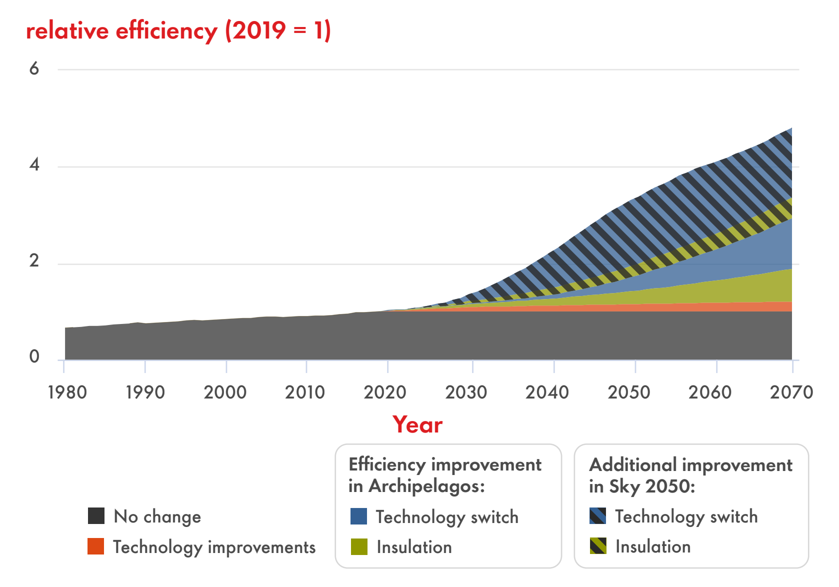
The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by people consuming less.

In terms of economics, dematerialisation happens when progressively fewer resources are needed to achieve the same economic benefit. Today, many consumer choices, especially those of young people, are either purposefully or indirectly contributing towards such a dematerialisation of the economy. More and more, consumers are choosing services over products, and experiences over the possession of things.

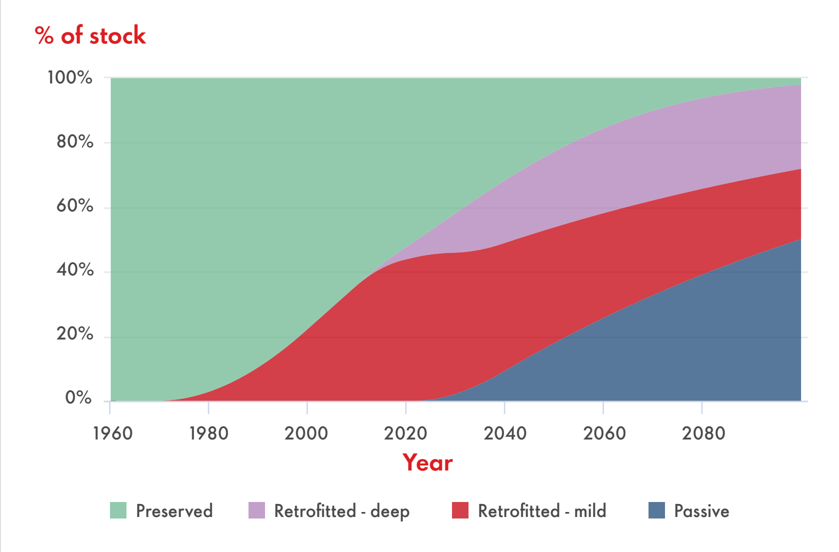
Increasing digitalisation means that many of these experiences occur online, bypassing the need for transport to interact with others. This substitution of screen experiences for in-person meetings, and of websites for paper, has increased exponentially since the COVID-19 pandemic, leading many companies to adopt a hybrid workplace model.

Another factor contributing to dematerialisation is urbanisation. By 2040, 64% of the global population will live in towns and cities. Typically, urban dwellers live in smaller spaces, which need fewer material furnishings, and rely on services (laundries) rather than products (washing machines). If the metaverse becomes a reality and achieves its potential, dematerialisation will only increase.

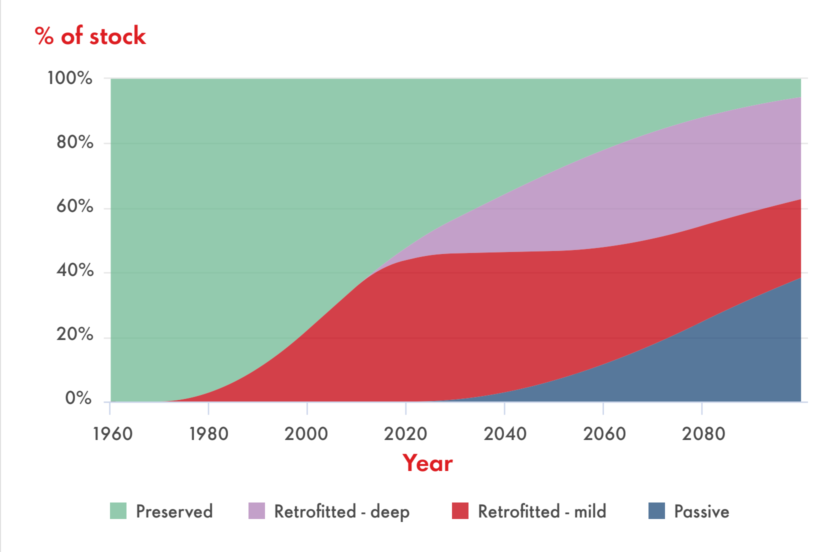
Relative efficiency in space heating



Building stock in leading countries in Sky 2050



Building stock in leading countries in Archipelagos



Diet and the consumption of meat

The gap between the future the world may be headed for, as set out in the **Archipelagos** scenario, and a future that is consistent with net-zero emissions by 2050, as set out in **Sky 2050**, is significant. One of the important ways society could seek to bridge this gap is by people changing what they eat.

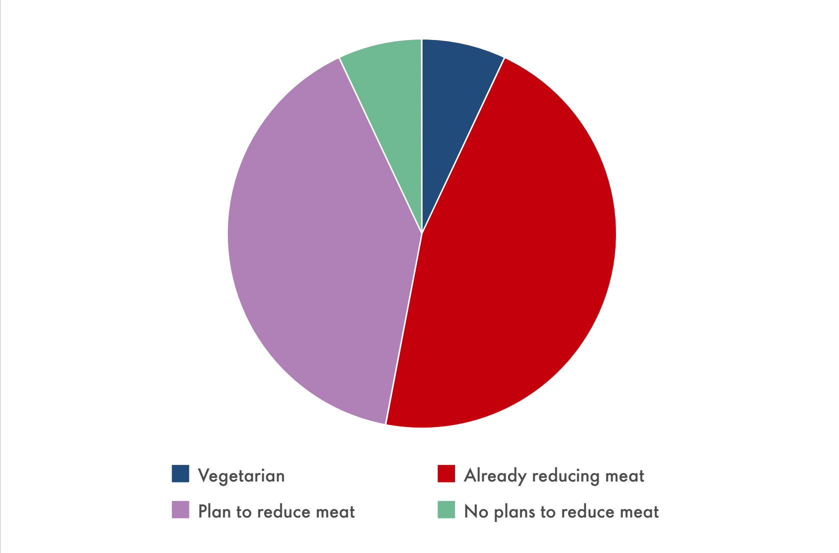
One of the most important behavioural changes people could make would be to change their diet away from meat to alternative proteins.

Cows have multi-chamber stomachs that rely on bacteria to break down plant-based food. In this digestive process, a fully grown cow can release up to 500 litres of methane – a potent greenhouse gas – into the atmosphere each day. Although not all cows produce methane at the same rate, the methane produced by the 1.4 billion cows on the planet soon adds up. When the entire meat and dairy supply system is taken into consideration, livestock accounts for 14.5% of total greenhouse gas emissions.

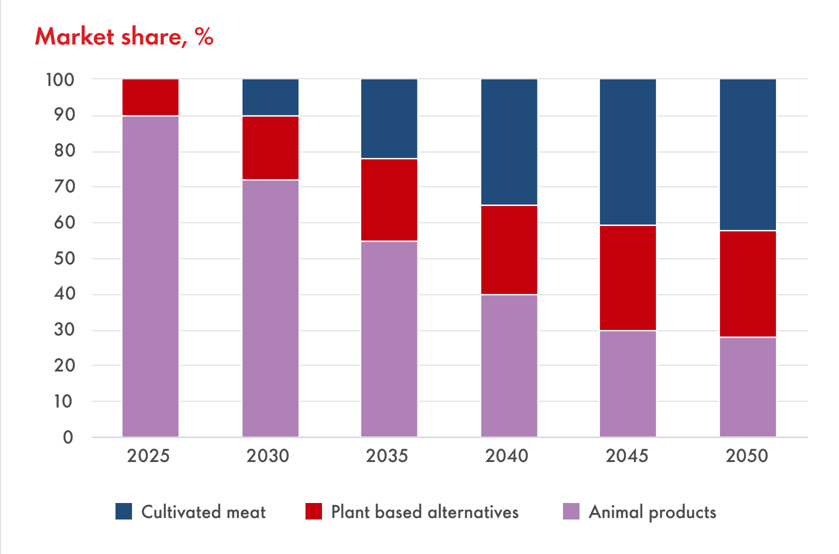
But what could encourage and maximise a shift away from meat consumption?

A global shift in diet requires a consumer push and several conditions to be met. This could start with consumer food preferences moving away from meat to alternative proteins for environmental and health reasons, particularly in advanced economies and especially among younger consumers. To an extent, this is already happening and such progress, in turn, accelerates advances in alternative proteins, increasing consumer choice and reinforcing the shift.

Meat Consumption in the EU



Protein market composition in Sky 2050



A series of changes ensue:

- Consumer demand for plant-based proteins and cultivated meat increases at a rapid rate, as social food norms change away from meat consumption.
- Businesses increase the range and quality of novel alternative proteins by investing in research and development and commercialisation to match taste and price with meat-based products.
- Governments respond to consumer preference changes by funding and favourably regulating cultivated meats and plant-based proteins, while also regulating the agriculture sector so that its effects on the environment are fully reflected in prices.
- As their incomes grow, developing countries use alternative proteins to meet nutritional shortfalls and reduce cross-border food dependence.

A 1% shift in market share from meat to alternative proteins could save around 120 million tonnes of CO_2 equivalent (Mt CO_2e) per year, through reduced livestock numbers, lower fertiliser use for feed crops and increased afforestation. On a cumulative basis, this amounts to 90 gigatonnes of CO_2e by 2050, or about 0.05°C of warming. Signs of a transition are already under way:

- about half of EU consumers have eliminated or reduced meat in their diets;
- plant-based and novel vegan meat replacements are already selling at a premium price;
- alternative proteins already have up to 9% market share in advanced economies, illustrating that sales could grow rapidly; and
- investments in alternative proteins grew tenfold between 2017 and 2021.

Types of alternative proteins

- **Classic vegetarian and vegan meat replacements**, such as tofu, jackfruit, beans and other proteins, are already well established. However, most do not taste like meat, which limits their attractiveness to most consumers.
- **Novel vegan meat replacements** are made from plants but have a taste and texture similar to meat. Existing novel vegan products include Impossible Foods and Beyond Meat.
- **Cultivated meat** is produced using exponential cell growth in bioreactors. Cultivated meat is exactly the same as animal meat, and so has a large commercial potential among today's omnivores.

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We also wish to thank the International Energy Agency (IEA). The modelling is founded on historical data from IEA Extended Energy Balances (2021) (www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics), all rights reserved. The work in these scenarios was prepared by Shell International B.V. and does not necessarily reflect the views of the IEA. We also wish to acknowledge Rystad Energy, whose upstream data cube is an important input for our oil and natural gas supply modelling.

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