Invesco

Global Thought Leadership
The 21st Century Portfolio*

From Invesco's Global Market Strategy Office
November 2019

Data as of 30 September 2019 unless stated otherwise.
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* The 21st Century Portfolio is a theoretical portfolio and is for illustrative purposes only. It does not represent an actual portfolio and is not a recommendation of any investment or trading strategy.

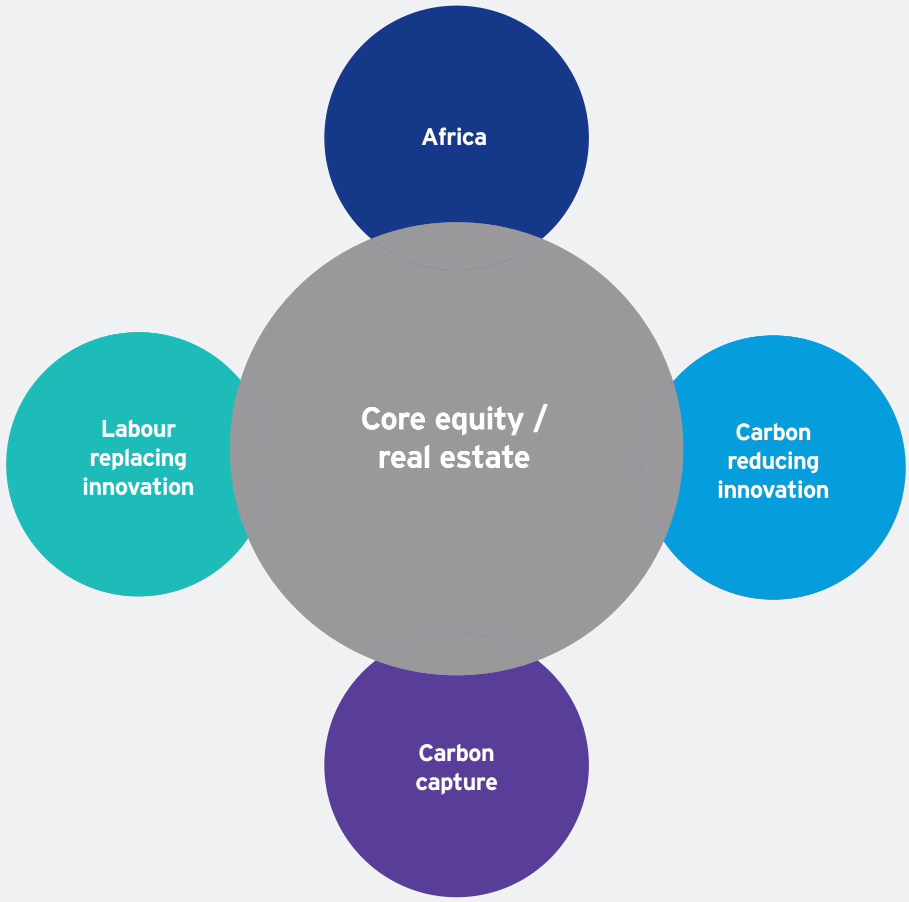
The 21st Century Portfolio*
Investing for the grandchildren

We have lived charmed lives: income, inflation, interest rates and investment returns were boosted by a heady mix of demographics, debt and disregard for the environment. In short, we have been living beyond our means. We believe the future will be different and expect the interaction of four themes to dominate portfolios during the lives of our grandchildren: low interest rates, demographics, climate change and innovation.

Our main conclusions are:

- Low bond yields could encourage growth and innovation but penalise investors
- Decelerating populations and climate change could dampen economic growth
- Innovation will be key to dealing with shrinking populations and limiting climate change
- Businesses and individuals can help mitigate climate change – we suggest how
- Low bond yields and dampened growth estimates to 2100 result in optimisation outcomes that favour equities and real estate
- We favour a core of equity and real estate, with equal country/regional weightings
- And four satellite portfolios focused on the following themes:
  – Africa
  – Carbon reducing innovation
  – Carbon capture
  – Labour replacing innovation

Figure 1 – The 21st Century Portfolio*



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Summary and conclusions: investing for the grandchildren

We rarely get the chance to extend time horizons and thought it would be interesting to consider what should be placed in the pension portfolio of our (yet to be born) grandchildren. This obliges us to imagine what forces will shape the world over the rest of this century and to consider how they will change optimal asset allocations. We focus on four related themes: low bond yields, demographics, climate change and innovation.

Our analysis of historical US data suggests that an investor armed with perfect foresight in 1915 (and a 100-year time horizon) would have been well served to focus on stocks (equities) and perhaps commodities. Optimal allocations at the riskier end of the efficient frontier (built using that historical data) would have been entirely invested in stocks, with commodities and then investment grade-credit (IG) entering as we reduce the desired volatility (note that government bonds would play no role in any of the optimal portfolios, no matter how little risk was desired). We would argue that such a long investment horizon allows us to disregard volatility and therefore focus the portfolio on equities.

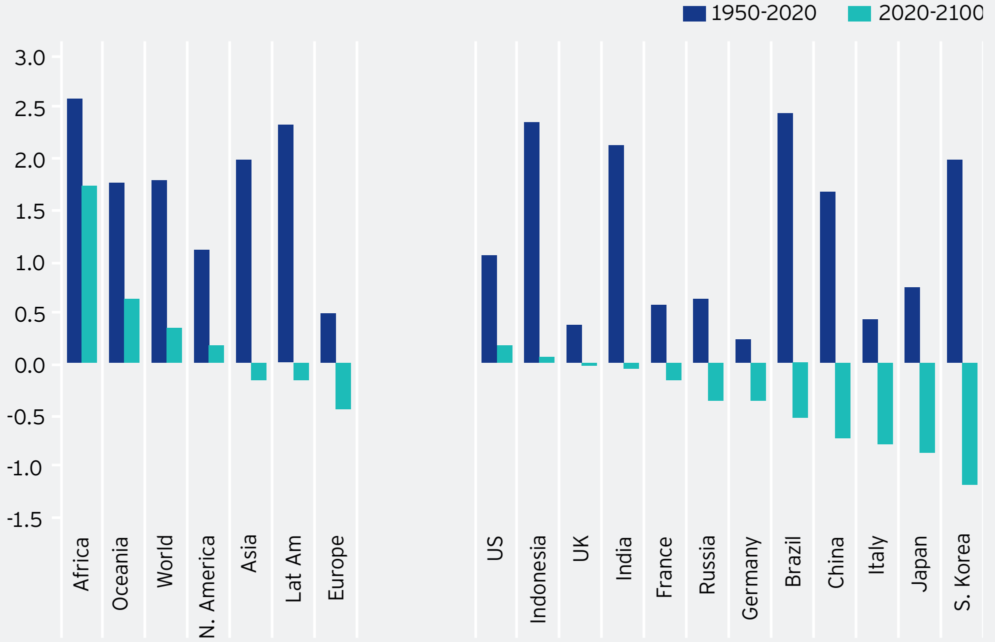
Applying those lessons of history to the future poses two major problems: first, the past is the past and may not be repeated and, second, we do not have perfect foresight. Hence, though we want to learn the lessons of the past and use it as a template, we also need to consider how it may be misleading. This report is not an exercise in trying to predict the next recession or the next disaster but rather one of thinking about the forces that will have an enduring impact on portfolio returns. After all, who in 1915 (during the First World War) being told that there would be another (bigger) world war within 25 years, a Great Depression between those two wars and a Global Financial Crisis (GFC) within 100 years would have bought equities? We have no doubt that similar dramatic events will unfold during the rest of this century but expect life (and markets) to go on.

Indeed, the first of our themes suggests that some assets are currently priced for disaster. **Bond yields are extremely low**, with ultra-long long government bond yields close to zero in real terms in many countries (100-year maturities do exist). We believe they are so low for two reasons: first, that savings have exceeded investment spending in the developed world since the GFC and, second, that developed world central banks have depressed yields by reducing policy rates and buying large quantities of government debt.

This is a double-edged sword: low yields could eventually encourage investment spending and boost economic growth (a lot of investment is needed to mitigate and adapt to climate change) but those buying government bonds seem to be condemned to low investment returns. Even worse, demographics suggest the pressure on government finances is likely to increase, thereby increasing the risk of default. We believe the prospective long-term return on other assets is more attractive. When it comes to equities, our analysis suggests that global equity returns have been enhanced by weighting countries equally, rather than by market capitalisation (though with higher volatility). Among ultra-long government bonds, we believe that Mexico's 2114 sterling bond is an interesting example, given a yield above 5% (in a Brexit battered currency).

The second of our themes is **demographics**, both population deceleration and ageing. The post-war period witnessed a global demographic explosion, the like of which has not been seen before (to our knowledge). The upshot, we believe, was a period of strong economic growth and high inflation. The problem is that we are now on the other side of that explosion: if United Nations (UN) forecasts are to be believed, the 1.8% annualised growth in the world's population in the fifty years to 2000 will become 0.2% in the second of this century (taking the population to 10.9 billion in 2100). Our analysis suggests this deceleration will be enough to reduce global GDP growth by 1.0%-1.5% over the rest of this century versus what was seen in the 1950-2000 period. Given that world GDP growth has been an annualised 3.5% since 1960, that represents quite some deficit. Of course, this assumes no change in productivity growth, a topic covered in the section on innovation. In fact, the problem is even worse because ageing suggests an even greater deceleration in working age populations and a greater financial burden on those who do work (as dependency ratios rise).

Figure 2 – Working age population growth past and future (% annualised)



Note: working age is 20-64. Data based on United Nations estimates and medium variant projections. Latin America ("Lat Am") includes Caribbean countries. Regions and countries are ordered by 2020-2100 projections. Source: United Nations and Invesco.

Figure 2 shows that nowhere is immune to deceleration, and Africa is the only part of the world where future working age population growth will resemble that of the world since 1950. Indeed, UN estimates suggest that Africa will account for more than 40% of the world's working age population by 2100 (from 14% in 2020). Not only does Africa have the potential to become the world's bread basket it could also be its factory. Given the population shrinkage expected in other parts of the world, a choice will have to be made: either capital moves to where the workers are (Africa) or the workers will come to where the capital is. We believe Africa will be the investment story of the 21st century.

Unfortunately, other countries and regions will suffer declines in their populations (see **Figure 2**). In South Korea, for example, the working age population is expected to decline from 34m in 2020 to 13m in 2100, with big declines also expected in Japan (69m to 35m), Italy (36m to 19m) and China (930m to 528m). If those forecasts prove to be anywhere near correct, such countries will have to rely heavily on labour-replacing technology and could well be in the forefront of such innovations (necessity being the mother of all invention). Also, such population shrinkage is likely to depress local housing markets, as well as putting government finances under strain (legacy debt will be serviced by less workers). On that basis, we would avoid assets linked to government finance and housing markets in those countries.

Four to five degrees of warming are possible, even with less population growth

However, there is a silver lining: less population growth means less **climate change**. We think this could be the defining theme of the 21st century, given its potential impact and given its dependence on population growth and technology. The bad news is that a lot of climate change is already baked-in as a result of human activity since the industrial revolution. Using global average temperature in the 1850-1900 period as a baseline, there has already been an increase of 0.8 degrees Celsius. Our model (based on historical CO_2 concentrations), suggests the gain will be 1.14 degrees by 2050 (or rather in the 20 years to 2050), 2.58 degrees by 2100 and 3.54 degrees to 2118. And that doesn't allow for emissions that take place in the meantime. Such temperature changes could result in the sea level rising by 0.5m, an additional 250,000 deaths per year linked to climate change, increased migration flows (200m live in coastal regions at risk of flooding; 250m-550m could experience hunger due to failed crops and the numbers at risk of water shortages could run into billions). The permanent loss of global GDP could be in the 3%-10% range and the welfare cost could be the equivalent of a 20% loss in consumption per head in the worst cases.

The good news is that we can still act to limit the damage. Our analysis suggests that global GDP growth will slow from an annualised 3.5% since 1960 to 2.4% to 2100, simply because there will be less population growth. That helps reduce the growth of emissions but not by enough (the temperature gain will be a ceteris paribus four to five degrees, we think).

Technological innovation will also help by reducing the CO_2 intensity of economic activity. Carbon intensity is trending down over time but is highest in the middle-income countries that have recently industrialised (and that are growing the most rapidly). Assuming an acceleration in the move to carbon efficiency helps to reduce the final temperature gain but even under very aggressive assumptions the temperature gain would still be three to four degrees. Low financing costs could encourage the necessary investment to bring about those innovations (some of which we discuss in the chapter on climate change) but we think it will also require government actions such as mandating the ending of the sale of internal combustion engine autos, the use of green taxes and limiting the supply of carbon permits. Though a lot of innovation will be aimed at labour-saving technology, we expect carbon-reducing technology to become just as, if not more, important over the coming decades.

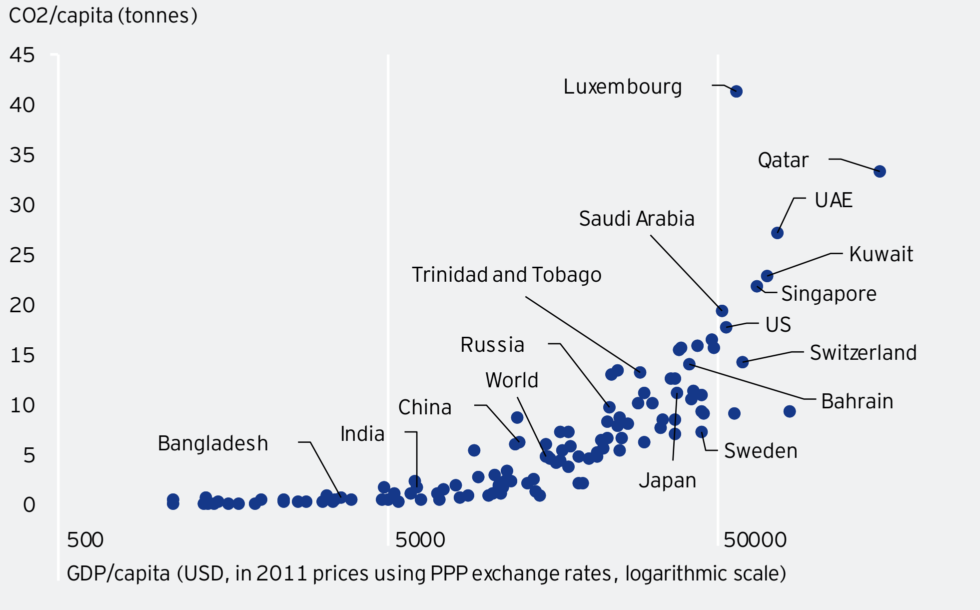
If we are unable to reduce carbon intensity rapidly enough, there are two other solutions available: lifestyle change (suppress growth) or carbon capture. One way to limit the temperature change to two-three degrees, would be to limit GDP per capita growth (**Figure 3** shows the link between income per head and CO2 emissions). Our models suggest that limiting global GDP growth to 1.7% (annualised to 2100) would have the desired effect but that would be around half the growth rate seen since 1960. To get an idea of the sort of lifestyle changes involved, this would allow each citizen of the world to be responsible for two tonnes of CO2 emissions per year, which sounds a lot until it is considered that it takes two to three tonnes of CO2 per year just to feed the average westerner (1.5 tonnes for a vegan). That leaves nothing for all the other things we do with our lives (consumption based per capita emissions in 2016 were 8.5 tonnes in the UK and 17.8 tonnes in the US).

The good news is that trees can help! It has recently been calculated that 0.9bn hectares of land are available for tree planting (an area almost as large as the US). We reckon that if that capacity were used, we could avoid dramatic lifestyle changes while still limiting the temperature gain to two to three degrees. But that is a lot of trees (900 billion), so there is no time to waste. We reckon the cost would be $900bn in today's prices, which sounds a lot but would only be $60bn per year if done by 2035. This is 0.07% of 2018 global GDP, which is small compared to the 0.7% per year extra growth that it would allow while limiting the temperature gain to three degrees.

So, climate change brings risks (changed lifestyles, economic loss, physical and human damage, loss to insurers etc.) but it also brings opportunities for those companies that can help with: infrastructure projects, building design (to avoid heating and air conditioning), innovation (battery technology, electric planes, magnetic cooling systems, CO2 extractors, drones to manage forests etc.), forestry management etc.

We can make a difference in our personal and work lives (see **Figure 41** and **Appendix 1**). Flying less, increasing the lifecycle of durables and planting trees are a good start.

Figure 3 – Consumption CO2 emissions per capita versus GDP per capita in 2016



Notes: CO2 emissions are based on consumption in the country. Source: Peters et al (2012 updated), Global Carbon Project (2018), Our World in Data, United Nations, World Bank Development Indicators and Invesco

As should already be clear, **innovation** will be of critical importance, both to replace labour in countries with shrinking populations and to reduce or capture carbon emissions. However, there are many fears about technology and its potential to replace humans, thereby leaving large parts of society without employment. The recent flattening of incomes and increase in inequality add to those fears.

This has been a recurring concern over many centuries and we suspect the current "fourth industrial revolution" is reminiscent of the first. Now, as then, despite all the new technology, there has been a noticeable deceleration in productivity. Our analysis of that first industrial revolution is that technological innovation at first benefited the owners of capital (see the rise in the profit share of GDP over recent decades), while workers gained very little. This was the labour-replacing phase of the new technology. However, after multiple decades, the workers learned the skills necessary to properly leverage the technology and the subsequent productivity gains also benefited the labour force (the labour-enhancing phase). We suspect we are still in the labour replacing phase of computers and artificial intelligence (AI) and that it may take decades until the full potential is realised to the benefit of capital and labour alike. We are not aware of innovation having caused mass unemployment in the past and doubt that it will now. However, different skill-brackets will feel the consequences differently. Rather than being concerned about innovation, we look forward to the help it can bring and we believe climate change related innovation will be a big investment theme.

So, what does the **21st Century Portfolio*** look like? Allowing for current low bond yields and lower expected economic growth rates causes us to reduce our return expectations versus what has been delivered in the past. Optimal portfolios based on those projections to 2100 suggest we should still have a portfolio that is dominated by equities and real estate (we introduce the latter in an analysis of global asset groups). The 21st Century Portfolio* consists of a core equity and real estate component, with four thematic satellite portfolios:

A core portfolio with thematic satellites

- **Core equity/real estate**: designed to give exposure to what growth is available (fixed income assets are of little interest given the ultra-low yields). Country/regional markets should be equally weighted (why would you want exposure to yesterday's winners?). Minimise exposure to coastal real estate and also to housing markets in shrinking population countries such as China, Italy, Japan, Russia and South Korea. Boost exposure to labour saving technology in those same countries.
- **Africa**: the dark continent will be the story of the century (in our opinion). Gaining exposure is not easy but we think it will become increasingly so. Exposure can be in the form of fixed income assets (yields are higher than in the developed world) but would preferably be in equities and real estate. We suspect an increasing number of Africa infrastructure investment vehicles will appear. Exposure may need to come via venture capital and private equity.
- **Carbon reducing innovation**: much of the technical innovation over the coming decades will be aimed at reducing the emission of CO_2 and other GHG's. There are a multitude of companies working in areas such as battery technology, renewable energy, electric autos and planes, AC technology etc. We give examples in the report, many of which are small and privately owned. Hence, this may need to be sub-contracted to venture capitalists and private equity specialists. The purchase of carbon certificates could also be a way to capture the assumed increase in the price of carbon but needs active management.
- **Carbon capture**: an important part of enabling the world to grow while not overheating will be schemes to capture emitted CO_2. The obvious way is to invest in land that can be reforested and/or to buy ESG responsible forestry companies. The report also gives examples of companies that are developing scrubbers etc as well as one company that uses drones to plant trees.
- **Labour-replacing innovation**: if we are correct in believing that we are still in the labour-replacing phase of the fourth industrial revolution, it is the owners of innovating companies that stand to gain. We suspect this will be the case for several decades. The pool of quoted companies in this area is much bigger than for carbon reducers but some early stage investment expertise may also be useful.

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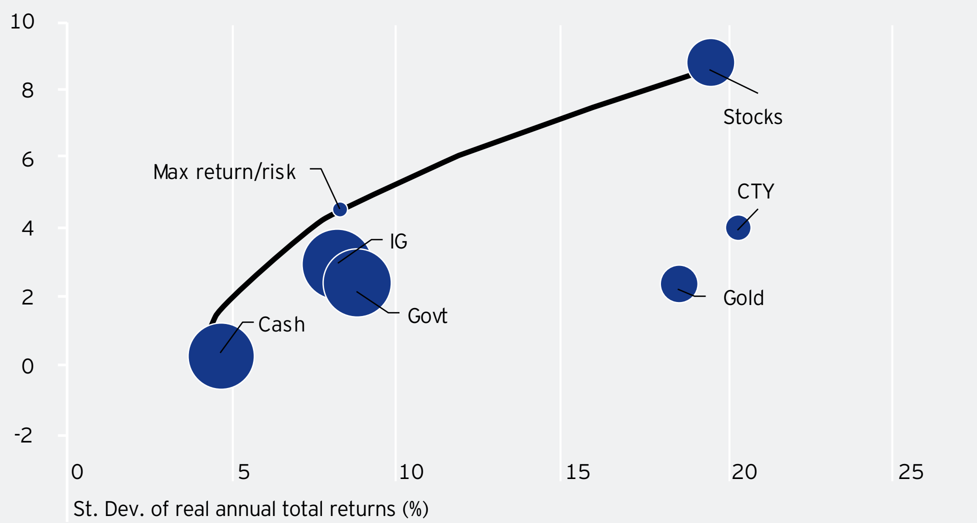
Four key themes for the 21st century

Thinking about the future of our children and grandchildren forces us to lengthen time horizons. Those born in 2020 will be 80 at the end of the century and will have lived through changes that we can only begin to imagine. How could we help them prepare for their retirement years?

One answer could be to rely on the past as a guide to the future. **Figure 4** shows that from 1915 to 2018, the best performing US asset was stocks (equities). However, stocks are more volatile than fixed income alternatives, which is why investors expect a risk-premium (commodities and gold were as volatile as stocks but didn't offer much of a risk-premium versus government debt). Given our multi-decade time-horizon, the answer seems obvious: invest in stocks (based on a shorter data set, we suspect that real estate has a similar profile, so we would consider adding real estate to the portfolio).

Figure 4 – US annual total returns 1915-2018 and efficient frontier (CPI adjusted)

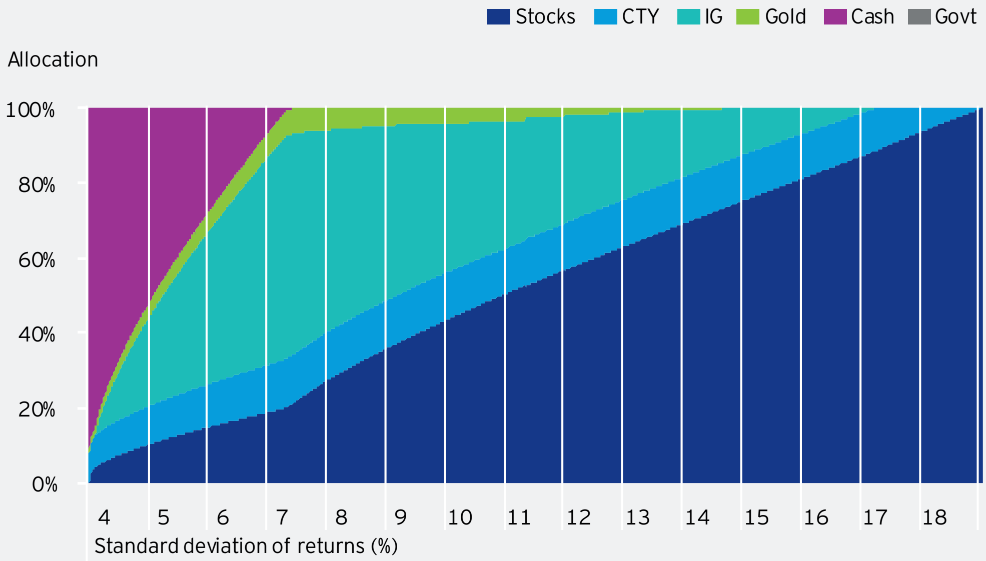


Note: Based on calendar year data from 1915 to 2018. Area of bubbles is in proportion to average correlation with other assets. Calculated using: spot price of gold, Global Financial Data (GFD) US Treasury Bill total return index for cash, our own calculation of government bond total returns (Govt) using 10-year treasury yield, GFD US AAA Corporate Bond total return index (IG), Reuters CRB total return index until November 1969 and then the S&P GSCI total return index for commodities (CTY) and Robert Shiller's US equity index and dividend data for stocks. Indices are deflated by US consumer prices. "Max return/risk" is the point on the efficient frontier that gives the highest ratio of return to standard deviation of returns. Past performance is no guarantee of future results.
Source: Refinitiv Datastream, Global Financial Data, Reuters CRB, S&P GSCI, Robert Shiller, Invesco

However, even when looking out over many decades, it may feel uncomfortable to put all the grandchildren's eggs into one basket. Based on 1915-2018 data, **Figure 5** shows how optimal allocations vary with risk appetite (note the absence of government debt).

History may rhyme but as Mark Twain is often reported to have said it doesn't repeat itself. Hence, though historical returns tell us what happened in the past, we need to be aware of how the future may be different.

Figure 5 - Optimal allocations along the efficient frontier for US assets (1915-2018)

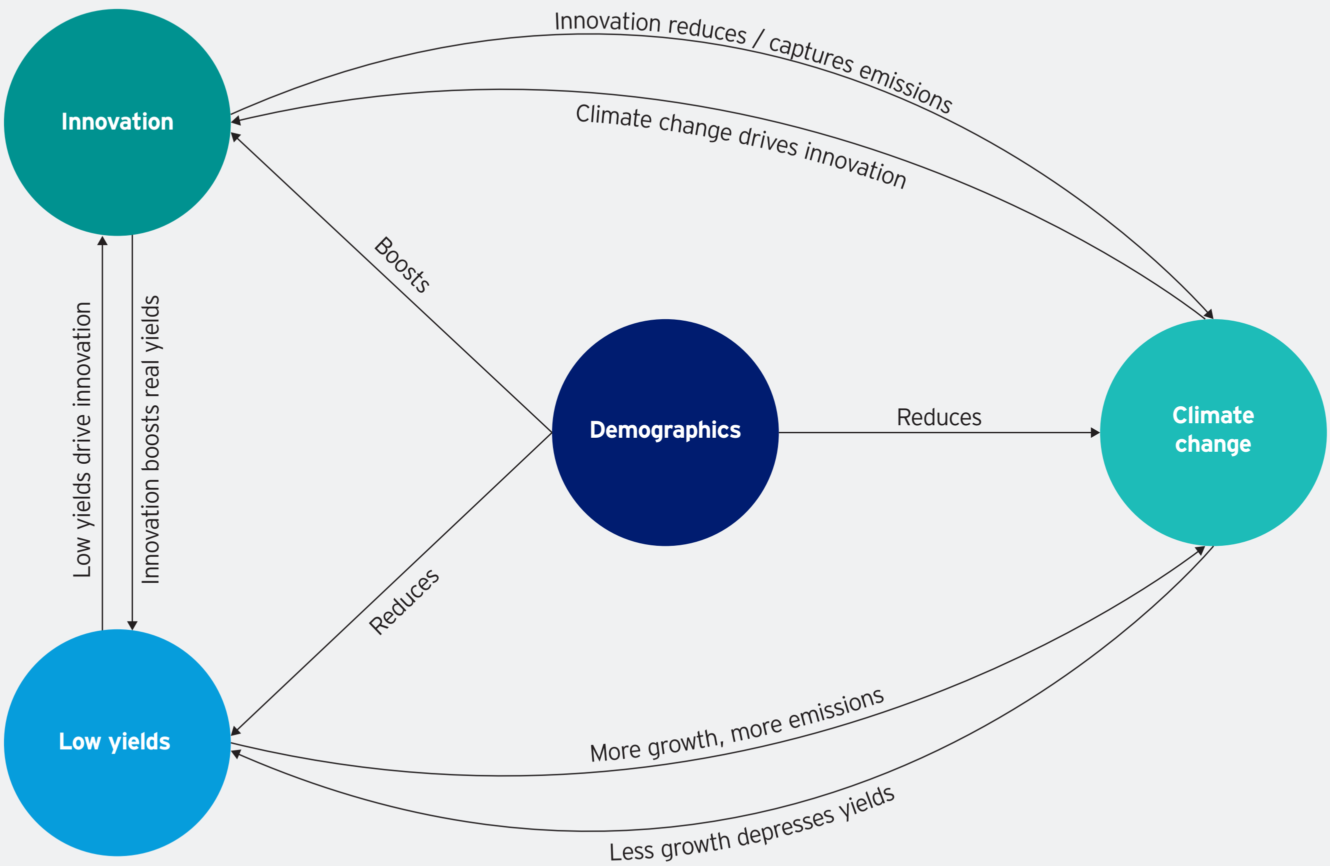


For each level of risk (standard deviation of returns), the chart shows the allocation of assets that would maximise returns and therefore be on the efficient frontier (based on calendar year returns 1915-2018 inclusive). Past performance is no guarantee of future results. Source: Global Financial Data, Robert Shiller, Reuters CRB, S&P GSCI, Refinitiv Datastream and Invesco (see detailed notes to Figure 4).

The period since 1915 has been extraordinary in many ways: there were two world wars, many diseases were vanquished, the global population exploded, computers were invented and man landed on the moon, to name but a few.

Looking ahead, we identify four themes that we believe have the potential to change the global economic and financial market outlook over the rest of this century: historically low bond yields; demographic deceleration; climate change and technological innovation. The interlinkages are obvious and shall be explored throughout the analysis.

Figure 6 - Four interlinked themes for the 21st Century



Source: Invesco

Theme 1: Low yields - boon or bane?

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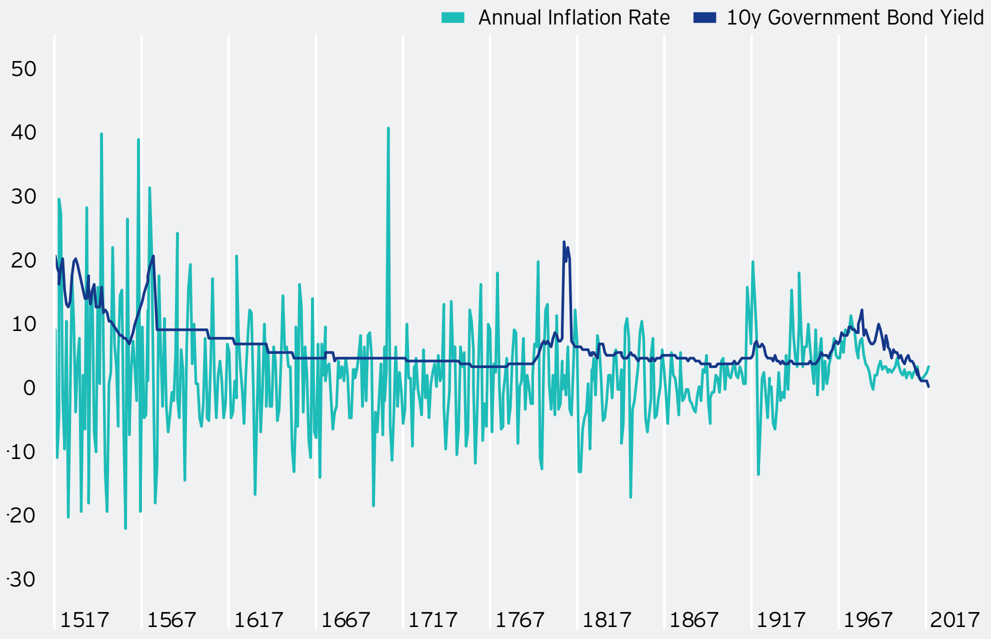
We live in extraordinary times. Bond yields have never been as low as they are now.

Figure 7 - Dutch inflation and bond yield since 1517 (%)



Data is annual, with 2019 data as of 30 September 2019. Past performance is no guarantee of future results.
Source: Global Financial Data, Refinitiv Datastream and Invesco

Figure 7 shows that Dutch 10-year yields are lower than at any time during the last 500 years, despite the lack of deflation (which has been common over that time frame). Some $14.8 trillion worth of debt now offers a negative yield, around one-quarter of outstanding global debt (on 30 September 2019, according to Bloomberg Barclays indices).

Whether this is good or bad depends upon whether you are a creditor or a debtor. The ability to source funds so cheaply should be a boon for those seeking to finance capital expenditure, be they households, companies or governments. A world confronted by decelerating/ageing populations and dealing with climate change will need lots of investment and technological innovation. Low financing costs should render profitable an increasing number of projects, especially since market based real 10-year government bonds yields are 0.1% in the US, -1.4% in the eurozone and -3.0% in the UK (as of 30 September 2019).

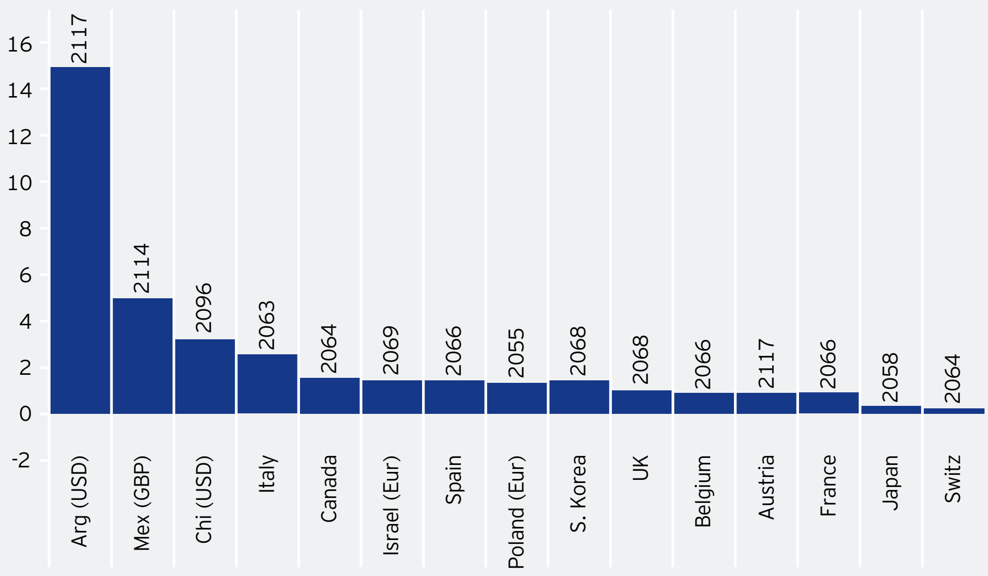
Figure 8 shows a selection of the longest maturity bonds that we could find. Few are the countries that have yields high enough to discourage reasonable investment projects, in our opinion. If anything, such low nominal yields, in a world economy growing by around 6% per year (nominal GDP), should encourage long-term investment projects. On the other hand, those seeking to invest in financial instruments would normally be discouraged by such paltry yields. It requires a dark view of the future, in our opinion, to believe that better returns cannot be earned on other assets (equities and real estate, for example).

$14.8tn

of debt now offers a negative yield

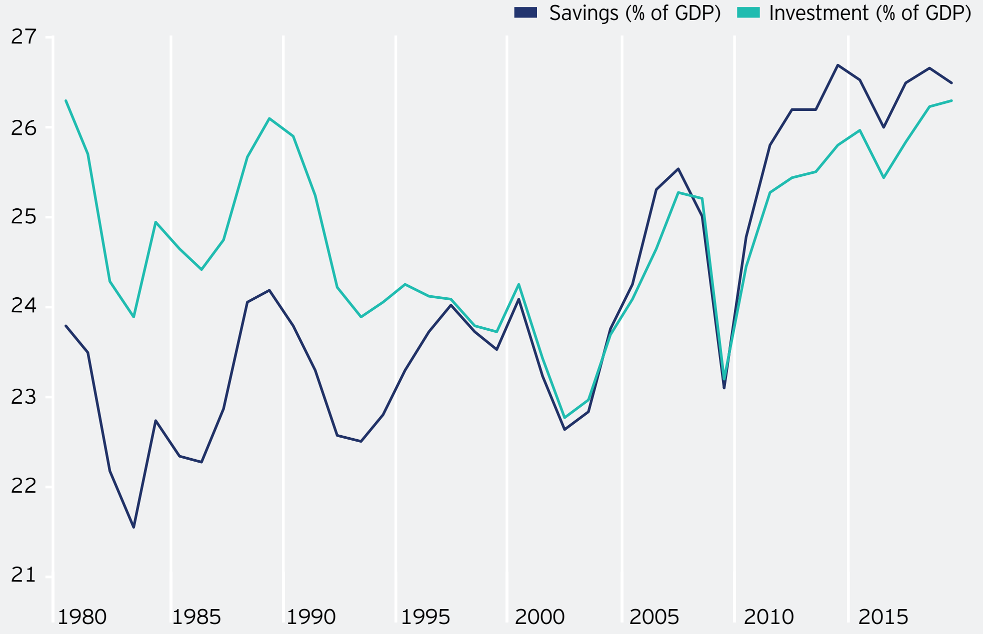
Ultra low yields reflect excess saving and central bank debt purchases, both in the developed world

Figure 8 - Ultra-long government bond yields (%)



Local currency yields (unless stated otherwise). Labels show the year of maturity. "Arg" = Argentina; "Mex" = Mexico; "Chi" = China; "Switz" = Switzerland. As of 11 October 2019. Source: Bloomberg and Invesco

Figure 9 - World savings and investment (% of GDP)



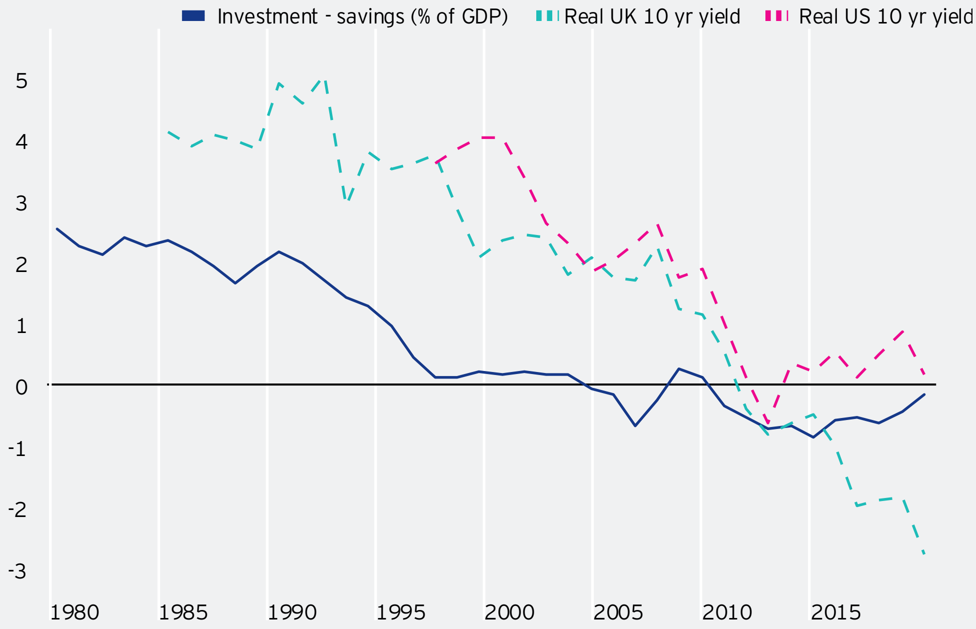
Note: annual data from 1980 to 2019 (based on IMF data and forecast for 2019).
Source: IMF, Refinitiv Datastream and Invesco

Why are yields so low? **Figure 9** suggests the problem is not a lack of investment spending: the world investment/GDP ratio is currently as high as it has been since the IMF data series started in 1980. Rather, it is that savings have risen even more rapidly. During the 1980s and 1990s there seemed to be a lack of savings (investment was consistently higher than savings). Then in the early part of this century, the two were roughly in balance. However, since the Global Financial Crisis (GFC), there appears to have been a surplus of savings.

It may seem odd that world savings and investment are not always equal. Though an individual country can have a mismatch, with a corresponding balance of payments imbalance, that should not be possible across all countries. However, apart from mismeasurement problems, it is possible to have periods of disequilibrium and interest rates can be thought of as one of the balancing factors that should eventually return the world to equilibrium.

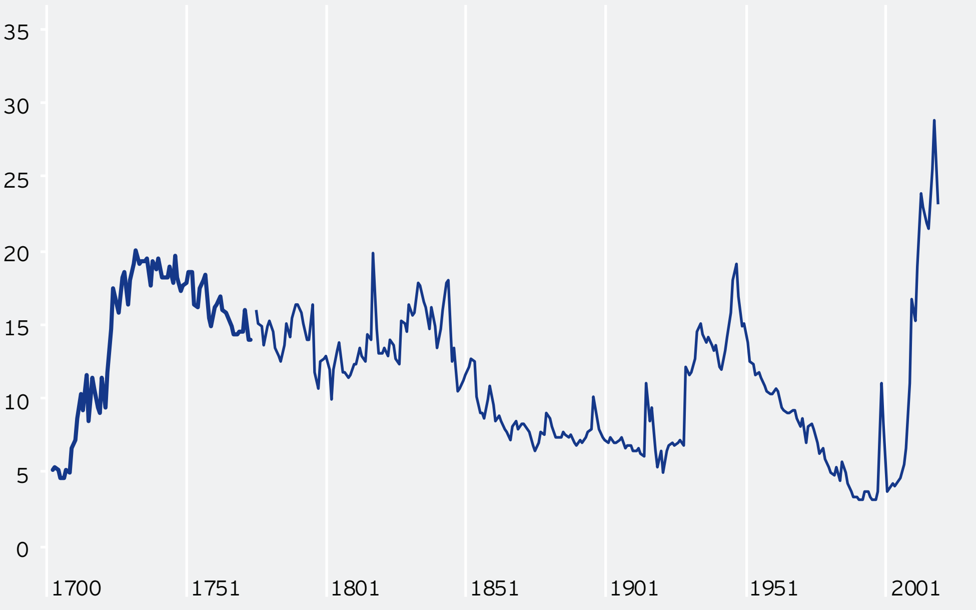
Figure 10 shows that this may indeed have been the case over recent decades. The lack of savings (relative to investment) in the 1980s and 1990s could explain why real bond yields were so high at that time – real UK 10-year yields reached 5% in 1992, well above what any reasonable estimate of growth might have been at that time. In theory, those high real financing costs should have discouraged investment spending while encouraging savings. Indeed, savings trended upward and investment trended lower (both as a share of GDP) and the gap between them had disappeared by the late 1990s.

Figure 10 – Global investment minus savings and real bond yields (%)



Note: Annual data from 1980 to 2019. Savings and investment data is from the IMF (2019 is IMF forecast). Real bond yields are market-based measures taken from inflation protected government bonds, showing the longest available data (2019 is as of 30 September 2019). Source: IMF, Refinitiv Datastream and Invesco

Figure 11 – Bank of England balance sheet 1701-2019 (% of GDP)



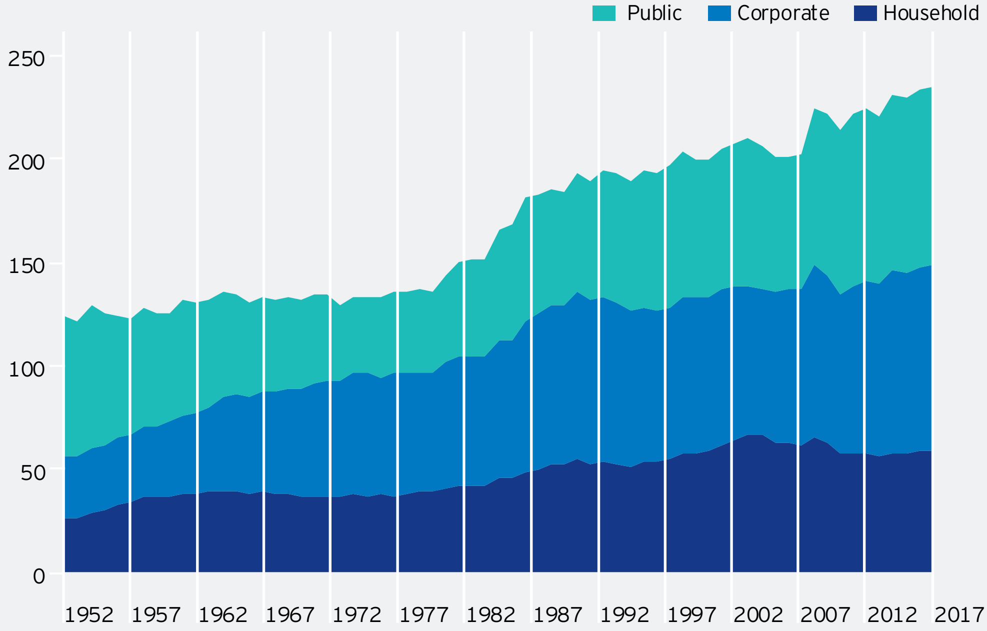
Note: annual data (2019 ratio based on BOE balance sheet as of end-March 2019 and GDP in the four quarters to 2019 Q1). Source: Bank of England, UK Office for National Statistics, Hills, Thomas & Dimsdale, Refinitiv Datastream and Invesco

The rough equilibrium between investment and savings in the early part of this century allowed real bond yields to stabilise but then two things happened that we think contributed to the decline in real yields towards current levels: first, savings started to exceed investment (and the gap widened after the GFC); second, central bank asset purchase programmes added to the demand for government bonds (**Figure 11** puts the Bank of England's recent balance sheet expansion into a historical perspective).

That savings remain so high in the presence of such low yields may be due to a lingering sense of caution after the GFC. It is commonly thought that rising levels of debt contributed to the financial crisis and it is possible that elevated savings ratios are part of a deleveraging process.

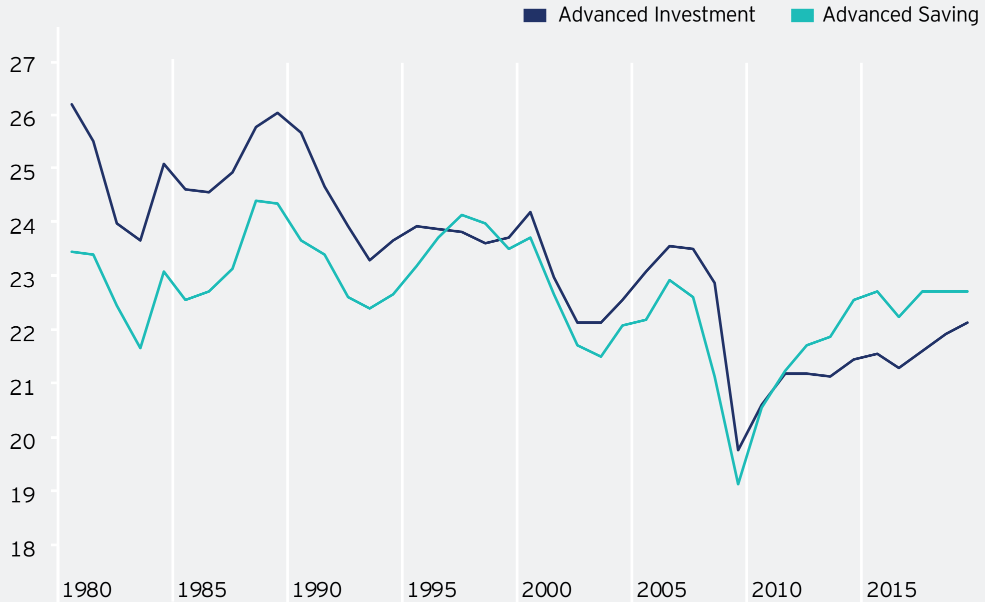
Figure 12 shows there was a near constant rise in the global debt-to-GDP ratio during the post-war era, with a notable acceleration since the late-1970s. The debt ratio has trended upward since the GFC but household debt-to-GDP would appear to have peaked before then. **Figure 12** uses market exchange rates but when using PPP exchange rates, BIS data suggests total global debt has stabilised in the last two years.

Figure 12 - Global non-financial sector debt (% of GDP)



Note: Based on annual data for the 25 largest economies in the world (as of 2018). Data was not available for all 25 countries over the full period considered. Starting with only the US in 1952, the data set was based on a successively larger number of countries until in 2007 all 25 were included in all categories. The data for all countries is converted into US dollars using market exchange rates. Unfortunately, debt is a stock measured at the end of each calendar year, whereas GDP is a flow measured during the year so that when the dollar trends in one direction it can distort the comparison between debt and GDP. To minimise this problem, we use a smoothed measure of debt which takes the average over two years (for example, debt for 2018 is the average of debt at end-2017 and at end-2018).
Source: BIS, IMF, OECD, Oxford Economics, Refinitiv Datastream and Invesco

Figure 13 - Advanced world saving and investment (% GDP)



Note: annual data from 1980 to 2019 (based on IMF data and forecast for 2019).
Source: IMF, Refinitiv Datastream and Invesco

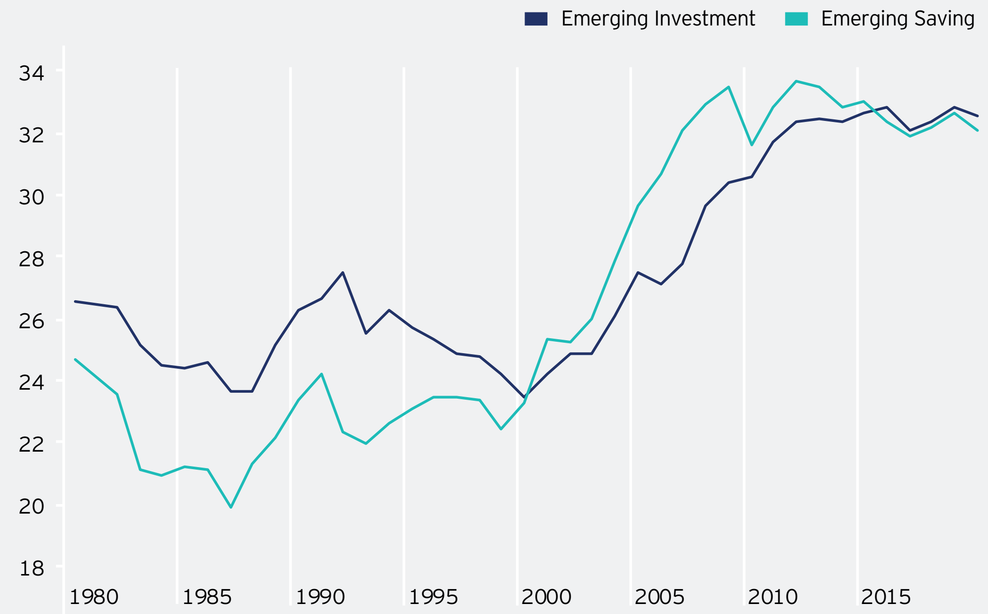
A comparison of **Figures 13 and 14** reveals a stark contrast between advanced and emerging economies: investment spending in the advanced world has been trending lower for several decades (though with recovery since the GFC) and there is an excess of savings over investment. On the other hand, both savings and investment increased markedly in the emerging world in the early part of this century (we suspect due to China) and savings and investment have levelled out since the GFC and are now roughly in balance.

The developed world has a particular problem: weak investment and excess savings, despite extremely low interest rates and bond yields. It is then worth remembering that it is the developed world that has the biggest debt problems (see Global debt review 2019 published in July 2019) and the central banks that have employed quantitative easing. It is therefore in the developed world where we would expect the biggest efforts to encourage investment and discourage savings over the coming years and decades, which may suggest bond yields will remain abnormally low for a long time. In our view, fiscal policy will have to play a much bigger role, as central banks seem to have reached the limit of their powers.

In theory, if governments can reignite economies and boost confidence, low financing costs could pave the way to a strong gain in investment spending in the developed world. Few are the countries that would not benefit from a sustained rise in infrastructure spending. Climate change mitigation and adaption are obvious areas where spending will be needed and it can be financed cheaply (of which, more later).

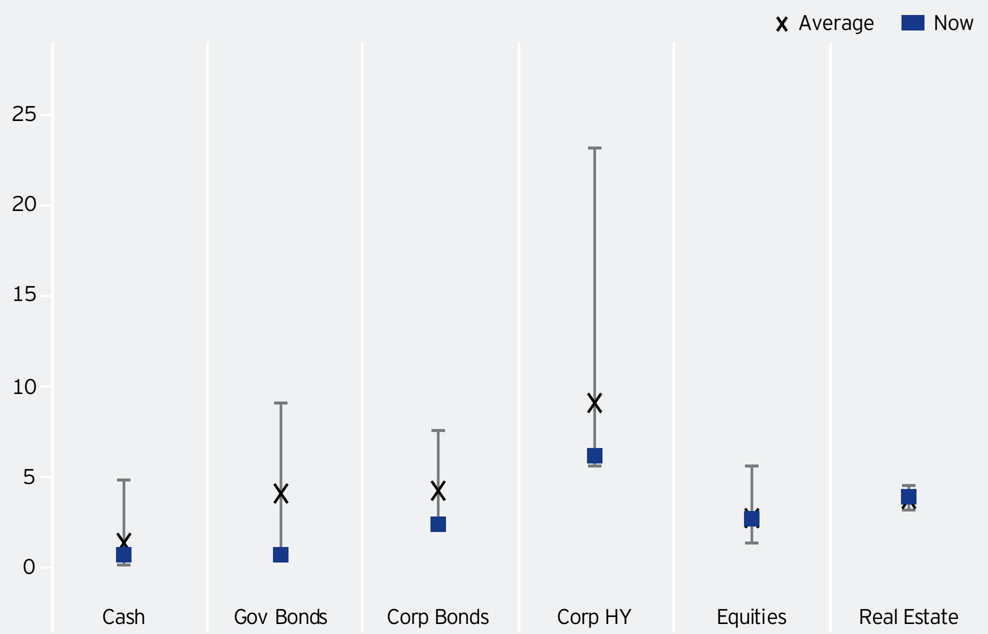
Low rates are here to stay and could help with climate change

Figure 14 – Emerging world saving and investment (% of GDP)



Note: annual data from 1980 to 2019 (based on IMF data and forecast for 2019).
Source: IMF, Refinitiv Datastream and Invesco

Figure 15 – Global asset yields within historical ranges (%)



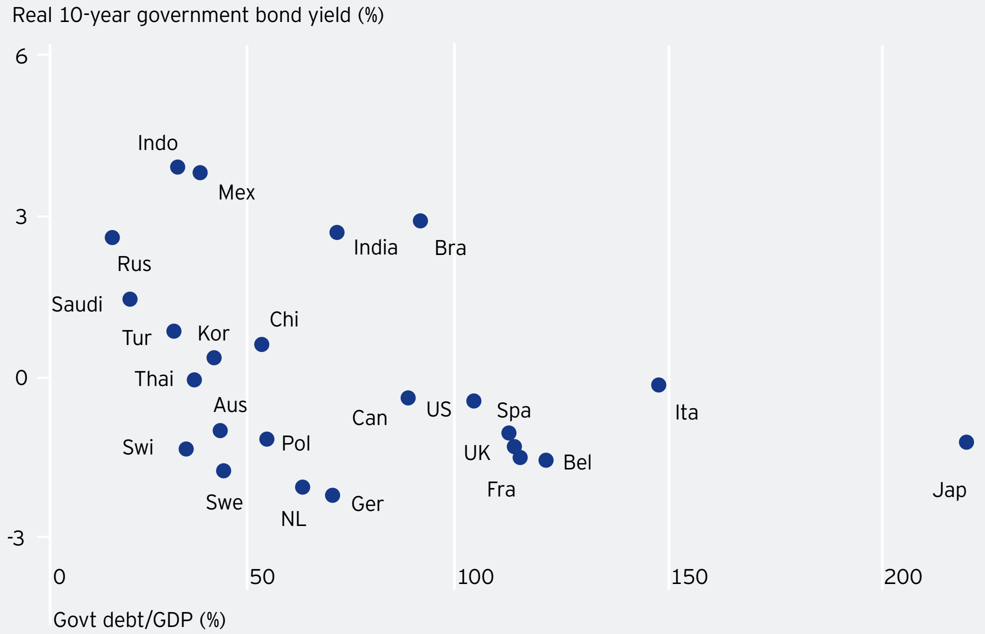
Start dates are: cash 1/1/01; govt bonds 31/12/85; corp bonds 31/12/96; corp HY 31/12/97; equities 1/1/73; REITs 18/2/05. See appendices for definitions, methodology and disclaimers. As of 30 September 2019.
Source: Datastream and Invesco

Much as low interest rates are a boon to governments, companies and households looking to finance spending projects, they are a bane to investors looking to generate investment returns. A 100-year bond with a yield of 1% will, by definition, offer an annualised nominal return of 1% if held to maturity (assuming no default). That does not seem very encouraging, especially if there is inflation.

Luckily, other assets can offer better yields (see **Figure 15**). Equity and real estate yields do not appear unusual, compared to their historical norms. We believe this is a strong argument for sticking with such assets, as suggested by the historical returns shown in **Figure 4**.

Further, within fixed income assets, we think there are better alternatives than developed world government debt. First, higher yields (and we believe higher returns) are available on investment-grade (IG) and high-yield (HY) corporate debt (see **Figure 15**). Also, within sovereign debt markets, the real yield available on emerging country debt tends to be higher (and government debt lower) than in the developed world (see **Figure 16**). As stated at the outset, we would expect higher returns to be associated with higher volatility but over the sort of multi-generational time-frame that we are talking about, we are not so concerned about volatility and would simply go with the higher projected returns.

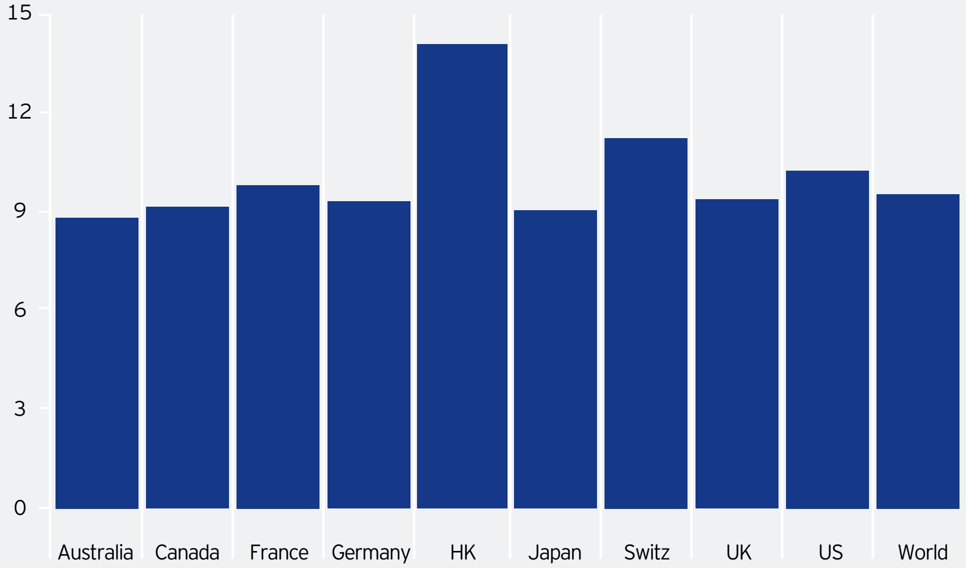
Figure 16 – Real yields and government debt



Note: The countries shown are the 25 largest in the world by GDP, as of 2018 (excluding Argentina). Real bond yield uses IMF forecasts of CPI inflation to 2024 (nominal bond yields were as of 30 October 2019). Govt debt/GDP is as of 2018. See appendix for guide to country name abbreviations.
Source: BIS, IMF, OECD, Oxford Economics, Bloomberg, Refinitiv Datastream and Invesco

We do not have equity indices for many non-US markets since 1915 but **Figure 17** shows a comparison of annualised total returns across countries since 1969. What is striking is the similarity of returns, especially when it comes to major markets. Hong Kong is the stand-out but how many people in 1969 (when Mao was still in power) foresaw how things would turn out in China? This then begs the question as to whether international diversification pays off over the long term?

Figure 17 – Annualised total equity returns since December 1969 (%)



Based on monthly data from 31 December 1969 to 30 September 2019, using MSCI total return indices in US dollars. Past performance is no guarantee of future results. Source: MSCI, Refinitiv Datastream and Invesco

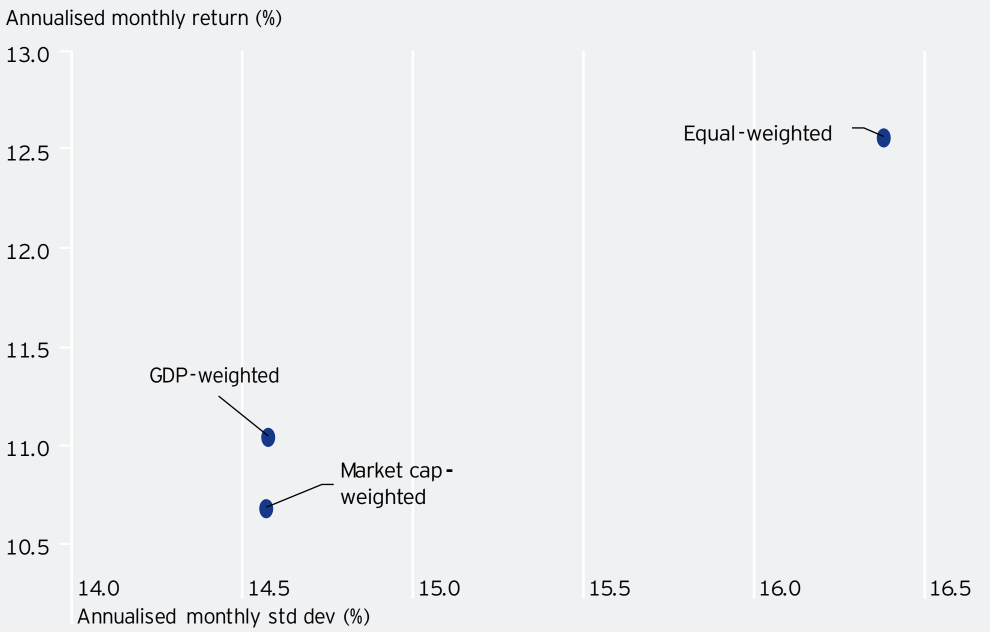
Why lock the grandchildren into the world as it exists today?

However, and as the disclaimer says, the past may not be a guide to the future. It may not be prudent to put all the grandchildren's eggs into one national basket, given the difficulty of foreseeing events over the next 80 years. Our default option would therefore be to invest in a broad version of World equity indices (to include emerging and frontier markets).

Simply buying a capitalisation weighted version of global indices may be the easy thing to do but it may not make sense given the timescales involved (why lock the grandchildren into the world as it exists today, with a built-in bias to the US equity market?). A more balanced approach would be to equally-weight a range of countries (or to GDP-weight them). Historically, this would have produced better returns than a simple capitalisation-weighted index, though with more volatility, which we are willing to tolerate for such a portfolio (see **Figure 18**). Though equal-weighting has produced better results over the full period shown, it has not done so since the GFC.

An equally-weighted country allocation approach has tended to outperform classic market capitalisation-weighted schemes

Figure 18 – MSCI World risk and reward since December 1969 (%)



Based on monthly data from 31 December 1969 to 30 September 2019, using MSCI total return indices in US dollars. "Market cap weighted" is the standard MSCI World Index. "GDP-weighted" is provided by MSCI, with countries weighted by GDP rather than by market capitalisation. "Equal weighted" is our recalculation of the World Index, with countries weighted equally (and reweighted each month). Past performance is no guarantee of future results. Source: MSCI, Refinitiv Datastream and Invesco

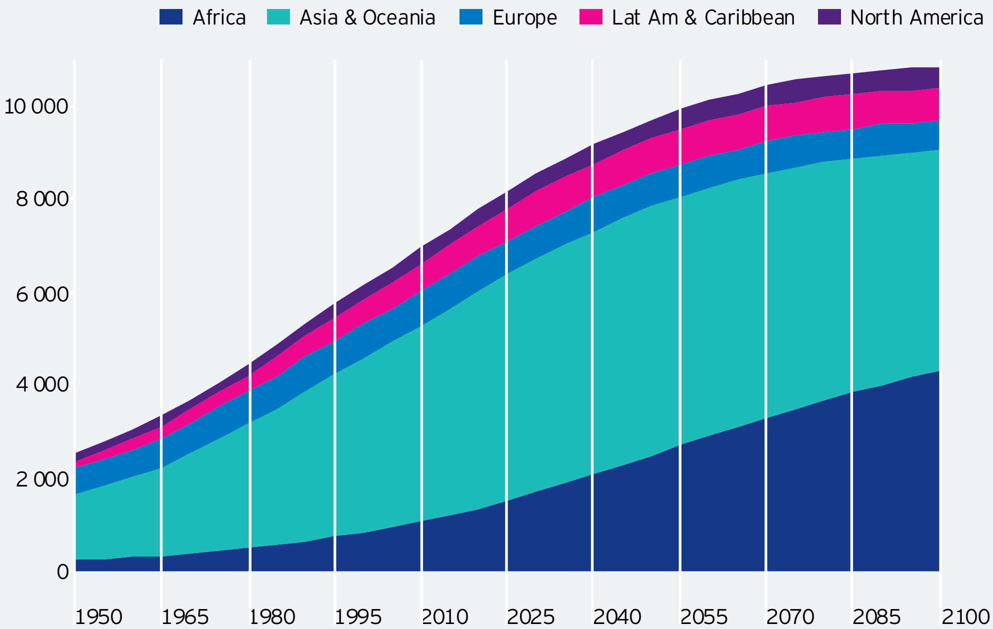
Theme 2: Demographics – help or hindrance?

Theme 2: Demographics – help or hindrance?

The underlying presumption of this document is that somebody born in 2020 will live to the end of the century. In the immediate aftermath of WW2, this sort of lifespan would have seemed optimistic: the UN estimates that life expectancy for somebody born in 1950-55 was 47 years (65 years in high-income countries). However, the UN estimate of life expectancy for those born in 2020-2025 is 73 years, with a range from 54 in the Central African Republic to 85 in Hong Kong (81 in high-income countries).

Apart from living longer, there are now many more of us: the world's population has more than tripled from 2.5 billion in 1950 to an expected 7.8bn in 2020 (UN estimates). This has been both good and bad: on the good side, it has promoted exceptional economic growth but the downside is the extreme pressure it has placed upon the world's resources, including Earth's ability to absorb the by-products of our labours (one of the results being climate change).

Figure 19 – World population by region (million)



Using UN estimates and medium variant projections, from 1950 to 2100.
Source: United Nations and Invesco

Figure 19 suggests that world population growth has already started to ease and that by the end of the century it will have virtually flattened out. Having reached 10.2 billion in 2060, the UN reckons the world's population will be 10.9 billion in 2100, which makes an interesting comparison with the doubling that occurred in the same period of the previous century (from 3.0bn in 1960 to 6.1bn in 2000). That flattening out should help limit the effects of climate change but will also limit global growth potential (of which more later).

Asia has been the motor of global population growth over recent decades (from 1.4bn in 1950 to 4.6bn in 2020) and will remain the dominant population block. However, the real growth over the rest of this century will be in Africa, with the population going from 1.3bn in 2020 to 4.3bn in 2100. On this basis alone, ignoring Africa in a portfolio for the 21st century would be the equivalent of ignoring Asia in 1950 (though, of course, the Asian development story has been about more than just demographics).

On the other hand, Europe and North America will account for an ever-shrinking part of the world's population (from 28% in 1950 to 14% in 2020 and 10% in 2100). We suspect that also implies a smaller share in economic, financial and geo-political power. Though population does not equate to

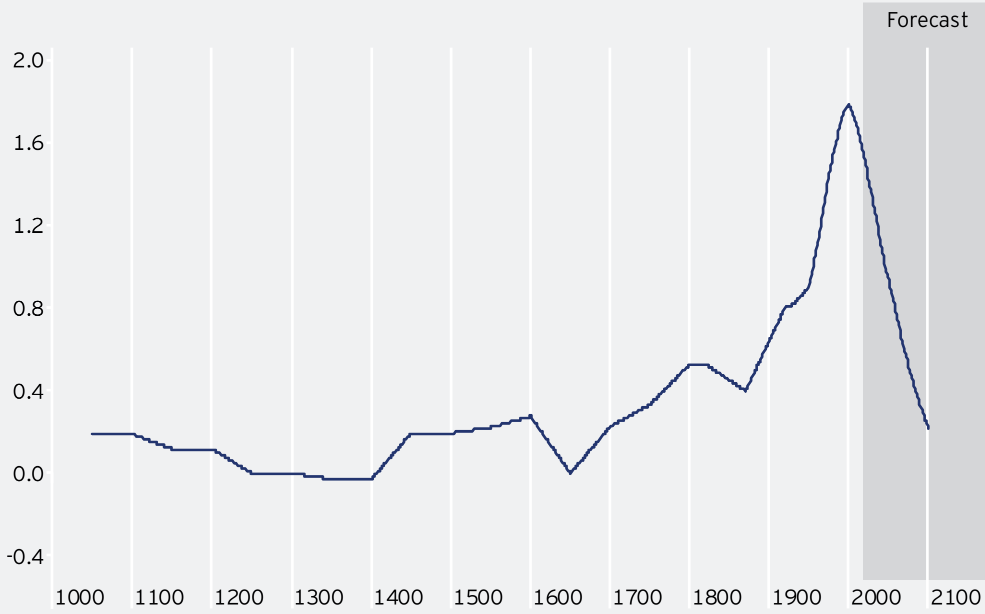
10.9bn

The world's population in 2100

market capitalisation, we doubt that in 2100 the US and UK will account for 60% of the MSCI ACWI index, as they do today.

The demographic downside – the end of the bubble
The demographic deceleration imagined by the United Nations will take world population growth back to where it was prior to the post-WW2 demographic explosion. **Figure 20** shows that world population growth, which had never exceeded 0.5% before 1900 (rolling 50-year annualised basis), reached 1.8% in the 50 years to 2000.

Figure 20 – World population growth (rolling 50-year change, % annualised)



Note: based on historical data from Global Financial Data (with interpolations by Invesco where necessary) and projections from the United Nations (medium variant). From 1000 to 2100.
Source: Global Financial Data, United Nations and Invesco.

Unfortunately, if UN projections are to be believed, that 1.8% growth in 2000 represents the peak. Even worse, as the century progresses, the growth rate is expected to fall back toward 0.2%, which is roughly where it was for most of the pre-1800 period (or at least since the year 1000, when our data set starts).

Why does this matter? Well, **Figure 21** suggests that countries with higher population growth have tended to enjoy higher nominal GDP growth in the period since 1980. Though we don't have the space to show the other charts, our research suggests the correlation improves if we use working age (20-64) population rather than total population (which makes sense) and if we use real rather than nominal GDP.

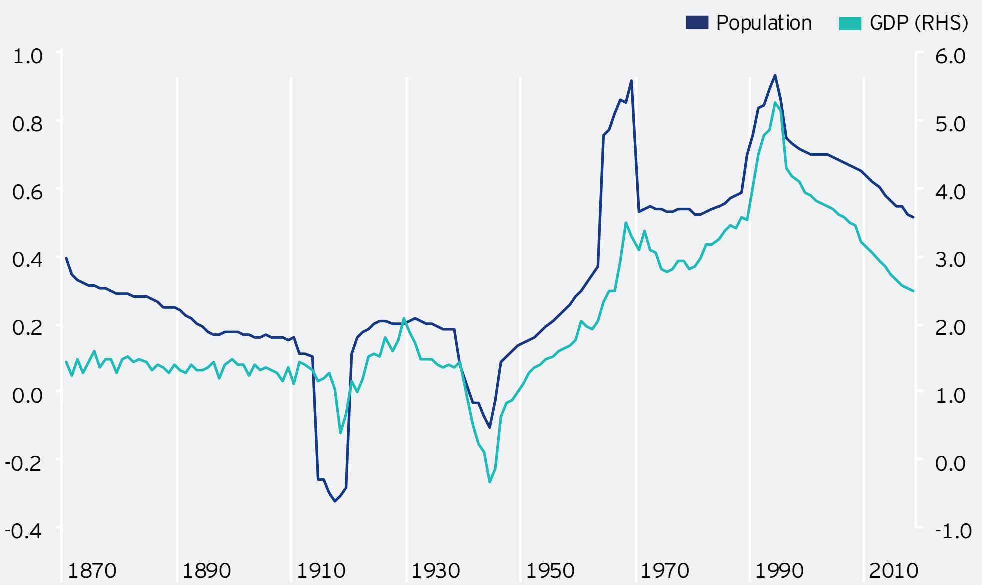
Based on this cross-sectional evidence we suspect that periods of strong world population growth are associated with high economic growth and vice-versa. Unfortunately, we do not have measures of global GDP over a sufficiently long period to test that assertion but we do have long term data on some individual countries.

Though the relationship is not so clear for all countries, **Figure 22** shows the case of France, where trend real economic growth has historically ebbed and flowed with trend population growth. The big downward blips in population growth are explained by the two world wars, as are upward blips 50 years later (both population and GDP are shown as rolling 50-year annualised growth rates).

Figure 21 - Population and nominal GDP growth 1980-2018 (% annualised)

Note: population data is from 1980 to 2020 (annualised). Nominal GDP is IMF data in US dollars. See appendix for country abbreviations. Source: IMF, United Nations, Refinitiv Datastream and Invesco.

Figure 22 - France population and real GDP growth (rolling 50-yr chge, % ann)



Note: based on historical data from Global Financial Data. From 1870 to 2018.
Source: Global Financial Data and Invesco.

If the above continues to be true, we believe global economic growth will be lower during the rest of this century than during the post-war period. To give an idea of the possible growth deficit, consider that annualised world working age population growth was 1.78% in the 1950-2020 period but is projected to be only 0.34% from 2020 to 2100 (taking the total from 4.5bn in 2020 to 5.9bn in 2100). That 1.44% deficit is likely to lead to a similar dip in world real GDP growth, unless there are offsetting gains in employment rates and/or productivity (see the section on technological change).

Figure 23 shows the gap between past and future working age population growth (WAPG) by region and by major country. UN projections suggest nowhere will escape the slowdown: Africa may enjoy 1.74% annualised WAPG to the end of the century but that is lower than the 2.58% seen since 1950. Of the countries that we analyse (the world's 20 largest economies), South Korea is expected to suffer the biggest gap (-3.14%) between future and past WAPG, with Brazil not far behind (-2.95%). Others with a gap in excess of 2% are China, India, Indonesia, Mexico and Turkey.

1.0% - 1.5%

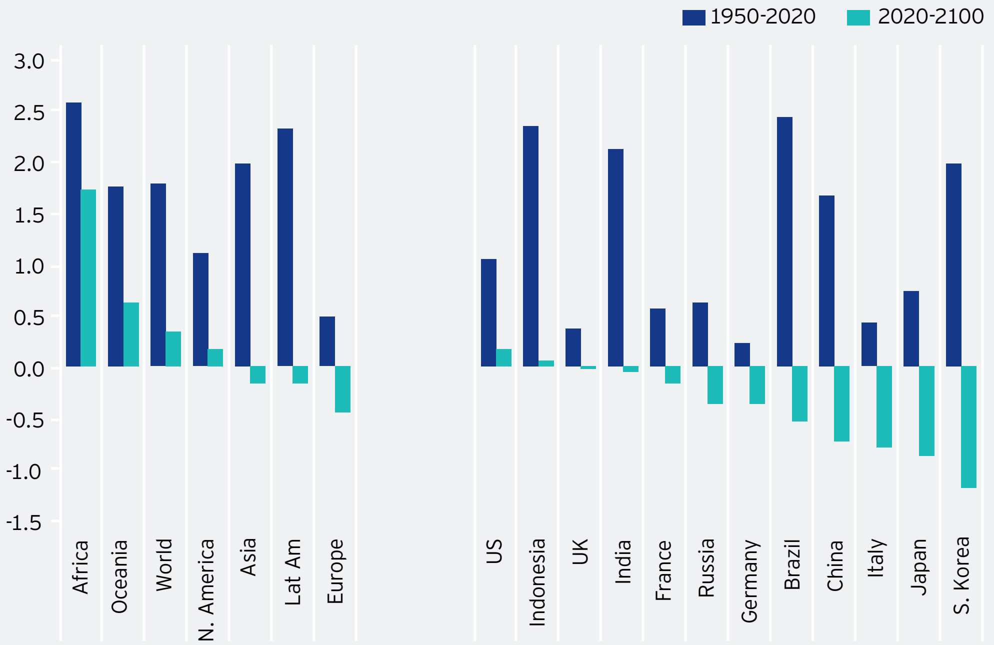
Global growth deficit versus post-war period

61%

The decline in South Korea's working-age population by 2100

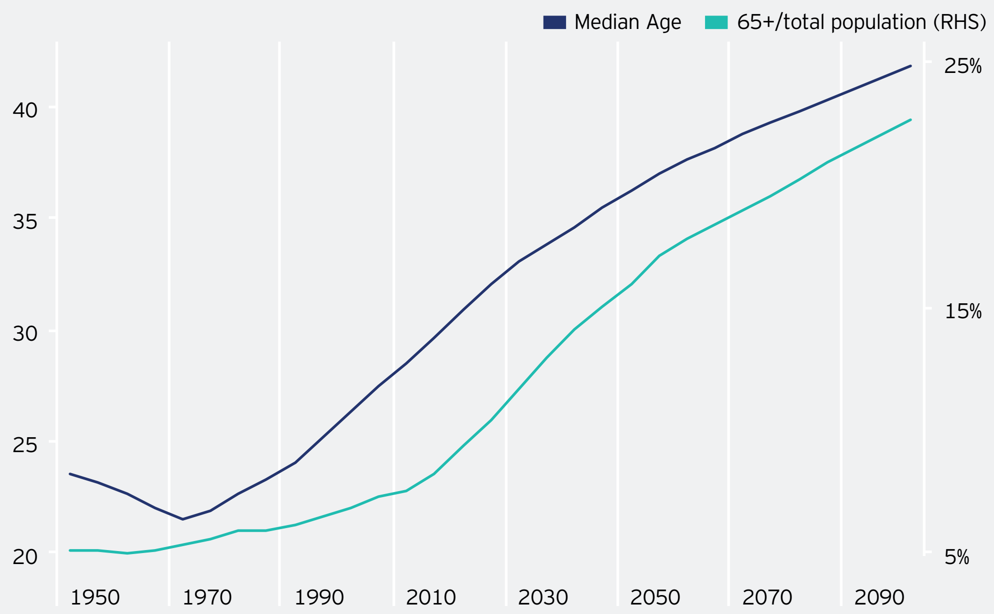
Even worse, many countries will see declines in their working age populations. The biggest decline is likely to be in South Korea, where UN projections suggest the 20-64-year population will go from 34m in 2020 to 13m in 2100. Similar declines are expected in Japan (69m to 35m), Italy (36m to 19m) and China (930m to 528m). Were it not for Africa (0.6bn to 2.4bn), the global total would be in decline.

Figure 23 - Working age population growth past and future (% annualised)



Note: working age is 20-64. Data based on United Nations estimates and medium variant projections. Latin America ("Lat Am") includes Caribbean countries. Regions and countries are ordered by 2020-2100 projections. Source: United Nations and Invesco.

Figure 24 - The ageing of the world's population



Note: from 1950 to 2100 using United Nations estimates and medium variant projections.
Source: Global Financial Data and Invesco.

42%

Africa's share of global working-age population in 2100

As well as suggesting a big slowdown in global growth, these UN projections imply a massive redistribution of growth (and perhaps economic power). Leaving aside Africa, the areas with the strongest WAPG to 2050 are expected to be Oceania (0.9% annualised), India (0.7%), Mexico (0.7%) and Indonesia (0.6%). However, with the exception of Oceania (+0.5%), they are all projected to have negative WAPG during the second half of the century. That leaves Africa in a class of its own, with annualised WAPG growth of 2.6% until 2050, followed by 1.3% for the remainder of the century.

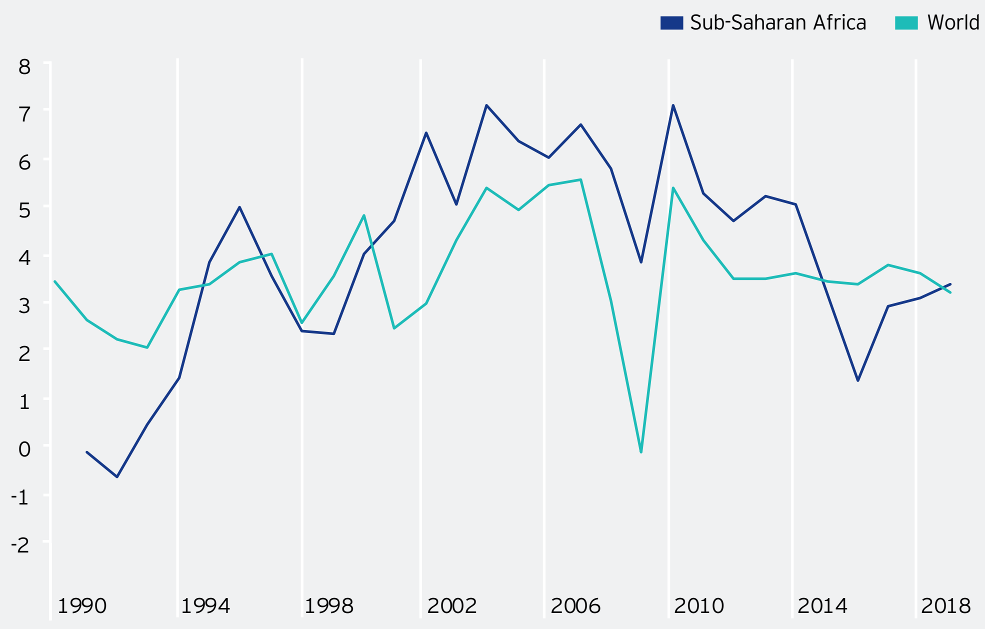
That should take Africa's share of the world's working-age population from 14% in 2020 to 24% in 2050 and 42% in 2100. Over the same period, Asia's share will have fallen from 62% to 56% and then 42%. China's share of the world's working-age population peaked at around 24% at the start of this century and India's is projected to peak at around 19% in 2035 (when Africa's will be 18% and that of China 17%). Africa has the potential to become the world's factory, just as Asia did over recent decades.

Figure 24 shows how the world is expected to age over the rest of the century. Africa is no exception to that trend but it today suffers the curse of low life expectancy which explains why its dependency ratio is so high (many children per working-age person). Luckily, the rapid growth in Africa's working-age population is expected to lower the dependency ratio from the current highest-in-the-world level to the lowest by the end of the century (see **Figure 25**). Africa's workers will be many and relatively unburdened.

Figure 25 – Dependency ratios on the rise everywhere except Africa

Note: dependency ratio is the non-working-age population divided by the working-age (20-64) population. Based on United Nations estimates and medium variant projections. Latin America ("Lat Am") includes Caribbean countries. Regions and countries are ordered by 2100 projections.
Source: United Nations and Invesco.

Figure 26 – Africa has been outperforming the global economy (GDP growth, %)



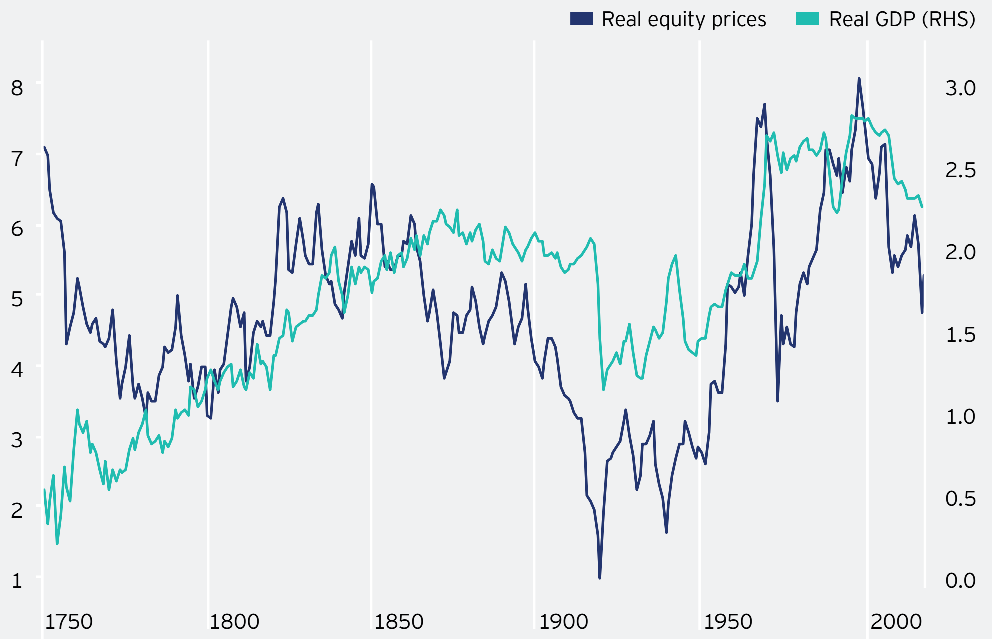
Note: from 1990 to 2019 using IMF forecast for 2019.
Source: IMF, Refinitiv Datastream and Invesco.

Of course, population growth is one thing but economic growth is another, especially for a continent as disparate as Africa. Despite concerns that it may fail to capitalise upon its strengths (demographics and agricultural/mineral resources), sub-Saharan Africa has grown more rapidly than the global economy for much of this century (see **Figure 26**) and the demographic advantage described above suggests to us that it has a fair chance of doing so over the remainder of the century.

It is possible, in our opinion, that during the lives of our children and grandchildren Africa will play a similar role to Asia during our life-times, with the added advantage of large natural resources. Where China became the factory of the world, Africa has a chance of becoming both the bread basket and the factory of the world. This will require a lot of investment and we wouldn't be surprised to see a multiplication of Africa investment vehicles (especially infrastructure). China is already investing heavily, as has the private sector from elsewhere. The choice is simple for the rest of the world: direct capital flows to the labour supply or the labour supply will seek out the capital. Whether capital will need such a supply of labour in the future is the subject of the chapter on technological innovation.

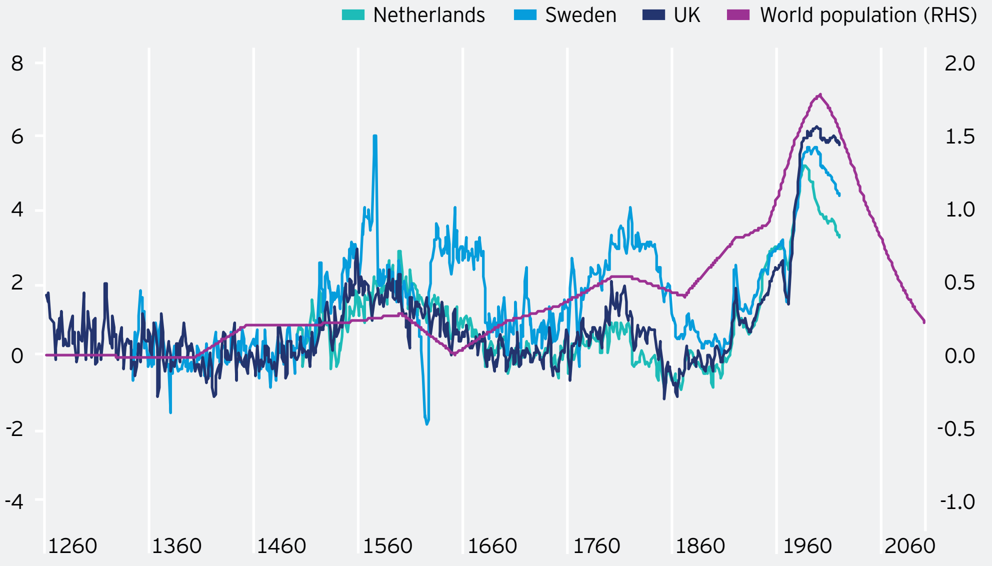
Post-war data casts doubt upon the idea that strong economic growth is associated with strong equity returns but **Figure 27** gives some hope about the possibility of a long-term correlation. This could be good news for African equities, in our opinion.

Figure 27 – UK GDP and equity prices (rolling 50-year annualised change, %)



Note: from 1750 to 2019 (GDP as of 2018 and equity prices as of July 2019). Real equity prices are calculated as total return equity index divided by CPI index. Equity index is based on FT All-Share Index, with extension prior to existence of FT All-Share provided by Global Financial Data. Past performance is no guarantee of future results. Source: Global Financial Data and Invesco.

Figure 28 – CPI inflation has ebbed and flowed with world population growth (%)



Note: from 1260 to 2100 showing annualised rolling 50-year changes, based on annual data. For earlier periods, when population data is not annual, the data has been interpolated on a straight-line basis. Population projections are from the United Nations Medium Variant scenario.
Source: Global Financial Data and Invesco.

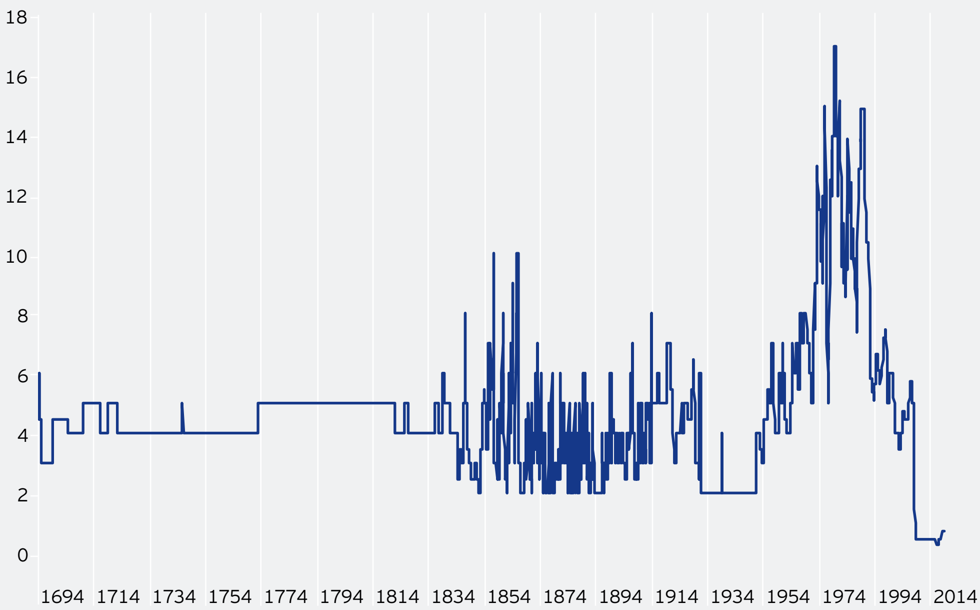
Based on the Malthusian concept that population follows an exponential path, whereas as agricultural productivity is linear, it is only natural to assume that the ebb and flow of population growth will be closely associated with the ebb and flow of inflation. Indeed, **Figure 28** lends some credence to that notion. In particular, the post-war demographic explosion preceded the historically rare burst of inflation from the 1960s onwards. It may be thought that the inflation of the 1970s and 1980s was caused by OPEC's oil price hikes but we would argue that OPEC was just the tool: the demographic explosion created the market conditions that allowed OPEC to get away with it.

As already mentioned, we are now on the other side of that demographic explosion and the global population is expected to decelerate over the rest of this century. Assuming there is a relationship with inflation, we expect the latter to be lower over the coming decades than it was in the 1950-2000 period. Note that inflation has tended to be in the 0%-2% range (calculated as a rolling 50-year average) for most of the history shown in **Figure 28** (for the three countries shown). Hence, current levels of inflation may become the norm, though seeming low in the context of recent history.

It may therefore be imagined that central bank interest rates will stay at current low levels. However, **Figure 29** shows to what extent current interest rates are out of line with historical norms. Inflation may remain low but we very much doubt that central bank rates (and therefore bond yields) will remain this low for the rest of this century.

Inflation back to the "old normal" but interest rates are abnormal

Figure 29 – Bank of England Base Lending Rate since 1694 (%)



Note: monthly data from August 1694 to September 2019 Source: Global Financial Data and Invesco.

Demographics conclusions
The world's population will continue to expand from the current 7.8bn to 10.9bn by the end of the century. That 40% rise suggests we will place an increasing burden on the resources of the planet: space, food, water, minerals and environment. As we shall see in the chapter on climate change, this will require changes in the way we live and work.

However, the rate of growth will slow radically from that of the post-WW2 period, with, we believe, a knock-on effect on the rate of economic growth, inflation, policy rates and bond yields. In the absence of productivity enhancing technological change, we expect real global GDP growth in the rest of this century to be 1.0-1.5 percentage points lower than the 3.5% seen since 1960 (annualised world real GDP growth from 1960 to 2018, based on World Bank data in 2010 US dollars).

Consequently, we believe that inflation will return to the 0%-2% range that prevailed (on average) for much of pre-WW2 history. We also believe that developed world central banks will struggle to consistently meet the 2% rate that many of them target. This has implications for what are considered to be "normal" central bank rates and bond yields but we suspect that new "normal" will be above current rates (which are depressed by the extreme policies operated by many developed world central banks).

The distribution of the world's population will change radically. Some countries are already experiencing a decline in population (Japan and Russia, say) and by the end of the century this will become more commonplace (Brazil, China, Germany, India, Italy, Japan, Mexico, Russia, South Korea and Turkey are good examples). The growth in Africa's population is expected to offset this shrinkage and more. Hence, we expect economic (and perhaps geo-political) power to shift first towards China and India and then, in the second half of the century, towards Africa.

Without a change in migration flows, this suggests less economic growth and inflation in many countries but also less pressure on resources (including land, water, environment etc). This implies a big drop in demand for housing in some countries and, we suspect, a decline in house prices and housebuilding activity. For example, the populations of both Japan and South Korea are expected to decline by more than 40% by the end of the century, while those of China, Italy and Spain are expected to decline by 25%-35%.

Layered on top of shrinkage will be an ageing of the population. The decline in the working age (20-64) population will be even more dramatic than for the total population (for instance, South Korea's 20-64 population is projected to decline by 61% by the end of the century and that of Japan by 50%). Without a change in migration flows, participation rates and/or a large rise in productivity, this implies a dramatic reduction in economic growth and, in some cases, perhaps a drop in GDP. Workers will face an increased burden in terms of supporting non-workers (rising dependency ratios) but will also face an increased burden in terms of debt financing (legacy debt will be shared among fewer workers). This may place an intolerable burden and we think raises the risk of default (reneging on promises to the population and/or reneging on promises to creditors). So-called "safe" government debt may not seem so safe by the end of the century. Young workers are likely to see an increasing share of their incomes dedicated to the support of others and debt servicing, while also needing to set aside an increasing share of their disposable incomes to provide for their own old-age (for fear of state provision of pensions and healthcare no longer being available).

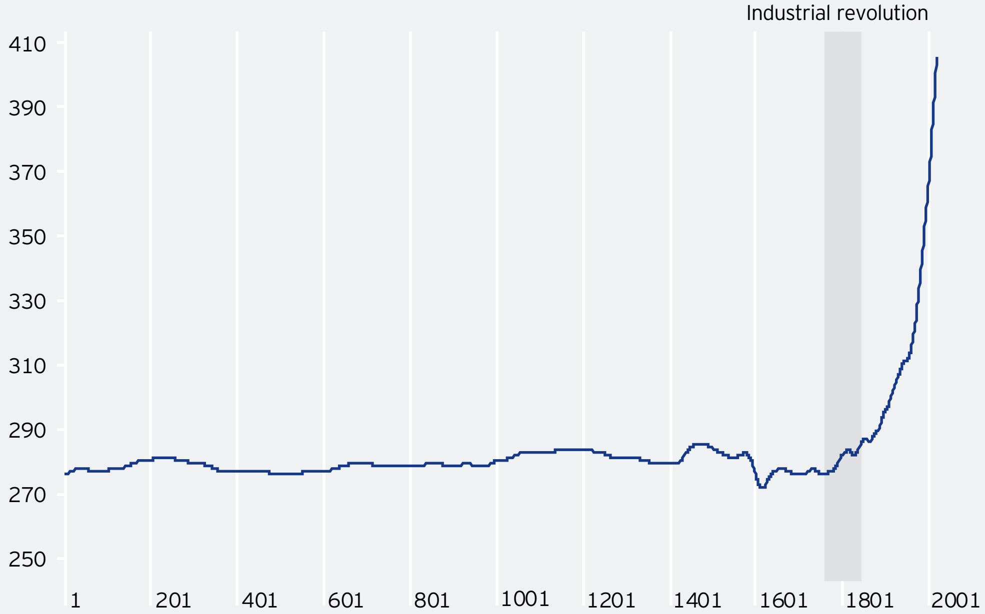
Apart from Africa (+219%), the places expected to experience population growth above 10% to the end-of the century are Australia, Canada, Indonesia, Sweden, Switzerland, the UK and the US. This puts them on a relatively strong footing (especially when it comes to the per capita burden of legacy debt) but nowhere is expected to escape the deceleration in working age population (and therefore GDP growth, we believe) nor the ageing of the population/rising dependency ratios. They will experience an increased burden upon their resource bases (land, water, minerals, environment etc.) and an increased demand for housing. Without a big change in migration flows, Africa will experience the best economic growth but also the biggest strain on resources.

Theme 3: Climate change - a drag or an opportunity?

Theme 3: Climate change - a drag or an opportunity?

NASA says multiple studies "show that 97 percent or more of actively publishing climate scientists agree: Climate-warming trends over the past century are extremely likely due to human activities".

Figure 30 - Atmospheric concentration of CO2 in ppm and the industrial revolution

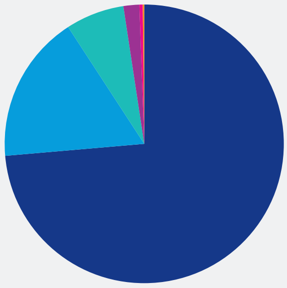


Note: Annual data from year 1 to 2018. ppm is parts per million. Based on ice-core records up to 1958 and direct observation since. The industrial revolution period is 1760-1840.
Source: Scripps CO2 Program, Our World in Data and Invesco.

Figure 30 shows that something extraordinary has happened since the industrial revolution. Ice core records suggest the carbon dioxide (CO2) concentration in the atmosphere did not go above 300 parts per million (ppm) until the industrial revolution. It has since climbed rapidly, reaching 405 ppm in 2018, likely the result of human activity.

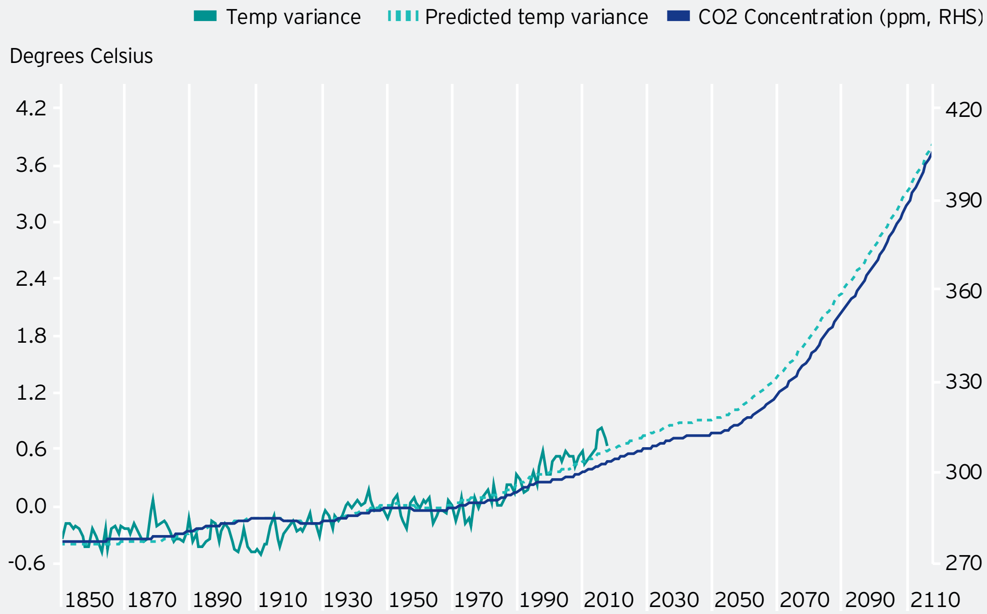
This is important because CO2 is reckoned to be the biggest contributor to the greenhouse effect, whereby gases in the atmosphere lead to global warming by trapping heat that would otherwise have escaped. **Figure 31** shows that CO2 is likely to account for around three-quarters of the warming effect caused by greenhouse gases (GHG) over the next 100 years: though the other gases are far more potent (see footnote to chart), the volume of CO2 emissions is far greater. Methane (CH4) and Nitrous Oxide (N2O) are also expected to be important contributors to global warming but for the most part we shall focus on CO2, as do the broader literature and governmental initiatives.

Figure 31 – Share of greenhouse gas emissions in 2010 in CO2 equivalent (%)



Note: Using CO2 equivalent measures allows the warming effect of different gases to be compared (assuming that a kilogramme of each gas has the following multiple of the warming effect of CO2 over 100 years: Methane 28x, HFC gases 138x, Nitrous Oxide 265x, PFC gases 6630x and SF6 23,500x).
Source: European Commission (JCR), Netherlands Environmental Assessment Agency (PBL), Emission Database for Global Atmospheric Research (EDGAR), Global Warming Potential Factors (GWP100) IPCC 2014, Our World in Data and Invesco.

Figure 32 – Global temperature variance* and lagged CO2 concentrations



Note: annual data from 1850 to 2118. *Temperature variance is the global average land-sea temperature anomaly relative to the 1961-1990 average temperature in degrees Celsius (ºC), median estimate, as provided by UK Met Office Hadley Centre. CO2 concentrations are shown with a 100-year time lag (the 1850 reading was that of 1750 etc.). The predicted temperature variance is our estimate based on a simple regression between historical temperature variance and the natural logarithm of the lagged CO2 concentration (using the latter to estimate future temp. variance). The simple correlation between the two variables (from 1850 to 2018) is 0.88 and the R-squared of the regression is 0.77, with highly significant t-stats. Correlation is not causation. Source: Met Office Hadley Centre, Scripps CO2 Program, Our World in Data and Invesco

3.5 degrees

The "baked-in" temperature gain

It therefore seems uncontroversial (to us) to suggest that human activity has caused the build-up of CO2 and other greenhouse gases in the atmosphere. The next step is to explore the link between greenhouse gases and global temperatures. First, there are good theoretical reasons for believing that higher concentrations of greenhouse gases will raise temperatures (the molecules of such gases absorb energy, thus holding heat in the atmosphere that would otherwise escape). Second, **Figure 32** suggests a reasonable correlation between CO2 concentrations and temperature (note that it compares temperature with the CO2 concentration of 100 years earlier to allow for the build-up of the warming effect). The correlation between the two is 0.88 and the R-squared of the regression is 0.77. Though correlation does not imply causality, the theoretical foundation and the strength of relationship leads us to agree with the bulk of scientists who believe that human activity is leading to global warming.

According to UK Met Office Hadley Centre data, the global average temperature has risen by around 0.82 degrees Celsius since 1850-1900 (by comparing the average annual variance in the 1850-1900 period with that in the 20 years to 2018, where the variance is calculated by comparison with the 1961-1990 average). That may not seem a lot but remember the effect of greenhouse gases accumulates over time and we are only now feeling the full effect of emissions made a century ago.

Unfortunately, that means that what happens next is already baked in (excuse the pun). **Figure 32** shows our temperature projection to 2118 based on the regression model described above. If comparisons are made to the 1850-1900 baseline, our model suggests the global average temperature will have risen by 1.14 degrees in the 20 years to 2050, 2.58 degrees in the 20 years to 2100 and 3.54 degrees in the 20 years to 2118 (due to the acceleration of the concentration of greenhouse gases).

A number of words of caution are warranted: first, this is an extremely simple model and other factors no doubt impact temperature; second, the assumption that warming is related only to century-ago concentration levels is a gross oversimplification and we suspect it would be more accurate to relate it to some form of average concentration level over that 100-year time frame; third, if that is right, our temperature forecasts capture some elements of truth (rising and accelerating) but overstate the gains; finally, no allowance is made for how future actions could change the temperature path.

Though a more accurate and detailed approach is beyond the scope of this study, others have done the necessary work, especially the Stern Review and various IPCC reports.

The human influence

The climate does vary naturally and goes through cycles. It can also be influenced by non-human factors. However, the scientific consensus is that the temperature change since 1850-1900 has been faster than previous natural cycles and that the bulk of the rise is due to the effect of human activity on the composition of the atmosphere.

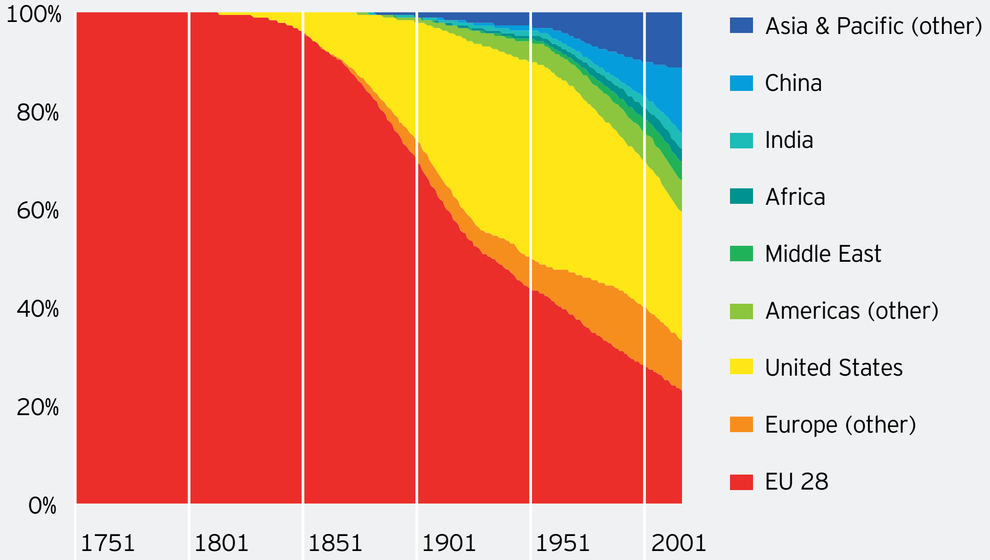
As made clear in the 2014 Report of the Intergovernmental Panel on Climate Change (IPCC), the effect of humans on atmospheric composition depends on: population growth, economic growth (GDP per capita) and the GHG intensity of economic activity. Given that population growth is a matter of personal choice (in most places) and that economic growth is desirable, the bulk of our efforts to control GHG emissions must focus on changing the GHG intensity of economic activity (either doing different things or doing the same things differently). This could be costly but it could also present new opportunities.

Policymakers originally aimed to limit temperature change to 1.5 degrees versus the pre-industrial norm in order to avoid the worst effects of climate change. We are already half way there. More recently, the aim seems to have weakened to limiting the change to 2.0 degrees but even that will be challenging. The seminal Stern Review (The Economics of Climate Change, 2006) warned that at then existing emission flows, by 2050 the GHG concentration would reach a level likely to cause 2.0 degrees of warming. Even worse, if emissions continued to grow, it was likely the 2.0-degree concentration threshold would be reached by 2035.

According to the European Environment Agency, the GHG concentration was 449ppm CO_2 equivalent (CO_2e) in 2016, up from around 280ppm in pre-industrial times and 322ppm in 1970. The 478ppm threshold consistent with giving ourselves a 50% chance of limiting the temperature gain to 1.5 degrees is almost upon us and could be crossed in the 2035-40 period. The 545ppm threshold consistent with limiting the gain to 2.0 degrees could be crossed in the 2040-45 period, given recent trends.

How much of a limitation on economic growth is implied by the meeting of these standards? It is worth bearing in mind that the bulk of the problem so far has been created by the developed world, with around two-thirds of cumulative CO_2 emissions coming from Europe and the United States (see **Figure 33**). If we think of it in resource terms, the developed world has got rich by using up the CO_2 absorbing capacity of the atmosphere, leaving little room for the rest of the world to develop. If the emerging world develops as the developed world did, it would be a disaster, especially given the ongoing expansion of the global population.

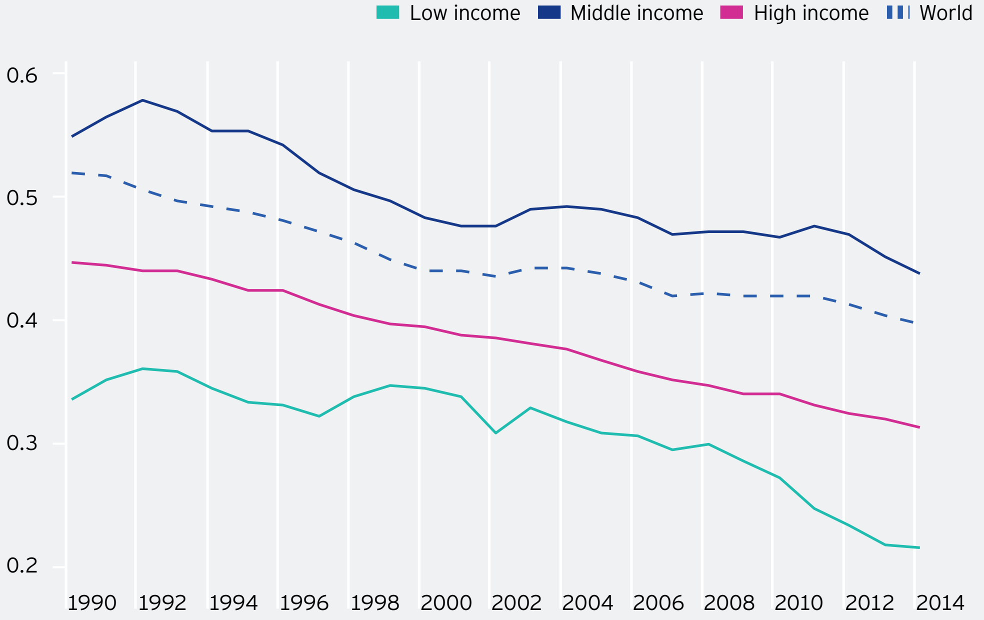
Figure 33 – Share of cumulative CO2 emissions by region 1751-2017



Notes: Annual data from 1751 to 2017. Source: Our World in Data (based on Carbon Dioxide Information Analysis Centre and The Carbon Project (2018) and Invesco

However, there are some elements of good news. First, as already seen in the section on demographics, we are likely to witness a deceleration of the world's population over the rest of this century, which will help control carbon emissions. Second, **Figure 34** shows that economic activity has become less carbon intensive, no matter which group of countries are analysed (low, middle or high-income).

Figure 34 – CO2 intensity of economic activity (kg of CO2 per 2011 PPP $ of GDP)



Notes: Annual data from 1990 to 2014 for low, middle and high-income countries.
Source: World Bank Development Indicators, Refinitiv Datastream and Invesco

Business-as-usual suggests four to five degrees of warming

As can also be seen from **Figure 34** low-income countries are the least CO2 intensive. This is because they are not yet industrialised. Unfortunately, it is the industrialising middle-income countries (such as China and India) that are the most polluting and they are the most populous (currently accounting for around three-quarters of the world's population). Though they may become less energy and CO2 intensive as they develop toward the high-income model, we fear the low-income countries will become more polluting as they start to industrialise. Hence, there are many moving parts to consider when projecting the path of emissions (population growth, GDP per capita growth and the path of CO2 intensity for each of the income groups).

In what follows, we consider a number of scenarios to better judge the scale of the problem and assess whether economic growth will need to be sacrificed to limit global warming to manageable levels. We analyse the current low, middle and high-income groups separately and aggregate across the three to obtain global totals. In all scenarios we use UN medium variant population projections to 2100. The difference between the scenarios comes from assumptions about the path of GDP per capita and the CO2 intensity of economic activity (measured in kg of CO2 per 2011 PPP US dollar of GDP). Not surprisingly, CO2 (and GHG) emissions tend to be positively correlated with both GDP per capita and CO2 intensity.

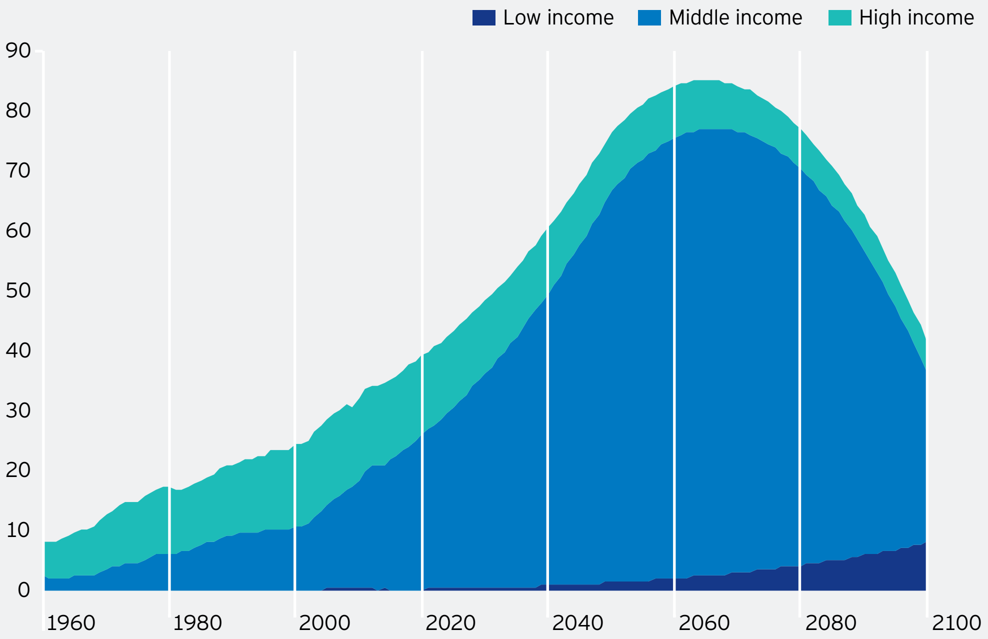
As an example, one of the chosen scenarios is based on recent trends, by which we mean the rate of change seen in the last 10 years (see footnote to **Figure 35** for the detail). Essentially, we assume that high-income countries follow recent trends: that GDP per capita continues to grow at the annualised rate seen in the 10 years to 2018 and that CO2 intensity continues to improve at the annualised rate seen in the 10 years to 2014 (the last available data). These trends are assumed to continue until 2100.

We then assume that the GDP per capita and CO2 intensity of middle-income countries (such as India and China) follow recent trends until 2050 and then converge on high-income levels by 2100, as their structure adjusts. The path for low-income countries is more complex: we assume they progressively industrialise by following recent GDP per capita trends until 2050 and thereafter switch to the recent middle-income growth rate; CO2 intensity is assumed to converge on (increase to) the then middle-income rate by 2050 and to thereafter improve at the same rate as middle-income countries have done in the last 10 years.

Figure 35 show that such a scenario will result in a more than doubling of annual CO2 emissions to 85 billion tonnes by 2065, though with a decline thereafter. It also makes it clear that middle-income countries will account for the bulk of the increase: CO2 intensity reductions will be outweighed by rising populations and rising GDP per capita.

Figure 36 suggests that under such a scenario (Scenario A), the cumulative CO2 emissions necessary to trigger a 2-degree rise in global temperatures from the 1850-1900 average (3150 billion tonnes) would be reached in 2047/48, with worse to come (a conclusion in line with the European Environment Agency analysis mentioned above). A back-of-the-envelope calculation suggests to us that the 7000 billion tonnes of cumulative emissions by 2100 risk causing an eventual temperature gain of four to five degrees.

Figure 35 – Annual CO2 emissions by income group on recent trends (tonnes bn)



Notes: Annual data from 1960 to 2100 for low, middle and high-income countries. World Bank historical data is used from 1960 to 1989; then we derive estimates based on World Bank data for 1990 to 2014 and then we project future emissions on the following basis: population estimates are taken from the UN Medium Variant projection; high-income GDP per capita and CO2 intensity (kg of CO2 per 2011 PPP $ of GDP) are assumed to follow the trend of the last 10 years; middle-income GDP per capita and CO2 intensity are assumed to follow the trend of the most recent 10-years until 2050, from which time they are assumed to converge on high-income values by 2100; low-income GDP per capita is assumed to follow the trend of the last 10 years until 2050 and thereafter to grow at same rate as middle-income countries in the last 10 years; low-income CO2 intensity is assumed to converge on the then middle-income level by 2050 and thereafter to improve at same rate as middle-income countries in last 10 years. Last 10 years is to 2018 for GDP per capita and to 2014 for CO2 intensity. Source: World Bank Development Indicators, United Nations, Refinitiv Datastream and Invesco.

Figure 36 also shows that even if we double the historical rate of CO2 intensity reductions (Scenario B), that 2-degree temperature threshold would still be crossed in 2053 (with a final temperature gain in the three to four degree range, in our opinion), though the peak annual CO2 emission would be a much lower 53 billion tonnes (in 2060) and emissions would fall below today's level by the early 2080s.

That latter point gives hope that once we get into the second half of the century, the problem will become more manageable. Indeed, the earth has capacity to absorb CO2 in carbon sinks such as oceans and plant life. Hence, at some reduced emission level it is possible that atmospheric concentrations of GHG could decline. It is reckoned that the earth has absorbed around half of our annual CO2 emissions over recent decades, even as emissions have risen (see, for example, a 2012 paper by researchers at the University of Colorado and the US National Oceanic and Atmospheric Administration, published in Nature Magazine called "Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years").

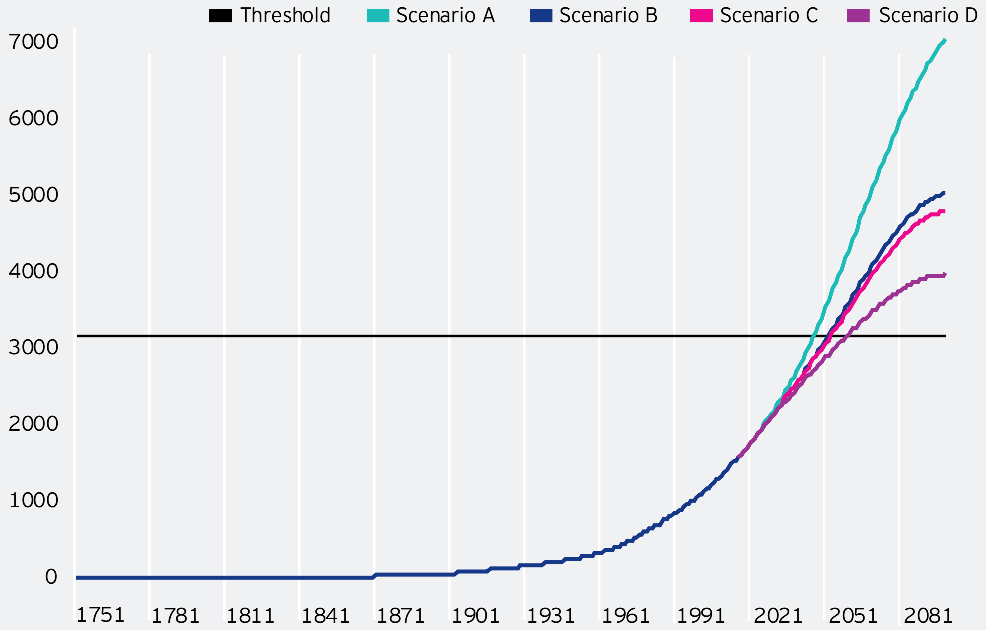
However, there is still a race against time: first, we need to get through the intervening hump in GHG emissions (the bigger it is, the greater is likely to be the long-term damage) and, second, it is feared the earth cannot forever absorb carbon at the current pace (global warming may reduce the ability of plants to absorb CO2 and the acidification of the oceans, caused by higher CO2 concentrations, is believed to reduce their ability to absorb more CO2).

Also, while easy to double the rate of decline in CO2 intensity in a spreadsheet, it is another thing to do it in real life, especially given the resistance in many countries and the natural desire of emerging countries to catch up with the developed world. For example, in the last 10 years (to 2014), the CO2 intensity has improved more rapidly than in prior decades for low and high-income groups but more slowly for the middle-income group (due to industrialisation).

Sticking with **Figure 36**, Scenario C uses the augmented carbon efficiency of Scenario B and also assumes that high-income countries achieve zero emissions by 2050 (which has a knock-on effect on the middle and low-income groups, as their CO2 intensity rates are assumed to be linked to that of the high-income group). This is more ambitious than the zero net carbon emission target for 2050 recently announced by the UK government, as the latter allows for offsetting from carbon capture etc. As can be seen, this changes very little versus Scenario B (peak emissions would occur in 2061 at 49 billion tonnes, falling close to zero by 2100). The 2-degree threshold would be crossed in 2053, with a final gain in the three to four-degree range, we believe.

GDP growth may need to be halved to limit warming

Figure 36 – Cumulative global CO2 emissions by scenario 1751 to 2100 (tonnes bn)



Notes: Annual data from 1750 to 2100, with forecasts from 2018 onward calculated as aggregate of low, middle and high-income country groups. "2-degree threshold" is our estimate (3150 billion tonnes) of the cumulative CO2 emissions necessary to produce a two-degree celsius heating from the 1850-1900 global average (based on historical patterns). Historical emissions have been calculated by Our World in data based on annual CO2 emissions published by the Global Carbon Project (GCP) and Carbon Dioxide Information Analysis Centre (CDIAC). Forecast emissions are a function of population, GDP per capita and the CO2 intensity of economic activity. All scenarios use UN Medium Variant population projections; Scenario A; is described in the footnote to Figure 35 and the text that precedes that figure; Scenario B assumes that CO2 intensity declines twice as rapidly as in Scenario A; Scenario C is Scenario B, with the further assumption that high-income countries have zero emissions beyond 2050 and that middle-income country emissions trend to zero from 2050 to 2100; Scenario D is Scenario C but with lower GDP per capita growth rates (low and high-income country growth rates are reduced by 0.5 percentage points, while that for middle-income countries is reduced by 1.0 percentage point and with a 2100 level that is 80% of the high-income level, rather than 100%).
Source: Our World in Data, Global Carbon Project, Carbon Dioxide Information Analysis Centre, World Bank Development Indicators, United Nations, Refinitiv Datastream and Invesco.

Having examined what we think are aggressive efficiency gain scenarios (which imply big technology and lifestyle changes) and concluded they are unlikely to do all that is necessary to avert the worst outcomes, we must now consider what would happen if economic growth is somehow limited (perhaps as part of the process to contain emissions). To provide context, world real GDP growth was an annualised 3.5% between 1960 and 2018 and scenarios A, B and C all imply annualised world GDP growth of 2.4% to the year 2100 (based on population and GDP per capita assumptions, aggregated across the low, middle and high-income categories). This is consistent with the 1.0%-1.5% reduction in GDP growth rates suggested by reduced working age population growth mentioned in the earlier section on demographics.

Scenario D shaves 0.5 percentage points from the assumed high-income GDP per capita growth rates (to a lowly 0.5%). The same reduction is made to low-income growth rates (to 1.5% in the period to 2050 and then to an industrialisation boosted 3.4%).

The middle-income growth rate is reduced by one percentage point in the period to 2050 (to 2.9%) and for the period thereafter it is assumed that GDP per capita reaches only 80% of the high-income group level by 2100 (rather than 100%).

As seen in **Figure 36**, these restrained growth rates are enough to delay crossing the 2-degree threshold to 2061, with emissions peaking in 2020 and the final temperature rise limited to two to three degrees, in our opinion. That good news is balanced by the fact that it implies annualised global GDP growth of only 1.7% to the end of the century.

So the choice is clear: if we continue along the recent path of growth and climate change mitigation (Scenario A), the world could achieve annualised real GDP growth of 2.4% to 2100 but cumulative CO2 emissions by the middle of the century would be consistent with a two-degree Celsius rise in the average global temperature (versus 1850-1900 norms) and by the end of the century would be consistent with a four to five degree increase. Such climate change would present immense challenges but could be self-correcting (essentially, the planet could protect itself by curbing economic activity).

A more urgent approach to mitigation (scenarios B and C) would imply a more rapid reduction in the CO2 intensity of economic activity and would still come with global GDP growth of 2.4% per year. Cumulative emissions consistent with a two-degree temperature gain would still be reached in the middle of the century but the eventual temperature gain would more likely be in the three to four-degree range, lower than under scenario A but still challenging.

In all likelihood, we believe it unlikely that the temperature gain could be limited to two degrees. Realistically, limiting it to two to three-degrees will require a sacrifice of economic growth (voluntary or imposed) – scenario D shows an example with global GDP growth limited to 1.7%, roughly half the pace of the 1960-2018 period.

What could be the consequences of climate change?
Casual observation suggests that climate change is already upon us: temperatures are rising and extreme weather events have become more common. This seems to be having some predictable effects: ice sheets are retreating, sea levels are rising, crop growing seasons are lengthening, oceans are becoming more acidic, marine habitats are moving to higher latitudes and ecosystems are under threat.

The evidence so far
Sourced from the Fourth National Climate Assessment of the US Global Change Research Program, unless specified otherwise:

- July 2019 was the hottest month on record (EU Copernicus Climate Change Programme).
- All but two of the 20 hottest years on record fell in the last 20 years (Met Office Hadley Centre data).
- The number of reported weather-related natural disasters has tripled since the 1960s, now causing 60,000 deaths per year (World Health Organisation).
- The length of US heatwaves has increased by 40 days since the 1960s.
- The share of US land area subject to heavy precipitation has doubled since 1910.
- The minimum Arctic sea ice extent (measured in September) has fallen by 11%-16% per decade since the early 1980s.
- Annual median sea level along the US coast has risen by around 9 inches (23 cm) since the early 1900s.
- US marine species have moved by an average 35 miles (56 km) since 1980 and are 30 feet (9 metres) deeper.
- Surface ocean water has become 30% more acidic since pre-industrial days (US National Oceanic and Atmospheric Administration).
- Around one quarter of worldwide coral reefs are considered damaged beyond repair (World Wildlife Fund).
- The land area burned by US wildfires has increased 10-fold since 1980.
- US heating degree days are down by around 10% since the early 1900s; cooling degree days are up by around 20%.

Unfortunately, this is only the start. As mentioned earlier, the global average temperature has so far risen by 0.82 degrees Celsius (from 1850-1900 to the 20-year average to 2018) and our analysis suggests the gain will eventually be above 2 degrees and quite likely in the 2-4-degree range. To put this into perspective, average temperatures have risen by around 5-6 degrees since the last Ice Age and such further gains would push the earth into unprecedented territory (at least within the history of the last five million years, according to data from World Data Service for Paleoclimatology, Boulder, NOAA Paleoclimatology Program and National Centers for Environmental Information).

0.5 metres

Potential rise in sea level

How bad could it become?
The IPCC 2014 and 2018 studies and Stern Review 2006 suggest the following consequences of such an outcome by the end of the century (2-4-degree rise):

- Though global average temperatures may rise by 2-4 degrees, the gains at higher latitudes (the poles) could be in the 4-10-degree range.
- The global average sea level will rise by around 0.5m (range of 0.3-0.8m) with a multi-metre rise possible over hundreds to thousands of years.
- Precipitation could increase by 20%-50% in high latitudes but the picture is more complex in the tropics (some areas could see 10%-20% declines, as could Southern Europe, but others could see 20%-50% gains). Large parts of Australia, Southern Africa and Central/South America could be more prone to drought.
- Approximately 13% of terrestrial land area is predicted to undergo a transformation of ecosystem from one type to another.
- Sea acidity is expected to increase by 60% (likely range 40%-100%).
- Arctic sea ice may disappear during summer months; the area of surface permafrost may decline by 50%-60% and glacier volumes could decline by 40%-60% (excluding glaciers on the periphery of Antarctica and Greenland/Antarctic ice-sheets).
- An increase in deaths as a result of climate change (the most recent WHO estimates suggest an extra 250,000 deaths per year between 2030 and 2050, from a mix of heat exposure, diarrhoea, malaria and childhood undernutrition).
- Migration flows are likely to increase: nearly 200m people currently live in coastal flood zones that are at risk (60m in South Asia alone and 25% of the population of the Netherlands could face regular floods); 250m-550m people are reckoned to be at risk of hunger if warming reaches three degrees, while warming of two degrees could put even higher numbers at risk of water shortages (the range of estimates is 0.7bn-4.4bn). By comparison, the Irish potato famine of the 1840s led to the death of one million and the migration of another million.
- Extreme weather events are thought more likely (more flooding, more intense storms and, of course, more wildfires). Even a moderate temperature gain (2 degrees) is expected to result in costs from such events in the 0.5%-1.0% of global GDP range (up from 0.1% in 2005). Interestingly, the major financial centres (Hong Kong, London, New York and Tokyo) are in coastal areas. The insurance industry is particularly vulnerable, with the risk of higher premiums charged to clients, greater capital needs and refusal to cover some risks.
- A permanent loss of global GDP of up to 3% if temperatures rise by 2-3 degrees and up to 10% if the warming is 5-6 degrees (with welfare losses equivalent to a reduction in consumption per head of up to 20% in the latter case). The impact is expected to be particularly severe in poor countries: they are often in already warm areas; rely heavily on agriculture (which will be severely impacted) and have fewer resources to adapt to climate change.
- Correlated changes could bring more severe changes. For instance, a collapse of the Atlantic Thermohaline Circulation could lead to cooling of around 2-degrees in the UK and Scandinavia, less rainfall in the Northern Hemisphere, water shortages, lower agricultural productivity and a threat to ecosystems.

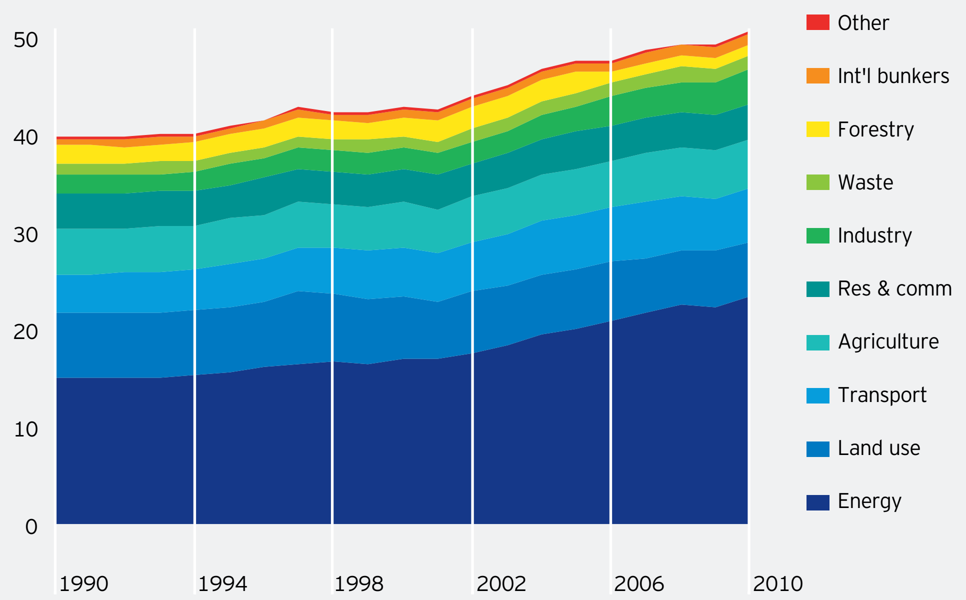
How can the worst consequences be avoided?
Strategies to minimise the consequences of climate change follow a hierarchy:

1. Reduce emissions via behavioural change and innovation
2. Capture as much released carbon as possible
3. Adapt to the changes

Though innovation is only explicitly mentioned as part of the Reduce strategy, it is an important feature of all three.

Reducing emissions
If we are going to mitigate the effects of climate change, we need an idea of what is causing the problem. The energy sector is the biggest emitter of greenhouse gases, accounting for around 46% of such emissions in 2010 (see **Figure 37**). Land use (11%), agriculture (10%) and forestry (2%) together account for around one-quarter of emissions. Transport (11%), residential & commercial (7%) and industry (7%) are the other big emitters. Though we can easily point fingers, it should be remembered that most of the emissions are done on our behalf, to enable us to live the lives we lead.

Figure 37 – Greenhouse gas emissions by sector 1990 to 2010 (bn tonnes of CO2e)



Notes: Annual data from 1990 to 2010 for the world. Shown in billion tonnes of CO2 equivalent. "Int'l bunkers" is international bunkers (fuel used to power international aviation, navigation and shipping) and "Res & comm" is residential and commercial. "Land use" is the emissions from conversion of forestry, cropland and grassland and the burning of biomass for agriculture and other purposes.
Source: UN Food and Agricultural Organisation, Our World in Data and Invesco

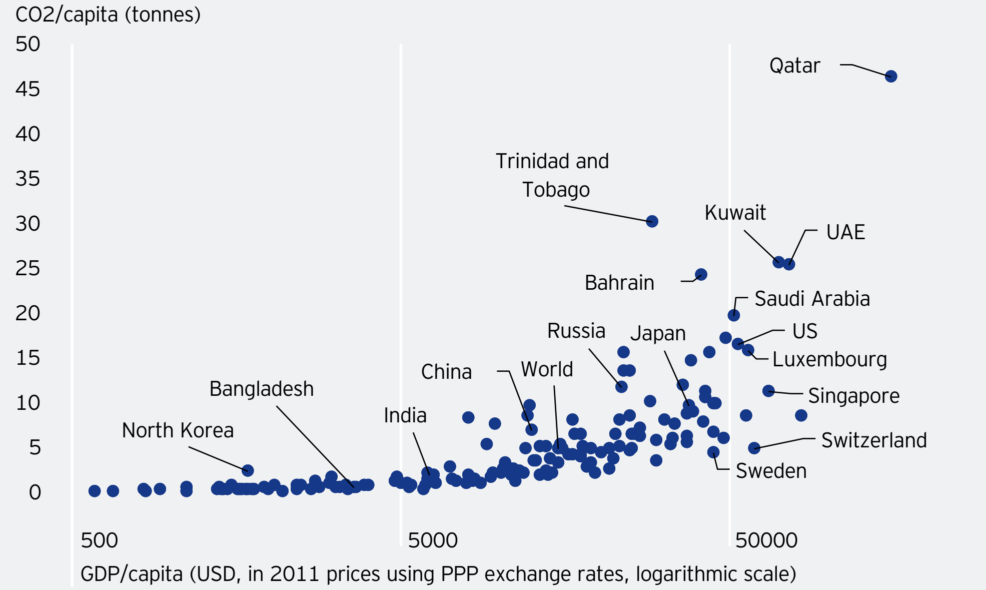
Hence, any serious attempt to reduce GHG emissions must be focused on energy, agriculture/land-use/forestry and transport. In all cases we need to rethink how much we consume and how it is produced. For example, becoming more energy efficient and using "clean" sources. However, if temperature gains are to be minimised, contributions will be needed from all sectors.

We have already seen that high-income countries account for the bulk of emissions. Not surprisingly, per capita emissions are also highest in high-income countries. The correlation seems quite clear in **Figure 38** but the direction of causality is not always what might be imagined. It seems obvious that low income countries such as North Korea and Bangladesh will emit little in the way of CO2 and other greenhouse gases, while richer countries such as the US will have higher emissions due to different lifestyles. CO2 emissions in tonnes per person in 2016 were: 0.5 in Bangladesh, 1.8 in India, 5.4 in France, 6.1 in the UK, 6.9 in China, 9.4 in Japan, 9.8 in Germany, 11.6 in Russia, 16.5 in the US and 46.2 in Qatar, for example, with a world average of 4.8.

However, **Figure 38** also suggests that the most CO2 intensive economies are involved in the production of oil and gas (including Trinidad and Tobago). They also happen to be among the richest, with high GDP/capita ratios. We suspect the high CO2 intensity is due to the nature of their economic activity, rather than lifestyle, although the high incomes generated by the oil & gas wealth will then contribute to further emissions via lifestyle.

Annual CO2 emissions (tonnes per capita)	
Bangladesh	0.5
United Kingdom	6.1
United States	16.5
Qatar	46.2

Figure 38 - Production CO2 emissions per capita versus GDP per capita in 2016



Notes: CO2 emissions are based on production in the country. Source: Global Carbon Project (2018), Our World in Data, United Nations, World Bank Development Indicators and Invesco

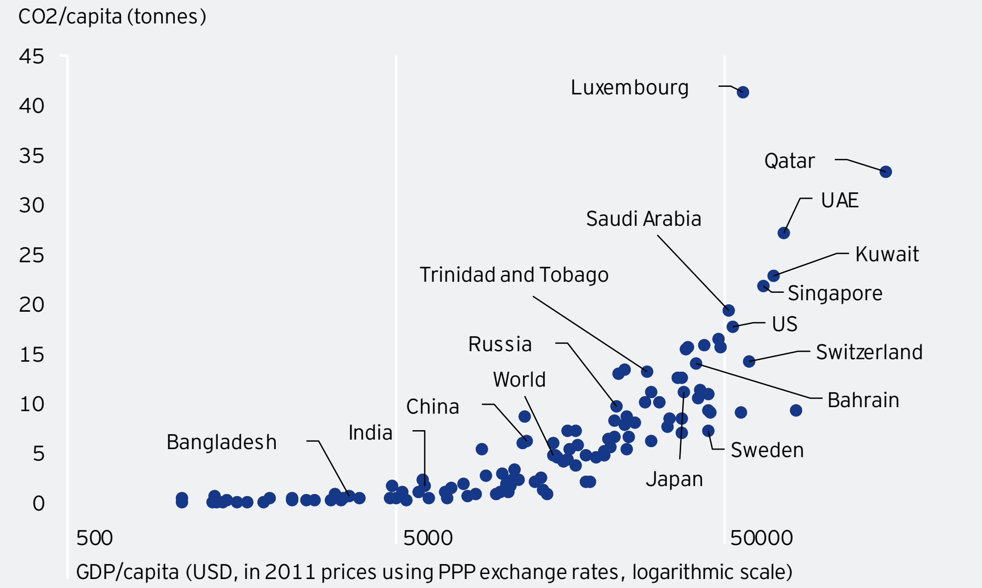
This seems unfair, as many countries sub-contract their polluting elsewhere. Effectively, they appear to generate a small amount of emissions but only because they buy a lot of energy and goods from other higher-polluting countries. Given that somebody has to produce the goods, a fairer way to judge national emission levels is by looking at what is consumed rather than what is produced (this is done by taking account of trade). This better captures the climate effect of their lifestyles.

Figure 39 shows the result of such an approach (the consumption approach data is not available for all countries, hence there are fewer dots). On this basis, energy producing nations have a CO2 intensity more in line with their income level (compare, for example, the positions of Qatar and Trinidad and Tobago in both charts). Nevertheless, it still shows the massive challenge of limiting total emissions while poor countries move up the development and income ladder.

In the other direction, Luxembourg is the most visible example of a rich country with CO2 intensive habits but which subcontracts the dirty work to other countries (it is 2.5 times more CO2 intensive on a consumption basis than on the traditional production basis). Switzerland is even worse (3.1x), with Hong Kong (2.9x) and Singapore (2.0x) not far behind. Sweden was less CO2 intensive than the global average on a production basis but is worse when measured by consumption (1.6x). The US is relatively balanced (1.1x), while China's status as the factory of the world means it looks better on a consumption basis (0.9x), as does India (0.9x).

But some countries sub-contract their dirty work

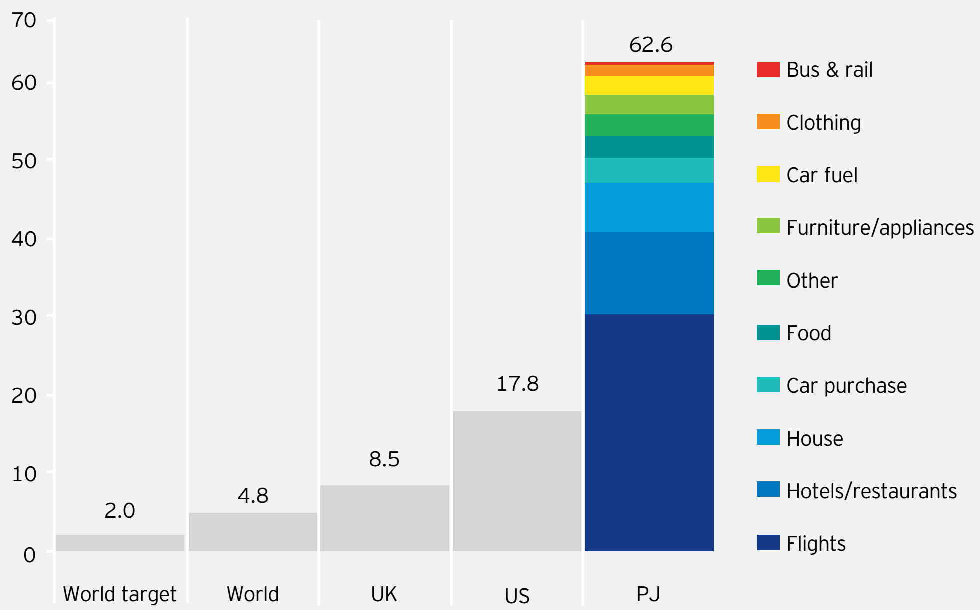
Figure 39 - Consumption CO2 emissions per capita versus GDP per capita in 2016



Notes: CO2 emissions are based on consumption in the country. Source: Peters et al (2012 updated), Global Carbon Project (2018), Our World in Data, United Nations, World Bank Development Indicators and Invesco

So, practically speaking, what do we need to do to reduce emissions? We know that most of the heavy lifting has to be done by the developed world and **Figure 40** gives an idea of what is involved by showing the carbon footprint of the author (Paul Jackson). The first thing that jumps out of the page is the scale of the problem, with carbonfootprint.com suggesting I am responsible for 62.6 tonnes of CO2 emissions per year, based on detailed inputs about my habits (with housing contributions being my pro-rated share) and being a UK resident. The results were cross-checked with The Nature Conservancy calculator, which suggested a similar outcome of 71 tonnes (but on the assumption I was based in Boston in the USA).

Figure 40 – Consumption based CO2 footprints (tonnes per year)



Notes: shows CO2 emissions based on consumption in the relevant country/area in 2016, except "World target" which is the long-term net-emission level we believe is consistent with limiting the temperature gain to two-to-three degrees (scenario D in the previous analysis). "PJ" shows the annual carbon footprint of one of the authors of this report (Paul Jackson), calculated using carbonfootprint.com and using a pro-rated share of housing elements. Source: Peters et al (2012 updated), Global Carbon Project (2018), Our World in Data, United Nations, World Bank Development Indicators, carbonfootprint.com and Invesco

In my defence, around two-thirds of my carbon footprint is work related (30 tonnes come from around 40 return flights and another 10 from hotels and restaurants). This suggests an obvious way for me to cut CO2 emissions would be to do less journeys. It is hard to imagine cutting out all personal contact but the day will surely come when technology will allow us to do presentations from London, while seeming to be in a room in another (or multiple) countries.

Otherwise, it is still daunting to see the carbon footprint from my share of running one house (6.4 tonnes per year), buying a car once every five years (3.1 tonnes per year), running the car (2.5), furnishing the house by replacing furniture and appliances once every 10 years (2.5), feeding myself on a low-meat diet (3.1) and clothing/shoeing myself (1.3). On the plus side, I do most of my commuting and travelling around London by train (0.4) and I reckon that food estimate is on the high side (Shrink That Footprint puts the CO2 footprint of the average US diet at 2.5 tonnes, ranging from 3.3 for meat lovers to 1.5 for vegans – cutting out beef and lamb is the easiest way to reduce emissions). The enormity of the task confronting the world is shown by the fact that a vegan diet in the US generates 1.5 tonnes of CO2 per year, which leaves little room before hitting the target world per capita emission of 2 tonnes.

Even if we could get down to the target level of emissions by changing lifestyle, it is not clear that it would be desirable to do so. If we all cut purchases to that extent in the short term, the global economy would crash. Rather, it seems the best we can sensibly hope for is to make incremental lifestyle changes and to progressively reduce the CO2 intensity of everything we do through technological innovation.

As seen earlier, such a scenario will still release massive quantities of GHGs into the atmosphere (and oceans) and still runs the risk of a rise in temperature in the two-to-four-degree range, with serious consequences. Hence, a successful strategy will involve carbon capture programmes to minimise the damage and adaptation necessary to cope with it.

Figure 41 gives examples of lifestyle changes that could reduce emissions, along with innovations that could help minimise the upheaval required to meet emission reduction targets. It also shows the likely broad implications of the changes.

Some concrete examples may help. We are all familiar with electric cars and many countries have mandated that hydrocarbon fuelled cars can no longer be sold beyond a certain date: Norway

(2025), Denmark (2030), Iceland (2030), Ireland (2030), Israel (2030), Netherlands (2030), Sweden (2030), France (2040), UK (2040, except for Scotland which is 2032). As is often the case on these matters, Costa Rica leads the way with a ban on hydrocarbon vehicles (not just sales) from 2021. China has said it will introduce a ban but has not specified from when. Tesla is perhaps the best known manufacturer of electric cars but most manufacturers are actively developing/ producing electric and hybrid cars

However, we are less familiar with the concept of electric planes. Zunum Aero (part financed by Boeing and Jet Blue) seemed like a good example, until it ran into financial difficulties (it is still seeking extra funding). Zunum's hybrid planes were designed to carry as many as 12 passengers up to 500 miles (principally powered by electric batteries but with top-ups possible from fuel). Eviation is an Israeli start-up that has developed a nine-seater, all-electric aircraft that can fly 650 miles (the Alice was described by its CEO at the 2019 Paris Air Show as a "huge battery with some plane painted on it"). Eviation uses motors from Seattle-based magniX, which has also developed an electric motor that can replace traditional motors in small planes. As an aside, magniX reckons that 45% of all flights are less than 500 miles.

Figure 41 - What can we do in our daily lives? Some examples

	Lifestyle changes	Innovations	Implications
Energy (46% of emissions)	Less heating (wear jumpers) Less air conditioning Lengthen durable goods cycles Fuel efficient/smaller cars	More efficient solar panels More effficent wave, tidal and current power More efficient electricty transmission More efficient air conditioners Building design (less AC and heating) Safer nuclear generation & disposal Carbon capture and storage	Increased R&D Less consumer demand Lower demand for fossil fuels/ lower real prices Higher demand for battery ingredients (lithium, cobalt, manganese, etc) Lower profitability for energy intensive activities Healthier lifestyle
Agriculture, land use & forestry (23% of emissions)	Waste less food Eat less meat and dairy Buy local produce Go paperless/recycle Lengthen furniture cycles Buy land/plant trees	Appetising alternatives to meat/ dairy Food and nutrition education at school Forestry investment funds Faster growing trees (to speed capture process) Pay landowners to plant/keep trees	Less demand for meat/dairy Smaller herds/flocks Higher land prices (for forestry use) Higher wood/paper prices Healthier lifestyle
Transport (11%)	Less flying/sailing Work from home Stay at home vacations Use public transport More walking/cycling	Lighter materials (planes, trains & automobiles) Battery technology (planes, ships and autos) Electric cars, ships & planes Hologram remote conferencing facilities	Increased R&D Less profitable/more expensive transport provision Increased public transport investment Investment in car charging point networks Healthier lifestyle

Source: Invesco

According to the International Energy Agency (IEA), the global stock of air conditioners (AC) will grow from 1.6 billion in 2018 to 5.6 billion in 2050 (see "Air conditioning use emerges as one of the key drivers of electricity-demand growth"). Air conditioners and fans use around 20% of the total electricity used in buildings around the world or 10% of total electricity consumption. AC use is expected to become the second largest source of electricity demand growth (after the industrial sector) and the strongest driver for buildings by 2050. There are already differences in the energy efficiency of AC units (those sold in Japan and the EU are typically 25% more efficient than those sold in the US and China), so introducing global standards could make a big difference to electricity consumption and GHG emissions (likewise for building standards to avoid the need for AC in the first place).

Making existing technology more efficient would be a start and innovations such as "smart" AC systems could help. However, the real prize would be revolutionary AC technology, for example: solar powered AC units (solar panels can also have a cooling effect on roofs); geothermal heating and cooling systems could be incorporated into new buildings and use the constant temperature below the surface of the earth (6 feet below, say) to either heat or cool depending on the season; a team at the National University of Singapore has developed a water based AC system that uses 40% less energy than traditional compression systems and contains no hydrofluorocarbons (HFC's); similarly, a team at the Denmark Technical University has developed magnetic fridges that use 30-40% less energy (and no HFC's), technology that can be applied to air conditioning (a US company called Astronautics is working on such AC applications). The problem, as ever with new technology, is that existing AC technology has been around for long enough to become comparatively cheap. Government taxation and subsidy polices may be needed to give the new technology a chance.

Nevertheless, if real progress is to be made, we need to find cleaner forms of energy. According to the BP Statistical Review of World Energy 2019, 15% of the world's energy came from non-carbon emitting sources (nuclear, hydro-electricity and renewables). That ratio was 35% if we focus on sources of electricity generation (16% hydro-electricity, 10% nuclear and 9% renewables). Henceforth, when we refer to renewables, we are including hydro-electricity.

The rapid replacement of carbon emitting sources of energy (coal, oil and gas) must be a big part of any mitigation strategy. However, nuclear brings its own long-term risks, while renewables depend upon the supply of water, wind, waves, sunshine etc and they may not be available everywhere, though, one or other is usually present.

The biggest issue for renewables has historically been cost. However, according to the International Renewable Energy Agency (IRENA): "Electricity from renewables will soon be consistently cheaper than from fossil fuels. By 2020, all the power generation technologies that are now in commercial use will fall within the fossil fuel-fired cost range, with most at the lower end or even undercutting fossil fuels." (see IRENA's "Renewable Power Generation Costs in 2017" publication).

According to IRENA, the cheapest renewable source of energy is hydro, with a global weighted average cost of new hydropower plants commissioned in 2017 around USD 0.05 per kilowatt-hour (kWh), which is at the lower end of the range for fossil-fuel powered electricity in 2017 (USD 0.05-0.17/kWh). Onshore wind plants (USD 0.06/kWh) and bioenergy and geothermal projects (USD 0.07/kWh) were not much more expensive.

Technology has played a critical role in the reduction of renewable costs. For example, driven by an 81% decrease in solar photovoltaic (PV) module prices since the end of 2009, the global weighted average cost of utility-scale solar PV fell 73% between 2010 and 2017, to USD 0.10/kWh (according to IRENA). Solar cell and module manufacturing are dominated by Chinese companies (such as Jinko Solar, JA Solar and Trina Solar) but non-Chinese companies are present in the market, with Canadian Solar and First Solar being good North American examples (based on PV Tech and Solar Media rankings for 2018).

Sahara desert solar power could supply the world with electricity but...

According to IRENA, offshore wind power and concentrated solar power (CSP) are still in their infancy. The global weighted average cost of offshore wind projects commissioned in 2017 was USD 0.14/kWh, while for CSP, it was USD 0.22/kWh. However, costs are falling rapidly: auction results in 2016 and 2017, for CSP and offshore wind projects that will be commissioned in 2020 and beyond, show costs falling to between USD 0.06 and USD 0.10/kWh.

One of the big remaining challenges for renewables is that they are unable to offer a constant supply and electricity is difficult to store. Hence, they can be used to supplement electricity supply but cannot form the core of a supply strategy. However, technology may change that. For instance, it has recently been announced that UK company Highview Power will use cryobattery technology to build Europe's largest long-term energy storage facility (renewable electricity is used to chill air to -196C, transforming it into a liquid that can be stored and then turned back into gas when needed to turn a turbine and generate electricity). Hence, it can "store" excess electricity that can then be used when supply is low.

A further issue is that of transmission (getting the electricity to where it is needed). For instance, it is often said that Sahara Desert solar power could supply the world's electricity needs many times over. Apart from the effect on the local environment (it is thought it could cause cloud formation and greening of the desert), the big issue has been transmission of the resultant electricity. However, Siemens and ABB have worked together on a project in China that transmits high-voltage direct current (HVDC) over nearly 2000 kilometres (enough to get electricity from the Sahara to Europe). Technological solutions may be at hand.

Capturing emissions

If we continue to rely on polluting sources of energy, one solution is to capture CO_2 and other GHGs at source, with the use of scrubbers at power stations and industrial plants. Such technology has been around for decades (originally to limit sulphur dioxide emissions and acid rain) and is getting more efficient. However, researchers at the University of Michigan reckon that such technology is unlikely to be viable at large scale due to the energy required in the carbon capture process (see "*The latest bad news on carbon capture from coal power plants: higher costs*" by Sarang Supekar and Steve Skerlos, 2015).

Short of technologies to reduce emissions, we may need to rely on the removal of CO_2 and other GHG's from the atmosphere. Carbon capture and storage has been used for decades in spacecraft and submarines but has also been developed to remove CO_2 from the atmosphere (air is sucked into a machine and CO_2 is captured by a sorbent material and then heated, isolated and stored, with the sorbent material then ready for use again). Such machines have been proven to capture significantly more CO_2 than results from the generation of the energy necessary to power the system, so could form the basis of large carbon removal systems. The stored CO_2 could simply be "buried" deep underground but could also have commercial applications: in greenhouses to encourage plant growth, in natural gas exploitation to drive out the gas or be transformed into fuel for buses, say. Swiss company Climeworks launched the world's first direct air capture facility in 2017, aiming to capture 900 tonnes of CO_2 per year (equivalent to the output of 200 cars), which is then sold to a local vegetable producer. They have since launched other facilities (including one with underground sequestration in Iceland) and have a stated aim to capture 1% of the world's CO_2 emissions by 2025.

350mn

Trees planted by Ethiopia in one day

Of course, the technology already exists to remove large quantities of CO_2 from the atmosphere: the tree. According to researchers at the Grantham Institute (Imperial College), the average tree absorbs one tonne of CO_2 during its lifetime (assumed to be 100 years). Ethiopia announced that it planted 350 million trees in a day (29 July 2019) and aimed to have planted 4.7 billion trees by October 2019, capable of removing 4.5-5.0 bn tonnes of CO_2 during their lifetime (the UN reckons that forest cover in Ethiopia fell from 35% of total land area in the early 20th century to around 4% in the early 2000s).

It is commonly thought that one of the advantages of climate change is that it will increase tree growing potential, particularly in parts of the Northern hemisphere (see **Figure 42**). However, business-as-usual losses in rainforest areas (particularly the Amazon) are expected to outweigh those gains. Researchers at the Crowther Lab in Zurich reckon that a net 223 million hectares of forest could disappear due to climate change by 2050 (compare this to the 5 million hectares that we reckon were planted in Ethiopia during 2019 and the existing 2.8 billion hectares of global canopy cover). Hence, even without human deforestation (around 7.5 million hectares per year according to WWF), there is a risk that tree cover could decline if more countries do not behave like Ethiopia.

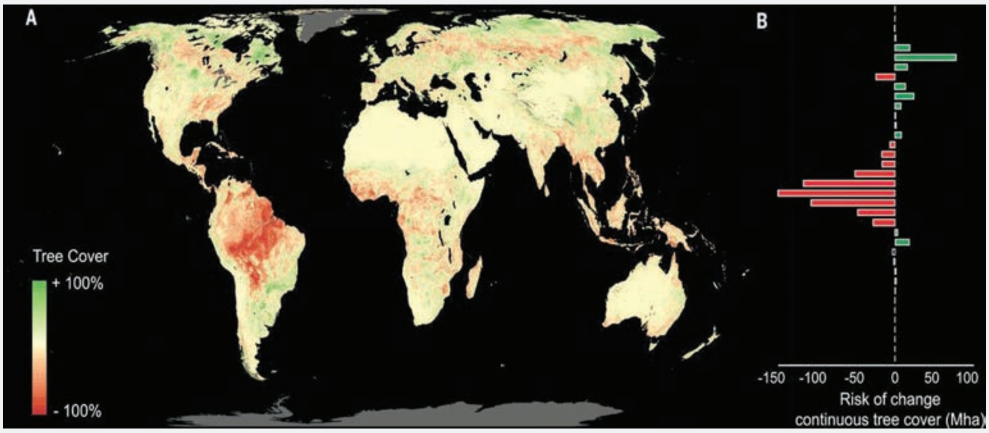
Luckily, The Bonn Challenge of 2011 (later extended at the 2014 UN Climate Summit) set a challenge to restore 350 million hectares of deforested and degraded land by 2030 (an area larger than India that could eventually absorb up to 1.7 bn tonnes of CO_2 per year). However, the UN's IPCC Special Report of 2018 suggests an increase of 1 billion hectares of forest would be needed to limit global warming to 1.5 degrees by 2050; the sooner the better. Is such an increase feasible? Well the above referenced Crowther Lab report concluded that 0.9 billion hectares of land outside urban and agricultural areas could support new forests under current climate conditions (versus the 2.8 billion hectares that already exist). That is an area almost as large as the US and the six countries reckoned to have the greatest capacity are: Russia (151 million hectares), US (103), Canada (78), Australia (58), Brazil (50) and China (40). If this area were planted with trees that are allowed to mature, the authors estimate it would absorb 750 billion tonnes of CO_2 (our conversion from their 205 billion tonnes of carbon calculation), which is around 20 years' worth of global emissions at the 2018 rate and is almost enough to close the gap (816 billion tonnes) between scenarios C and D in **Figure 36**. Put another way, mass planting of trees could help us to limit the eventual temperature gain to two to three degrees, without the need to suppress growth (or radically change lifestyles).

900bn

Trees that could be planted, enough to avoid the need to suppress GDP growth

How much would such an endeavour cost? The budget in Ethiopia was nearly $1.5bn for 4.7 billion trees (around $320 per hectare, assuming 1000 trees per hectare). However, Ethiopia has the advantage of low-cost labour and other cost estimates range from $500 to $1500 per hectare. If we assume a global average of $1000/hectare ($1/tree), the cost of meeting the Bonn Challenge would be $350bn or $23bn per year, if spread over 15 years. The cost of the full 0.9bn hectare project would be $900bn, which is $30bn per year if completed by 2050 or $60bn per year if done by 2035. Those annual costs are 0.035% and 0.07% of 2018 global GDP, respectively, which seems small compared to the extra economic growth (0.7% per year) that it would allow while still keeping temperature gains at a manageable level (2-3 degrees).

Figure 42 – Risk assessment of future changes in potential tree cover



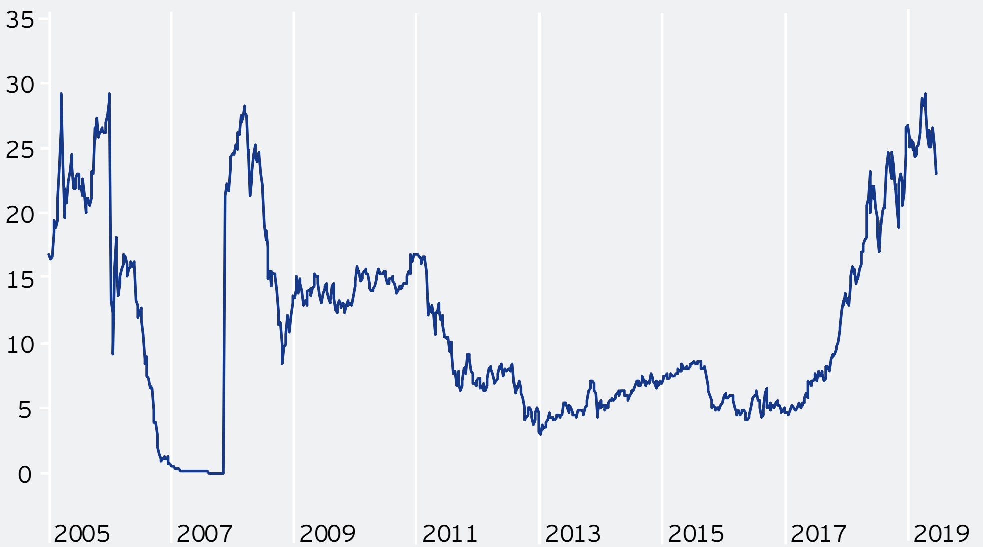
Notes: (A) Illustration of expected losses in potential tree cover by 2050, under the "business as usual" climate change scenario (RCP 8.5), from the average of three Earth system models commonly used in ecology (cesm1cam5, cesm1bgc, and mohchadgem2es). (B) Quantitative numbers of potential gain and loss are illustrated by bins of 5° along a latitudinal gradient. Source: Crowther Lab, Department of Environmental Systems Science, Institute of Integrative Biology, ETH-Zurich (published in Science Magazine on 5 July 2019)

The ultimate market failure: putting a price on carbon

The Stern review reckons "climate change is the greatest market failure the world has ever seen". For example, the cost of an airline ticket will reflect the cost of the aircraft, fuel, staff, inflight services and airports but will not reflect the cost of dealing with the environmental damage occasioned. If these externalities are not accounted for, somebody else will have to pick up the bill for dealing with the damage. Government action is usually required to change behaviours, either directly by regulation or indirectly via financial signals such as taxation (polluter pays principle, for example).

Some form of carbon tax seems the obvious way to do this in the case of GHG emissions. In theory, making consumers pay a supplement that forces them to allow for the environmental cost of their actions would lead to a change in behaviour that would reduce emissions. However, taxes are never popular, are difficult to calibrate and countries can always use them as a competitive weapon (by driving taxes lower). Emissions trading systems (ETS) are designed to tackle some of these problems: each country or region decides how many tonnes of carbon can be emitted collectively by a set group of production facilities (including airlines) within a year and issues the corresponding number of permits (which should be on a declining trend). The permits are then traded among users, with the market setting the price according to demand and supply (a price which should eventually be reflected in the final price of goods and services). Those users with insufficient permits at the end of the year to cover their actual emissions will face heavy penalties. Such a system reduces emissions (by successively reducing the number of permits issued) but allows the market to decide the best way of doing so and directs investment toward less polluting activities (the most carbon intensive activities will eventually be forced out of business).

Figure 43 – The price of carbon in the European Union (€ per tonne)



Notes: From 22 April 2005 to 4 October 2019. Based on the ICE ECX EUA Daily Futures Contract, which shows the price of buying EU allowances (EUA) on the European Climate Exchange (ECX). One unit gives the right to emit one tonne of carbon. Past performance is no guarantee of future results.
Source: Refinitiv Datastream and Invesco

The Stern Review calculated a social cost of carbon on a business-as-usual trajectory of $85 per tonne. If such a carbon price were imposed, Stern calculated that it would add around 1% to consumer prices in an economy such as the UK. The price of carbon permits on the oldest ETS (EU) has never scaled such heights, as shown in **Figure 43**. It was originally thought the price would trend higher as permit numbers were reduced but carbon intensity seems to have fallen as quickly, thus allowing relative price stability (although it has increased approximately five-fold since mid-2017). There is not yet a global ETS market but rather a range of national and regional initiatives (California, Chinese regions, EU, New Zealand, Quebec, South Korea, Switzerland, US Regional Greenhouse Gas Initiative (RGGI), for example), with end-May 2019 prices ranging from US$5.8 per tonne in the US RGGI to US$27.3 in the EU (International Carbon Action Partnership). Perhaps one day permits will be tradeable across regions and maybe a more rapid reduction in permits will force prices higher (and GHG emissions lower).

Adaptation: living with the consequences

If all else fails, we will just have to live with the consequences of climate change. The earlier "How bad could it become" on page 39 shows some of the likely consequences of a rise in global temperatures. The Stern Review emphasised that adaptation may be costly but that without it the economic outcomes would be even worse. Hence, it is an investment worth making. Given that poorer countries are likely to suffer the worst consequences, adaptation spending should be focused there, though that will rely on transfers from rich countries.

Examples of adaptation actions include: changing crop planting dates, installing irrigation systems, refusing planning permission in flood plains, infrastructure spending (reservoirs, drainage systems, sea walls), early-warning systems, insurance to pool risks (high risk, low probability events), weather derivatives (low risk, high probability events). Some of this will be done autonomously by individuals but much will require public sponsorship.

Adaptation will cost money but will offer opportunities for several industries:

- Agricultural suppliers (seed technology) and agro-chemicals
- Construction (housing and infrastructure)
- Finance (insurance and derivatives)

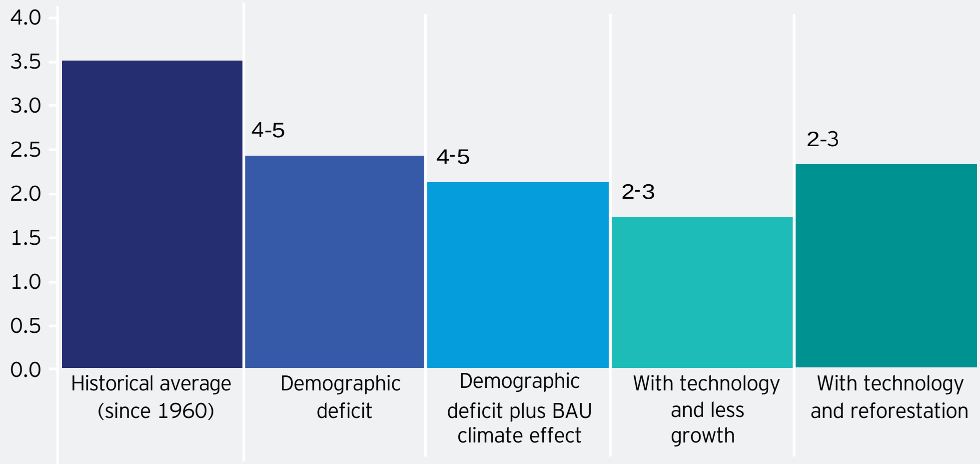
Climate change versus economic growth

As we have already identified, there is a natural trade-off between global economic growth and the extent of global warming. The nature of that trade-off can be changed by technological innovation/ lifestyle changes. Large-scale reforestation can also offset much of the damaging effect of that growth, thus buying us some time.

To put some numbers on this trade-off, The Stern Review estimated that if no action is taken, the net economic cost could be 5% of world GDP each year, forever (and could be as high as 20% if all risks are considered). On the other hand, it estimated that the cost of stabilising CO2 at 500-550 ppm (thereby avoiding the worst effects) could be 1% of GDP per year (costs grow with delay). On that basis alone, it would appear the necessary investments are worthwhile.

Figure 44 uses our own analysis along with the worst-case Stern Review BAU scenario. Shifting demographics alone is enough to pull global GDP growth down from the post-1960 average of 3.5% to 2.4% annualised to 2100.

Figure 44 – World GDP growth to 2100 under various scenarios (% annualised)



Notes: Numbers shown above bars are our estimate of eventual global temperature change versus the 1850-1900 average. "Historical average" is the annualised growth in real GDP between 1960 and 2018. "Demographic deficit" shows the effect of simply allowing for less population growth. "Demographic deficit plus BAU climate effect" adjusts the "Demographic deficit" estimate by the economic cost of a business-as-usual approach (worst-case Stern Review analysis). "With technology and less growth" adjusts the "Demographic deficit" numbers by assuming a combination of aggressive technological advancement and suppressed economic growth (as per Scenario D in Figure 35). "With technology and reforestation" adjusts the demographic deficit forecast by assuming aggressive technological innovation and massive reforestation (0.9bn hectares). Source: World Bank, The Stern Review (2006) and Invesco

However, that is not the end of the story: if we continue with business as usual (by which we mean carbon intensity falls in line with recent trends), we reckon the world would be on course for a four-to-five degree rise in temperature. That would reduce global GDP growth to 2.1% (based on our interpretation of the Stern Review worst case scenario). So, we would have to deal with a four-to-five-degree temperature change and would have less growth with which to finance the necessary adaptation measures.

However, if we adopt a more optimistic view of technological progress (more aggressive investment and a steeper path of carbon intensity reduction), along with suppressed growth (perhaps due to carbon pricing and taxation), the eventual temperature gain could be limited to two-to-three degrees but annualised GDP growth would be only 1.7%. Note that we are assuming no net contribution to growth from investment spending, simply that spending is skewed towards carbon efficient technology.

It is our view that a similar climate outcome could be achieved without the suppression of growth, if there were an aggressive reforestation programme (0.9bn hectares over the coming decades). We suspect such a path would see global GDP growth of around 2.3% (close to but just below the 2.4% baseline, given the costs involved).

In the end, the world must choose. It may be tempting to believe that the best path is a business-as-usual approach as that seems to deliver decent growth. However, such an approach risks even worse climate outcomes than suggested in **Figure 44**, as feedback loops produce unpredictable outcomes (a five-degree temperature change would take us outside anything ever experienced by humans). Also, such an outcome would entail big disruption and costs for large parts of the world's population. The outcomes listed in **'How bad could it become' (p.39)** assumed an average global temperature gain of 2-4 degrees and we think it is safe to assume more dramatic effects at higher temperatures (including damage to ecological systems that could render human life more difficult).

In our opinion, even if there is a risk that climate change is not being caused by humans, behaving as though that were the case is too risky, given all the evidence. In truth, we believe we are already on a path toward a two-to-three-degree temperature change and how much we go beyond that depends upon current choices. We suspect it will be difficult to avoid going beyond three degrees but that if we are to do so, the solution will involve a mix of technological innovation, changes in life and work patterns and mass reforestation. We therefore suspect that annualised global GDP growth will be in the 2.0%-2.3% range over the rest of this century, down from the 3.5% seen since 1960.

Given the above, we draw the following investment conclusions:

- Global economic growth is likely to be lower than it would otherwise be, whether we do nothing or whether we try to mitigate the effects. This suggests lower ceteris paribus returns on assets such as equities and real estate than would otherwise have been the case.
- Given the global warming that we think is already "baked-in", we believe it would be wise to review exposure to real estate in coastal plains (exposure could be in the form of ownership of assets or the provision of insurance). Apart from obvious problem areas such as Bangladesh, the Netherlands and low-lying islands, it should also be remembered that many major financial centres are near the sea (Hong Kong, London, New York and Tokyo, for example). Also, large parts of the US Eastern Seaboard are under threat (including Florida golf courses), especially given that tropical storms are likely to become more frequent. Insurers are likely to suffer losses but are also likely to see higher demand, curtail cover and/or increase premiums.
- Infrastructure spending is likely to be boosted by adaptation spending, as dams, drainage systems and sea defences are built (or reinforced). This suggests large-scale construction companies are likely to benefit.
- Reforestation activity could boost the demand for (and price of) suitable idle land. Based on tree-planting capacity and the cost of farm land (as a proxy), we would focus on Australia, Brazil, Canada and the US.
- Existing forests can also provide investment opportunities and can be accessed via quoted forestry companies, notably in countries such as Canada, Finland and Sweden, with forestry REITs also available in the US. Such companies are a double-edged sword in that their business is usually the management of forests with the aim of supplying paper, timber and other wood products. For current purposes, we would seek those that increase forestry acreage over time (and not simply by buying existing forests), that leave a proportion of trees to die naturally and that are energy efficient (another problem for this industry). Reforestation also calls to mind the multitude of tree-planting services that offer carbon offset opportunities. However, they are mainly not-for-profit or not quoted, as are many tree suppliers. As an aside, there is a search engine called Ecosia that donates part of its profits to tree planting (they have so far planted more than 70 million trees and on average it takes 45 searches for another tree to be planted).

- Technology is likely to be at the forefront of the fight against climate change but not technology as many investors think of it. We are not talking about FANG-type companies but rather those that reduce the carbon intensity of economic activity in spheres such as solar panel technology, battery technology, electricity distribution networks, electric cars and aircraft, AC technology, CO2 scrubbers and extractors. We have given some examples but there are (and will be) many more. For example, BioCarbon Engineering aims to plant 500 billion trees by 2060 with the help of drones to map-out areas of forest (or potential forest), plant seeds/saplings and monitor growth (it currently operates in the UK and Australia). Many such companies are not publicly quoted, seek early stage financing and accessing them will require more of a venture capital/private equity approach. We would anticipate a constant search for companies that can make a real difference, on a large scale.
- Carbon allowances could be one way to capture future rises in the price of carbon (assuming it does rise) but requires management like any other futures contract (roll-overs etc.) and we would expect a cyclical element to the price (the demand for carbon rises with economic activity). However, assuming governments reduce the supply of certificates faster than economic activity would justify, the price should trend upward.
- Of course, there are assets that we would avoid because the businesses are unlikely to survive the move to a low carbon environment. However, in many cases it will be incumbents that continue to supply the lower carbon versions: for example, the suppliers of internal combustion engines for cars (the major auto companies) are likely to be the suppliers of most electric cars. The problems faced by Tesla are testament to how difficult it is to break into such a market, even with leading technology. Also, many (but not all) suppliers of renewable energy are also suppliers of old energy (both utilities and energy companies).

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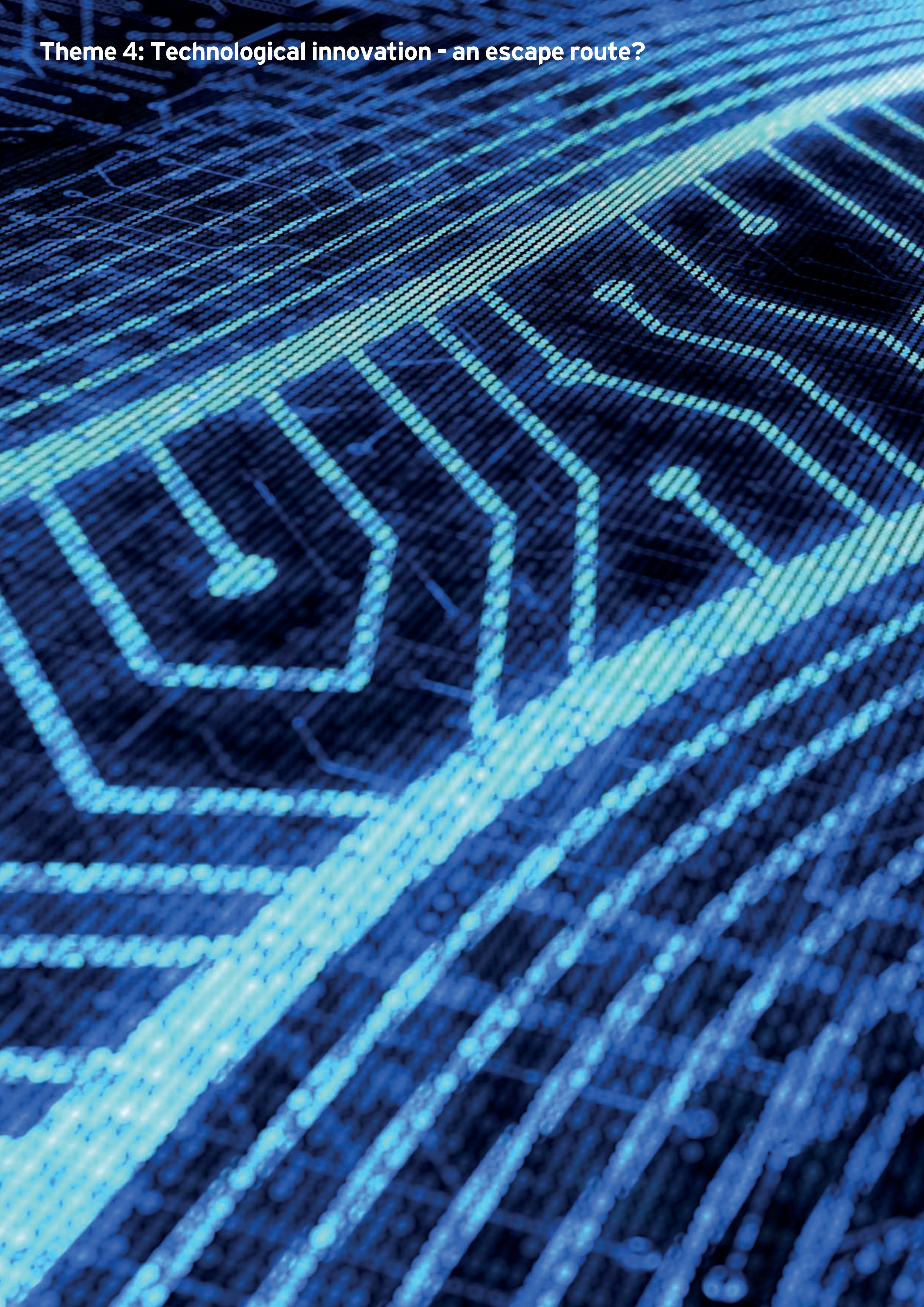
Theme 4: Technological innovation - an escape route?



Theme 4: Technological innovation - an escape route?

Earlier sections were all linked to innovation in one way or another: low interest rates could encourage investment spending in general, including research and development activity; low population growth (shrinking populations in some cases) could encourage labour replacing innovation out of necessity rather than choice and the mitigation of climate change will rely heavily on technological innovation. Indeed, in the chapter on climate change we suggested that innovation over the coming decades will be skewed towards the enhancement of carbon efficiency, in order to maintain lifestyles while having the least possible effect on the world's climate. In what follows, we examine the history of technological innovation and how it has impacted productivity, economic performance, the demand for labour and the distribution of income and wealth.

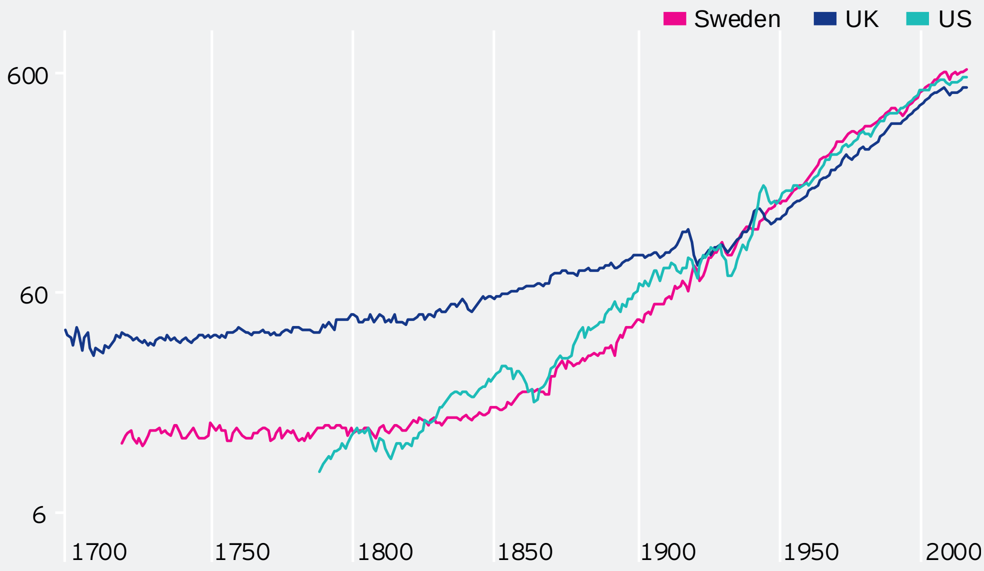
Technological change and innovation have been a permanent feature throughout human history. It has variously inspired awe and fear and we think fear of technological change is once again a dominant sentiment. Many, especially in the developed world, are now afraid they will cease to be useful or even necessary, if machines driven by artificial intelligence are able to replace humans in the workplace. In our opinion, this stems from the nature of the technological change that we are experiencing at the moment.

Technology can be labour saving or labour enhancing

As Carl Benedikt Frey outlined in his book, The Technology Trap, we can categorise technological innovation depending on how it impacts labour markets: it can either be labour-enhancing or labour-replacing (we will use his analysis as our framework for the rest of this chapter). The current wave of technological change, dubbed the Fourth Industrial Revolution, featuring artificial intelligence-enabled and networked computers and gadgets, seems to fall into the latter category. A variety of estimates circulate on what proportion of jobs can and will be replaced by these machines but the consensus is that the change will be significant and that it will eventually include jobs currently requiring a university degree.

For economists, technological innovation is about productivity and its rate of growth. New technologies allow economies to produce more output with less factors of production (labour and capital). They also explain the changes in trend economic growth that cannot be explained by developments in population and international trade. **Figure 45** suggests there was an acceleration in productivity in the late 1800s (and in the UK post-WW2). Based on Frey's framework, labour-enhancing innovations tilt the balance of power towards labour (wages rise), while labour-replacing technologies favour capital (and its owners, who reap higher returns). However, once labour adjusts to new technologies by acquiring the skill set required to lever them, previously labour-replacing technologies generate new jobs and the balance tilts back towards labour. However, this adjustment can take decades and may even last several generations, resulting in resistance from those who may lose out (think previous centres of manufacturing in the Developed West and the rise of populism). This reticence could slow the adoption of new technologies.

Figure 45 - Real GDP per capita 1700-2015 (logarithmic scale, 1929=100)



Notes: Annual data based on GDP in local currency. Rebased to 100 in 1929.
Source: Global Financial Data, United Nations and Invesco

Innovation has been random and unpredictable but for most of the pre-First Industrial Revolution period, the ruling classes actively prevented the adoption of labour-replacing technologies for fear of revolution from the unemployed masses (see the flat GDP per capita prior to 1850 in Sweden and the UK in **Figure 45**). Also, for most of this period, economic growth simply resulted in higher populations, so per capita incomes barely improved, which perhaps limited the enthusiasm for innovation. Finally, labour costs were low in an era of mass slavery in antiquity and serfdom in the Middle Ages (at least in Europe). Slaves were unable to purchase more than required for mere subsistence and serfs were not much better off. At the same time, the nobility could afford artisan goods and were not troubled by their scarcity.

What finally enabled the First Industrial Revolution was the reversal of all these variables in 17th century Britain, enabled by the growth in global trade. This also kickstarted an age of rapid technological innovation that resulted in economic and population growth. It also created a relatively affluent middle class, that nevertheless had to work for a living and to acquire new or improved skills. As these merchants acquired more political power and leadership their interests became aligned with those of innovators. International trade expanded potential markets, thus boosting the upside for entrepreneurs. International trade also pitted kingdoms and empires against each other as competing suppliers. Military power more or less equalled economic power and innovation had the potential to provide a competitive edge. Finally, the Age of Enlightenment elevated the relative importance of science, which continued developing throughout the 18th and 19th centuries.

All the above factors were necessary for the first wave of labour-replacing technologies to spread en-masse across Britain, the first country to industrialise. Interestingly, the new machinery and steam power were not necessarily the real enablers of higher returns on capital. It was a novel way to organise production, the factory system, that enabled new technologies to replace humans.

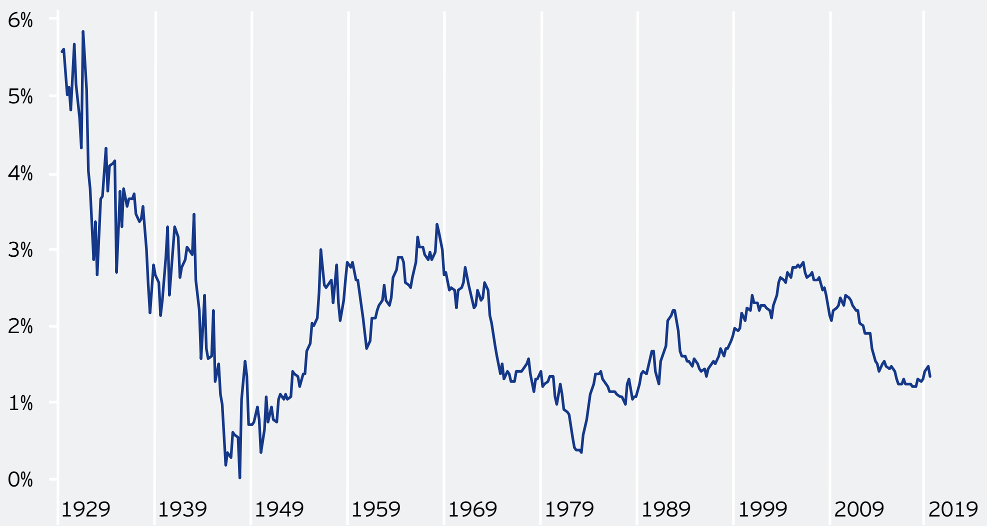
Nevertheless, even though factories put highly skilled artisans out of jobs, the new machines still needed operators. Since they were easier to operate, highly skilled adult males were replaced by women and children in the labour force. Though machines did not necessarily replace humans, it seems they resulted in the replacement of expensive labour by cheaper labour. They increased the productivity of the textile industry when they were first introduced but this initially boosted only the income of the factory owners (in other words, the owners of capital).

The adjustment was brutal. Robert C. Allen, the economic historian, referred to this period as "Engels' Pause". It required time before the new technology was embedded enough to increase productivity to the point where economic growth could raise the demand for labour. Also, workers needed time to learn the new skills required to participate in the labour market, a process which created previously unheard-of jobs. In Britain, between 1780 and 1840, output per worker grew by 46%, while real weekly wages increased by only 12%. In the period 1760-1830, average working hours rose by 20%, which suggests a more modest gain in productivity and a decline in real hourly wage rates. Based on food consumption and data on adult height, living standards are thought to have declined in the late 18th-early 19th century. In the meantime, the rate of profit doubled, the capital share of income expanded, and the income share captured by the top 5% almost doubled from 21% in 1759 to 37% in 1867. It was not until the second half of the 19th century that this new technology became labour-enhancing, with productivity and wages increasing in the whole economy. Literacy rates and average years of schooling increased with the demand for skilled workers. In the end, new technology became more labour-enhancing than replacing, and in the period 1840-1900, output per worker increased by 90% and real wages by 123%.

The Second Industrial Revolution, characterised by electrification and the internal combustion engine (ICE), refined and turbocharged the factory system. Again, a new method of organising production, standardisation and increasing precision, led to higher productivity. However, these technologies benefited workers and employers alike.

Electrification provided a safer work environment and created manual jobs that were relatively easy to master, thereby increasing the demand for labour. The ICE replaced horses, who could not resist its adoption. These two technologies also entered the home, unlike steam power, thereby freeing up women to join the workforce. There was nevertheless a period of adjustment before productivity was boosted: productivity fell between 1919 and 1925 (Woirol, 2006, "New Data, New Issues", 481). However, machinery angst in the 20th century was cyclical and flared up only when unemployment increased for other reasons. It is difficult to pinpoint how much unemployment has been caused by technological progress but automation anxiety sprang from this period (first with automatic elevators but mostly linked to computerisation).

Figure 46 – US productivity growth since 1929 (10-year, annualised)



Notes: This chart shows a combination of the index of output per production worker manhour for US manufacturing industries in the period 1929-1946 and nonfarm business sector real output per person after 1947. Source: Global Financial Data, National Bureau of Economic Research, Federal Reserve Bank of St. Louis, Invesco

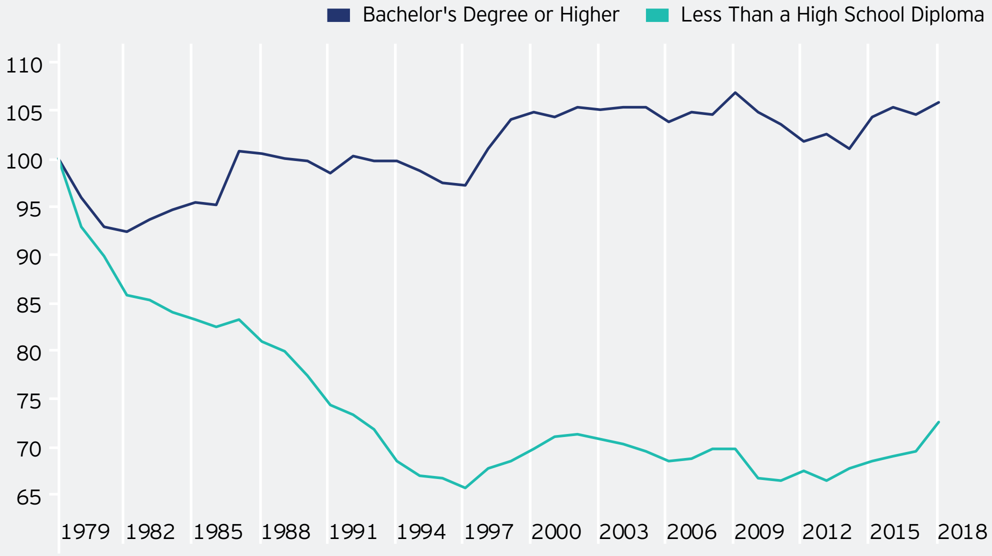
The second half of the 20th century saw the broadening of what we call the middle class. It was largely underpinned by strong productivity growth from the late-1940s to the late 1960s-early 1970s (**Figure 46**). A large proportion of this productivity growth can be attributed to workers shifting from agricultural jobs into factory and office jobs. This led to the mechanisation of agriculture, which boosted productivity even further. Unskilled and semi-skilled workers had access to good working conditions, stable jobs for decent pay, while labour unions provided a mechanism for settling disputes and making sure that labour shared the gains of progress, thus reducing inequality.

Recent decades resemble the first industrial revolution; not good for low-skilled workers

On the other hand, the last 40 years have seen a rise in anxiety and populism, because (we believe) they resemble the period at the start of the First Industrial Revolution. Since the 1980s, a wedge has grown between the pay of skilled workers and the rest but, more worryingly, middle class wages have stagnated or even fallen, at least in the US (**Figure 47**). Productivity growth has also struggled to return to the highs of the early post-war period (the brief uptick in the 2000s was probably driven by an unsustainable period of strong credit growth – see **Figure 46**). One of the keys to the lack of productivity growth, we suspect, is structural change in the labour market driven by new technologies. Admittedly, globalisation also plays a part further confusing the picture, but our current period of globalisation has been largely enabled by new technologies providing higher connectivity and faster real-time information flows via the internet.

The factory system and its enhanced version, mass manufacturing, broke processes down into standardised routine jobs, which were easy to learn for unskilled workers. However, these jobs are the easiest to "teach" computer-controlled machines, too, and therefore have been the most susceptible to automation. Even office jobs changed dramatically with the introduction of computers, and most employers now require university degrees to fill jobs that people with more limited educational backgrounds were able to carry out in the past.

Figure 47 – US median usual weekly earnings for full-time employees (rebased 1979 = 100, US CPI-adjusted)

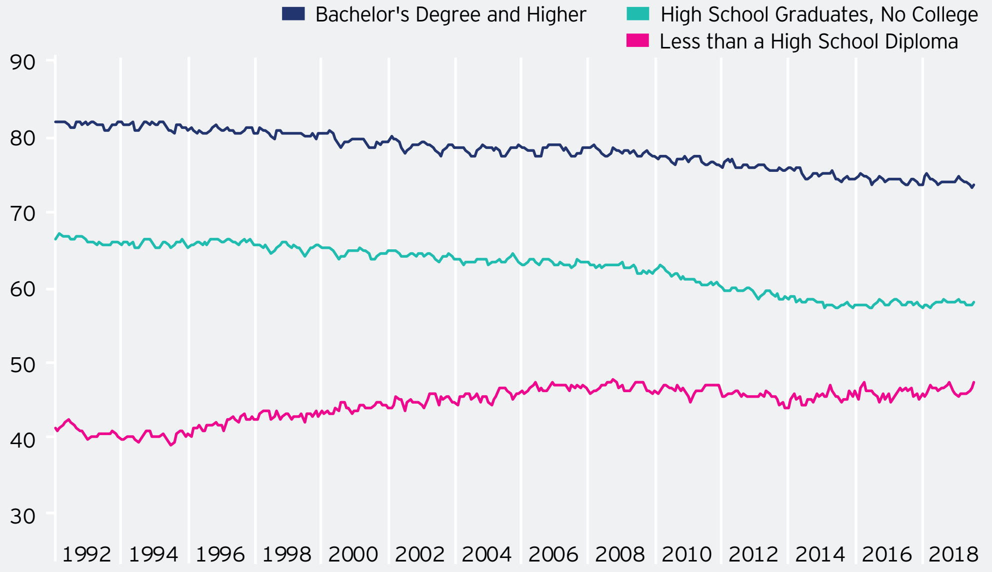


Source: Federal Reserve Bank of St. Louis, InvescoLouis, Invesco

However, there are limits to what computers and even artificial intelligence can learn currently. Machines need standardised processes and controlled environments. Any artificial intelligence-powered algorithm will only succeed using rich datasets with a high signal-to-noise ratio and processes where we can assume that the future will be like the past. This is because they are basically statistical engines on steroids that can adapt to how data is organised and can alter algorithms if new data changes statistical relationships. Machines at their current stage of development do not cope well with uncertainty, making decisions using few data points, interpersonal contact and navigating everyday human environments (like our homes, for example). A key bottleneck in automation remains what is dubbed as Polanyi's paradox: "We know more than we can tell". In other words, for many of the things we do, we struggle to define the rules that describe them.

This is good news for us strategists, especially considering Robert Reich's analysis published in his book, The Work of Nations. He classified jobs into three broad categories: symbolic analysts (knowledge workers), routine jobs and in-person services. Routine jobs are the easiest to automate (or outsource) and have been decimated in developed markets, leaving workers previously doing them little choice but to move into in-person services (for example waiting tables, care work, housekeeping etc). The latter are lower productivity and lower paid, which goes some way to explaining the current productivity and wage puzzles. By contrast, symbolic analysts and in-person services do not look to be endangered for now because they necessitate traits and skills that machines are currently unable to reproduce.

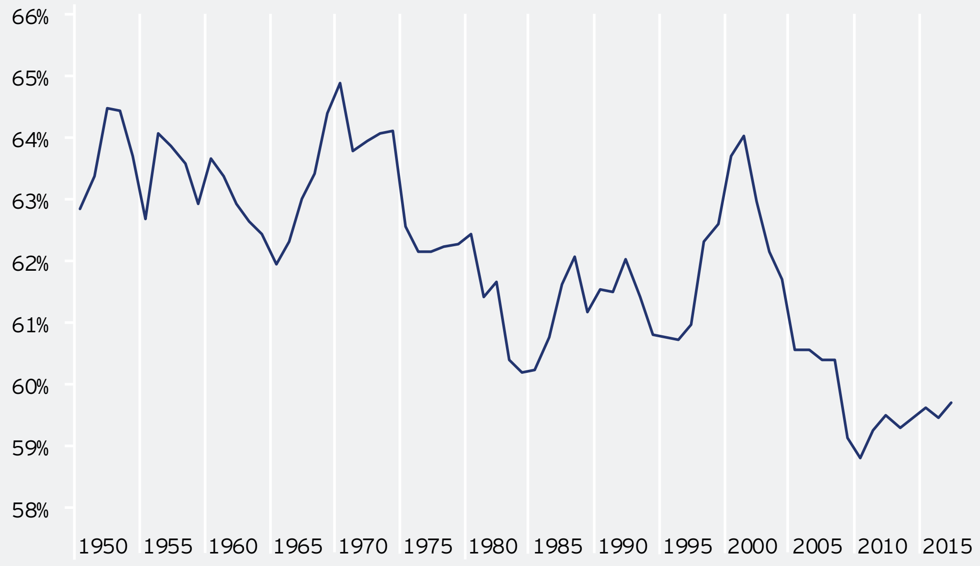
Figure 48 – US civilian labour force participation rate 25 years and over (%)



Source: Federal Reserve Bank of St. Louis, Invesco

Daron Acemoglu and Pascual Restrepo (2018) estimated that each multipurpose robot has replaced about 3.3 jobs in the US. A 2014 study by the Economic Policy Institute concluded that labour productivity has grown eight times faster than hourly pay since 1979 in the US. Real wages have been stagnant, more people are out of work (**Figure 48**) and the labour share of income has fallen (**Figure 49**). Based on work by Loukas Karabarbounis and Brent Neiman, most countries have experienced declines in the labour share of national income since the 1980s, perhaps due to cheap computers.

Figure 49 – US Share of Labour Compensation in GDP at Current National Prices

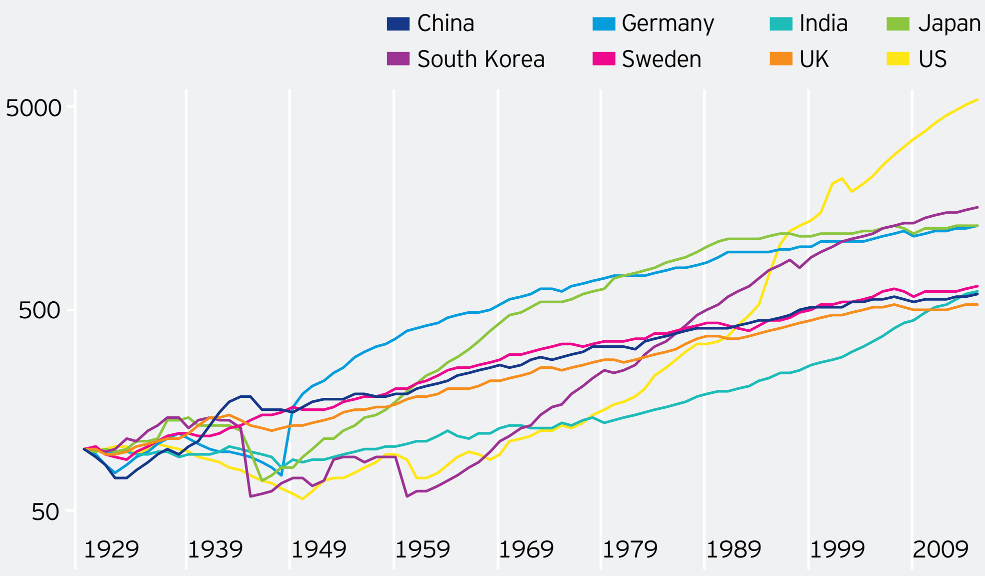


Source: Federal Reserve Bank of St. Louis, Invesco

All of the above suggests that we are at the early stages of the Fourth Industrial Revolution: we are still developing the complementary organisational and strategic changes needed to take full advantage of artificial intelligence, robotics and networking. If history rhymes with previous industrial revolutions, we can expect this adjustment to take at least 40-50 years. For example, according to Paul David, it took roughly 40 years for electricity to appear in the productivity statistics after Thomas Edison's first power station was constructed in 1882, while it took almost a century to reap the rewards of innovation during the First Industrial Revolution. Thus, we can reasonably assume that productivity growth will struggle to accelerate in the next decade or so, even if we take the 1980s as our starting point for the AI revolution (note the flattening of developed country productivity in recent decades, as shown in **Figure 50**).

More optimistically, none of the previous episodes of intense technological innovation resulted in permanent structural unemployment. However, unskilled jobs are once again the most exposed to automation and alternative job options for unskilled workers are narrowing. Without government help, they are unlikely to acquire the skills needed for conversion into the knowledge workers for whom new types of jobs may be emerging.

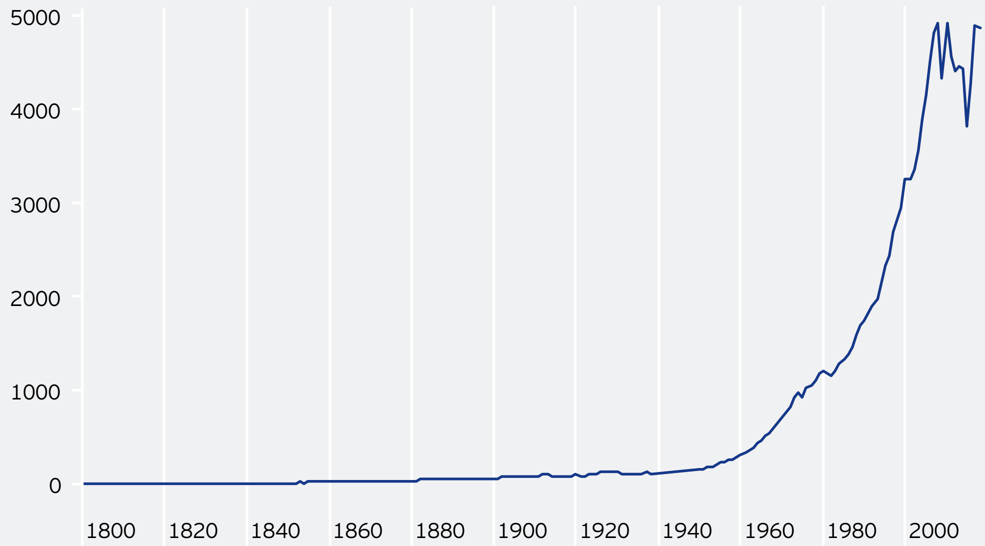
Figure 50 – Real GDP per capita 1929-2015 (logarithmic scale, 1929=100)



Notes: Annual data based on GDP in local currency. Source: Global Financial Data, United Nations, Invesco

According to Acemoglu and Restrepo (2016), about half of US employment growth between 1980 and 2007 was explained by the additional employment growth in occupations with new job titles. Therefore, workers whose skillset does not match the supply of new jobs may be limited to switching into in-person services, although even those may be threatened in certain industries as an increasing number of jobs are expected to be automated in logistics, retail, construction and transport. Based on a study by Aguiar and Hurst (2006), the increase in leisure between 1965 and 2003 in the US was greatest among the least educated adults, which mirrors trends in income and expenditure inequality, suggesting that higher educational levels lead to more and higher paid work. After allowing for the growing share of citizens at work, Ramey and Francis (2009) found that the average weekly hours worked fell by only 4.7 hours between 1900 and 2005. Most of this decline occurred among the young (they now spend more time in education) and the elderly (they can now retire). Among those aged 25-54, the average workweek got longer, even though weekly hours among men declined. Thus, despite signs of structural changes in employment, we think that fears of technology replacing all work is possibly overblown.

Figure 51 – Value of global exports since 1800 (1913 = 100)



Notes: Data from 1800 to 2014 shows the time series of value of world exports at constant prices, relative to 1913 (Ortiz-Ospina, Beltekian, Roser (2014)). That is combined with WTO data showing merchandise export value indices from 2014 to 2018.
Source: World in Data, World Trade Organisation, Invesco

It seems to us that we are likely to remain in the current environment of low productivity growth for the foreseeable future. This comes at a time of slowing population growth (see demographics section) and stagnation in international trade (**Figure 51**). If we want to maintain economic growth, raising our productivity will be crucial. The good news is that based on previous experience during the first three industrial revolutions, productivity growth should eventually return.

284 tonnes

The CO2 footprint of training a single AI (16 years of emissions by the average US citizen)

However, we face three big obstacles that can slow down the adoption of new technologies. First, an increasingly polarised political environment favouring populists, who might enact legislation that focuses on the losers of technological changes, perhaps trying to reverse current automation trends. Second, a nascent US-China technology stand-off, which might develop into a new "cold war" creating separate standards and networks, thus limiting the benefits of innovation. Third, though we believe that innovation will be critical in mitigating climate change, the latter may also limit the spread of some new technologies, given the environmental costs of employing increasing amounts of computing power. According to a study by The Shift Project, greenhouse gas emissions by the global ICT sector based on the current global energy mix, contributed 2.5% of the 2013 total. They estimate that assuming current energy efficiency gains and data usage trends are maintained, this will jump to 4% in 2020 and that such emissions will continue growing by about 8% per year. Also, new estimates suggest the carbon footprint of training a single AI is as much as 284 tonnes of carbon dioxide equivalent – five times the lifetime emissions of an average car (according to Emma Strubell at the University of Massachusetts Amherst). In comparison, a human being uses only two to three tonnes of carbon dioxide equivalent per year to feed itself, which suggests it may be better for the environment to educate a person, say over 21-22 years, than to train an AI (unless we power the latter by renewable energy, as will increasingly be the case).

This suggests the boost to productivity that will eventually accompany AI and robotics may be delayed, with the First Industrial Revolution making a better template than the Second. This can happen, even though ageing societies not only benefit from automation, they will increasingly need more of it. Based on research carried out by Daron Acemoglu and Pascual Restrepo (2018), ageing leads to greater automation and to more intensive use and development of robots. They concluded that this relationship holds mostly for technologies that are labour-replacing, especially for middle-aged workers (those between the ages of 21 and 55). Reinforcing the notion that automation is reactive, Ethan Lewis (2011) found that US metropolitan areas that received fewer low-skilled immigrants between 1980 and 1990 adopted more automation technologies. This suggests that societies that have a combination of slower ageing and higher immigration flows, such as the US and UK will lag China, Japan, South Korea, Germany and Italy in adopting new technologies. This may even result in a further strengthening of China's economy and perhaps a reversal of the relative long-term decline of Europe and Japan, while the relative importance of the US economy could be eroded.

Hence, it could be well into the 21st century before these new technologies have boosted growth enough to supplement the demand for labour. Unfortunately, by then many countries may be experiencing labour shortages.

There is one important area in which technological progress is of paramount importance: climate change. The more carbon efficient we can become, the less we will need to change lifestyles while meeting emission targets. As outlined in the chapter on climate change, these are emission-reducing rather than labour-saving technologies. They are likely to be focused on things such as: battery technology, materials science (including more efficient transmission of electricity), architectural and building standards (and/or more efficient air conditioning) etc. Rather than destroying jobs, such advances could spurn new activities and industries that create employment opportunities.

Countries with labour shortages are likely to make the most labour-replacing innovations

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The 21st Century Portfolio

We started with an analysis of long-term historical returns on US assets. Our analysis leads us to believe that the future will differ from the past and **Figure 52** shows how we would adjust those historical returns. In short, low interest rates and bond yields (and the high real price of gold), along with lower prospective economic growth lead us to lower the projected real returns on all assets versus historical precedent.

Figure 52 – US historical and projected returns (CPI adjusted)

	1915-2018		2019-2100		
	Yield (%)/ Price in 1915	**Average annual real total return in USD (%)**	**Yield (%)/ Price in 2019**	**Projected average annual real total return in USD (%)**	**Comments**
Gold*	531	2.3	1474	-0.5	Gold expensive (average price since 1833 = $600 in today's prices)
Cash	5.0	0.4	2.0	0.0	Real rates are close to zero
Govt	4.2	2.2	1.7	0.5	Long-term TIPS yield currently close to 0.5%
IG**	5.1	3.0	2.8	1.0	Yields low but still better than treasuries
Stocks	5.6	8.6	1.9	4.0	Yield low compared to 1915 and growth prospects limited
CTY***	37.0	3.9	53.6	2.0	Global growth prospects limited

Notes: Historical data based on calendar year data from 1915 to 2018. Calculated using: spot price of gold, Global Financial Data (GFD) US Treasury Bill total return index for cash, our own calculation of government bond total returns (Govt) using 10-year treasury yield, GFD US AAA Corporate Bond total return index (IG), Reuters CRB total return index until November 1969 and then the S&P GSCI total return index for commodities (CTY) and Robert Shiller's US equity index and dividend data for stocks. Indices are deflated by US consumer prices. . Yields and prices in 2019 are as of 30 September 2019. *Gold price in 1915 is expressed in today's prices (using US CPI). ** IG yields in both 1915 and 2019 are the yield on the Dow Jones Corporate Bond Index. *** The price for CTY in 1915 and 2019 is the price of WTI oil expressed in 2019 prices (using US CPI). The oil price is used merely as an illustration of commodity prices. **Past performance is no guarantee of future results. Projected returns are our own estimates. There is no guarantee these views will come to pass.**
Source: Refinitiv Datastream, Global Financial Data, Reuters CRB, S&P GSCI, Robert Shiller, Invesco

Lower returns expected on all assets than in the past

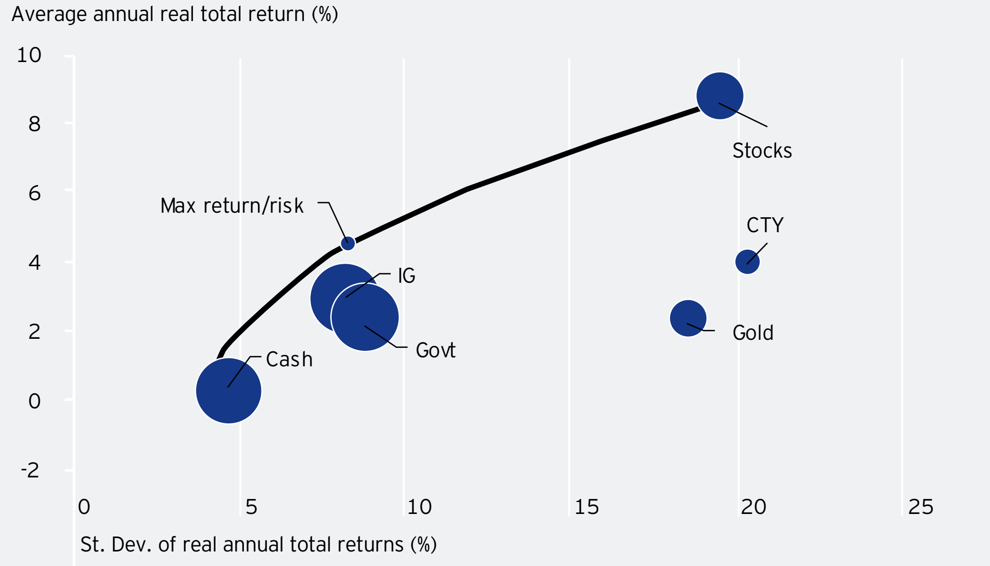
US cash rates are currently close to the rate of inflation and we assume that cash will do no more (nor less) than preserve its value in real terms (zero assumed annual real return to the end of the century). Likewise, treasury yields offer little in the way of prospective real returns (the 30-year TIPS yield is currently close to 0.5% and that is the annual return we assume on government debt for the rest of this century). We expect IG returns (1.0%) to be slightly higher than for government debt, as has been the case historically.

Linked to interest rates and bond yields is the price of gold (our research suggests that gold moves inversely with real treasury yields). We think this is why gold is currently so expensive compared to historical norms (expressed in today's prices, the average price of gold since 1833 has been around $600). We project some normalisation of that price over the rest of the century, with a projected real return of -0.5% (consistent with a price of $1000 in today's prices in 2100).

Predicting the return on equities (stocks) is more problematic, as we also need to allow for growth. It is our belief that over the long term the return on stocks is largely a function of dividend yield and dividend growth. Unfortunately, the yield on US stocks (1.9%) is well below where it was in 1915 (5.6%), so it would be naïve to expect a repeat of post-1915 returns. Even worse, as outlined in earlier sections, we believe that economic growth (global and US) will be lower in the future because of demographic deceleration and the limitations/costs imposed by climate change. On the other hand, low rates may encourage more investment spending which could stimulate growth. For the purposes of this exercise, we assume that investment spending to reduce carbon intensity will offset the damaging growth effects of climate change. Hence, the drag on growth comes purely from demographic deceleration, which could be enough to reduce real economic growth by around one percentage point per year. Our projections assume a similar diminution of the real growth of dividends. The overall effect causes us to project an average real return of 4% on US stocks from now to the end of the century (versus 8.6% in the post-1915 period).

The commodity asset class is also complex: it will likely suffer from the same economic deceleration that should impact equities and will also suffer from the fact that use of many components directly contribute to GHG emissions. Hence, there is a desire to leave as many of these resources unused as possible. Further, the drive to reduce carbon intensity is likely to reduce the overall demand for certain commodities as we strive to make trains, planes and automobiles lighter. Of course, some specific commodities may see enhanced demand (lithium, for example) and agricultural products could become scarce (and more expensive) if the worst climate change effects occur. However, overall, we assume lower returns than in the past, with a projected 2% annual return for the rest of the century.

Figure 53 – US asset returns and the efficient frontier 2019-2100 (CPI adjusted)

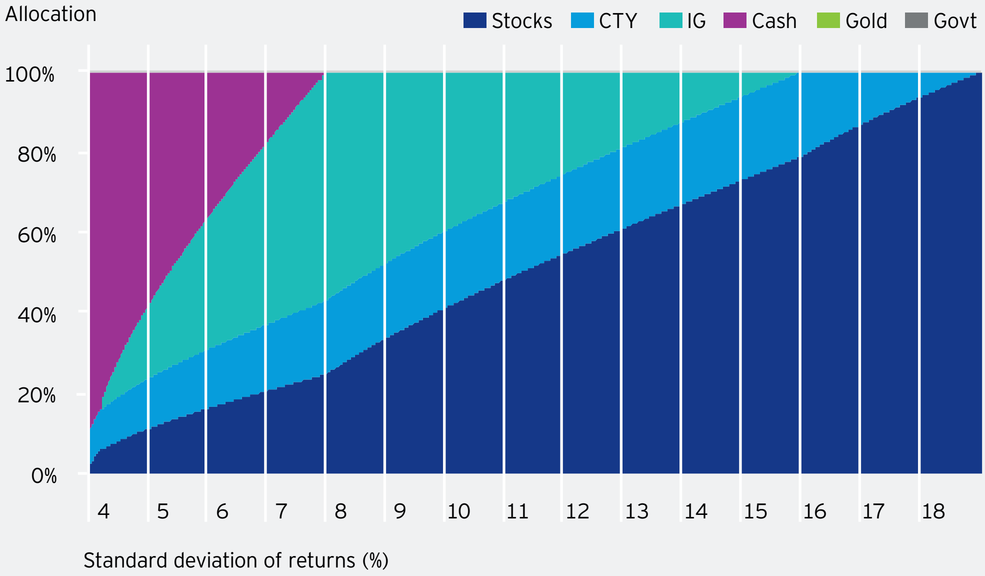


Note: Projected CPI-adjusted total returns from 2019 to 2100 (using the historical covariance matrix from 1915 to 2018). Area of bubbles is in proportion to average correlation with other assets. Projections are based on the same assets used to generate historical returns: spot price of gold, Global Financial Data (GFD) US Treasury Bill total return index for cash, our own calculation of government bond total returns (Govt) using 10-year treasury yield, GFD US AAA Corporate Bond total return index (IG), Reuters CRB total return index until November 1969 and then the S&P GSCI total return index for commodities (CTY) and Robert Shiller's US equity index and dividend data for stocks. Indices are deflated by US consumer prices. "Max return/risk" is the point on the efficient frontier that gives the highest ratio of return to standard deviation of returns. **Past performance is no guarantee of future results. Projected returns are our own estimates. There is no guarantee these views will come to pass.**
Source: Refinitiv Datastream, Global Financial Data, Reuters CRB, S&P GSCI, Robert Shiller, Invesco

Apart from the fact that all projected returns are lower than their historical counterparts, **Figure 53** looks very similar to **Figure 4**. This should be no surprise as we have assumed that the covariance matrix will be the same going forward as in the past. This may be an oversimplification but the fact we expect a different level of returns does not imply that we should expect the volatilities and correlations to vary from the past.

The efficient frontier still runs from near cash to stocks but is flatter (suggesting less of a payoff for each unit of risk taken) and the "max return/risk" mix of assets is now further up the efficient frontier (i.e. at a higher level of volatility). When it comes to optimal allocations (**Figure 54**), there are some interesting differences compared to those derived using purely the historical data (**Figure 5**) but the broad themes are the same: optimal portfolios are dominated by a combination of stocks, CTY, IG and cash, with no role for government debt; if we are not worried by volatility (as should be the case given the time frame), the optimal solution is to invest entirely in stocks (with perhaps some commodities added if we don't want to be at the very extreme end of the efficient frontier). An ultra-conservative approach would be invested almost entirely in cash but a touch of CTY and gold (hard to spot in the chart) could dampen volatility. Not surprisingly, given the projections, gold is far less visible in **Figure 54** than in **Figure 5**.

Figure 54 - Optimal allocations along the efficient frontier (US assets, 2019-2100)



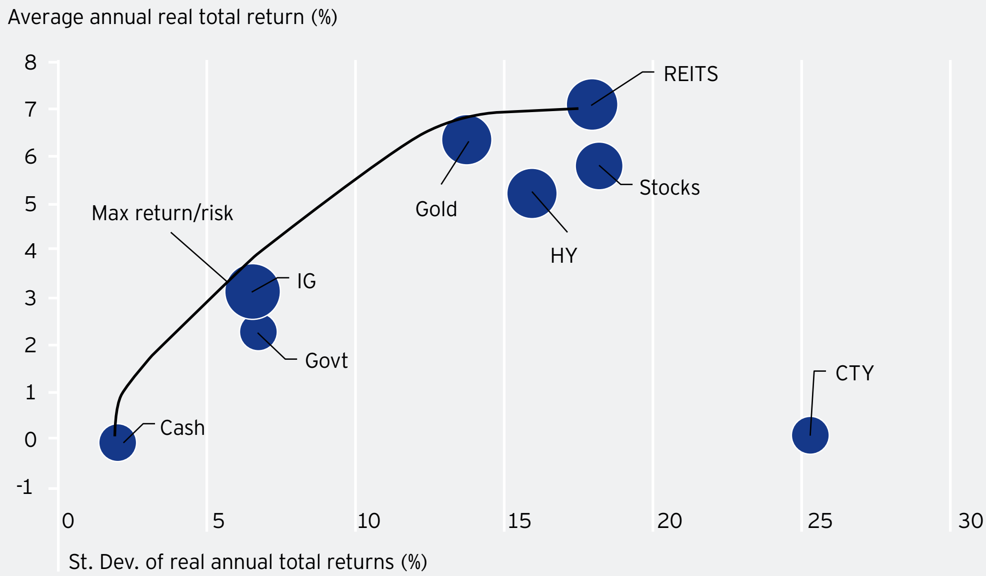
For each level of risk (standard deviation of returns), the chart shows the allocation of assets that would maximise returns and therefore be on the efficient frontier (based on projected average annual returns 2019-2100 and using the historical covariance matrix from 1915 to 2018). **Past performance is no guarantee of future results. Projected returns are our own estimates. There is no guarantee these views will come to pass.** Source: Global Financial Data, Robert Shiller, Reuters CRB, S&P GSCI, Refinitiv Datastream and Invesco (see detailed notes to Figures 52 and 53).

What about a global approach?

The above is very US centric and is based on a historical period that may no longer be relevant. We have therefore adopted a similar approach using global assets and have included high-yield credit (HY) and real estate investment trusts (REITS). Unfortunately, for that expanded asset universe there is less data history: we have data starting in 1998, which gives 21 years' worth of data, if we annualise returns so far during 2019 (up to end-September).

Figure 55 shows real global asset returns over that period in risk-return space (with some data shown in **Figure 56**). Though the overall pattern of returns is much as we might have expected, there are a few surprises: first, cash returns have been slightly negative (though remember these are CPI adjusted returns); second, broad commodity returns have been close to zero in real terms (our bias is to believe commodities struggle to deliver positive real returns over the long haul, despite the evidence in **Figure 4**) and third, gold has been one of the best performing assets (bettered only by REITS).

Figure 55 - Global asset returns and the efficient frontier since 1998 (CPI adjusted)



Notes: Based on annual total return data from 1998 to 2019 in USD (2019 is created by annualising data up to 30 September). Area of bubbles is in proportion to average correlation with other assets (hollow bubble implies negative correlation). Calculated using: spot price of gold, JP Morgan 1-month USD cash index (Cash), BofAML Global Government Index (Govt), BofAML Global Corporate Index (IG), BofAML Global HY Index (HY), GPR General World Index (REITS), S&P GSCI total return index for commodities (CTY) and MSCI World Index (Stocks). Indices are deflated by US consumer prices. "Max return/risk" is the point on the efficient frontier that gives the highest ratio of return to standard deviation of returns. **Past performance is no guarantee of future results**. Source: BofAML, GPR, JP Morgan, MSCI, S&P GSCI, Refinitiv Datastream and Invesco.

Those with short memories may believe that gold always produces good returns. However, the period covered in **Figure 55** is exceptional, in that gold was below $300/ounce in early 1998 and close to a multi-decade low in real terms. As already noted, it is today well above the long-term historical average of $600 measured in today's prices. Hence, the period covered in **Figure 55** may exaggerate the long-term potential for gold.

Looking forward, the reasoning behind the projections for global assets is similar to that for US assets, with the following exceptions:

- Non-US developed world yields are lower than in the US, hence global government bonds are projected to produce an average annual real return of zero (versus 0.5% in the US).
- HY is expected to continue providing higher returns than both government and IG equivalents, despite the current narrowness of spreads.
- Global stocks are projected to give better returns than US counterparts (4.5% annual average versus 4.0%), because starting yields are higher. Nevertheless, returns are projected to be below historical precedent.
- REITS are also expected to suffer due to the effects of demographic deceleration (with some dramatic effects in some countries) and also due to the effects of climate change on some real estate. However, yields are attractive and higher than those on equities.

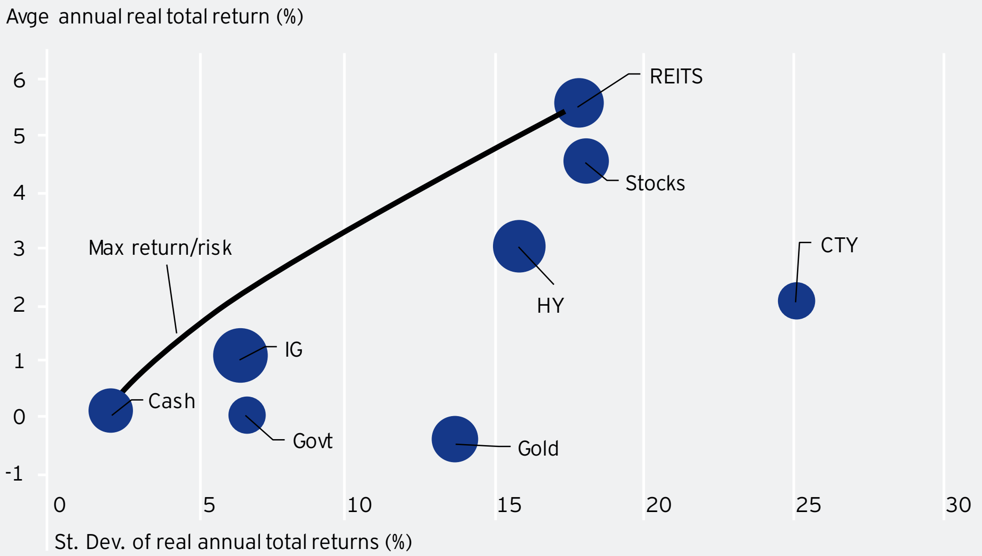
Figure 56 gives the detail along with some benchmark yield and price data to put the projections into perspective. **Figure 57** puts those returns into risk-return space, if the covariance matrix over the rest of the century is the same as for the period since 1998 (a heroic assumption but it is hard to do otherwise).

Figure 56 – Global historical and projected returns (CPI adjusted)

	1998-2019		2019-2100		
	Yield (%)/ Price in 1998	**Average annual real total return in USD (%)**	**Yield (%)/ Price in 2019**	**Projected average annual real total return in USD (%)**	**Comments**
Gold*	462	6.3	1474	-0.5	Gold expensive (average price since 1833 = $600 in today's prices)
Cash	5.5	-0.1	2.0	0.0	Real rates are close to zero
Govt	4.9	2.2	0.7	0.0	Long-term real yields are close to zero (at best)
IG	5.7	3.1	2.3	1.0	Yields low but still better than government bonds
HY	8.9	5.2	6.0	3.0	Yields low (and spreads are narrow) but higher than on Govt and IG
Stocks**	1.8	5.8	2.6	4.5	Yield higher than in 1998 but growth prospects limited
REITS	NA	7.0	3.9	5.5	Yield better than stocks: climate change and demographics negative
CTY***	28.0	0.1	53.6	2.0	Global growth prospects limited

Notes: Based on annual total return data from 1998 to 2019 in USD (2019 is created by annualising data up to 30 September). Historical data is calculated using: spot price of gold, JP Morgan 1-month USD cash index (Cash), BofAML Global Government Index (Govt), BofAML Global Corporate Index (IG), BofAML Global HY Index (HY), GPR General World Index (REITS), S&P GSCI total return index for commodities (CTY) and MSCI World Index (Stocks). Indices are deflated by US consumer prices. Yields and prices in 2019 are as of 30 September 2019. *Gold price in 1998 is expressed in today's prices (using US CPI). ** The yield on stocks is that for the Datastream World Index. *** The price for CTY in 1998 and 2019 is the price of WTI oil expressed in 2019 prices (using US CPI). The oil price is used merely as an illustration of commodity prices. **Past performance is no guarantee of future results. Projected returns are our own estimates. There is no guarantee these views will come to pass.**
Source: BofAML, GPR, JP Morgan, MSCI, S&P GSCI, Refinitiv Datastream and Invesco.

Figure 57 – Global asset returns and the efficient frontier 2019-2100 (CPI adjusted)



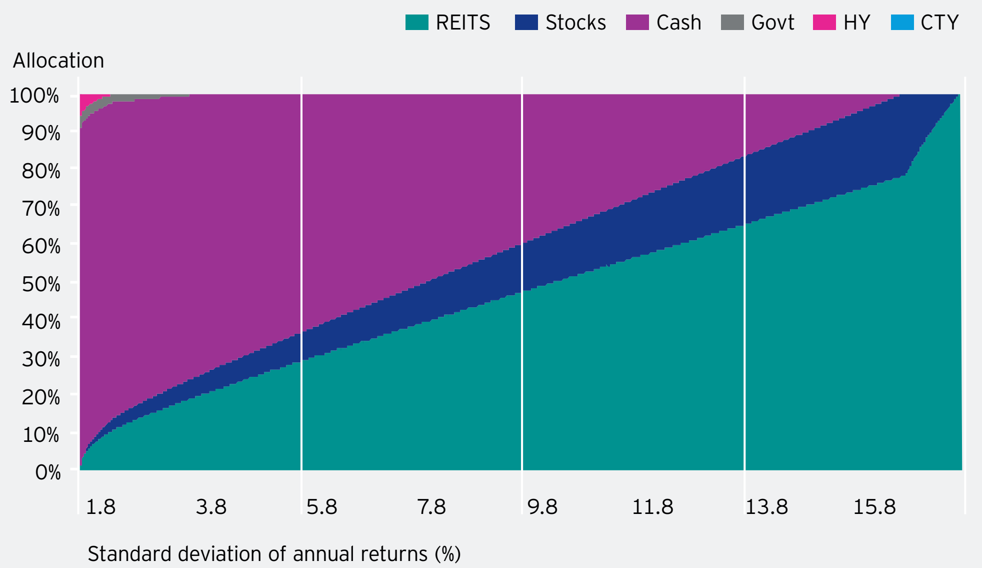
Notes: Projected CPI-adjusted total returns from 2019 to 2100 in USD (using the historical covariance matrix from 1998 to 2019). 2019 data is based on an annualisation of returns to 30 September 2019. Area of bubbles is in proportion to average correlation with other assets (hollow bubbles reflect negative correlation). Projections are based on the same assets used to generate historical returns: spot price of gold, JP Morgan 1-month USD cash index (Cash), BofAML Global Government Index (Govt), BofAML Global Corporate Index (IG), BofAML Global HY Index (HY), GPR General World Index (REITS), S&P GSCI total return index for commodities (CTY) and MSCI World Index (Stocks). Indices are deflated by US consumer prices. "Max return/risk" is the point on the efficient frontier that gives the highest ratio of return to standard deviation of returns. **Past performance is no guarantee of future results. Projected returns are our own estimates. There is no guarantee these views will come to pass.** Source: BofAML, GPR, JP Morgan, MSCI, S&P GSCI, Refinitiv Datastream and Invesco

The big change versus the historical data is the negative return projected for gold and the more positive outlook for broad commodities. Otherwise, the returns for all assets are projected to be lower than over recent decades and the efficient frontier is flatter (less marginal return for additional units of risk).

Nevertheless, the efficient frontier still runs from cash to REITS and it should therefore be no surprise that both those assets feature prominently in the optimal allocations shown in **Figure 58** (cash dominates the low volatility allocations and REITS dominate the more volatile end of the spectrum). In fact, the bulk of those optimal allocations consist of a mix of REITS, stocks and cash, with government debt, HY and CTY barely featuring (CTY is in the very top-left corner but is hard to see). Interestingly, neither gold nor IG feature in any of the optimal allocations (due to low return projections and lack of diversification properties). Given the length of our time horizon, we are not worried about volatility and are therefore tempted to focus investments on REITS and stocks.

Forward-looking optimal allocations dominated by REITS, stocks and cash

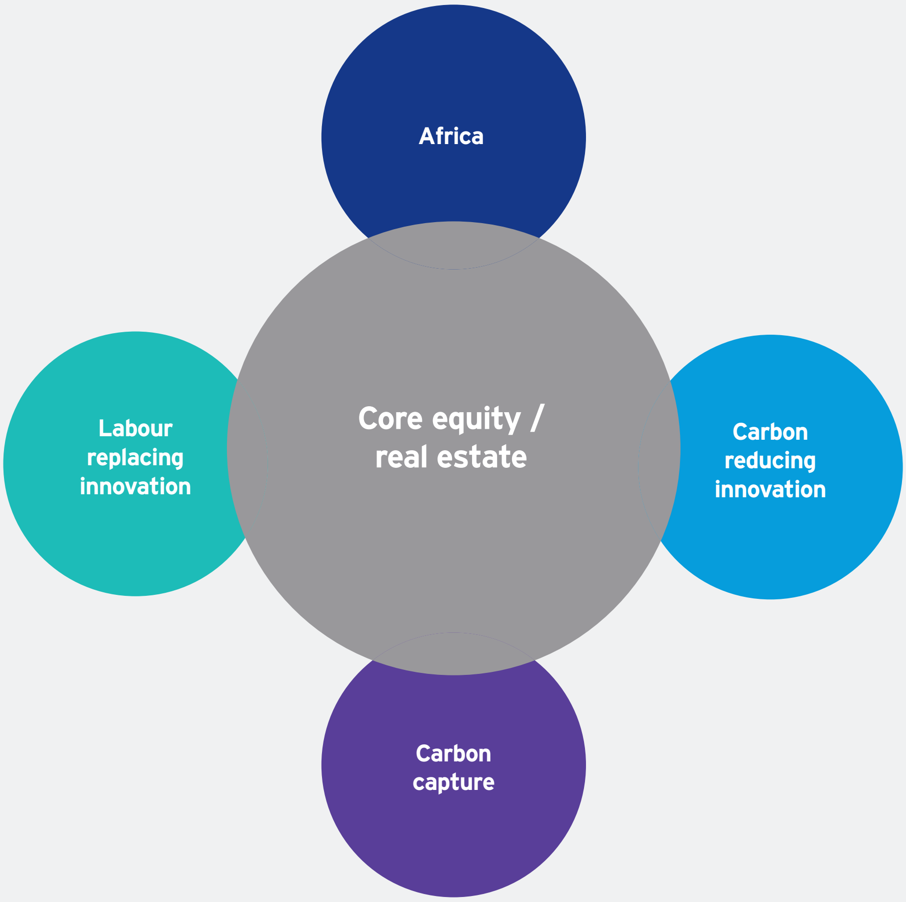
Figure 58 – Optimal allocations on the efficient frontier (global assets, 2019-2100)



For each level of risk (standard deviation of returns), the chart shows the allocation of assets that would maximise returns and therefore be on the efficient frontier (based on projected average annual returns 2019-2100 and using the historical covariance matrix from 1998 to 2019). **Past performance is no guarantee of future results. Projected returns are our own estimates. There is no guarantee these views will come to pass.** Source: BofAML, GPR, JP Morgan, MSCI, S&P GSCI, Refinitiv Datastream and Invesco (see detailed notes to Figures 56 and 57).

A core equity/real estate structure with four thematic satellites

Figure 59: The 21st Century Portfolio*



- **Core equity/real estate:** designed to give exposure to what growth is available (fixed income assets are of little interest given the ultra-low yields). Country/regional markets should be equally weighted (why would you want exposure to yesterday's winners?). Minimise exposure to coastal real estate and also to housing markets in shrinking population countries such as China, Italy, Japan, Russia and South Korea. Boost exposure to labour saving technology in those same countries.
- **Africa:** the dark continent will be the story of the century (in our opinion). Gaining exposure is not easy but we think it will become increasingly so. Exposure can be in the form of fixed income assets (yields are higher than in the developed world) but would preferably be in equities and real estate. We suspect an increasing number of Africa infrastructure investment vehicles will appear. Exposure may need to come via venture capital and private equity.
- **Carbon reducing innovation:** much of the technical innovation over the coming decades will be aimed at reducing the emission of CO_2 and other GHG's. There are a multitude of companies working in areas such as battery technology, renewable energy, electric autos and planes, AC technology etc. We give examples in the report, many of which are small and privately owned. Hence, this may need to be sub-contracted to venture capitalists and private equity specialists. The purchase of carbon certificates could also be a way to capture the assumed increase in the price of carbon but needs active management.
- **Carbon capture:** an important part of enabling the world to grow while not overheating will be schemes to capture emitted CO_2. The obvious way is to invest in land that can be reforested and/or to buy forestry companies. The report also gives examples of companies that are developing scrubbers etc as well as one company using drones to plant trees.
- **Labour-replacing innovation:** if we are correct to believe that we are still in the labour-replacing phase of the fourth industrial revolution, it is the owners of innovating companies that stand to gain. We suspect this will be the case for several decades. The pool of quoted companies in this area is much bigger than for carbon reducers but some early stage investment expertise may also be useful.

* The 21st Century Portfolio is a theoretical portfolio and is for illustrative purposes only. It does not represent an actual portfolio and is not a recommendation of any investment or trading strategy. Source: Invesco

Appendices and important information

Appendix 1: The CO2 footprint of every-day activities and items

Consumable	Carbon footprint	Unit	Unit consumed
London-NY flight - economy	0.440	metric tonnes	
London-NY flight - business	1.720	metric tonnes	
London-NY flight - first	1.770	metric tonnes	
Cruise ship crossing Atlantic ocean	2.206	metric tonnes	
NY to LA - train	0.190	metric tonnes	
NY to LA - flight - economy	0.290	metric tonnes	
NY to LA - flight - business	0.840	metric tonnes	
NY to LA - car ICE (Audi A4)	0.960	metric tonnes	
NY to LA - car electric (Tesla Model S)	0.300	metric tonnes	
Car manufacturing - standard gasoline	5.600	metric tonnes	
Car manufacturing - hybrid electric	6.500	metric tonnes	
Car manufacturing - plug-in hybrid electric	6.700	metric tonnes	
Car manufacturing - battery electric	8.800	metric tonnes	
Bicycle	0.240	metric tonnes	
Washing machine	0.060	metric tonnes	
Sofa	0.090	metric tonnes	
TV	0.200	metric tonnes	
Dell laptop	0.150	metric tonnes	
Fridge/freezer	0.100	metric tonnes	
Suit - wool	0.014	metric tonnes	
Suit - polyester	0.007	metric tonnes	
Cotton shirt	0.009	metric tonnes	
Pair of jeans	0.033	metric tonnes	
Underwear	0.002	metric tonnes	
Pair of trainers	0.014	metric tonnes	
Beef (beef herd)	50.0	kg	100g of protein
Lamb & mutton	20.0	kg	100g of protein
Beef (dairy herd)	17.0	kg	100g of protein
Crustaceans (farmed)	18.0	kg	100g of protein
Cheese	11.0	kg	100g of protein
Pig meat	7.6	kg	100g of protein
Fish (farmed)	6.0	kg	100g of protein
Poultry meat	5.7	kg	100g of protein
Eggs	4.2	kg	100g of protein
Tofu	2.0	kg	100g of protein
Groundnuts	1.2	kg	100g of protein
Other pulses	0.8	kg	100g of protein
Peas	0.4	kg	100g of protein
Nuts	0.3	kg	100g of protein
Grains	2.7	kg	100g of protein
Milk	3.2	kg	1 litre
Soymilk	1.0	kg	1 litre
Cassava	1.4	kg	1000 kcal

Consumable	Carbon footprint	Unit	Unit consumed
Rice (flooded)	1.2	kg	1000 kcal
Oatmeal	0.9	kg	1000 kcal
Potatoes	0.6	kg	1000 kcal
Wheat & rye (bread)	0.6	kg	1000 kcal
Maize (meal)	0.4	kg	1000 kcal
Palm oil	7.3	kg	1 litre
Soybean oil	6.3	kg	1 litre
Oilve oil	5.4	kg	1 litre
Rapeseed oil	3.8	kg	1 litre
Sunflower oil	3.6	kg	1 litre
Tomatoes	2.1	kg	1kg
Brassicas	0.5	kg	1kg
Onions & leeks	0.5	kg	1kg
Root vegetables	0.4	kg	1kg
Berries	1.5	kg	1kg
Bananas	0.9	kg	1kg
Apples	0.4	kg	1kg
Citrus	0.4	kg	1kg
Cane sugar	3.2	kg	1kg
Beet sugar	1.8	kg	1kg
Beer (5% ABV)	0.2	kg	1 unit
Wine (12.5% ABV)	0.1	kg	1 unit
Dark chocolate (50g)	2.3	kg	1 serving
Coffee (15g, 1 cup)	0.4	kg	1 serving

Notes: the table shows the GHG footprint of the items or activities shown (measured in CO2 equivalent) . "Unit" shows the unit of measurement for CO2 (note that one tonne = 1000 kgs). "Unit consumed" is how much of the consumable is counted in the calculation. The CO2 footprints for the food and drink items are global averages.
Source: carbonfootprint.com, The Daily Telegraph, Green Car Congress, Pubs ACS, Slate Magazine, Furniture Industry Research Association, Waste and Resources Action Programme, Dell, Ecotricity, Oxford University Research Archive and Invesco

Appendix 2: Definitions of data and benchmarks

US Shiller PE and Earnings Per Share (EPS): the Shiller PE is a price to earnings ratio constructed by dividing price by the average earnings per share in the previous 10 years (with both numerator and denominator adjusted for inflation). It is what is commonly known as a cyclically-adjusted PE ratio. It is constructed by US academic Robert Shiller. We also use the raw EPS data from his database to calculate EPS momentum on a 3m/3m basis (the percentage change in the latest three months versus the previous three months). Data is monthly from 1881 (source Robert Shiller - see here). EPS momentum data since June 1973 is derived from S&P 500 index and PE data sourced from Datastream.

US stock/equity index: we have calculated a total return index for broad US stocks based on index and dividend data from US academic Robert Shiller and Datastream. The index prior to 1926 is Robert Shiller's recalculation of data from Common Stock Indexes by Cowles & Associates (see here). From 1926 to 1957, the Shiller data is based on the S&P Composite Index and thereafter is based on the S&P 500 as we know it today.

Abbreviations for country names in Figure 16

Aus = Australia
Arg = Argentina
Bel = Belgium
Bra = Brazil
Can = Canada
Chi = China
Fra = France
Ger = Germany
India = India
Indo = Indonesia
Ita = Italy
Jap = Japan
Kor = South Korea
Mex = Mexico
NL = Netherlands
Pol = Poland
Rus = Russia
Saudi = Saudi Arabia
Spa = Spain
Swe = Sweden
Swi = Switzerland
Tur = Turkey
UK = United Kingdom
US = United States of America

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