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GROWTH-POSITIVE ZERO-EMISSION PATHWAYS TO 2050

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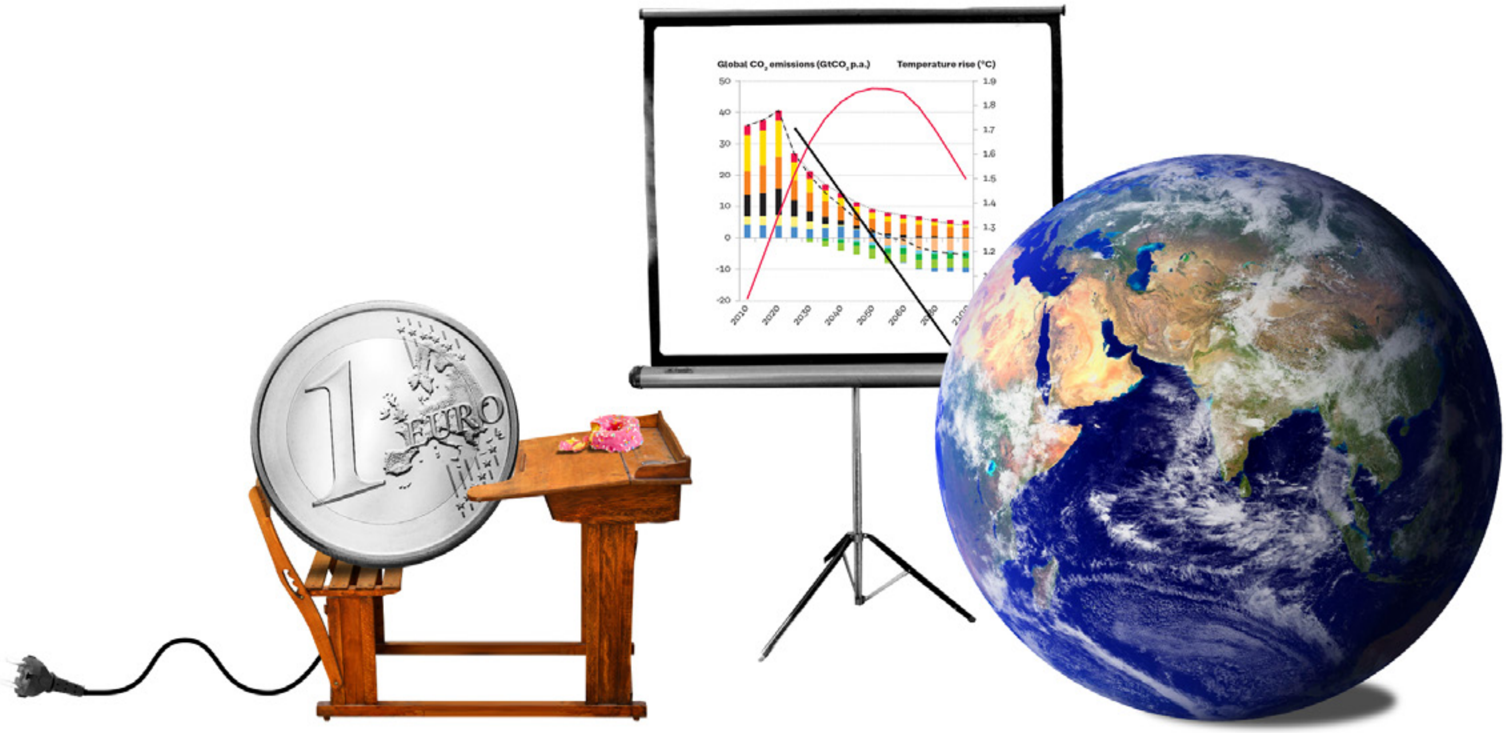

2nd edition
For this second edition a typing error in figures 7, 8, 9 and 10 was corrected, where the correct unit in GWP/GDP was changed to $US2010 bn instead of $US2010.

Sitra studies 185

Growth-positive zero-emission pathways to 2050

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Foreword

Our world is facing an existential threat from the climate and biodiversity crises. We need to stop biodiversity loss and increase the vitality of nature. We also need to drive our net emissions down to zero by 2050 to meet the targets set in the Paris Agreement to limit global warming.

Historically, CO_2 emissions have tended to increase alongside economic growth. To reduce CO_2 emissions to zero by 2050, this link between emissions and economic growth needs to be broken – what is known as "emissions decoupling". However, some seem to worry that emissions decoupling is not possible at the necessary speed and scale to meet the targets set in the Paris Agreement and that the economy should decline compared to the current levels. Others worry that low or negative economic growth would make emission reductions very difficult or impossible, since significant investments in new low-carbon technologies are needed. New investments, again, boost economic growth.

Sitra commissioned this study to investigate whether and under what assumptions and policy measures the decoupling of CO_2 emissions from economic growth could occur at a sufficient rate for CO_2 emissions to decline to net zero by 2050. The analyses were carried out on a global level, but some of the economic impacts are presented separately for the EU and Finland as well. As the topic of emissions decoupling alone is extensive, this study does not cover wider environmental considerations, such as the effects on biodiversity or on materials and resource use. It is strongly recommended that these important issues be analysed in other studies.

The results of this study show that deep CO_2 emission cuts in line with the 1.5 °C target and positive GDP growth can occur at the same time. However, it requires profound changes in most of society's fundamental techno-economic systems as well as fast development and deployment of negative-emission technologies. Further, the results do not mean that simply aiming for positive economic growth would be sustainable or sufficient to keep us within the planetary boundaries. On the contrary, the results show that economic growth can result from ambitious climate policies and improved productivity. On the other hand, overlooking costs to the environment from the pursuit of economic growth would result in significant economic damage.

The results underline the importance of fast emission reductions and a strong policy regime across the whole world to reach the 1.5 °C target and to enable emissions decoupling. In particular, quickly reducing the use of coal seems vital. Additionally, efforts should be made to obtain more negative-emission technologies (NETs) that would safely and permanently remove carbon already accumulated in the atmosphere.

A natural next step would be to also analyse in detail the decoupling of other harmful environmental impacts from economic growth. For example, a global shift to more circular business models could reduce CO_2 emissions and help cut the use of materials and natural resources while maintaining economic growth. The importance of NETs on the emission-reduction pathways presented in this study stress again the need to analyse in detail the land-use and biodiversity impacts of wide-scale use of NETs.

We thank the whole consortium of researchers involved in this study for their great efforts to shed more light on the discussion on emissions decoupling.

The aim of this study is to open and encourage the necessary discussion on decoupling, to help us all build a sustainable future – a society that thrives within the limits of the earth's capacity.

Helsinki, 15 March 2021

Mari Pantsar	**Saara Tamminen**
Director	Leading specialist

Esipuhe

Maailmaa uhkaavat ilmastokriisi ja luontokriisi. Meidän on pysäytettävä luontokato ja kasvatettava luonnon elinvoimaisuutta. Lisäksi meidän on painettava nettopäästömme nollaan vuoteen 2050 mennessä, jotta voimme saavuttaa Pariisin ilmastosopimuksen tavoitteet maapallon lämpötilan nousun rajoittamiseksi.

Historiallisesti katsottuna hiilidioksidipäästöt ovat lisääntyneet talouskasvun myötä. Jotta hiilidioksidipäästöt voidaan ajaa nollaan vuoteen 2050 mennessä, päästöjen ja talouskasvun välinen yhteys pitää katkaista. Tätä kutsutaan päästöjen irtikytkennäksi. Jotkut ovat kuitenkin huolissaan siitä, ettei päästöjen irtikytkentä olisi mahdollista riittävän nopeasti ja sellaisessa mittakaavassa, jota Pariisin ilmastosopimuksen tavoitteiden saavuttaminen vaatii, ilman että taloudellinen tulotasomme heikkenee nykytasoon verrattuna. Toiset ovat taas huolissaan siitä, että matala tai negatiivinen talouskasvu tekisi päästöjen vähentämisestä erittäin vaikeaa tai mahdotonta, sillä uusiin vähähiilisiin teknologioihin tarvitaan merkittäviä investointeja. Uudet investoinnit taas lisäävät talouskasvua.

Sitra tilasi selvityksen tutkiakseen, onko hiilidioksidipäästöjen kytkeminen irti talouskasvusta mahdollista riittävän nopeasti, jotta nettopäästöt voidaan painaa nollaan vuoteen 2050 mennessä, ja minkälaisia politiikkatoimia ja oletuksia tämä vaatisi. Analyysit toteutettiin maailmanlaajuisella tasolla, mutta taloudellisia vaikutuksia esitellään erikseen myös EU:n ja Suomen osalta. Päästöjen irtikytkentä on aiheena mittava, joten tässä selvityksessä ei pystytty ottamaan huomioon muita ympäristövaikutuksia, kuten vaikutuksia luonnon monimuotoisuuteen tai materiaalien ja luonnonvarojen käyttöön. Suosittelemme vahvasti, että näitä vaikutuksia tutkittaisiin muissa selvityksissä.

Tämän selvityksen tulokset osoittavat, että hiilidioksidipäästöjen leikkaaminen merkittävästi 1,5 asteen tavoitteen mukaisesti ja BKT:n kasvu voivat tapahtua samanaikaisesti. Se vaatii kuitenkin syvällisiä muutoksia yhteiskunnan perustavanlaatuisiin teknologis-taloudellisiin järjestelmiin sekä onnistumista negatiivisten päästöteknologioiden (NET) nopeassa kehittämisessä ja käyttöönotossa. Lisäksi tulokset eivät tarkoita sitä, että pelkästään talouskasvun tavoitteleminen on kestävää tai riittää säilyttämään maapallon kantokyvyn. Tulokset osoittavat sen sijaan, että kunnianhimoinen ilmastopolitiikka ja tuottavuuden parantuminen voivat johtaa talouskasvuun. Toisaalta pelkän talouskasvun tavoittelun ympäristölle aiheuttamien kustannusten jättäminen huomiotta johtaisi merkittäviin taloudellisiin ja yhteiskunnallisiin haittoihin.

Tulokset korostavat nopeiden päästövähennysten tärkeyttä sekä vahvaa maailmanlaajuista poliittista ohjausta 1,5 asteen tavoitteen ja päästöjen irtikytkennän saavuttamiseksi. Erityisesti hiilen käytön nopea vähentäminen näyttää olevan oleellista. Lisäksi tulisi kehittää uusia negatiivisia päästöteknologioita, jotka poistaisivat ilmakehästä sinne kertynyttä hiilidioksidia turvallisesti ja pysyvästi.

Luonnollinen seuraava askel olisi analysoida myös muiden haitallisten ympäristövaikutusten irtikytkentää talouskasvusta yksityiskohtaisesti. Esimerkiksi maailmanlaajuinen siirtymä kohti kiertotalouden liiketoimintamalleja voisi pienentää hiilidioksidipäästöjä ja auttaa vähentämään materiaalien ja luonnonvarojen käyttöä vaikuttamatta talouskasvuun negatiivisesti. Negatiivisten päästöteknologioiden tärkeys selvityksen päästöttömissä kehityspoluissa korostaa lisäksi sitä, että negatiivisten päästöteknologioiden vaikutuksia maankäyttöön ja luonnon monimuotoisuuteen tulisi selvittää tarkasti.

Kiitämme kaikkia selvitykseen osallistuneita tutkijoita heidän panostuksestaan, jonka ansiosta ymmärrämme taas enemmän päästöjen irtikytkennästä.

Tämän selvityksen tarkoitus on aloittaa tarpeellinen keskustelu irtikytkennästä ja kannustaa kaikkia osallistumaan siihen sekä auttaa meitä kaikkia rakentamaan kestävää tulevaisuutta – yhteiskuntaa, joka menestyy maapallon kantokyvyn rajoissa.

Helsingissä 15. maaliskuuta 2021

Mari Pantsar johtaja	**Saara Tamminen** johtava asiantuntija

Förord

Vår värld står inför ett existentiellt hot från klimatförändringen och förlusten av biologisk mångfald. Vi måste stoppa den förlusten och istället förstärka naturens livskraft. Vi måste också driva ner våra nettoutsläpp till noll fram till år 2050 för att uppfylla målen i Parisavtalet om att begränsa den globala uppvärmningen.

Historiskt sett har koldioxidutsläppen tenderat att öka i samband med ekonomisk tillväxt. För att minska koldioxidutsläppen till noll fram till år 2050 måste denna koppling mellan utsläpp och ekonomisk tillväxt brytas – det som kallas decoupling, det vill säga att "frikoppla ekonomisk tillväxt från utsläpp". Somliga verkar dock oroa sig för att en frikoppling inte är möjlig med den hastighet och i den omfattning som krävs för att uppfylla målen i Parisavtalet och att en nedgång i ekonomin skulle ske jämfört med nuvarande nivåer. Andra oroar sig för att en låg eller negativ ekonomisk tillväxt skulle göra utsläppsminskningar mycket svåra eller rentav omöjliga, eftersom det krävs betydande investeringar i ny teknik med låga koldioxidutsläpp. Nya investeringar bidrar dock till en ökad ekonomisk tillväxt.

Sitra beställde denna studie för att undersöka om och under vilka antaganden och policyåtgärder frikopplingen av ekonomisk tillväxt från koldioxidutsläpp skulle kunna ske i en tillräcklig takt för att koldioxidutsläppen skulle minska till nettonoll fram till år 2050. Analyserna genomfördes på en global nivå, men en del av de ekonomiska effekterna presenteras även separat för EU och Finland. Eftersom ämnet frikoppling från utsläpp i sig är omfattande täcker inte den här studien bredare miljööverväganden, som till exempel effekterna på biologisk mångfald eller på material- och resursanvändning. Det rekommenderas starkt att dessa viktiga frågor analyseras i andra studier.

Resultaten av denna studie visar att stora nedskärningar av koldioxidutsläppen i linje med 1,5 °C-målet och en positiv BNP-tillväxt kan ske samtidigt. Detta kräver emellertid djupgående förändringar i de flesta av samhällets grundläggande teknisk-ekonomiska system samt snabb utveckling och användning av teknik med negativa utsläpp. Vidare betyder resultaten inte att enbart en målsättning om positiv ekonomisk tillväxt skulle vara hållbar eller tillräcklig att för att hålla oss inom planetens gränser. Tvärtom visar resultaten att en ekonomisk tillväxt kan vara resultatet av en ambitiös klimatpolitik och förbättrad produktivitet. Samtidigt skulle det medföra betydande ekonomisk skada att bortse från miljökostnaderna i jakten på ekonomisk tillväxt.

Resultaten understryker vikten av snabba utsläppsminskningar och en stark politisk vilja över hela världen för att kunna uppnå 1,5 °C-målet och möjliggöra en frikoppling från koldioxidutsläpp. En snabbt minskad användning av kol verkar särskilt avgörande. Dessutom bör försök göras för att få fram mer teknik för negativa utsläpp (NET) som säkert och permanent avlägsnar koldioxid som redan har ackumulerats i atmosfären.

Ett naturligt nästa steg skulle vara att även i detalj analysera frikopplingen från annan skadlig miljöpåverkan från ekonomisk tillväxt. Till exempel kan en global övergång till mer cirkulära affärsmodeller minska koldioxidutsläppen och minska användningen av material och naturresurser, samtidigt som den ekonomiska tillväxten upprätthålls. NET:s betydelse för de vägar till utsläppsminskningar som presenteras i denna studie betonar återigen behovet av att i detalj analysera effekterna av markanvändning och hur biologisk mångfald påverkas av en storskalig användning av NET.

Vi vill tacka hela den forskargemenskap som deltagit i denna studie för deras betydande ansträngningar för att berika diskussionen om frikoppling från utsläpp.

Syftet med denna studie är att öppna upp och främja den nödvändiga diskussionen om frikoppling som krävs för att hjälpa oss alla att bygga en hållbar framtid – ett samhälle som blomstrar inom gränserna för jordens kapacitet.

Helsingfors den 15 mars 2021

Mari Pantsar
Direktör

Saara Tamminen
Ledande expert

Executive summary

1 Rationale and motivation for this report

"Net-zero emissions by 2050" is the new target for climate policy, following the goal stipulated in the 2015 Paris Agreement of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2015). The aim of this study is to use energy system and macroeconomic models to explore whether and how these objectives could be reached and, in particular, whether achieving them is compatible with continuing economic growth through to 2100.

With its focus on the objectives of the Paris Agreement, the study does not consider wider environmental issues that may be affected by changes in the energy system, such as the use of non-energy natural resources and land use for bioenergy, with implications for biodiversity. These issues are important and should be taken into account in decisions about the quantity and location of any bioenergy that may be used to help to meet the Paris targets. The models used also cannot take into account the changing impacts on material use and emissions of moving towards either a low-carbon energy system or a circular economy.[1] If greater circularity in material use were to significantly reduce the extraction and processing of primary materials, then it may be that this could be another source of emission reduction. However, this is not analysed here and warrants further study.

2 Existing knowledge about the relationship between emissions and economic growth

Global greenhouse gas (GHG) emissions, which are responsible for anthropogenic global warming, have increased along with growth in the economy since records began. This is not surprising, as the major source of GHGs are CO_2 emissions, which come from burning fossil fuels. Fossil fuels have been the predominant source of energy since the Industrial Revolution, and energy use is at the heart of most economic activity. The question to be addressed by this report is, if emissions are reduced at the rate required to achieve the Paris target, can the economy keep on growing? In other words, can emissions be "decoupled" from economic growth?

The evidence that this may be possible comes from the European Union and some individual member states. Between 1990 and 2016 the EU economy grew by more than 50%, while CO_2 emissions from fuel combustion fell by 25%. Moreover, in Finland and the UK, even consumption-based emissions (which include emissions from the manufacture of imports but exclude the emissions from manufacturing exports) fell from 2007 to 2016. However, the rate of emissions reduction over these periods was nowhere near fast enough to meet the Paris target, so such evidence is not conclusive that economic growth could continue if emissions were to be reduced much faster.

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[1] Please see Annex 2 of the report for further discussion of the circular economy.

The energy-related emissions reduction that occurred in these economies came about through three main drivers:

- increasing efficiency in the use of energy;
- replacing fossil fuels with low- or zero-carbon energy sources;
- structural changes in the economy involving increasing consumption of low-carbon services and the offshoring of energy-intensive industries (though the calculation of consumption emissions takes this latter effect into account).

These drivers have been combined in different ways and to different extents in the UK and Finland, but a common characteristic is that they have been driven by public policy stimulating and reinforcing some market forces and constraining others.

It is evident that achieving the Paris targets will require a considerable intensification of the policies that have generated or reinforced these drivers, as will be seen.

3 Existing knowledge about the 1.5° C target

The 2018 Special Report on 1.5 °C from the Intergovernmental Panel on Climate Change (IPCC) set out the existing knowledge on the emissions, technology and economic implications of attaining the Paris 1.5 °C target. The IPCC report reviewed numerous scenario exercises with different input assumptions to determine whether and how easy it was to reach the Paris targets under different assumptions about world developments. The starting point was a set of five scenarios called the Shared Socio-economic Pathways (SSPs), which differ according to various assumptions. These include population and economic growth rates, trade intensity, environmental concern, rates of technological development and international co-operation. These are described in more detail below.

Using these broad assumptions, the modellers then chose the values of parameters that seemed broadly consistent with them in the following areas:

- Developments in economic structure and output
- Energy demand and efficiency
- Material demand and efficiency
- Use of low-carbon energy carriers and technology
- Availability and use of Carbon Capture and Storage (CCS) and Negative Emission Technologies (NETs[2])
- Land use and the availability of biomass for energy
- Choice and implementation of policy measures
- Costs of carbon reduction technologies.

Depending on the assumptions and models used, a wide variety of different pathways of GHG emission reduction were generated. Many of them were in line with the Paris target of limiting warming to 1.5 °C by 2100, though usually not without overshooting[3] it in the later decades of this century (as happened also in the modelling in this study, as discussed further below). These scenarios also showed continuing growth in the economy, and in general the reduction in economic growth by 2100 from a baseline without decarbonisation (which did not include any costs from climate change and was therefore probably optimistic) was small. Certainly,

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[2] NETs comprise technologies that suck CO_2 from the atmosphere and then store it securely so that it does not re-enter it. NETs include bioenergy with CCS (BECCS), afforestation with the resulting timber left intact, carbon sequestration in soils or "Direct Air Capture" (DAC) machines that scrub CO_2 from the air. DAC technology is at an early stage of development.

[3] "Overshooting" refers to the global average temperature increase rising above 1.5 °C. In the modelling the temperature increase is then reduced to 1.5 °C by technologies that remove large quantities of CO_2 from the atmosphere. There is in fact considerable uncertainty as to whether global temperatures would behave in this way, or whether allowing temperature increases to go beyond 1.5 °C would result in "tipping points" that resulted in large GHG emissions from other sources and caused the climate to flip permanently into a different state that was worse for humans. See Lenton et al. (2019).

none of the scenarios came anywhere near declines in economic output from the 2020 level (i.e. they all experienced economic growth). The scenarios therefore all exhibited "decoupling".

The modelling carried out in this project sought to explore this phenomenon more deeply and to explain, if the models used in this study exhibited the same result, why this result came about and what the reasons for it were.

4 The modelling approach in this study

This study has used two energy system models (PRIMES and TIAM-UCL) and one computable general equilibrium (CGE) macroeconomic model, GEM-E3 FIT. The energy system models show how energy demands could be met until 2100 while seeking to reduce CO_2 emissions to net zero in 2050 and to limit the global temperature increase to no more than 1.5 °C by 2100. As will be seen below, it turned out that the models with the assumptions discussed below could only reach net-zero CO_2 emissions in 2055 (not 2050). The temperature target of a maximum increase of 1.5 °C by 2100 could be reached, but only with overshooting in later decades of this century, as noted above. However, for simplicity, the text below continues to refer to the 2050 net-zero target for CO_2 emissions.

The macroeconomic model projects the economic output using the energy demands and technologies, and associated costs, that are generated by the energy system models in their carbon reduction scenarios. How the models have been combined is described in the report below, and the models themselves are described briefly in Annex 1 to this report.

The starting point for the scenarios explored in the modelling was the SSP1 scenario, which, because of its assumptions about how the world develops, is most favourable for global decarbonisation. The assumptions include global co-operation, rapid technology development, strong environmental policy, low population growth, declining inequality, dietary shifts and forest protection. The use of any of the other SSPs would have made decarbonisation more difficult and expensive, and this should be borne in mind when interpreting the results. However, all the assumptions in SSP1, while not necessarily pertaining to today, may be considered reasonable.

As already noted, the macroeconomic model takes the results from the energy system models through to the end of the century and projects the economic outcomes. There are essentially three drivers of economic growth in GEM-E3 FIT, as in other macroeconomic models: population growth, net investment and technical progress. Economic growth for the world as a whole could be negatively affected by decarbonisation if it raises the cost of energy or reduces rates of technical progress. With renewable electricity now competitive with that produced from fossil fuels in many countries, the impact on economic growth from the switch to zero-carbon energy sources seems likely to be limited and may even be positive. With regard to technical progress, this is likely to be stimulated by decarbonisation, with fossil-fuel industries being relatively mature and low-carbon energy generating whole new industries. At a national level, additional key considerations for the impacts of decarbonisation on economic growth are whether investments in low-carbon energy generate a domestic supply chain or imports, whether they result in a reduction in the net imports of fossil fuels (and, conversely for fossil fuel-exporting countries, whether they reduce exports of these fuels), and whether such activities draw on unused resources (capital or labour) or result in the "crowding out"[4] of other activities. These issues are explored further below.

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[4] "Crowding out" occurs when new investment replaces existing investment rather than adding to it. In situations where existing investment is more productive than new investment, "crowding out" will reduce GDP.

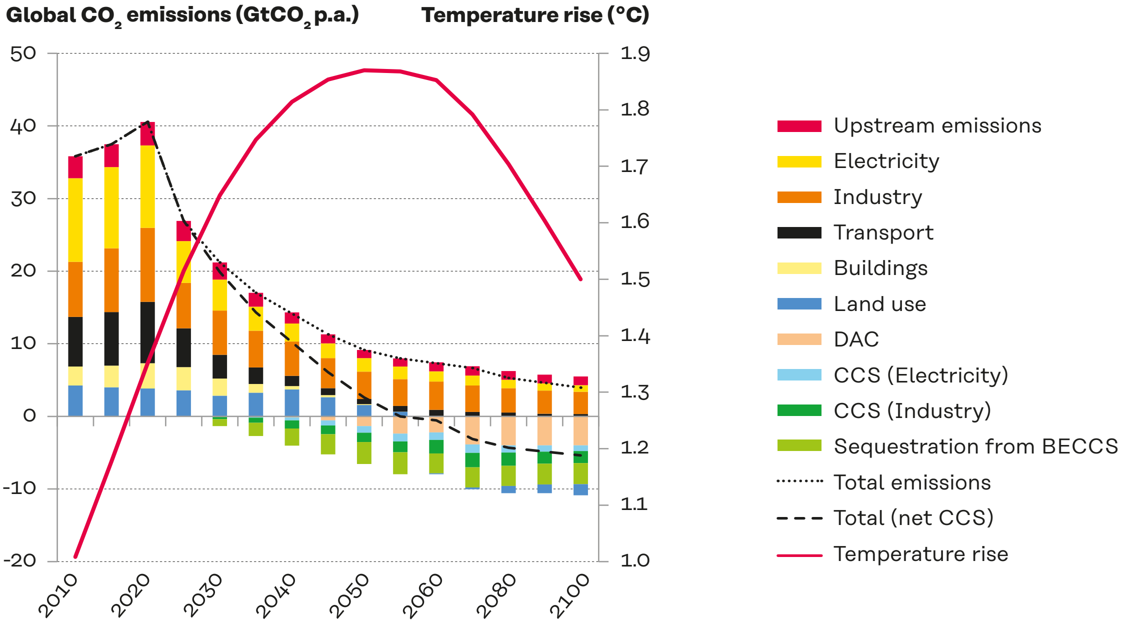
5 The scenarios

As noted above, the starting point for the scenarios to be modelled was the SSP1 assumptions. These assumptions produced energy demands from the PRIMES and GEM-E3 FIT models, which were fed into the global energy system model TIAM-UCL, which has a detailed representation of energy supply and demand technologies across the energy system. TIAM-UCL was constrained to produce net-zero CO_2 emissions in 2050, and a maximum global average temperature increase in 2100 of 1.5 °C (as projected using TIAM-UCL's in-built climate module).[5] This was the central decarbonisation scenario (hereafter "the central scenario"), the results of which are shown in the next section.

Inspection of these results showed that two factors, concerning which there is considerable uncertainty, were important in generating the central scenario results: 1) the rate of phase-out of coal use; and 2) the availability of CCS and NETs, which were heavily used in the central scenario. In order to explore the sensitivity of the results to these factors, further model runs were carried out with:

- half the rate of coal phase-out in the central scenario;
- no availability of CCS and NET technologies;
- a combination of the reduced rate of coal phase-out and no availability of CCS and NET technologies.

Figure 1: CO_2 emissions trajectory (central scenario)



(Authors' note: land use includes all CO_2 emissions from agriculture, forestry, land use and land-use change)

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[5] See the Technical Supplement for details of the climate module.

6 Results

6.1 The central decarbonisation scenario

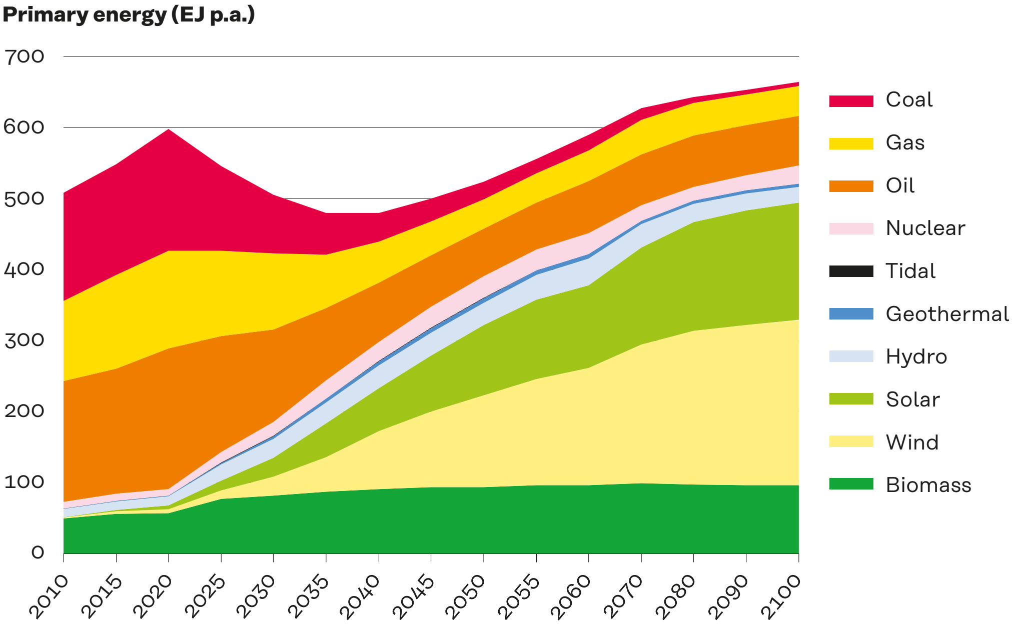
Figure 1 shows the CO_2 emissions trajectory for the central scenario.[6]

It can be seen that emissions reach net zero in 2055, missing the 2050 target. The average global temperature increase in 2100 is just below 1.5 °C, but it reaches nearly 1.9 °C around 2050, before declining to the end of the century. This temperature reduction is caused by a substantial use of CCS and NETs technologies (the bars below the zero-emission line), which by 2100 are capturing and storing carbon emissions or removing carbon from the atmosphere, in excess of 10 $GtCO_2$ per year. This outcome is broadly comparable to those of the SSP1 IPCC studies discussed above. However, there is significant uncertainty as to whether, even if it were possible to deploy CCS and NET technologies on this scale, the climate would respond in such a way as to reduce global average temperatures as shown.

Figure 2 and Figure 3 show the primary energy and electricity use in the central scenario respectively.

Figure 2 shows the huge growth in the use of wind and solar resources. This is used, as shown in Figure 3, to decarbonise almost completely the electricity system in 2100, even while it generates seven times as much electricity as in 2010. This extra electricity goes to decarbonise heat in buildings, mainly cars in transport, and some industrial processes. Hydrogen is also used in transport for HGVs, buses, trains, ships and some cars, while aviation largely switches to biofuels. Such natural gas, oil and coal as remains in the energy system is largely used in industry in sectors that are hard to decarbonise (e.g. steel and cement).

Figure 2: Primary energy (central scenario)



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6 Our illustrations focus on CO_2 (from all sources) as the dominant GHG and one for which there is an additional net-zero target in the model. However, the temperature constraint and trajectory reflect all GHGs.

Figure 3: Electricity generation (central scenario)

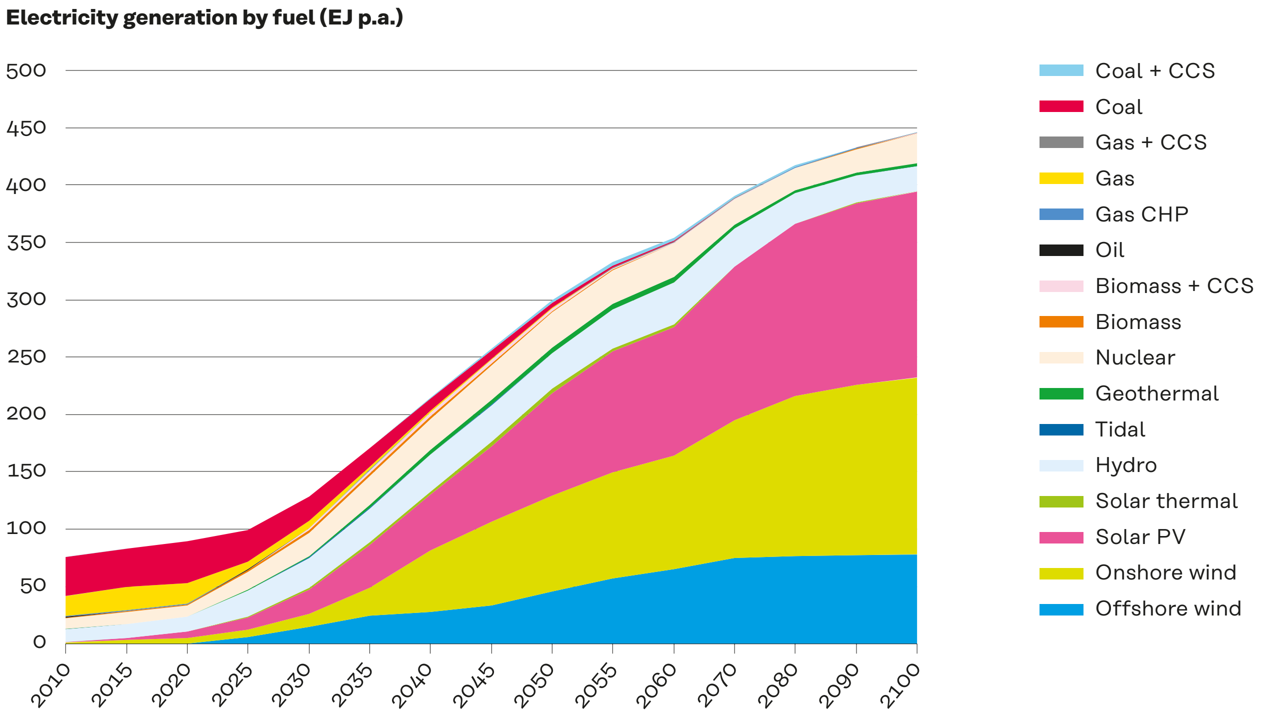


Figure 4: Decomposition of Gross World Product's annual growth rate to its key drivers

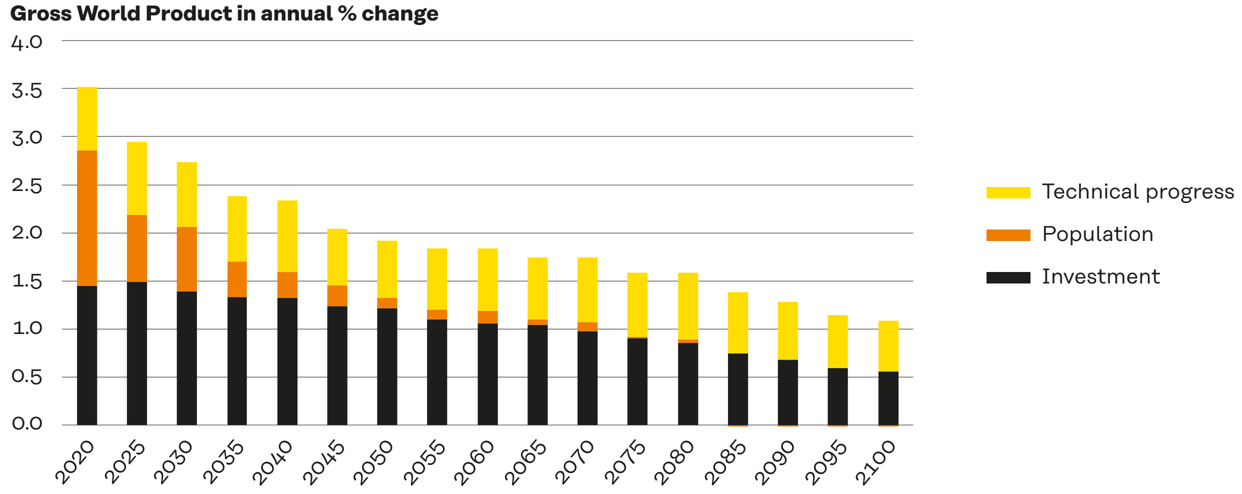
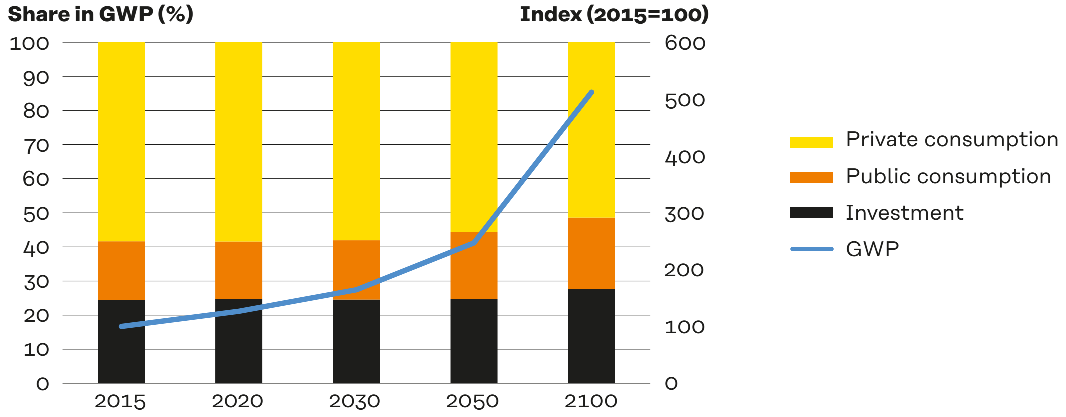


Figure 5: Annual Gross World Product (GWP), growth rate and components



The economic implications of this revolution in the energy system are shown in Figure 4 and Figure 5.

Figure 4 shows how the drivers of economic growth develop under decarbonisation. Population growth falls away over the century, leaving continuing growth in investment and technical progress, but at lower rates. Figure 5 shows that this results in continuing economic growth over the century (note the compressed scale in the later years), although per capita GWP growth in 2100 is about half what it was in 2020. Even so, the world economy in 2100 is nearly four-and-a-half times its size in 2015, having grown at an average rate of 1.76% p.a. over the period 2015-2100.

6.2 The sensitivity runs

Table 1 presents the results of the sensitivity runs, which focus on technologies and dynamics that are important in the central scenario but characterised by considerable uncertainty.

With a slower coal phase-out it is still possible to reach the 1.5 °C target by 2100, but only by making significantly greater use of CCS and NETs – the cumulative emissions stored or removed by these technologies rise from 583 $GtCO_2$ to 638 $GtCO_2$, compared to total CO_2 emissions in 2020 of around 40 $GtCO_2$. The peak temperature under this scenario rises from 1.87 °C to 1.89 °C. If CCS is not available, even with the fast coal phase-out, cumulative CO_2 emissions double over the central scenario, and it is no longer possible, with the rest of the assumptions of that scenario, to keep the temperature rise to 1.5 °C by 2100 – it rises to 1.74 °C by then.

Slow coal phase-out reduces GWP growth minimally compared to the central scenario, especially during the period 2030-2060, since other more expensive emission-reduction options have to be used for emission reductions. Notwithstanding, GWP continues to grow during the entire period to 2100. Lack of CCS and NETs does not affect GWP growth much.

7 Policy implications

The modelling results of this study clearly suggest that, with stringent public policy, the Paris target of a maximum warming of 1.5 °C in 2100 is feasible, albeit with overshooting this temperature increase in the decades after 2050, and that this can be achieved with continuing global economic growth. However, for this outcome public policy will need to generate increases in energy efficiency, investment in renewables, coal phase-out and CCS and NETs deployment at rates that greatly exceed anything that has yet been achieved at the global level. Moreover, the results also rest on the assumption that the removal of CO_2 from the atmosphere by future deployment of CCS and NETs will cause the global average temperature to fall as shown. Avoiding the uncertainties related to this and the possibility of triggering tipping points would require emissions to be reduced even faster than the

Table 1: Sensitivity results

	Central scenario	Slow coal phase-out	No CCS or NETs	
Coal phase-out rate	5.4% p.a.	2.7% p.a.	5.4% p.a.	2.7% p.a.
Net-zero date	2055	2055	-	-
Offset emissions from CCS, BECCS and DAC (2020-2100)	583 $GtCO_2$	638 $GtCO_2$	0 $GtCO_2$	0 $GtCO_2$
Peak temperature	1.87 °C	1.89 °C	1.89 °C	1.92 °C
Final temperature by 2100	1.5 °C	1.5 °C	1.74 °C	1.79 °C

already unprecedentedly fast rates shown in the modelling.

Decarbonisation at scale and at speed will require a mix of different policy instruments and approaches to remove the many barriers and constraints that impede it. The instruments and approaches include regulation, consumer information, digitalisation, carbon pricing, infrastructure provision, innovation support, and institutional and behaviour change across a range of policy areas. The changes required are both systemic and transformational. Most of society's fundamental techno-socio-economic systems will need to be refashioned: the energy system and the transport system; how buildings are constructed, and how businesses and individuals occupy and heat and cool them; the food system, what people eat and where it comes from; and how practically everything is made, used and disposed of at the end of its life.

The policy approaches to achieve this transformation must be consistent, coherent, credible and comprehensive to be effective, and be projected to be maintained over the decades that the low-carbon transition will take, so that the businesses that invest in the products and processes of decarbonisation in the various systems know that they will get the financial return that such investment requires.

No government in the world is yet close to the kind of policy architecture that will enable its country to achieve the level of emission reductions that would play its part in achieving the global goals of the Paris Agreement, and reaching the Paris target will require all the world's major emitters to do so.

8 Conclusions

This study began by enquiring what the conditions were for the world to achieve net-zero CO_2 emissions by mid-century and to limit the average global temperature increase to 1.5 °C by 2100. Evidence from the IPCC has already shown that it is possible to reach 1.5 °C by 2100 under the wide range of future worlds characterised by the SSP scenarios – but not under all of them. The baseline assumptions that make it easiest to reach the Paris targets are global co-operation, rapid technology development, strong environmental policy, low population growth, declining inequality, dietary shifts and forest protection, and these assumptions provided the foundation for the modelling in this study. Absence of any of these assumptions would make the achievement of the Paris 1.5 °C target more difficult or impossible.

The modelling quantified the Paris-consistent level of some of these factors:

- Increases in energy efficiency need to slow the growth of global primary energy demand so that in 2100 primary energy demand is little more than it is in 2020.
- The deployment of renewable technologies needs to decarbonise electricity generation almost completely by 2100 and produce seven times as much power as the world used in 2010, in order to replace fossil fuels in transport, heating and in some industrial processes.
- The use of coal must be phased out globally as fast if not faster as it has reduced in the USA in recent years.

- CCS technologies need to be installed at scale from 2030 to prevent residual industrial emissions from getting into the atmosphere.
- Soils and trees need to become carbon sinks on a large scale, and this will need a significant reduction in the amount of meat in the diets of the world's middle class.
- And there need to be, through innovation and deployment at scale, the kinds of reduction in the costs of hydrogen technologies as have already been seen in the generation of electricity from renewable sources.

None of this will happen without a strong and comprehensive policy framework. In the past it has been assumed by many that reductions in emissions on the scale required would be bound to require economic contraction, at least in the industrialised countries. The remarkable thing about modelling in this area is that there is unanimous agreement that this does not need to be the case. Every study of Paris-compliant economic development through to 2100 has shown global economic growth over this period, though with considerable differences in national impacts, depending on whether countries are fossil-fuel importers or exporters. Certainly, investment needs to take a larger share of national income, to create the new infrastructures and industries required by a zero-carbon world, but average levels of income across the world can keep growing. Policymakers need to understand this new reality, created by the enormous reductions in renewables costs that have already been achieved. This will not make the policies that they need to introduce easy to implement, but it means that they can be couched in a narrative of transformation towards greater prosperity in contrast to the very large climate damage costs that an absence of these policies seems likely to bring about.

"The 2020s is the decade that will either put the world's emission trajectory on track for this target or put it beyond reach."

Tiivistelmä

1 Selvityksen perustelut ja lähtökohdat

Kansainvälisessä ilmastopolitiikassa tavoitellaan päästöjen ja hiilinielujen tasapainoa, eli nettopäästöjen painamista nollaan, vuoteen 2050 mennessä. Tavoite pohjautuu Pariisin ilmastosopimukseen (2015), joka pyrkii rajaamaan maapallon keskilämpötilan nousun selvästi alle 2 asteeseen esiteolliseen aikaan verrattuna. Lisäksi Pariisin sopimuksessa tähtää toimiin, joilla keskilämpötilan nousu jäisi 1,5 asteeseen (UNFCCC, 2015). Tämän selvityksen tarkoituksena on tutkia makrotaloudellisen ja energiajärjestelmämallinnuksen avulla, voidaanko nämä tavoitteet saavuttaa, miten ne voidaan saavuttaa ja – ennen kaikkea – onko niiden saavuttaminen sopusoinnussa talouskasvun jatkumisen kanssa. Tarkasteluajanjakso ulottuu vuoteen 2100.

Selvitys keskittyy Pariisin sopimuksen tavoitteisiin, eikä siinä tarkastella laajempia ympäristökysymyksiä, joihin energiajärjestelmän muutokset voivat vaikuttaa. Muiden luonnonvarojen kuin energianlähteiden käyttö ja bioenergiaan liittyvä maankäyttö sekä näiden vaikutukset luonnon monimuotoisuuteen ovat kuitenkin myös tärkeitä kysymyksiä, ja nekin olisi otettava huomioon. Kun maailman maat tekevät päätöksiä ilmastotoimista, olisi mietittävä tarkkaan esimerkiksi se, kuinka paljon ja missä bioenergiaa käytetään. Tällaiset päätökset voivat vaikuttaa maankäyttöön ja luonnon monimuotoisuuteen. Käytettävissä malleissa ei myöskään voida ottaa huomioon vähähiiliseen energiajärjestelmään tai kiertotalouteen siirtymisen muuttuvia vaikutuksia materiaalien käyttöön tai kiertotalouden päästövaikutuksia.[7] Jos materiaalien lisääntynyt kierrätys vähentää merkittävästi ensiömateriaalien käyttöä ja käsittelyä, se voisi olla yksi tapa vähentää päästöjä. Tätä ei kuitenkaan analysoida tässä selvityksessä, vaan aihetta on syytä tutkia tarkemmin toisissa yhteyksissä.

2 Nykytiedot päästöjen ja talouskasvun välisestä suhteesta

Maailman kasvihuonekaasupäästöt, jotka ovat syynä ihmisen toiminnan aiheuttamaan ilmaston kuumenemiseen, ovat lisääntyneet talouskasvun myötä koko mittaushistorian ajan. Tämä ei ole yllättävää, sillä fossiilisten polttoaineiden polttamisesta aiheutuvat hiilidioksidipäästöt ovat merkittävin kasvihuonekaasujen lähde. Fossiiliset polttoaineet ovat olleet pääasiallinen energianlähde teollisesta vallankumouksesta lähtien, ja energiankäyttö on avaintekijä suurimmassa osassa taloudellista toimintaa. Tämä selvitys pyrkii löytämään vastauksen kysymykseen "Jos päästöjä vähennetään Pariisin ilmastosopimuksen tavoitteen edellyttämällä tahdilla, voiko talous jatkaa kasvuaan?". Toisin sanoen: voidaanko päästöt kytkeä irti talouskasvusta?

Euroopan unionista ja yksittäisistä jäsenvaltioista on saatu näyttöä siitä, että tällainen irtikytkeminen voi olla mahdollista. Vuosina 1990–2016 EU:n talous kasvoi yli 50 prosenttia, mutta polttoaineiden käytöstä aiheutuvat hiilidioksidipäästöt vähenivät 25 prosenttia. Lisäksi Suomessa ja Isossa-Britanniassa jopa kulutusperäiset päästöt (jotka sisältävät tuontitavaroiden valmistuksen päästöt, mutta eivät vientitavaroiden valmistuksen päästöjä) vähenivät vuodesta 2007

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[7] Kiertotaloutta käsitellään tarkemmin tämän selvityksen liitteessä 2.

vuoteen 2016. Päästöjen väheneminen näillä aikaväleillä ei kuitenkaan ollut läheskään niin nopeaa kuin Pariisin ilmastosopimuksen tavoite edellyttäisi. Tätä ei siis voi katsoa ratkaisevaksi näytöksi siitä, että talouskasvu voisi jatkua, jos päästöjä vähennettäisiin paljon nopeammin.

Edellä mainituissa talouksissa tapahtunut energiaan liittyvien päästöjen väheneminen oli kolmen keskeisen tekijän ansiota:

- energiankäytön tehostamisen nostaminen
- fossiilisten polttoaineiden korvaaminen vähähiilisillä tai hiilettömillä energianlähteillä
- talouden rakennemuutokset, joihin liittyy vähähiilisten palvelujen kulutuksen lisääminen ja energiaintensiivisten teollisuudenalojen siirtäminen muualle (vaikka jälkimmäisen vaikutukset otetaan huomioon kulutusperäisten päästöjen laskennassa).

Isossa-Britanniassa ja Suomessa näitä tekijöitä on yhdistelty eri tavoin ja eri laajuudessa. Maita yhdistää se, että energiaan liittyvät päästöt ovat vähentyneet julkisten politiikkatoimien myötä, jotka ovat stimuloineet ja vahvistaneet joitakin markkinavoimia ja rajoittaneet toisia.

On selvää, että Pariisin ilmastosopimuksen tavoitteiden saavuttaminen edellyttää näiden tekijöiden taustalla olevien tai niitä vahvistavien politiikkatoimien huomattavaa tehostamista, kuten tästä selvityksestä käy ilmi.

3 Tämänhetkiset tiedot 1,5 °C:n tavoitteesta

Hallitustenvälisen ilmastopaneelin IPCC:n julkaisema 1,5 asteen erikoisraportti (2018) kuvasi, millaisia päästövähennyspolkuja ja -teknologioita 1,5 asteen tavoite vaatisi. Raportti esitti myös arvioita, millaisia talousvaikutuksia tavoitteen saavuttamisella olisi. IPCC:n erikoisraportissa tarkasteltiin lukuisia skenaarioita, joihin sisältyi erilaisia oletuksia. Tavoitteena oli määrittää, onko Pariisin ilmastosopimuksen tavoitteiden saavuttaminen mahdollista erilaisissa globaaleissa kehitysskenaarioissa ja kuinka helppoa se olisi. Lähtökohtana olivat viisi skenaariota, joita kutsutaan SSP-skenaarioiksi (Shared Socio-Economic Pathways, yleiset sosioekonomiset kehityspolut) ja jotka pohjautuvat eri oletuksiin. Nämä oletukset liittyvät muun muassa väestönkasvuun ja talouskasvuun, kaupan intensiteettiin, ympäristönäkökohtiin, teknologisen kehityksen vauhtiin ja kansainväliseen yhteistyöhön. Oletuksia kuvataan tarkemmin jäljempänä.

Näiden laajojen oletusten perusteella eri tutkimusten mallintajat ovat valinneet seuraavilta osa-alueilta parametrien arvot, jotka vaikuttivat pääosin yhdenmukaisilta aikaisemmin lueteltujen pääoletusten kanssa:

- talouden rakenteen ja tuotosten kehitys
- energian kysyntä ja energiatehokkuus
- materiaalien kysyntä ja materiaalitehokkuus
- vähähiilisten energiamuotojen ja teknologian käyttö
- hiilidioksidin talteenoton ja varastoinnin (CCS) ja hiilensidonnassa käytettävien erilaisten negatiivisten päästöteknologioiden (NET[8]) saatavuus ja käyttö
- maankäyttö ja biomassan saatavuus energiantuotantoa varten
- politiikkatoimien valinta ja toteuttaminen
- päästövähennysteknologioiden kustannukset.

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[8] NET-teknologiat koostuvat tekniikoista, jotka ottavat hiilidioksidia talteen ilmakehästä ja varastoivat sen niin, ettei hiilidioksidi enää pääse takaisin ilmakehään. NET-tekniikoihin kuuluvat hiilidioksidin talteenotto ja varastointi bioenergian tuotannossa (BECCS), metsitys ilman puutavaran korjaamista, hiilen sidonta maaperään ja hiilidioksidia suoraan ilmakehästä talteen ottavat DAC (Direct Air Capture) -laitteet. DAC-teknologia on varhaisessa kehitysvaiheessa.

IPCC:n mallinnuksissa kasvihuonekaasupäästöjen vähentämiseen löydettiin monia eri polkuja sen mukaan, mitä oletuksia ja malleja käytettiin. Monet näistä poluista olivat linjassa Pariisin ilmastosopimuksen tavoitteen – rajata lämpötilan nousu vuoteen 2100 mennessä 1,5 asteeseen – kanssa, mutta yleensä niissä ylitettiin9 tämä taso väliaikaisesti vuosisadan loppupuolella (näin kävi myös tässä selvityksessä tehdyssä mallinnuksessa, kuten jäljempänä käy ilmi). Tehdyt mallinnukset osoittivat myös, että talouskasvu jatkuu. Talouskasvu näytti hidastuvan vuoteen 2100 mennessä vain vähän verrattuna tilanteeseen, jossa ei pyritä saavuttamaan hiilineutraaliutta (tähän ei sisältynyt ilmastonmuutoksesta aiheutuvia kustannuksia, joten laskelma on siksi todennäköisesti optimistinen). Missään skenaariossa ei päästy lähellekään taloudellisen tuotoksen laskua vuoden 2020 tasosta, eli kaikissa skenaarioissa havaittiin talouskasvua. Näin ollen kaikissa skenaarioissa havaittiin, että päästökehityksen irrottaminen talouskasvusta on mahdollista.

Tässä hankkeessa tehdyillä mallinnuksilla pyrittiin tutkimaan kyseistä ilmiötä tarkemmin ja selvittämään, johtavatko tutkimuksessa käytetyt mallit samaan tulokseen, miksi tähän tulokseen päädyttiin ja mitkä olivat sen taustasyyt.

4 Selvityksessä käytetyt mallinnustavat

Tässä selvityksessä käytettiin kahta energiajärjestelmämallia (PRIMES ja TIAM-UCL) ja yhtä laskennallista yleisen tasapainon (CGE) makrotaloudellista mallia (GEM-E3 FIT). Energiajärjestelmämallit laskevat, miten energiatarpeet voitaisiin täyttää vuoteen 2100 ulottuvalla ajanjaksolla samalla, kun nettohiilidioksidipäästöt pyrittäisiin vähentämään nollaan vuoteen 2050 mennessä ja maapallon lämpötilan nousu vuoteen 2100 mennessä pyrittäisiin rajaamaan enintään 1,5 asteeseen. Kuten jäljempänä tässä selvityksessä todetaan, esitettyjen oletusten mukaisilla malleilla nettopäästöt saataisiin vähennettyä nollaan vasta vuonna 2055 (ei vuonna 2050). Asetettu lämpötilatavoite eli enintään 1,5 asteen nousu vuoteen 2100 mennessä pystyttäisiin saavuttamaan, mutta vain niin, että tämä tavoitetaso ylitettäisiin väliaikaisesti vuosisadan loppupuolella, kuten edellä todettiin. Yksinkertaisuuden vuoksi jäljempänä kuitenkin viitataan edelleen nettopäästöjen saamiseen nollaan vuoteen 2050 mennessä.

Makrotaloudellisessa mallissa ennakoidaan taloudellista tuotosta käyttäen perusteena energiatarpeita ja teknologiaa sekä niihin liittyviä kustannuksia, joita syntyy energiajärjestelmämallien hiilidioksidipäästöjen vähentämisskenaarioissa. Mallien yhdistämistapa kuvataan jäljempänä tässä selvityksessä, ja itse malleja kuvataan lyhyesti tämän selvityksen liitteessä 1.

Mallinnuksessa tarkasteltujen skenaarioiden lähtökohtana oli SSP1-skenaario, joka on maailman kehitystä koskevien oletustensa vuoksi helpoin tapa hiilineutraaliuden saavuttamiseen maailmanlaajuisesti. Oletuksia ovat muun muassa maailmanlaajuinen yhteistyö, teknologian nopea kehitys, vahva ympäristöpolitiikka, alhainen väestönkasvu, eriarvoisuuden väheneminen, ruokavalion muutokset ja metsien suojelu. Muiden SSP-skenaarioiden käyttö olisi tehnyt hiilineutraaliuden saavuttamisesta vaikeampaa ja kalliimpaa, mikä tulisi ottaa huomioon tuloksia tulkittaessa. Kaikkia SSP1:n oletuk-

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9 Ylityksellä tarkoitetaan maapallon keskilämpötilan nousua yli 1,5 asteella. Mallinnuksessa lämpötilan nousu lasketaan ylityksen jälkeen takaisin 1,5 asteen tasolle teknisillä ratkaisuilla, jotka poistavat suuria määriä hiilidioksidia ilmakehästä. On kuitenkin erittäin epävarmaa, käyttäytyisivätkö maapallon lämpötilat tällä tavalla vai johtaisiko yli 1,5 asteen nousun salliminen kriittisiin ilmaston keikahduspisteisiin, joissa muista lähteistä syntyisi merkittäviä kasvihuonekaasupäästöjä ja jotka muuttaisivat ilmaston pysyvästi ihmisten kannalta huonommaksi. Ks. Lenton ym. (2019).

sia voidaan kuitenkin pitää järkevinä, vaikka ne eivät välttämättä liitykään nykyhetkeen.

Kuten jo todettiin, makrotaloudellisessa mallissa käytetään energiajärjestelmämallien tuloksia vuosisadan loppuun ulottuvalta jaksolta ja arvioidaan niiden pohjalta mahdollisia taloudellisia vaikutuksia. Muiden makrotaloudellisten mallien tapaan GEM-E3 FIT mallissa on pääasiassa kolme talouskasvua vauhdittavaa tekijää: väestönkasvu, nettoinvestoinnit ja tekninen kehitys. Hiilestä irtautuminen voisi vaikuttaa kielteisesti koko maailman talouskasvuun, jos se kasvattaisi energiakustannuksia tai hidastaisi teknistä kehitystä. Koska uusiutuvista energianlähteistä tuotettu sähkö on nykyään monissa maissa kilpailukykyistä fossiilisista polttoaineista tuotettuun sähköön verrattuna, hiilettömiin energianlähteisiin siirtymisen vaikutukset talouskasvuun näyttävät olevan todennäköisesti vähäisiä ja jopa myönteisiä. Hiilestä irtautuminen todennäköisesti edistää teknologista kehitystä, sillä fossiilisia polttoaineita käyttävät teollisuudenalat ovat suhteellisen kypsiä ja vähähiilinen energia synnyttää täysin uusia teollisuudenaloja.

Kun tarkastellaan hiilestä irtautumisen vaikutuksia talouskasvuun kansallisella tasolla, on huomioitava joitakin avaintekijöitä: edistävätkö vähähiiliseen energiaan tehdyt investoinnit kotimaista tuotantoa vai tuontia, vähentävätkö ne fossiilisten polttoaineiden nettotuontia (ja vähentävätkö ne toisaalta fossiilisten polttoaineiden viejämaiden osalta näiden polttoaineiden vientiä) sekä hyödynnetäänkö näissä toimenpiteissä käyttämättömiä resursseja (pääomaa tai työvoimaa) vai johtavatko ne muun toiminnan syrjäyttämiseen[10]. Näitä kysymyksiä tarkastellaan yksityiskohtaisemmin jäljempänä.

5 Skenaariot

Kuten edellä todettiin, mallinnettavien skenaarioiden lähtökohtana olivat SSP1-oletukset. Näiden oletusten pohjalta PRIMES- ja GEM-E3 FIT mallit arvioivat ensin energiankulutusta. Nämä arviot energian kysynnästä syötettiin sitten globaaliin TIAM-UCL-energiajärjestelmämalliin, joka mallintaa yksityiskohtaisesti energian tarjonta- ja kysyntäteknologioita koko energiajärjestelmässä. TIAM-UCL -mallia rajoitettiin niin, että nettohiilidioksidipäästöt vähenisivät nollaan vuoteen 2050 mennessä ja maapallon keskilämpötilan nousu vuoteen 2100 mennessä olisi enintään 1,5 C (TIAM-UCL:n sisäisen ilmastomoduulin ennusteen mukaisesti).[11] Näin luotiin selvityksen pääskenaario hiilineutraaliuteen (jäljempänä "pääskenaario"), jonka tulokset esitetään seuraavassa osiossa.

Tulosten tarkastelu osoitti, että pääskenaarion tuloksiin vaikuttivat merkittävästi kaksi tekijää, joihin liittyy huomattavaa epävarmuutta: 1) hiilen käytön asteittaisen lopettamisen etenemistahti ja 2) hiilidioksidin talteenoton ja varastoinnin (CCS) sekä NET-teknologioiden saatavuus, sillä näitä teknologioita tarvittiin tavoitteiden saavuttamiseen merkittävissä määrin pääskenaariossa. Tulosten herkkyyttä näiden tekijöiden suhteen selvitettiin seuraavilla lisäskenaarioilla:

- hiilen käytön asteittaisen lopettamisen etenemistahti on puolet pääskenaariossa käytetystä
- CCS- ja NET-teknologioita ei ole käytettävissä
- molemmat edellä mainitut.

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[10] Syrjäyttäminen tarkoittaa sitä, että uudet investoinnit korvaavat olemassa olevia investointeja sen sijaan, että investoinnit kokonaisuudessaan lisääntyisivät. Tilanteissa, joissa olemassa olevat investoinnit ovat tuottavampia kuin uudet investoinnit, syrjäyttäminen pienentää bruttokansantuotetta.

[11] Lisätietoja ilmastomoduulista on selvityksen teknisessä täydennysosassa.

6 Tulokset

6.1 Pääskenaario hiilineutraaliuteen

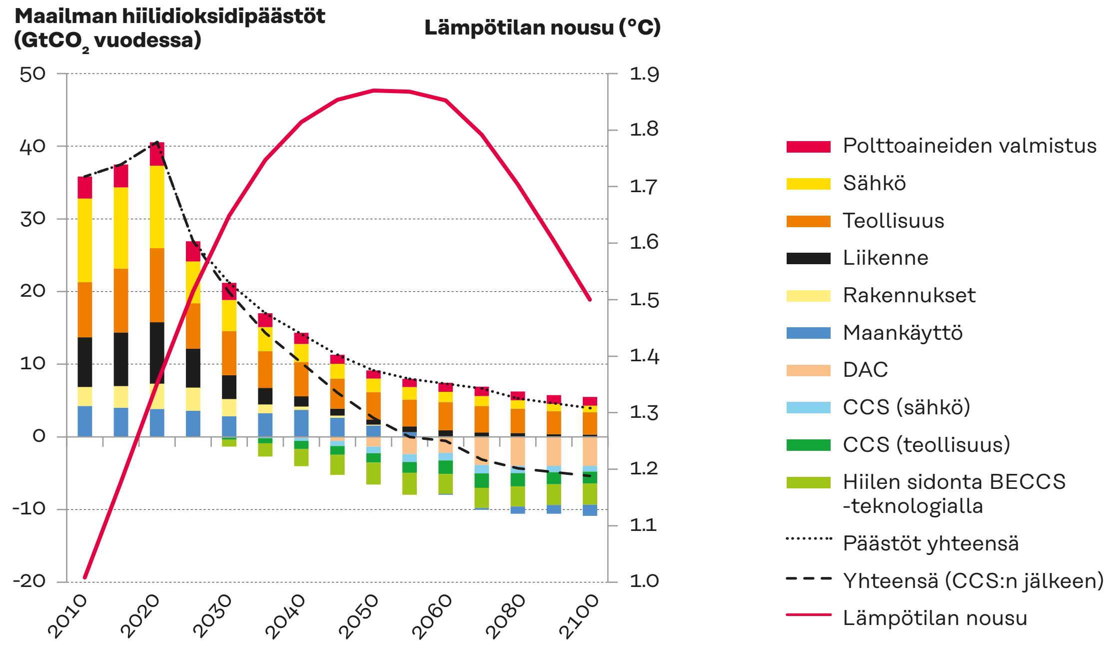
Kuvassa 1 esitetään hiilidioksidipäästöt pääskenaariossa.[12]

Kuvasta voidaan havaita, että nettopäästöt saavuttavat nollatason vuonna 2055 eli tavoitevuoden 2050 jälkeen. Maapallon keskilämpötilan nousu vuoteen 2100 mennessä on hieman alle 1,5 astetta. Lämpötilan nousu kuitenkin saavuttaa lähes 1,9 asteen tason noin vuonna 2050, minkä jälkeen se laskee vuosisadan loppua kohti. Lämpötilan aleneminen johtuu CCS- ja NET-tekniikoiden (nollapäästöviivan alapuolella olevat pylväät) huomattavasta käytöstä. Vuoteen 2100 mennessä niillä otetaan talteen ja varastoidaan hiilidioksidipäästöjä tai poistetaan hiiltä ilmakehästä yli 10 $GtCO_2$:n verran vuodessa. Tämä tulos on pitkälti verrattavissa edellä käsiteltyihin IPCC:n SSP1-tutkimuksiin. On kuitenkin huomattavaa epävarmuutta siitä, alenisiko maapallon keskilämpötila kuvatulla tavalla, vaikka CCS- ja NET-tekniikoita voitaisiin käyttää tässä mittakaavassa.

Kuvissa 2 ja 3 ovat pääskenaarion primäärienergian ja sähkön käytön mallinnustulokset.

Kuvassa 2 näkyy tuuli- ja aurinkoenergian käytön merkittävä kasvu. Kuten kuvasta 3 näkyy, näitä käytetään lähes koko sähköjärjestelmän päästöjen vähentämiseen vuoteen 2100 mennessä, samalla kun sähköä tuotetaan seitsemän kertaa niin paljon kuin vuonna 2010. Tällä "lisäsähköllä" irtaudutaan paljon päästöjä tuottavista teknologioista erityisesti rakennusten lämmityksessä,

Kuva 1: Hiilidioksidipäästöt eri lähteistä tällä vuosisadalla (pääskenaario)



(Tekijöiden huomautus: Maankäyttö sisältää kaikki maa- ja metsätaloudesta, maankäytöstä ja maankäytön muutoksista aiheutuvat hiilidioksidipäästöt.)

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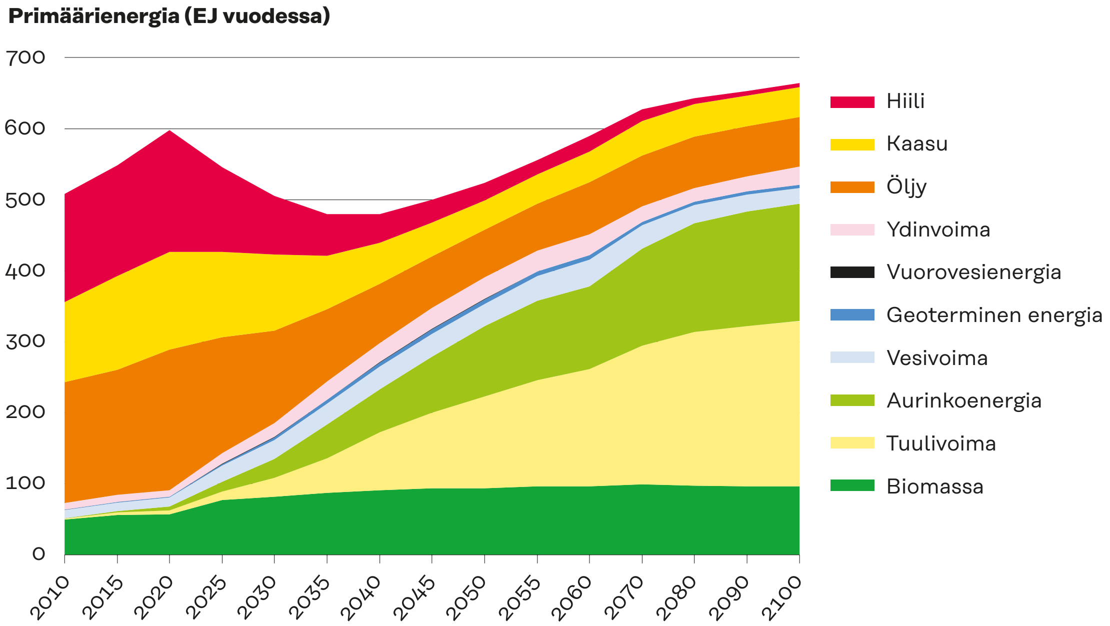
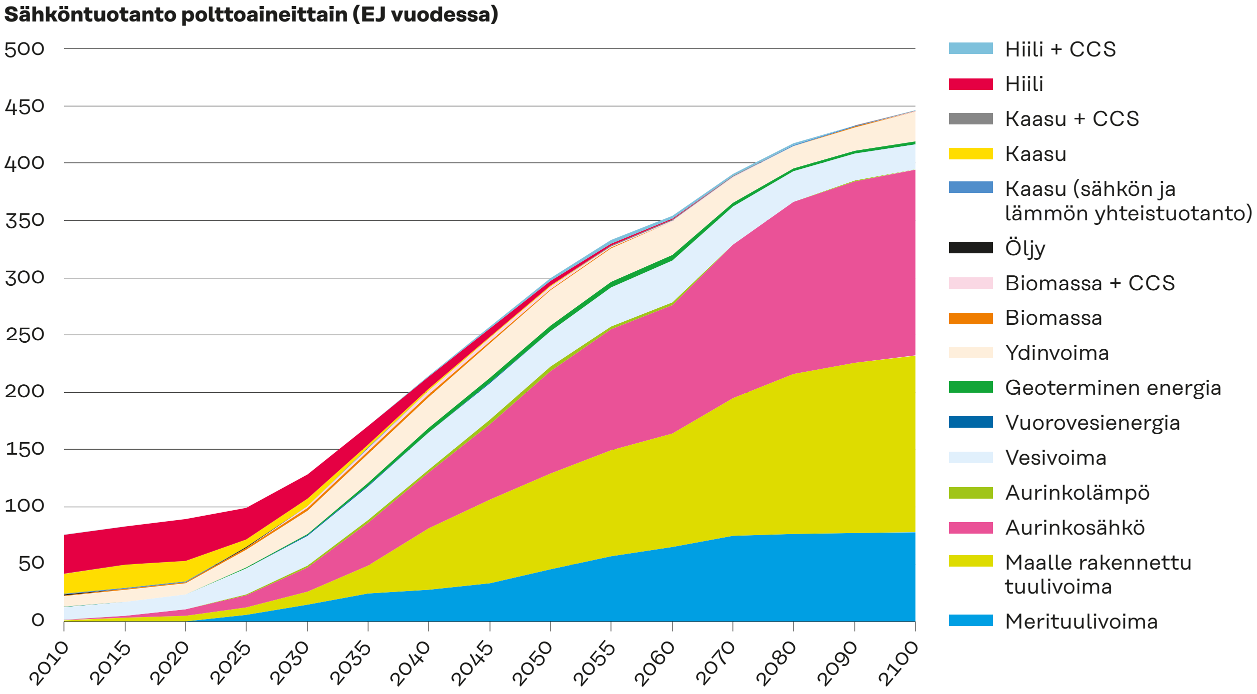
[12] Kaavioissamme keskitytään (mistä tahansa lähteestä peräisin olevaan) hiilidioksidiin pääasiallisena kasvihuonekaasuna, jolle on määritetty mallissa erillinen nettopäästöjen nollaan saamisen tavoite. Lämpötilarajoitus ja kehityskaari heijastavat kuitenkin kaikkia kasvihuonekaasuja.

Kuva 2: Primäärienergia (pääskenaario)



Kuva 3: Sähköntuotanto (pääskenaario)

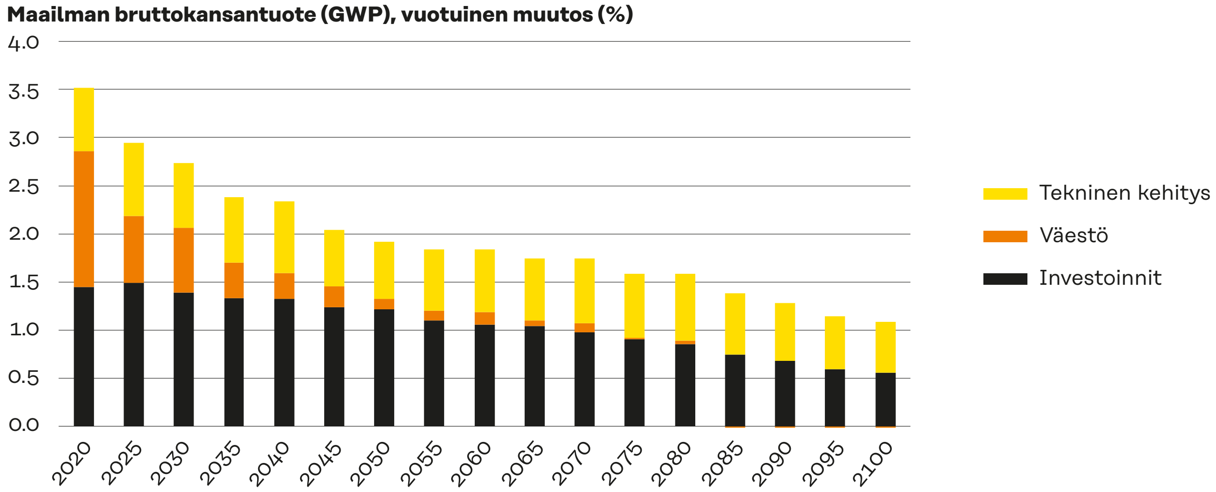


henkilöautoliikenteessä ja joissakin teollisuusprosesseissa. Vetyä käytetään maaliikenteessä raskaissa kuljetuksissa, linja-autoissa, junissa, laivoissa ja joissakin henkilöautoissa, kun taas ilmailussa siirrytään suurelta osin biopolttoaineisiin. Jäljelle jäävät määrät maakaasua, öljyä ja hiiltä käytetään energiajärjestelmässä pääasiassa teollisuudenaloilla, joilla hiilestä irtautuminen on vaikeaa (esimerkiksi teräksen ja sementin valmistuksessa).

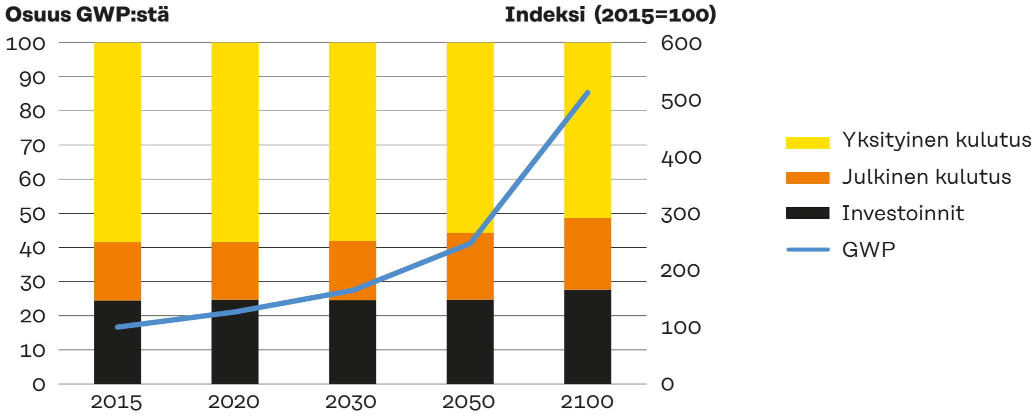
Tämän energiajärjestelmän mullistuksen taloudelliset vaikutukset esitetään kuvissa 4 ja 5.

Kuvasta 4 näkyy, miten talouskasvua vauhdittavat tekijät kehittyvät pääskenaariossa siirryttäessä hiilineutraaliuteen. Väestönkasvun merkitys hiipuu vuosisadan kuluessa, ja investointien ja teknisen kehityksen merkitys kasvaa jatkuvasti mutta aiempaa hitaammalla vauhdilla. Kuvasta 5 käy ilmi, että tämä johtaa talouskasvun jatkumiseen vuosisadan aikana (huomaa, että myöhemmissä vuosissa käytetään tiivistettyä asteikkoa), vaikka maailman kaikkien maiden yhteenlasketun bruttokansantuotteen eli GWP:n (Gross World Product) kasvu henkeä kohti vuonna 2100 on

Kuva 4: Maailman bruttokansantuotteen (Gross World Product, GWP) vuotuisen kasvun jakautuminen tärkeimpien tekijöiden kesken



Kuva 5: Vuotuinen maailman bruttokansantuote (GWP), kasvuvauhti ja osatekijät



noin puolet siitä, mitä se oli vuonna 2020. Maailmantalous on kuitenkin vuonna 2100 lähes 4,5 kertaa niin suuri kuin vuonna 2015, ja vuotuinen kasvu on keskimäärin 1,76 prosenttia vuosina 2015–2100.

6.2 Vaihtoehtoiset skenaariot

Taulukossa 1 esitetään vaihtoehtoisten skenaarioiden tulokset. Laskelmissa keskitytään pääskenaariossa tärkeisiin teknologisiin ratkaisuihin ja dynamiikkoihin, joihin liittyy huomattavaa epävarmuutta.

Myös skenaariossa, jossa hiilen käytön lopettaminen on hitaampaa kuin pääskenaariossa, on mahdollista saavuttaa 1,5 asteen tavoite vuoteen 2100 mennessä, mutta vain käyttämällä huomattavasti enemmän CCS- ja NET-teknologioita. Näiden ratkaisujen avulla varastoitujen tai talteen otettujen päästöjen kumulatiivinen määrä kasvaa 583:sta 638:aan gigatonniin hiilidioksidia (GtCO$_2$). Vertailukohtana mainittakoon, että hiilidioksidin kokonaispäästöt vuonna 2020 olivat noin 40 GtCO$_2$. Tässä skenaariossa suurin lämpötilan nousu kasvaa 1,87 asteesta 1,89 asteeseen. Jos hiilidioksidin talteenottoa ja varastointia ei ole käytettävissä (kolmas skenaario), kumulatiiviset hiilidioksidipäästöt kaksinkertaistuvat pääskenaarioon verrattuna. Näin käy, vaikka hiilen käytön lopettaminen tapahtuisi nopeasti. Lisäksi hiilidioksidin talteenoton ja varastoinnin puute ja muut kyseisen skenaarion oletukset johtavat siihen, että lämpötilan nousua vuoteen 2100 mennessä ei voida enää rajata 1,5 asteeseen, vaan nousu on 1,74 astetta.

Hidas hiilen käytön lopettaminen vähentää GWP:n kasvua vähän pääskenaarioon verrattuna etenkin vuosina 2030–2060, koska päästöjen vähentämiseksi on käytettävä muita, kalliimpia vaihtoehtoja. Tästä huolimatta GWP jatkaa kasvuaan koko vuoteen 2100 ulottuvan ajanjakson ajan. Se, että CCS- ja NET-teknologiaa ei olisi käytettävissä, ei juurikaan vaikuta GWP:n kasvuun.

7 Tulosten merkitys politiikkatoimille

Tämän selvityksen mallinnustulokset osoittavat selvästi, että tiukkojen poliittisten ohjauskeinojen avulla Pariisin ilmastosopimuksen tavoite rajata maapallon keskilämpötilan nousu vuoteen 2100 mennessä 1,5 asteeseen on saavutettavissa, vaikka keskilämpötilan nousu ylittyisikin väliaikaisesti vuoden 2050 jälkeisinä vuosikymmeninä. Lisäksi tämä tavoite voidaan saavuttaa niin, että maailmanlaajuinen talouskasvu jatkuu. Tämän lopputuloksen saavuttamiseksi politiikkatoimilla on kuitenkin edistettävä energiatehokkuutta, investointeja uusiutuviin energianlähteisiin, hiilen käytön asteittaista lopettamista ja CCS- ja NET-tek-

Taulukko 1: Vaihtoehtoisten skenaarioiden tulokset

	Pääskenaario	Hidas hiilen käytön lopettaminen	Ei CCS- ja NET-teknologioita	
Hiilen käytön asteittaisen lopettamisen etenemistahti	5,4 % vuodessa	2,7 % vuodessa	5,4 % vuodessa	2,7 % vuodessa
Nettopäästöt nollaan ajankohta	2055	2055	-	-
Hiilidioksidin talteenotto ja varastointi CCS-, BECCS- ja DAC-teknologioilla (2020–2100)	583 GtCO$_2$	638 GtCO$_2$	0 GtCO$_2$	0 GtCO$_2$
Suurin lämpötilan nousu	1,87 °C	1,89 °C	1,89 °C	1,92 °C
Lopullinen lämpötilan nousu vuoteen 2100 mennessä	1,5 °C	1,5 °C	1,74 °C	1,79 °C

nologioiden käyttöönottoa huomattavasti nopeammalla tahdilla kuin mitä maailmanlaajuisesti on tähän mennessä saavutettu. Lisäksi tulokset perustuvat oletukseen, että CCS- ja NET-teknologioiden tuleva käyttöönotto ja siitä seuraava hiilidioksidin poistaminen ilmakehästä laskevat maapallon keskilämpötilaa esitetyllä tavalla. Tähän liittyvien epävarmuustekijöiden ja mahdollisten ilmaston keikahduspisteiden välttäminen edellyttäisi, että päästöjä vähennettäisiin vieläkin nopeammin kuin mallinnuksessa esitettyä ennen näkemätöntä vauhtia.

Laajamittainen ja nopea nettonollatavoitteen saavuttaminen eli hiilidioksipäästöistä irtautuminen edellyttää, että sen tiellä olevat lukuiset esteet ja rajoitteet poistetaan käyttämällä erilaisia poliittisia ohjauskeinoja ja päästövähennyskeinoja. Näitä ovat sääntely, kuluttajavalistus, digitalisaatio, hiilen hinnoittelu, tarvittavat investoinnit infrastruktuuriin, innovaatioiden tukeminen sekä institutionaaliset ja käyttäytymiseen liittyvät muutokset useilla politiikan aloilla. Vaadittavat muutokset ulottuvatkin läpi koko yhteiskunnan, ja yhteiskunnan teknisiä, sosiaalisia ja taloudellisia rakenteita on uudistettava: energia- ja liikennejärjestelmiä, rakentamista sekä sitä, miten yritykset ja yksityishenkilöt käyttävät, lämmittävät ja jäähdyttävät rakennuksia, ruokajärjestelmää eli mitä ihmiset syövät ja miten ruoka tuotetaan, sekä käytännössä kaikkien tuotteiden valmistamista, käyttämistä ja uudelleenkäyttämistä sekä hävittämistä elinkaaren lopussa.

Jotta tämän muutoksen vaatimat poliittiset ohjauskeinot olisivat tehokkaita, niiden on oltava johdonmukaisia, yhtenäisiä, uskottavia ja kattavia. Lisäksi ennakoiva toimintaympäristö on tärkeä eli politiikkatoimien on oltava voimassa niiden vuosikymmenten ajan, jotka vähähiiliseen talouteen siirtyminen vie. Tämä on tarpeen, jotta vähäpäästöisiin tuotteisiin ja prosesseihin investoivat yritykset luottavat saavansa siirtymään tarvittavien investointien edellyttämän taloudellisen tuoton.

Yksikään maailman maa ei ole vielä tehnyt läheskään sellaisia poliittisia linjanvetoja ja ohjauskeinoja, jotka mahdollistaisivat Pariisin ilmastosopimuksen mukaiset päästövähennykset. Tavoitteiden saavuttaminen edellyttäisi isoja linjanvetoja kaikilta maailman suurimmilta päästöjen aiheuttajilta. **2020-luku on ratkaiseva vuosikymmen sen kannalta, saadaanko maailman päästöjen kehityssuunta oikeille raiteille vai lipuuko Pariisin ilmastosopimuksen tavoite ulottumattomiin.**

8 Johtopäätökset

Tämän selvityksen alussa kysyttiin, millaiset edellytykset on siihen, että maapallon nettohiilidioksidipäästöt saataisiin vähennettyä nollaan vuosisadan puoliväliin mennessä ja maapallon keskilämpötilan nousu saataisiin rajattua 1,5 asteeseen vuoteen 2100 mennessä. IPCC:n tutkimukset ovat jo osoittaneet, että 1,5 asteen tavoite on mahdollista saavuttaa vuoteen 2100 mennessä monissa SSP-skenaarioiden kuvaamissa tulevaisuudenkuvissa – mutta ei kaikissa. Pariisin ilmastosopimuksen tavoitteisiin pääsemistä helpottavia perusoletuksia ovat maailmanlaajuinen yhteistyö, teknologian nopea kehitys, vahva ympäristöpolitiikka, alhainen väestönkasvu, eriarvoisuuden väheneminen, ruokavalion muutokset ja metsien suojelu. Samoja oletuksia käytettiin tämän selvityksen mallinnusten pohjana. Jos jokin näistä oletuksista ei täyty, Pariisin sopimuksen 1,5 asteen tavoite muuttuu entistä vaikeammaksi saavuttaa, ellei mahdottomaksi.

Mallinnuksissa arvioitiin Pariisin ilmastosopimuksen tavoitteiden edellyttämiä tasoja joillakin näistä osa-alueista:

- Energiatehokkuuden parannusten on hidastettava primäärienergian maailmanlaajuisen kysynnän kasvua siten, että vuonna 2100 primäärienergian kysyntä on vain vähän suurempi kuin vuonna 2020.
- Jotta fossiiliset polttoaineet pystytään korvaamaan liikenteessä, lämmityksessä ja osassa teollisia prosesseja, on edistettävä uusiutuvan energiateknologian käyttöönottoa niin, että sähköntuotanto on lähes päästötöntä 2100 mennessä. Lisäksi sähköä on tuotettava seitsemän kertaa niin paljon kuin maailmassa käytettiin vuonna 2010.
- Hiilen käyttö on lopetettava asteittain koko maailmassa yhtä nopeasti tai jopa nopeammin kuin se on vähentynyt Yhdysvalloissa viime vuosina eli vähintään 5,4 prosentilla vuosittain.
- Hiilidioksidin talteenotto- ja varastointiteknologiaa (CCS) on otettava käyttöön laajamittaisesti vuodesta 2030 alkaen, jotta jäljelle jäävät teollisuuden päästöt eivät pääsisi ilmakehään.
- Maaperän ja puuston hiilinieluja on vahvistettava. Tämä edellyttää sitä, että maailman keskiluokka vähentää huomattavasti lihansyöntiä nykyisestä.
- Vetyteknologian tuotantokustannuksia on alennettava samalla tavalla kuin uusiutuvien energiamuotojen kohdalla on jo tapahtunut. Tämä edellyttää mm. laajaa innovointia ja uusien ratkaisujen käyttöönottoa.

Mitään edellä kuvatusta ei tapahdu ilman vahvaa ja kattavaa poliittista ohjausta. Usein on oletettu, että päästöjen vähentäminen vaaditussa mittakaavassa edellyttäisi talouden supistumista ainakin teollisuusmaissa. Tästä aiheesta tehdyt mallinnukset ovat kuitenkin johdonmukaisesti osoittaneet, että näin ei tarvitse olla. Kaikki selvitykset Pariisin ilmastosopimuksen mukaisesta talouskehityksestä vuoteen 2100 ulottuvalla ajanjaksolla ovat osoittaneet talouden kasvavan kyseisellä ajanjaksolla. Tosin kansallisissa vaikutuksissa on huomattavia eroja sen mukaan, ovatko maat fossiilisten polttoaineiden tuojia vai viejiä. On toki selvää, että entistä suurempi osuus kansantulosta on ohjattava investointeihin, jotta voidaan luoda vähäpäästöisen maailman tarvitsemaa uutta infrastruktuuria ja teollisuudenaloja, mutta keskimääräinen tulotaso voi kasvaa koko maailmassa. Poliittisten päättäjien on hahmotettava tämä uusi todellisuus, joka on seurausta siitä, että uusiutuvan energian kustannukset ovat jo laskeneet valtavasti. Toimeenpantavat politiikkatoimet eivät ole helppoja toteuttaa, mutta ne voidaan muotoilla kertomukseksi muutoksesta, joka johtaa suurempaan vaurauteen. Tässä on hyvin erilainen tulevaisuudennäkymä verrattuna niihin erittäin suuriin kustannuksiin ja vaikutuksiin, joita hillitsemätön ilmastonmuutos todennäköisesti tulee aiheuttamaan.

Sammanfattning

1 Syfte och bakgrund för denna rapport

"Nettonollutsläpp senast 2050" är det nya klimatpolitiska målet, i enlighet med det mål som fastställdes i Parisavtalet från år 2015 om att "hålla ökningen av den globala medeltemperaturen långt under 2 °C över de förindustriella nivåerna och att fortsätta ansträngningarna för att begränsa temperaturökningen till 1,5 °C över de förindustriella nivåerna" (UNFCCC, 2015). Syftet med denna studie är att använda energisystem och makroekonomiska modeller för att utforska om och hur dessa mål kan uppfyllas och i synnerhet om de är förenliga med en fortsatt ekonomisk tillväxt fram till år 2100.

Med fokus på målen i Parisavtalet tar studien inte upp mer omfattande miljöfrågor som kan påverkas av förändringar i energisystemet, såsom användning av andra naturresurser utöver energiresurser, eller markanvändning för bioenergi och dess konsekvenser för den biologiska mångfalden. Dessa frågor är viktiga och bör beaktas vid beslut om kvantitet och val av plats för all produktion av bioenergi som kan användas för att bidra till att uppnå målen i Parisavtalet. De modeller som används kan inte heller ta hänsyn till de förändrade effekterna på materialanvändningen och utsläppen vid en övergång till antingen ett koldioxidsnålt energisystem eller en cirkulär ekonomi.13 Om en ökad cirkularitet vad gäller materialanvändning avsevärt skulle minska utvinningen och bearbetningen av primärmaterial kan detta vara ytterligare ett bidrag till utsläppsminskningar. Detta analyseras dock inte här och kräver ytterligare forskning.

2 Befintlig kunskap om sambandet mellan utsläpp och ekonomisk tillväxt

De globala utsläppen av växthusgaser (GHG), vilka är orsaken till den antropogena globala uppvärmningen, har ökat i takt med den ekonomiska tillväxten ända sedan mätningarna påbörjades. Detta är inte förvånande, eftersom den största källan till växthusgaser är CO_2-utsläpp från förbränningen av fossila bränslen. Fossila bränslen har varit den dominerande energikällan ända sedan den industriella revolutionen, och energianvändning står i centrum för de flesta ekonomiska aktiviteter. Frågan som adresseras i denna rapport är om ekonomin kan fortsätta att växa om utsläppen minskar i den takt som krävs för att uppnå målet i Parisavtalet. Med andra ord, kan utsläppen "frikopplas" från ekonomisk tillväxt?

Bevisen på att detta kan vara möjligt kommer från EU och vissa enskilda medlemsstater. Mellan åren 1990 och 2016 växte EU:s ekonomi med mer än 50 %, medan CO_2-utsläppen från bränsleförbränning minskade med 25 %. I Finland och Storbritannien minskade dessutom även de konsumtionsbaserade utsläppen (däribland utsläpp från importerad tillverkning men inte utsläpp från exporterad tillverkning) från år 2007 till 2016. Utsläppsminskningarna under dessa perioder var dock inte alls tillräckligt snabba för att uppnå målen i Parisavtalet, och de är därför inte otvetydiga bevis på att den ekonomiska tillväxten skulle kunna fortsätta om utsläppen reducerades mycket snabbare.

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13 Se bilaga 2 i rapporten för ytterligare diskussioner om cirkulär ekonomi.

De energirelaterade utsläppsminskningar som ägde rum i dessa ekonomier skedde genom tre huvudsakliga drivkrafter:

- ökad effektivitet i energianvändningen,
- ersättande av fossila bränslen med energikällor med låga eller inga koldioxidutsläpp,
- strukturella förändringar i ekonomin som inbegriper ökad konsumtion av koldioxidsnåla tjänster och utflyttning av energiintensiva industrier (även om denna sistnämnda effekt beaktas vid beräkningen av konsumtionsutsläpp).

Dessa drivkrafter har kombinerats på olika sätt och i olika omfattning i Storbritannien och Finland, men ett gemensamt kännetecken är att de har drivits av en offentlig policy som stimulerar och förstärker vissa marknadskrafter och begränsar andra.

Det är uppenbart att uppfyllandet av målen i Parisavtalet kommer att kräva en avsevärd intensifiering av det policyåtgärder som har genererat eller förstärkt dessa drivkrafter, vilket kommer att visa sig.

3 Befintlig kunskap om 1,5 °C-målet

I 2018 års specialrapport om 1,5 °C från Förenta nationernas klimatpanel (IPCC) fastställs befintlig kunskap om utsläppen, tekniken och de ekonomiska konsekvenserna av att uppnå Parisavtalets mål om 1,5 °C. I IPCC-rapporten granskades ett flertal scenarioövningar med olika antaganden för att avgöra om och hur enkelt det var att uppnå målen i Parisavtalet under olika antaganden om utvecklingen i världen. Utgångspunkten var en uppsättning av fem scenarier som kallas Shared Socio-economic Pathways (SSP), som skiljer sig åt beroende på olika antaganden. Dessa inkluderar befolkningstillväxt och ekonomisk tillväxt, handelsintensitet, miljöhänsyn, den tekniska utvecklingstakten samt internationellt samarbete. Dessa beskrivs närmare i detalj nedan.

Med hjälp av dessa breda antaganden valdes sedan de värden på parametrar som i stort verkade överensstämma med dem inom följande områden:

- Utvecklingar inom ekonomisk struktur och produktion
- Energibehov och -effektivitet
- Materialbehov och -effektivitet
- Användning av koldioxidsnåla energibärare och teknik
- Tillgång till och användning av koldioxidinfångning och lagring (CCS) samt teknik för negativa utsläpp (NET[14])
- Markanvändning och tillgång till biomassa för energi
- Val och implementering av policyåtgärder
- Kostnader för teknik som reducerar koldioxidutsläppen.

Efter de antaganden och modeller som använts skapades en mängd olika vägval för att minska utsläppen av växthusgaser. Många av dem låg i linje med Parisavtalets mål att begränsa uppvärmningen till 1,5 °C fram till år 2100, men vanligtvis inte utan att överskrida[15] detta under de senare årtiondena i detta århundrade (vilket även skedde vid

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[14] NET omfattar teknik som suger upp CO_2 från atmosfären och sedan lagrar den säkert så att den inte släpps ut igen. NET omfattar bioenergi med CCS (BECCS), skogsplantering med det resulterande virket lämnat intakt, kolbindning i mark eller "Direct Air Capture" (DAC)-maskiner som renar luft från CO_2. DAC-tekniken befinner sig i ett tidigt utvecklingsstadium.

[15] "Överskridande" avser den globala genomsnittliga temperaturökningen som över 1,5 °C. I modelleringen reduceras temperaturökningen därefter till 1,5 °C med hjälp av teknik som avlägsnar stora mängder CO_2 från atmosfären. Det råder i själva verket stor osäkerhet om huruvida de globala temperaturerna skulle bete sig på detta sätt, eller om temperaturökningar som tillåts överstiga 1,5 °C skulle leda till "brytpunkter" som resulterade i stora utsläpp av växthusgaser från andra källor och få klimatet att permanent vändas till ett tillstånd som var sämre för människan. Se Lenton et al. (2019).

modelleringen i denna studie, som diskuteras närmare nedan). Dessa scenarier visade också på en fortsatt ekonomisk tillväxt, och generellt sett var minskningen av den ekonomiska tillväxten fram till år 2100 från ett utgångsläge utan minskade koldioxidutsläpp (som inte omfattade några kostnader till följd av klimatförändringarna och därför förmodligen var optimistiskt) begränsad. Inget av scenarierna kom ens i närheten av en nedgång i de ekonomiska resultaten jämfört med nivån år 2020 (dvs. de visade alla ekonomisk tillväxt). Alla scenarierna uppvisade därför "frikoppling".

Den modellering som genomfördes i detta projekt syftade till att ytterligare utforska detta fenomen och att förklara, om de modeller som användes i denna studie uppvisade samma resultat, varför detta resultat uppnåddes och varför.

4 Modelleringsmetoden i denna studie

Denna studie har använt sig av två energisystemmodeller (PRIMES och TIAM-UCL) och en beräkningsbar allmän (CGE) makroekonomisk jämviktsmodell, GEM-E3 FIT. Energisystemmodellerna visar hur energibehoven kan tillgodoses fram till år 2100 samtidigt som man strävar efter att minska CO_2-utsläppen till nettonoll fram till år 2050 och att begränsa den globala temperaturökningen till högst 1,5 °C fram till år 2100. Som framgår av nedanstående visade det sig att modellerna med de antaganden som diskuteras nedan endast kunde uppnå nettonollutsläpp av CO_2 år 2055 (inte 2050). Temperaturmålet på en maximal ökning med 1,5 °C fram till år 2100 kan uppnås, men endast med överskridande under senare årtionden i detta århundrade, enligt ovan. För enkelhetens skull hänvisar texten nedan dock fortfarande till nettonollmålet för CO_2-utsläpp fram till år 2050.

Den makroekonomiska modellen projicerar det ekonomiska resultatet med hjälp av energibehov och tekniker, och därmed sammanhängande kostnader, som genereras av energisystemmodellerna i deras scenarier som utgår från minskade koldioxidutsläpp. Hur modellerna har kombinerats beskrivs nedan i rapporten och själva modellerna beskrivs kortfattat i bilaga 1 till denna rapport.

Utgångspunkten för de scenarier som undersöktes i modelleringen var SSP1-scenariot som, på grund av sina antaganden om hur världen utvecklas, är mest gynnsamt för en global minskning av koldioxidutsläpp. Dessa antaganden omfattar globalt samarbete, snabb teknisk utveckling, en ambitiös miljöpolitik, låg befolkningstillväxt, minskad ojämlikhet, förändringar i våra kostvanor, samt skogsskydd. Användningen av någon av de andra SSP:erna skulle ha gjort minskade koldioxidutsläpp svårare och dyrare, och detta bör man ha i åtanke när man tolkar resultaten. Alla antaganden i SSP1 kan dock, även om de inte nödvändigtvis hänför sig till idag, anses vara rimliga.

Som redan nämnts tar den makroekonomiska modellen resultaten från energisystemmodellerna fram till sekelskiftet och projicerar de ekonomiska resultaten. Det finns i huvudsak tre drivkrafter för ekonomisk tillväxt i GEM-E3, liksom i andra makroekonomiska modeller: befolkningstillväxt, nettoinvesteringar och teknisk utveckling. Den ekonomiska tillväxten i världen som helhet skulle kunna påverkas negativt av minskade koldioxidutsläpp om detta ökar energikostnaderna eller minskar takten i den tekniska utvecklingen. Med förnybar el som nu kan konkurrera med den el som produceras med fossila bränslen i många länder verkar effekterna på den ekonomiska tillväxten från övergången till koldioxidfria energikällor sannolikt vara begränsad och kan till och med vara positiv. När det gäller den tekniska utvecklingen kommer denna sannolikt att stimuleras av minskade koldioxidutsläpp, på grund av relativt mogna industrier som är beroende av fossila bränslen och att koldioxidsnål energi ger upphov till helt nya industrier. På nationell nivå finns ytterligare viktiga överväganden om effekterna av minskade koldioxidutsläpp på den ekonomiska tillväxten, som huruvida investeringar i koldioxidsnål energi genererar en inhemsk försörjningskedja eller import, om de leder till en minskning av nettoimporten av fossila bränslen (och omvänt för länder som exporterar fossila bränslen, om de minskar exporten av dessa bränslen), samt om sådana aktiviteter drar nytta av outnyttjade resurser (kapital eller arbetskraft) eller leder till "utträngning"[16] av andra verksamheter. Dessa frågor undersöks närmare nedan.

5 Scenarierna

Som nämnts ovan utgjorde SSP1-antagandena utgångspunkten för de scenarier som skulle modelleras. Dessa antaganden producerade energibehov från PRIMES och GEM-E3 FIT-modellerna, som matades in i den globala energisystemmodellen TIAM-UCL, vilken har en detaljerad representation av energitillgångs- och efterfrågeteknik över hela energisystemet. TIAM-UCL begränsades till att producera nettonollutsläpp av CO_2 år 2050 och en maximal global genomsnittlig temperaturökning år 2100 på 1,5 °C (enligt projicering med hjälp av TIAM-UCL:s inbyggda klimatmodul).[17] Detta var det centrala scenariot för minskade koldioxidutsläpp (nedan kallat "det centrala scenariot"), vars resultat visas i nästa avsnitt.

En granskning av dessa resultat visade att två faktorer, som det råder stor osäkerhet om, var viktiga för att generera de centrala scenarioresultaten: 1) hastigheten på utfasningen av kolanvändning och 2) tillgången på CCS och NET, som i hög grad användes i det centrala scenariot. För att utforska resultatens känslighet för dessa faktorer genomfördes ytterligare modellkörningar med:

- halva hastigheten på utfasningen av kol i det centrala scenariot,
- ingen tillgång till CCS- och NET-teknik,
- en kombination av halva hastigheten på utfasningen av kol och ingen tillgång till CCS- och NET-teknik.

6 Resultat

6.1 Det centrala scenariot för minskade koldioxidutsläpp

Figur 1 visar CO_2-utsläppsbanan för det centrala scenariot.[18]

Det framgår att utsläppen når nettonoll år 2055, vilket innebär att målet för 2050 inte uppnås. Den genomsnittliga globala temperaturökningen år 2100 är strax under 1,5 °C, men den når nästan 1,9 °C runt 2050, innan den minskar fram till sekelskiftet. Denna temperaturminskning orsakas av en betydande användning av CCS- och NET-teknik (staplarna under nollutsläppslinjen), som fram till år 2100 fångar upp och lagrar koldioxidutsläpp eller avlägsnar kol från atmosfären, över 10 $GtCO_2$ per år. Detta resultat är i stort sett jämförbart med resultaten av de SSP1 IPCC-studier som diskuteras ovan. Det råder dock stor osäkerhet kring huruvida klimatet skulle reagera på ett sådant sätt att de globala medeltemperaturerna skulle minska enligt den angivna utsläppsbanan, även om det var möjligt att använda CCS- och NET-tekniker i denna skala.

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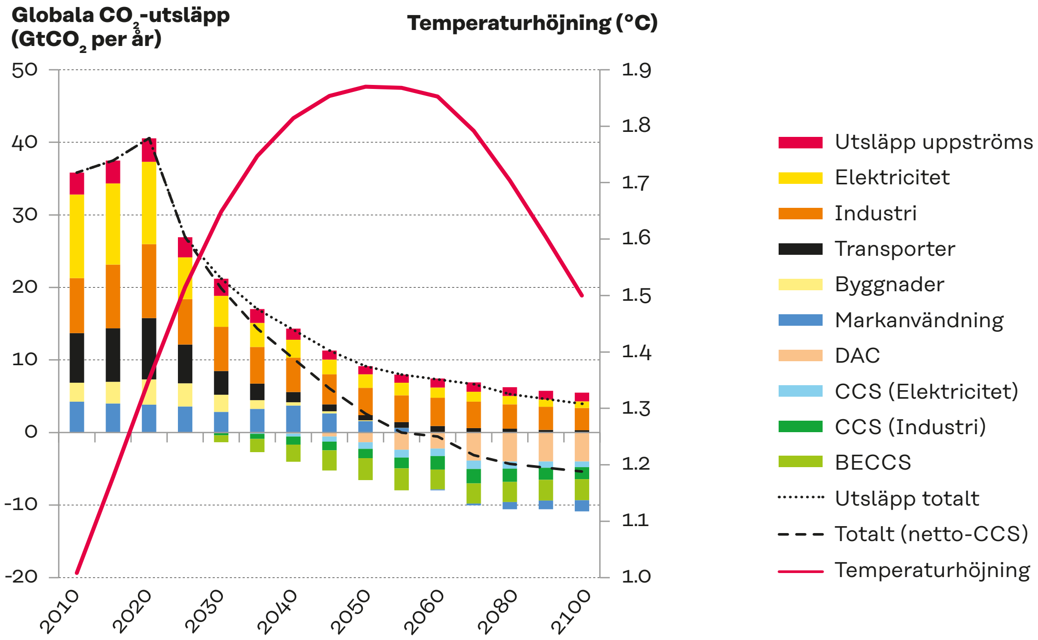
[16] "Utträngning" uppstår när nya investeringar ersätter befintliga investeringar i stället för att öka dem. I situationer där befintliga investeringar är mer produktiva än nya investeringar kommer "utträngning" att reducera BNP.

[17] Se den tekniska bilagan för detaljer om klimatmodulen.

[18] Våra illustrationer fokuserar på CO_2 (från alla källor) som den dominerande växthusgasen och en för vilken det finns ytterligare ett nettonollmål i modellen. Temperaturbegränsningen och banan återspeglar dock alla växthusgaser.

Figur 1: CO_2 -utsläppsbanan (centralt scenario)



(Författarens anmärkning: markanvändning omfattar alla CO_2-utsläpp från jordbruk, skogsbruk, markanvändning och förändrad markanvändning)

Figur 2 och Figur 3 visar primärenergi- respektive elanvändning i det centrala scenariot.

Figur 2 visar den stora tillväxten i användningen av vind- och solenergiresurser. Detta används, enligt vad som visas i Figur 3, för att avlägsna koldioxidutsläppen från elsystemet nästan helt år 2100, även om det producerar sju gånger så mycket el som år 2010. Denna extra el går till att minska koldioxidutsläppen från värme i byggnader, fordon inom transportsektorn och vissa industriella processer. Vätgas används också av tunga lastbilar vid transporter, bussar, tåg, fartyg och vissa bilar, medan luftfarten till stor del övergår till biobränslen. Den naturgas, olja och kol som finns kvar i energisystemet används i stor utsträckning inom industrin i sektorer där det är svårt att minska koldioxidutsläppen (t.ex. stål och cement).

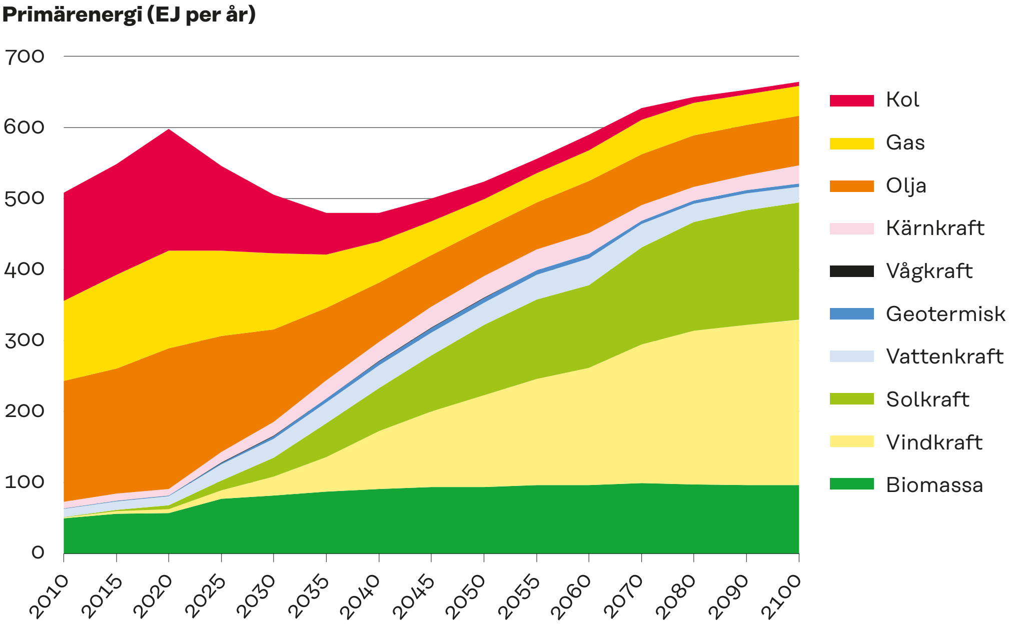
De ekonomiska konsekvenserna av denna revolution inom energisystemet visas i Figur 4 och Figur 5.

Figur 4 visar hur drivkrafterna för ekonomisk tillväxt utvecklas i takt med att utsläppskällorna fasas ut. Befolkningstillväxten minskar under århundradet och ger fortsatt tillväxt i investeringar och teknisk utveckling, men i lägre takt. Figur 5 visar att detta leder till fortsatt ekonomisk tillväxt under århundradet (observera den komprimerade skalan under de senare åren), även om GWP-tillväxten (Årlig bruttovärldsprodukt) per capita år 2100 är ungefär hälften så stor som år 2020. Trots detta är världsekonomin år 2100 nästan fyra och en halv gånger större än 2015, efter att ha vuxit i genomsnitt 1,76 % per år under perioden 2015–2100.

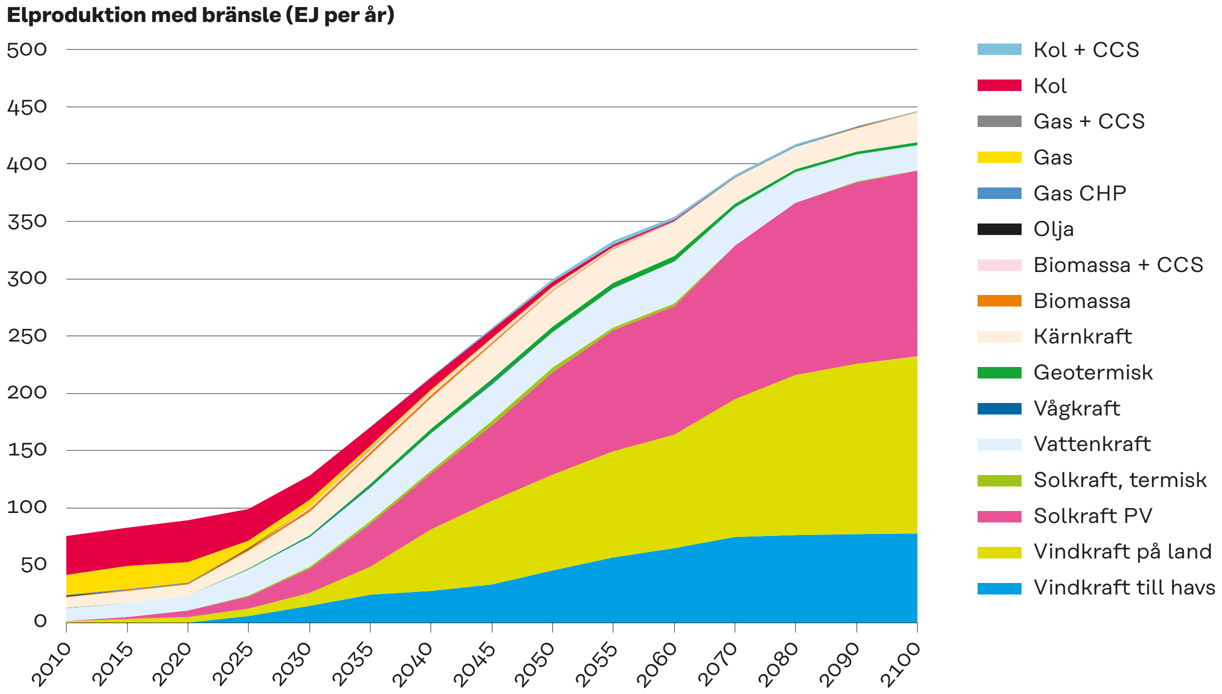
6.2 Sensitivitetskörningarna

Tabell 1 presenterar resultaten av sensitivitetskörningarna, som fokuserar på tekniker och dynamik som är viktiga i det centrala scenariot men som kännetecknas av stor osäkerhet.

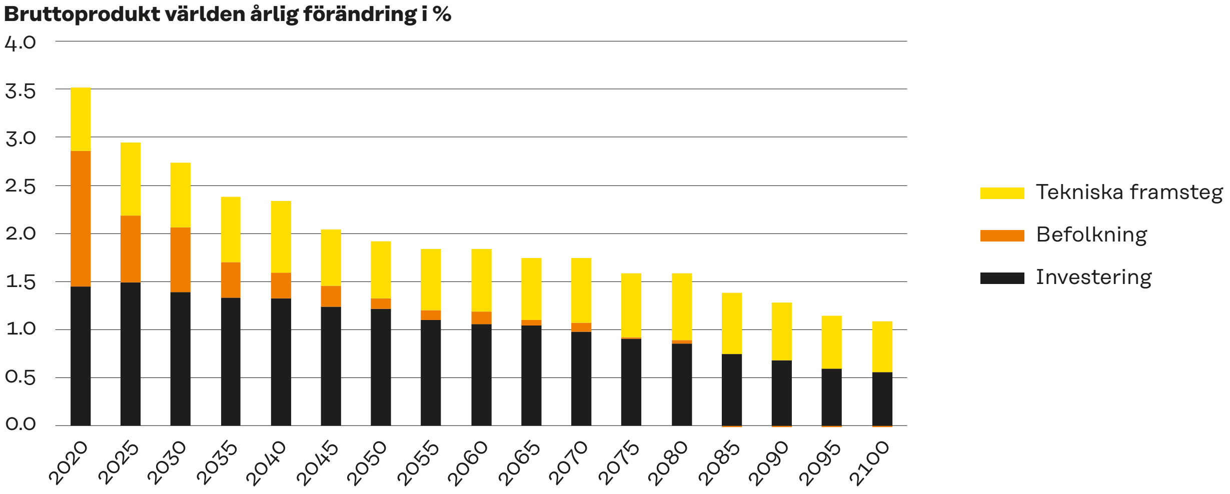
Figur 2: Primärenergi (centralt scenario)



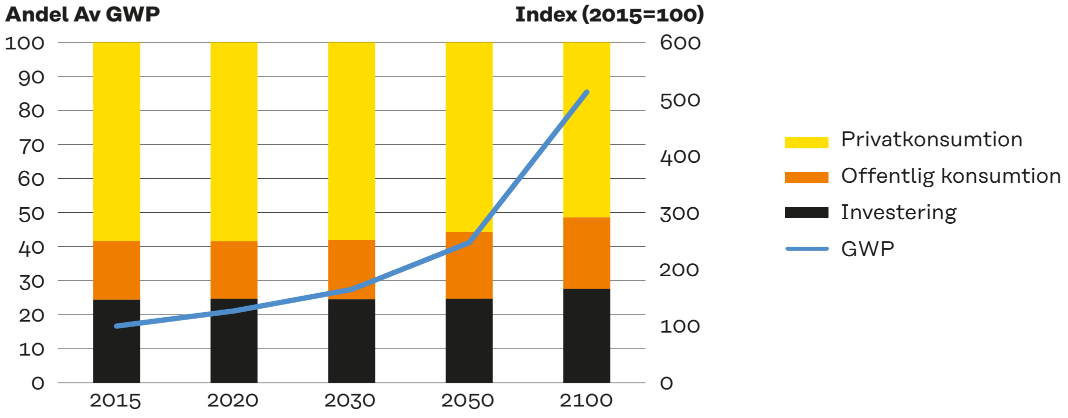
Figur 3: Elproduktion (centralt scenario)



Figur 4: Sammanställning av den årliga tillväxttakten för världens bruttoprodukt i dess viktigaste drivkrafter



Figur 5: Årlig bruttovärldsprodukt (GWP), tillväxttakt och komponenter



Tabell 1: Sensitivitet resultat

	Centralscenariot	Långsam utfasning av kol	Inga CCS eller NET	
Kolutfasningens takt	5,4 % per år	2,7 % per år	5,4 % per år	2,7 % per år
Nettonoll-datum	2055	2055	-	-
Kompenserade utsläpp från CCS, BECCS och DAC (2020–2100)	583 $GtCO_2$	638 $GtCO_2$	0 $GtCO_2$	0 $GtCO_2$
Peak-temperatur	1,87 °C	1,89 °C	1,89 °C	1,92 °C
Slutlig temperatur år 2100	1,5 °C	1,5 °C	1,74 °C	1,79 °C

Med en långsammare utfasning av kol är det fortfarande möjligt att nå 1,5 °C-målet åt 2100, men endast genom att i betydligt högre grad använda CCS och NET – de kumulativa utsläpp som lagras eller avlägsnas med hjälp av denna teknik ökar från 583 $GtCO_2$ till 638 $GtCO_2$, jämfört med de totala CO_2-utsläppen år 2020 på omkring 40 $GtCO_2$. Temperaturtoppen under detta scenario stiger från 1,87 °C till 1,89 °C. Om CCS inte finns tillgängligt, även med den snabba utfasningen av kol, fördubblas de kumulativa CO_2-utsläppen under det centrala scenariot, och det är inte längre möjligt, med resten av antagandena i detta scenario, att hålla temperaturökningen på 1,5 °C fram till år 2100 – den stiger till 1,74 °C fram till dess.

Långsam utfasning av kol minskar GWP-tillväxten minimalt jämfört med det centrala scenariot, särskilt under perioden 2030–2060, eftersom andra dyrare utsläppsminskningsalternativ måste användas för utsläppsminskningar. Trots detta fortsätter GWP att växa under hela perioden fram till år 2100. Brist på CCS och NET påverkar inte GWP-tillväxten särskilt mycket.

7 Policykonsekvenser

Modelleringsresultaten från denna studie visar tydligt att, med hjälp av en stringent allmän policy, är Parisavtalets mål om en maximal uppvärmning på 1,5 °C år 2100 genomförbart, om än med överskridande av denna temperaturökning under årtiondena efter år 2050, och att detta kan uppnås med fortsatt global ekonomisk tillväxt. För att detta resultat ska förverkligas måste dock den allmänna policyinriktningen generera ökningar av energieffektiviteten, investeringar i förnybara energikällor, utfasning av kol och utbyggnad av CCS och NET i hastigheter som vida överstiger allt som ännu har uppnåtts på global nivå. Dessutom bygger resultaten också på antagandet att avlägsnandet av CO_2 från atmosfären genom framtida användning av CCS och NET kommer att leda till att den globala medeltemperaturen sjunker enligt vad som visas. För att undvika osäkerhetsfaktorer och möjliga tröskeleffekter skulle utsläppen behöva minskas ännu snabbare än de redan oöverträffat snabba nivåer som visas i modelleringen.

Minskningen av koldioxidutsläpp i stor skala och i snabb takt kommer att kräva en blandning av olika policyinstrument och tillvägagångssätt för att undanröja de många hinder och begränsningar som fördröjer omställningen. Instrumenten och tillvägagångssätten omfattar reglering, konsumentinformation, digitalisering, prissättning av koldioxidutsläpp, tillhandahållande av infrastruktur, innovationsstöd samt institutionella förändringar och beteendeförändringar inom en rad policyområden. De förändringar som krävs är både transformativa och på systemnivå. De flesta av samhällets grundläggande tekno-socioekonomiska system kommer att behöva omdanas: energisystemet och transportsystemet, hur byggnader konstrueras, hur företag och individer bor, värmer upp och kyler ned dessa byggnader, livsmedelssystemet, vad människor äter, varifrån maten kommer samt hur praktiskt taget allt tillverkas, används och tas om hand om i slutet av sin livscykel.

De politiska strategierna för att uppnå denna omvandling måste vara konsekventa, sammanhängande, trovärdiga och heltäckande för att vara effektiva och förväntas upprätthållas under de årtionden som övergången till en koldioxidsnål ekonomi kommer att ta, så att de företag som investerar i produkter och processer för att minska koldioxidutsläppen i de olika systemen vet att de kommer att få den ekonomiska avkastning som sådana investeringar kräver.

Ingen regering i världen är ännu i närheten av att skapa den typ av policyramverk som krävs för att landet ska kunna uppnå de utsläppsminskningar som krävs för att uppnå de globala målen i Parisavtalet. För att nå målen behöver samtliga länder som står för de största utsläppen göra detta. **2020-talet är det årtionde som antingen kommer att sätta världens utsläppsbana på rätt spår för detta mål eller göra det omöjligt att uppnå det.**

8 Slutsatser

Denna studie inleddes med att man frågade vilka förhållanden som behöver råda för att världen ska kunna uppnå nettonollutsläpp av CO_2 i mitten av århundradet och begränsa den genomsnittliga globala temperaturökningen till 1,5 °C fram till år 2100. Evidens från IPCC har redan visat att det är möjligt att nå 1,5 °C vid år 2100 i de många olika framtida världar som kännetecknas av SSP-scenarierna – men inte under alla av dem. De grundläggande antaganden som gör det enklast att uppnå målen i Parisavtalet är globalt samarbete, snabb teknisk utveckling, en ambitiös miljöpolicy, låg befolkningstillväxt, minskad ojämlikhet, kostförändringar och skogsskydd. Dessa antaganden låg till grund för modelleringen i studien. Avsaknaden av något av dessa antaganden skulle göra det svårare eller omöjligt att uppnå 1,5 °C-målet.

Modelleringen kvantifierade den Pariskonsistenta nivån för några av dessa faktorer:

- Ökad energieffektivitet krävs för att bromsa den ökande globala efterfrågan på primärenergi så att efterfrågan på primärenergi år 2100 inte är större än 2020.
- Användningen av förnybar teknik måste minska koldioxidutsläppen från elproduktionen vid år 2100 och producera sju gånger så mycket energi som den som användes i världen år 2010, för att ersätta fossila bränslen inom transport, uppvärmning och i vissa industriella processer.
- Användningen av kol måste fasas ut globalt lika snabbt, om inte snabbare, som den har minskat i USA under de senaste åren.
- CCS-teknik måste installeras i stor skala från år 2030 för att förhindra att de då kvarvarande industriutsläppen hamnar i atmosfären.
- Mark och träd måste bli kolsänkor i stor skala, och detta kommer att kräva en betydande minskning av mängden kött i kosten hos världens medelklass.
- Genom innovation och storskalig utbyggnad måste man minska kostnaderna för vätgasteknik på samma sätt som man redan har sett i elproduktionen från förnybara energikällor.

Inget av detta kommer att hända utan ett starkt och omfattande policyramverk. Tidigare har många utgått från antaganden att utsläppsminskningar i den omfattning som krävs förutsätter en ekonomisk nedgång, åtminstone i industriländerna. Det anmärkningsvärda med modellering på detta område är att det råder enhällighet om att detta inte måste vara fallet. Varje studie av ekonomisk utveckling i linje med Parisavtalet fram till år 2100 har visat på global ekonomisk tillväxt under denna period, men med betydande skillnader i nationella effekter, beroende på om länderna är importörer eller exportörer av fossila bränslen. Investeringarna måste visserligen ta en större del av nationalinkomsten, för att skapa den nya infrastruktur och de industrier som krävs i en koldioxidfri värld, men de genomsnittliga inkomstnivåerna i hela världen kan fortsätta att växa. De politiska beslutsfattarna behöver förstå denna nya verklighet, som skapats av de enorma minskningar av kostnaderna för förnybara energikällor som redan har uppnåtts. Detta kommer inte att göra de policyåtgärder som de måste introducera enkla att genomföra, men det innebär att de kan ramas in i en större berättelse om omvandling mot större välstånd i motsats till de mycket stora kostnaderna för klimatskador som en avsaknad av dessa policyåtgärder sannolikt skulle medföra.

1 Purpose of the report

The Finnish Innovation Fund Sitra has commissioned the UCL Institute for Sustainable Resources (ISR) at University College London (UCL) and the modelling consultancy E3M in Athens to investigate whether it is possible for carbon dioxide ($CO_{2)}$ emissions to decline in the coming decades such that they reach net zero by 2050,[19] while the economy globally, as well as in Europe and Finland, keeps on growing.[20] Net-zero CO_2 emissions by 2050 is widely regarded as being required to meet the 1.5 °C temperature target of the Paris Agreement on climate change of 2015 (Rogelj et al., 2018a). The situation in which CO_2 emissions decline while economic output increases is referred to as "decoupling" throughout this report.

Thus the purpose of this study is to investigate whether and under what assumptions and policy measures decoupling can occur at a sufficient rate for CO_2 emissions to decline to net zero by 2050, while the economy – globally, in Europe and in Finland – keeps on growing.

In exploring this issue, the study uses two energy system models and a macroeconomic model, which are described further below. While the energy system models account for CO_2 emissions from land use, and allow the use of bioenergy, they do not cover the wider impacts of producing bioenergy, such as the effects on biodiversity. This study also does not investigate or report on two other important broader environmental and resource issues. Thus, the study does not consider how possible moves towards resource efficiency and a circular economy[21] could reduce the CO_2 emissions and other environmental impacts of the extraction and processing of primary materials. Nor does it explore other possible environmental impacts of energy system change, with the exception of the local air pollutants associated with the combustion of fossil fuels and traditional biomass. Finally, the economic focus of the study is economic growth as expressed by GDP. The report does not discuss broader issues of economic welfare or the extent to which these are reflected in GDP.

Further information on many of the more complex issues discussed in this report are given in the accompanying Technical Supplement, as indicated throughout the report.

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[19] This means that any CO_2 emissions globally in 2050 would be entirely offset by CO_2 removal from the atmosphere.

[20] Measured by the increase in Gross Domestic Product, GDP, for countries, and Gross World Product, GWP, for the world as a whole.

[21] Please see Annex 2 of the report for further discussion of the circular economy.

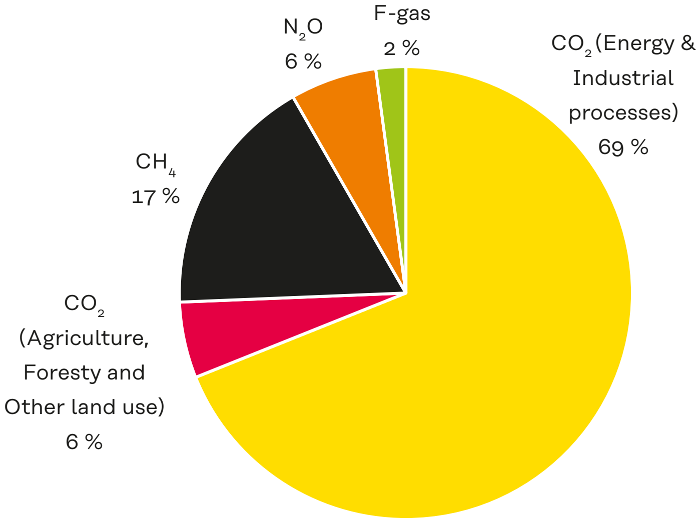
2 Introduction to the issues

Figure 6 shows the breakdown of global greenhouse gas (GHG) emissions in 2016. Energy-related CO_2 emissions have been supplemented by GHG emissions from agriculture, deforestation, land-use change and some industrial processes. The temperature increase in the energy system model TIAM-UCL is driven by the full range of GHG emissions, so that these are all implicitly constrained when global warming is limited to 1.5 °C in 2100. However, in the modelling reported on below, this constraint is supplemented by a further limit on CO_2 emissions over the century (called a "carbon budget"), which essentially determines the non-CO_2 GHG emission reductions that are necessary to hit the temperature target. The higher the carbon budget, the greater the required reductions on non-CO_2 GHG emissions if the temperature target is to be met, and vice versa.

Decoupling is said to have occurred when something that is normally connected to something else ceases to be so. Historically, as economies have grown, their use of energy has tended to increase and, with the great majority of that energy being provided by fossil fuels, so have their carbon emissions. For CO_2 emissions to go down while an economy keeps growing, one or more of four things would need to happen:

1. energy use would need to switch from high-carbon sources (fossil fuels) to low-carbon sources (e.g. renewables or nuclear);
2. energy use would need to become more energy-efficient, so that the same economic output (e.g. a tonne of steel, a warm home) was delivered with lower energy use;

Figure 6a: Global greenhouse gas emissions by gas, 2016



(data source: WRI, 2018)

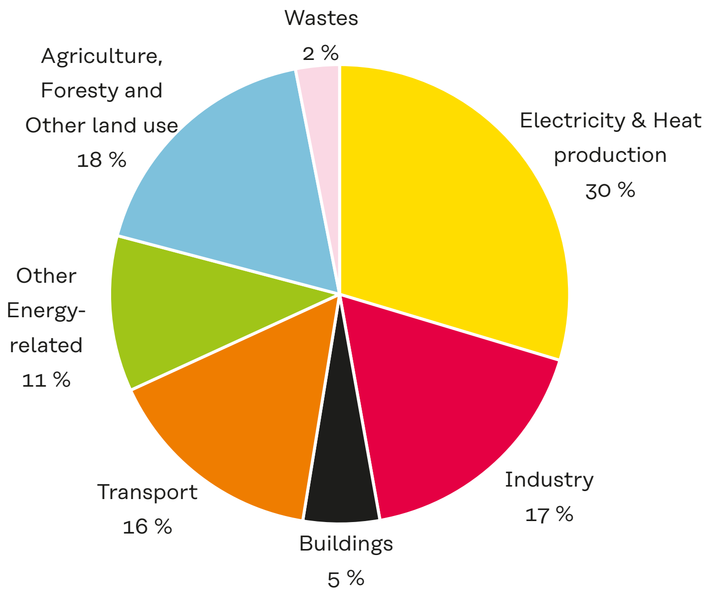
3. low-energy sectors of the economy (e.g. some services) would expand while high-energy sectors (e.g. cement manufacture) declined;
4. carbon emissions would need to be captured and stored securely underground, and/or removed from the atmosphere by a direct air capture (DAC) technology and, again, securely stored.

The next section will investigate in more detail the theoretical links between economic growth, energy use and CO_2 emissions. Section 3 will present some evidence on decoupling from the literature in this area. Sections 4 and 5 will discuss the implications of the net-zero target for, respectively, emissions reduction and the challenge of keeping the global average temperature increase to 1.5 °C (the aspiration in the Paris Agreement).

The paper then moves on to the modelling carried out for this project, with Section 6 giving a brief description of the models being used, and Section 7 describing the scenarios modelled. Section 8 gives the results of the modelling, while Section 9 contains a discussion of these results, with their policy implications, leading to the conclusions and policy recommendations in Section 10.

The global economy is complex and modelling its development over the rest of this century, with associated GHG emissions, is therefore also a complex task. It incorporates many different assumptions about population growth, the drivers of economic growth, the developments in the performance and costs of existing and new technologies, the cost of fossil fuels, and the policies that seek to reduce GHG emissions. Attempts have been made to keep this report accessible and relatively short. Further detail on all these issues may be found in the accompanying Technical Supplement, which is published along with this report.

Figure 6b: Global greenhouse gas emissions by sector, 2016



(data source: WRI, 2018)

3 Evidence on decoupling

Figure 7 and Figure 8 show how the global and European Union (EU) economies have grown between 1990 and 2016, with associated CO_{2e} missions from the combustion of fossil fuels, which is the major component of global GHGs, as seen in Figure 6. It can be seen that over this period, Gross World Product (GWP – world GDP) more than doubled, whereas CO_2 emissions from fuel combustion increased by a lower amount (around 50%). This is called relative decoupling. To reach net zero, absolute decoupling, where emissions reduce in absolute terms, even as the economy grows, will be required.

As noted in the previous section, the four factors that can lead to a decoupling of economic growth from GHG emissions are increases in the use of low-carbon energy, more efficient energy use, carbon capture and storage, and structural change in the economy towards services and away from energy-intensive industries.

For any given country, it is possible for the emissions it produces to decline if it moves away from manufacturing energy-intensive goods itself and imports them from other countries. Clearly the global emission benefits of such structural change are likely to be limited (and may even be negative if the new manufacturing country is either less efficient or uses dirtier fuels than the old manufacturing country).

It is to capture changes of this kind that a distinction is made between territorial emissions (the emissions produced within a territory) and consumption emissions (the emissions that derive from a country's consumption, irrespective of where the consumed goods are produced).[22] As Figure 9 and Figure 10 show for the UK and Finland, this distinction can make quite a difference to a country's total emissions.

Figure 9 and Figure 10 show how GDP and territorial and consumption CO_2 emissions for the UK and Finland have changed over the period 1990-2016. For the UK consumption emissions grew to 2007, whereas territorial emissions fell slightly, but even consumption emissions started to decline thereafter. In Finland, in contrast, consumption emissions were broadly constant to 2007, but then fell along with territorial emissions. The decline in emissions in both countries over the period 2007-2009 coincided with the Great Financial Crash and the subsequent recession, but since then GDP has grown, while emissions continued their downward trend. The years since 2010, therefore, show clear evidence of absolute decoupling of CO_2 emissions from economic growth in both Finland and the UK.

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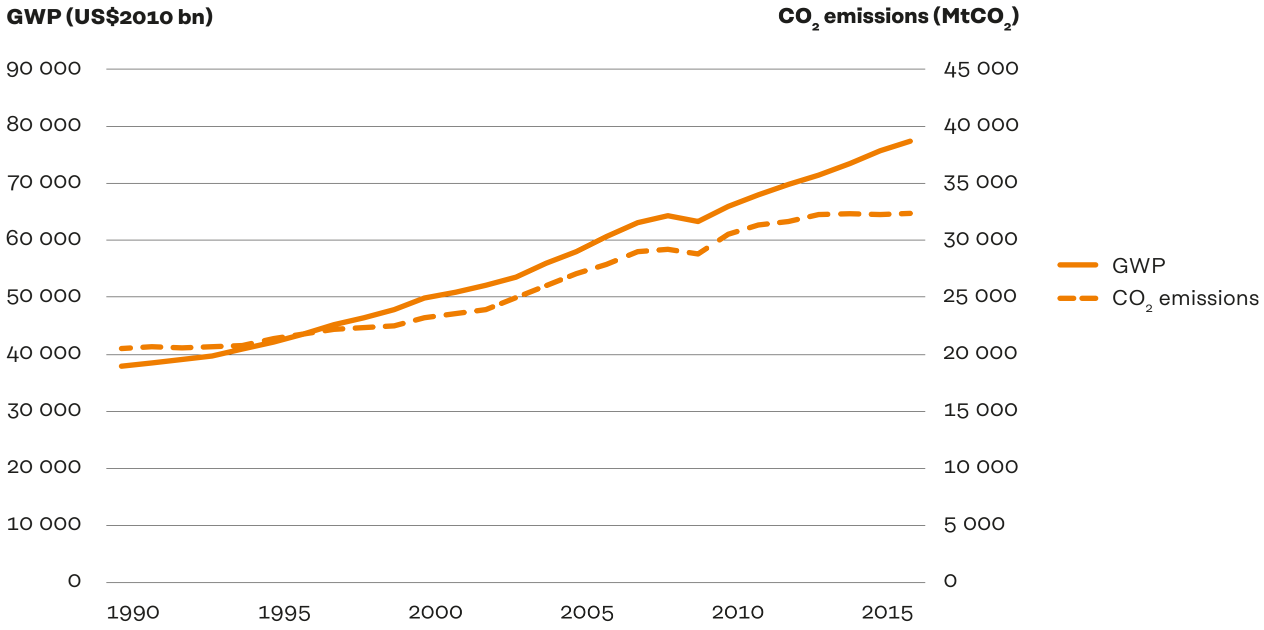
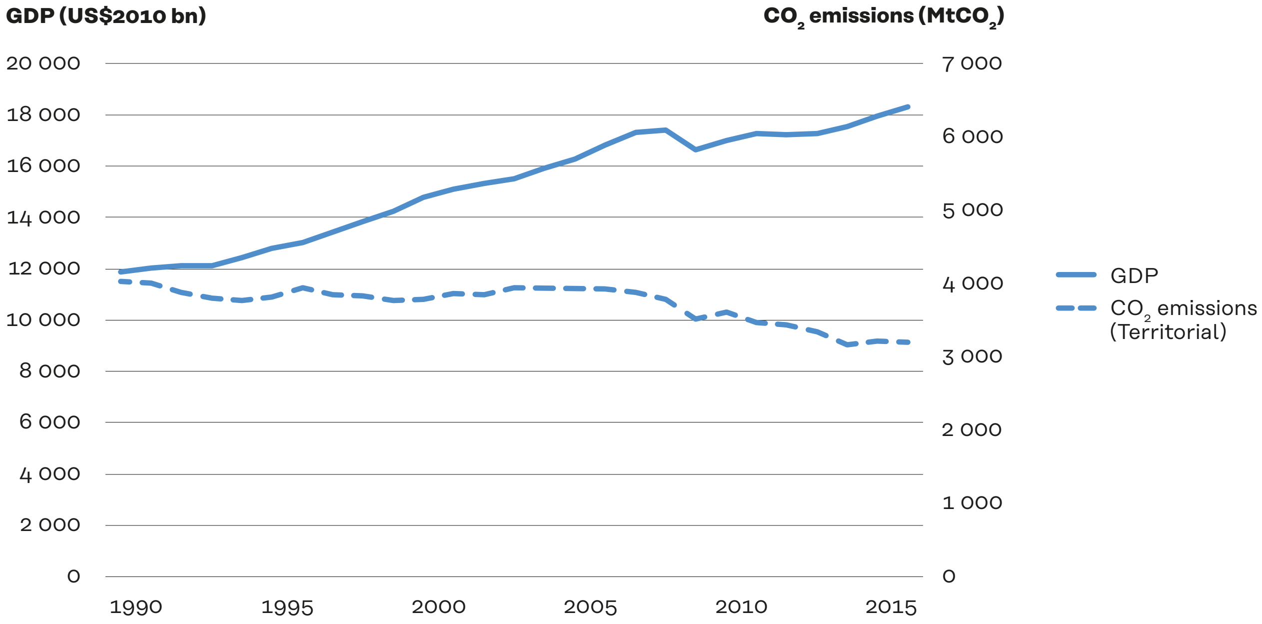
[22] Consumption emissions = Territorial emissions plus emissions from the production of imports minus emissions from the production of exports.

Figure 7: Gross World Product (left axis) and global CO_2 emissions (right axis) from fuel combustion 1990-2016



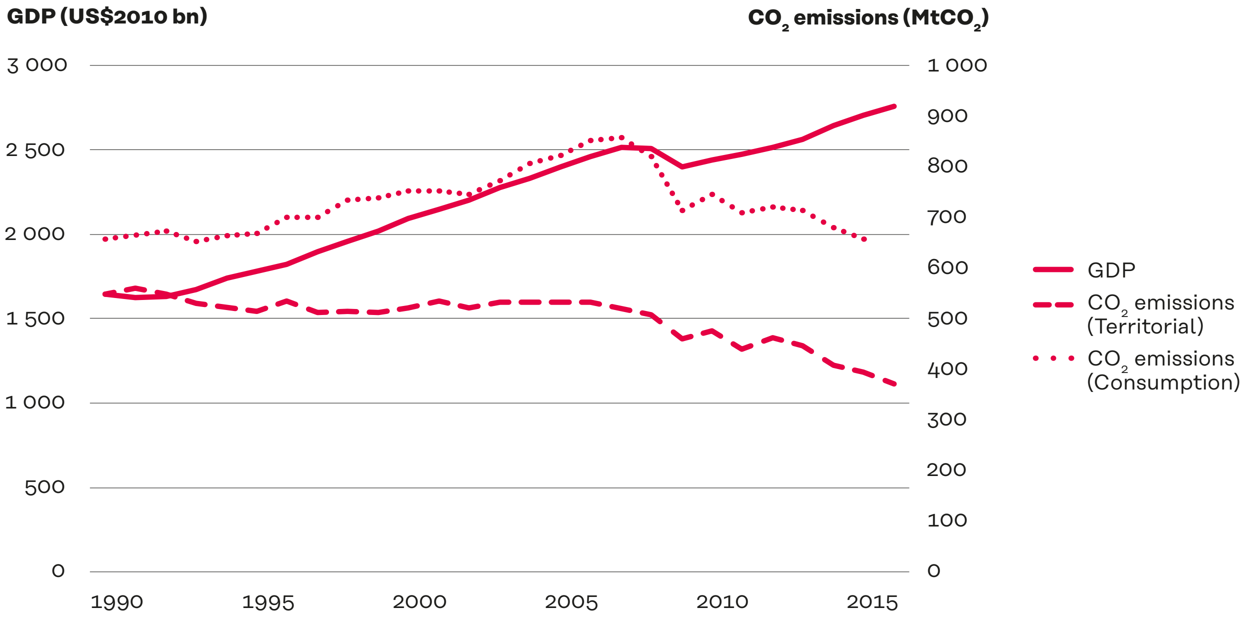
(data source: IEA, 2018a)

Figure 8: Gross Domestic Product (left axis) and CO_2 emissions (right axis) from fuel combustion in the European Union (EU-28, including the UK) 1990-2016



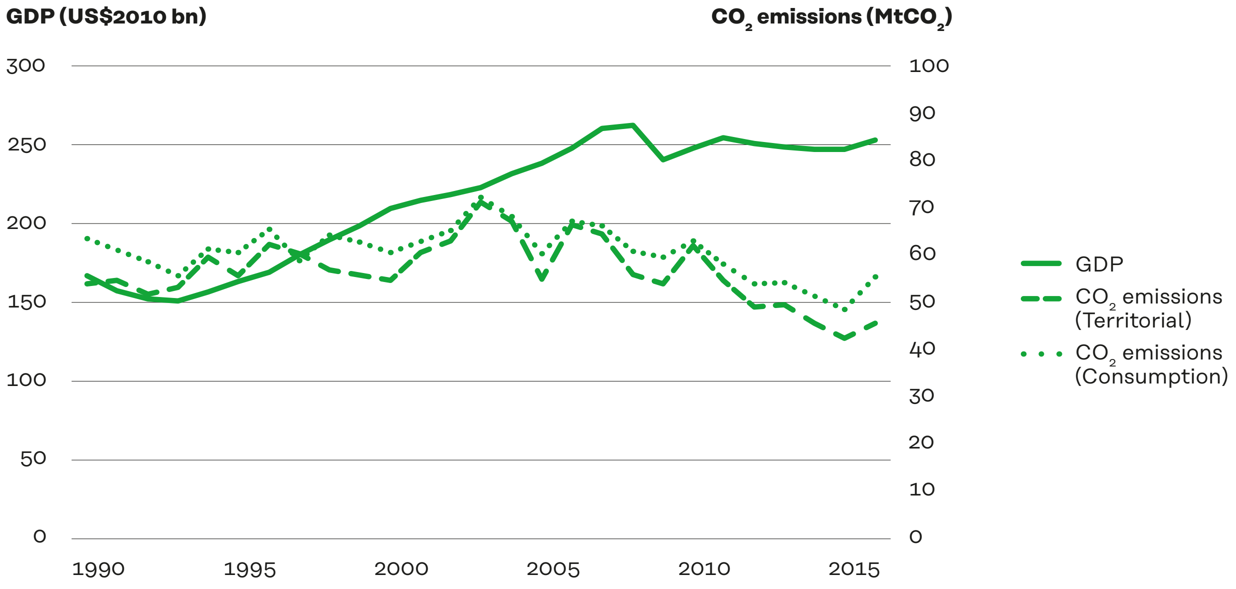
(data source: IEA, 2018a)

Figure 9: Gross Domestic Product and territorial and consumption CO_2 emissions from fuel combustion for the UK 1990-2016



(data source: IEA, 2018; Moran et al., 2019; ONS, 2019a)

Figure 10: Gross Domestic Product and territorial and consumption CO_2 emissions from fuel combustion for Finland 1990-2016



(data source: IEA, 2018; Moran et al., 2019)

4 Drivers of emission reduction

Emission reductions in different countries are driven by different factors, as the following illustrative examples of the UK and Finland show. Assumptions about how many of these factors will develop in the future need to be made in order to model the potential development of emissions in the future.

4.1 The UK

Since 1990 the UK's economy has undergone a substantial restructuring from energy- to knowledge-intensive industry, characterised to a substantial degree by a growth in the service sector rather than contracting manufacturing output – partially the result of the growing global market for services (BIS, 2012). However, the UK's consumption CO_2 emissions grew to 2007, though at a slower rate than GDP (relative decoupling, see Figure 9), indicating that the UK was continuing to consume emission- intensive goods and services, but increasingly imported them rather than satisfying demand through domestic production (ONS, 2019c).

Consumption-based emissions then declined in 2008 following the financial crisis and have continued to decline since, returning to 1990 levels by 2015. This indicates that although the value of imported goods to the UK has continued to grow since 2010 their carbon intensity may have declined, or more energy-intensive goods may have been exported from the UK. More detailed sectoral analysis would be required to resolve this.

Energy efficiency in the UK has grown particularly in the manufacturing and transport sectors, which have historically been the most energy-intensive sectors (ONS, 2019c). In the manufacturing sector this is driven by a combination of a structural shift within the sector towards higher-value, less energy-intensive products, the greater use of plant capacity, and other efficiency improvements (CCC, 2018). In the road transport sector, travel demand grew by 29% between 1990 and 2018 (DfT, 2019) while energy consumption grew by just 6.5% (BEIS, 2019b), largely due to the increasing efficiency of vehicles. Substantial efficiency improvements have also been achieved in energy consumption in buildings. Final energy demand in the residential sector in 2018 was just 1% higher than 1990 levels (BEIS, 2019b), despite a 17% growth in the number of households from 1991 to 2011, with further growth since. Electricity generated from fossil fuels in the UK reduced from 77% of the total in 1990 to 47% by 2018, with renewables (largely wind, solar, biomass and energy-from-waste[23]) increasing from around 2% to 30%. In addition, fossil-fuel generation has switched principally from coal to natural gas, with around half the CO_2 intensity. The efficiency of generating electricity has also improved, from 33.8% of the energy input being supplied to end users as electricity in 1990, to 45.5% in 2018 (BEIS, 2019a). These factors combined produced a 32% reduction in CO_2 emissions from the power sector between 1990 and 2018, which in turn accounted for nearly 60% of the total (territorial) emissions

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[23] In the EU, only the biodegradable (i.e. biomass) fraction of municipal and industrial waste is considered a renewable energy resource. However, according to the 2018 recast of the Renewable Energy Directive, biomass from such sources must generate a minimum level of GHG savings, depending on the sector and time of use, to be considered "renewable". Biomass from other sources, such as agriculture, must adhere to both this and a range of other "sustainability criteria" designed to prevent, for example, land-use degradation and biodiversity loss, to be considered "renewable", and thus contribute to targets for renewable energy use.

reduction achieved over this period in the UK (see Figure 9) (BEIS, 2019c). Switching to lower-carbon fuels has been seen to different degrees in other sectors, including away from coal and towards bioenergy and other fuels in the industry and residential sectors, and from petroleum to diesel (and biofuels) in the transport sector (BEIS, 2019b).

4.2 Finland

As Figure 10 illustrates, Finland has seen substantial variation in CO_2 emissions since 1990 but with relative consistency in reduction since 2010. Between 1990 and the time of the financial crisis in 2008, the contribution of energy-intensive industry and construction to Gross Value Added (GVA)[24] in Finland was relatively stable, at around 35%. The proportion of GVA from the service sector slowly grew (from 60.2% to 63.9%), at the expense of agriculture, forestry and fisheries. However, these shares sharply altered in 2009 and have since remained below and above 30% and 68%, respectively. Increasing use of renewable energy (particularly biomass) at the expense of coal and oil, but more recently also natural gas, is the primary driver behind the relative, and subsequently absolute, reduction in CO_2 emissions experienced by Finland since 1990 (Statistics Finland, 2019a). In contrast to the UK, consumption CO_2 emissions in Finland were broadly constant to 2007, but then fell along with territorial emissions (Figure 9), suggesting increasing exports and decreasing imports of products from energy-intensive industries over this time.

Due to forest growth resulting from active forest management, forest land in Finland plays a vital role in removing CO_2 from the atmosphere, as it is increasingly absorbed into forest biomass. During the last 20 years, the CO_2 stock in forest land has grown by 20 to 50 million tonnes annually. In 2017, such CO_2 sequestration was equivalent to more than half the CO_2 emissions from fossil-fuel combustion in that year (Statistics Finland, 2019b).

4.3 The role of policy in emissions reduction

The trends experienced in the EU, UK and Finland, particularly regarding energy efficiency and the increase in renewables and fuel switching, have been driven to a great extent by active policy, much of which may be linked to various requirements of the European Union, such as the EU’s "20-20-20" objectives; a 20% reduction in GHGs from 1990 levels, 20% of final energy from renewables and a 20% reduction in final energy demand (through greater energy efficiency) against a projected baseline, by 2020. Many policy instruments are instituted directly at the EU level, such as the EU Emissions Trading System (EU ETS), a carbon-pricing system introduced in 2005 and applicable to the power and industrial sectors throughout the EU, and increasingly stringent regulations on CO_2 intensity for new vehicles and on the energy efficiency of energy-using and energy-related products.

Many other policies, however, are designed and introduced in the EU at the member state level, according to local circumstances, but with the purpose of meeting overarching common objectives. This includes various renewable energy support mechanisms, and energy performance standards for building envelopes. Yet others are introduced by member states under their own initiative. In the UK power sector, for example, the switch from coal to gas for electricity generation was induced in large part by electricity market liberalisation in the

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[24] The total value of output from a sector or country, minus the costs involved in producing it.

1990s (Kern, 2012), and in 2013, the UK introduced a Carbon Price Floor (CPF) policy, comprising a carbon tax on the fossil inputs to power generation, in addition to the price of allowances in the EU ETS, which has further reduced generation from coal in favour of gas (Hirst, 2018).

Whether these actions add to or subtract from what GDP levels for a single country would otherwise have been (and to what degree) largely depends on five factors: 1) the relative cost of the investments made in low-carbon energy compared to fossil-fuel alternatives, and whether this makes energy use cheaper or more expensive; 2) whether the low-carbon investments increase or decrease the rate of technical progress; 3) whether these investments stimulate a domestic supply chain or imports; 4) whether they result in a reduction in the imports of fossil fuels (or, for fossil-fuel exporting countries, a reduction in fossil-fuel exports); and 5) whether such activities draw on unemployed capital or labour resources, or result in the "crowding out" of other activities. At the global level, only factors 1), 2) and 5) are relevant. On 1), electricity from renewable sources is now competitive in many countries with fossil fuels. On 2), decarbonisation seems likely to increase technical progress as whole new industries are created. And in respect of 5), these conditions will differ country by country. As will be seen below, the central decarbonisation scenario in this study assumes full "crowding out" of other investment.

In addition, reduced air pollution may avoid healthcare costs. As an example of the macroeconomic effects of such policies, the transition described above has generated substantial economic activity in the Low Carbon and Renewable Energy (LCRE) sector in the UK, which in 2017 generated £44.5 billion in turnover and employed 209,500 people – over 1% of total non-financial turnover and total employment in the UK. This is a 6.8% growth from 2016, around four times the rate of growth of the UK's economy as a whole (ONS, 2019b).

Figure 9 and Figure 10 show that the absolute decoupling in CO_2 emissions from fuel combustion achieved in the UK and Finland (in consumption as well as territorial emissions since 2010) has not been seen at the global level. This is not surprising given that in many countries outside Europe, there have been very limited efforts to realise it. And although economic restructuring through geographic redistribution of energy-intensive industry may contribute to decoupling at a country or regional level, it cannot do so at a global level, where emissions are aggregated across all regions. Global decoupling can only come about through increased energy efficiency and energy productivity,[25] and the increasing replacement of fossil fuels with low-carbon energy.

Although the energy intensity of the global economy is reducing, driven in part by economic incentives and innovation, and in part by policies (such as those in the EU, described above), the rate of improvement is slowing, reducing from 2.9% per annum in 2015 to 1.2% per annum in 2018. This is due to an increasing contribution of energy-intensive industry to economic growth in key countries such as China and the USA; more extreme weather increasing demand for both heating and cooling; larger cars (e.g. Sports Utility Vehicles – SUVs) with lower average occupancy; increasing building floor space per person; and a slowdown in the strength and coverage of efficiency policies (IEA, 2019a). Renewable energy, in contrast, has grown from 1.06% of global primary energy demand in 2008, to 4.05% in 2018 (BP, 2019). A primary driver for this is again a

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[25] Energy efficiency refers to the output of energy or physical goods and services per unit of energy input; energy productivity refers to the value added per unit of energy use; and energy intensity is the inverse of energy productivity.

strong policy push for the deployment of renewables in key countries and regions, such as the EU, but as their deployment has led to cost reduction through learning and economies of scale, some technologies (such as solar photovoltaics – PV) are increasingly cost-competitive with their fossil-fuel counterparts in many parts of the world.

However, with the exception of power generation, fossil fuels remain the least-cost option for providing energy for many purposes in most regions – particularly when the economic costs of their emissions are not reflected in the price paid for their use. As such, comprehensive policy action with a wide geographic and sectoral scope must be introduced as soon as possible to stimulate the appropriate drivers to achieve rapid decarbonisation to achieve the aims of the Paris Agreement. The question underlying this report is, if such action is implemented, what will its impact be on economic growth?

"Comprehensive policy action with a wide geographic and sectoral scope must be introduced as soon as possible to stimulate the appropriate drivers to achieve rapid decarbonisation to achieve the aims of the Paris Agreement."

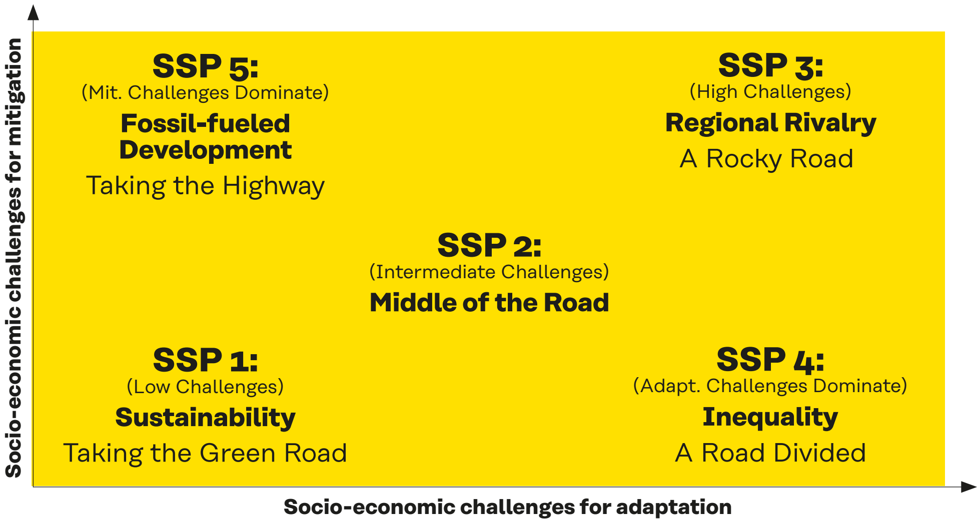
5 The challenge of net-zero emissions by 2050

In 2015 nearly all countries signed the Paris Agreement, which committed them to reduce their GHG emissions to keep the average global temperature increase to well below 2 °C above pre-industrial levels (where this average increase is currently around 1 °C) and to 1.5 °C if possible. Restricting the temperature increase in this way will require a dramatic reduction in global emissions, such that they reach net zero in the middle of the century or soon after.

As part of the IPCC's Special Report on Global Warming of 1.5 °C, Rogelj et al. (2018a) identified 90 decarbonisation scenarios in the modelling literature that were consistent with the 1.5 °C target,[26] using different modelling frameworks. The way such assessments are implemented may be briefly described as follows.

Different potential development pathways for the world are described. In this case these were called the Shared Socio-economic Pathways (SSPs), some of the main features of which are illustrated in Figure 11. Each of the SSPs (from SSP1 to SSP5) has its own plausible, internally consistent storyline about how the world's socio-economy and geopolitics might develop, and different quantitative assumptions on the basis of these storylines are made for population (growth), education, urbanisation, technology and GDP. More details about the SSPs are given in the Technical Supplement that accompanies this study.

Figure 11: Five Shared Socio-economic Pathways (SSPs) representing different combinations of challenges to mitigation and adaptation



(source: adapted from Figure 1 from O'Neill et al., 2014)

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[26] The scenarios fall into three categories: "Below 1.5 °C", which limit peak warming to below 1.5 °C during the entire 21st century with 50-66% likelihood (nine scenarios); "1.5 °C-low-OS", which limit median warming to below 1.5 °C in 2100 and with a 50-67% probability of temporarily overshooting that level earlier, generally implying less than 0.1 °C higher peak warming than Below-1.5 °C pathways (44 scenarios); and "1.5 °C-high-OS", which limit median warming to below 1.5 °C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1-0.4 °C higher peak warming than Below-1.5 °C pathways (37 scenarios).

For each SSP a "baseline" is constructed on the basis of these storylines and quantitative factors, generating levels of energy demand, supplied by different energy technologies (which will differ between the SSPs), and resulting in different levels of GHG emissions ("the baseline run" for the different SSPs). These GHG emissions are well above those required to meet the 1.5 °C temperature targets.

The emissions are then constrained in each model run such that the 1.5 °C temperature target is met. This requires energy demand to be met by radically different (low-carbon) technologies, with different costs. The models also generate an implicit carbon price that reduces the demand for energy, especially high-carbon energy. The characteristics (e.g. technologies used) in the 1.5 °C run may then be compared with those in the baseline run. The differences in energy costs and technologies then affect the GDP that was in the baseline. The difference between the GDP levels in the baseline and 1.5 °C runs is the macroeconomic cost of getting to 1.5 °C.

This report will detail some new modelling that has been carried out along these lines in Section 7, but to provide some context will first summarise the review of modelling of the 1.5 °C targets that provided the basis of the IPCC 1.5 °C Special Report.

"Each of the Shared Socio-economic Pathways has its own storyline about how the world's socio-economy and geopolitics might develop, and different quantitative assumptions on the basis of these storylines are made for population (growth), education, urbanisation, technology and GDP."

6 The IPCC 1.5 °C scenarios

Figure 12 reproduces the GWP and CO_2 emission and trajectories of the 1.5 °C model runs presented in the IPCC 1.5 °C Special Report. It can be clearly seen that all scenarios achieved dramatic reductions in global CO_2 emissions, alongside the real growth in GWP these scenarios envisage, thus achieving absolute decoupling (see Section 6.1 for how GWP projections are determined).

The numerous grey lines show all the studies, but from these five have been picked out that show the results for different models, different SSPs, and one particular run with low energy demand (LED).[27] All of them show economic growth continuing through to the end of the century, with the majority showing the world economy four to six times larger in 2100 than it was in 2010. This occurs while at the same time, shown in the lower panel, CO_2 emissions fall sharply to 2050, when they go negative. "Negative emissions" means that CO_2 is being captured from the atmosphere to a greater extent than it is being emitted to it. How this may come about is discussed further below, but for now it may be noted that the scale of these negative emissions is very substantial in some models: by 2090 in the REMIND-MAgPIE model run around 20 billion tonnes of CO_2 per year is being sucked out of the atmosphere. As the average global temperature increase is related to the cumulated stock of emissions in the atmosphere, rather than annual emissions, this scale of negative emissions is required to reach 1.5 °C because of the failure to reduce emissions adequately in previous years. Even so, the fall in CO_2 emissions shown in Figure 12 is many times larger than has ever been achieved with a growing economy, and this exemplifies the scale of the challenge presented by the 1.5 °C target.

Two further observations may be made at this stage. The first is that the model runs have been specified such that they meet the 1.5 °C target by 2100. But the great majority of them temporarily overshoot that target in the later decades of this century, and the temperature is only subsequently reduced by the scale of the negative emissions resulting from the use of various technologies, the cost and potential scale of which is highly uncertain. These issues – the extent of the temperature overshoot and the required scale of negative-emission technologies (NETs) – are explained and explored further below and in the Technical Supplement. The model runs have the further assumption that their removal from the atmosphere will in fact bring down the average global temperature in the same way that their emission increased it. But natural systems sometimes do not behave in this neat, symmetrical way. There can be tipping points or threshold effects that prevent them from returning to their prior state, and it is not currently known how the climate will behave in this respect. Although the likelihood of realising such tipping points increases with temperature, there is a risk that some may occur at well below 1.5 °C, and towards the 1 °C temperature rise compared to pre-industrial levels that has already been reached (Lenton et al., 2019).

The second point to note about these scenarios is that none of them considered the potential impact of damages from climate change on economic growth. These damages could be very substantial – indeed, that is why policymakers and citizens are concerned about climate change. The IPCC

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[27] The nature of the models and further details of the model runs are discussed further in the Technical Supplement.

1.5 °C Special Report showed that, even if global warming is limited to 1.5 °C, the damage from warming by 2100 – including damage to buildings and infrastructure from extreme events and sea level rise, and the damage to ecosystems and the value of the services they provide to society – could be around two thirds of the size of the 2018 global economy. While for 1.5 °C warming, this damage can be broadly estimated, the damage is normally left out of model runs such as those shown in Figure 12 because of radical uncertainty as to where, when and at what scale they will arise. At progressively higher rates of warming such estimates become increasingly difficult, as the physical and associated economic consequences of climate change and their interconnections become more complex, pervasive and uncertain. For these reasons, the new modelling results in the following sections do not contain a baseline with much higher levels of global warming than 1.5 °C.

The profile of both economic growth and emissions reduction in these scenarios varies considerably by region. See the Technical Supplement for further information.

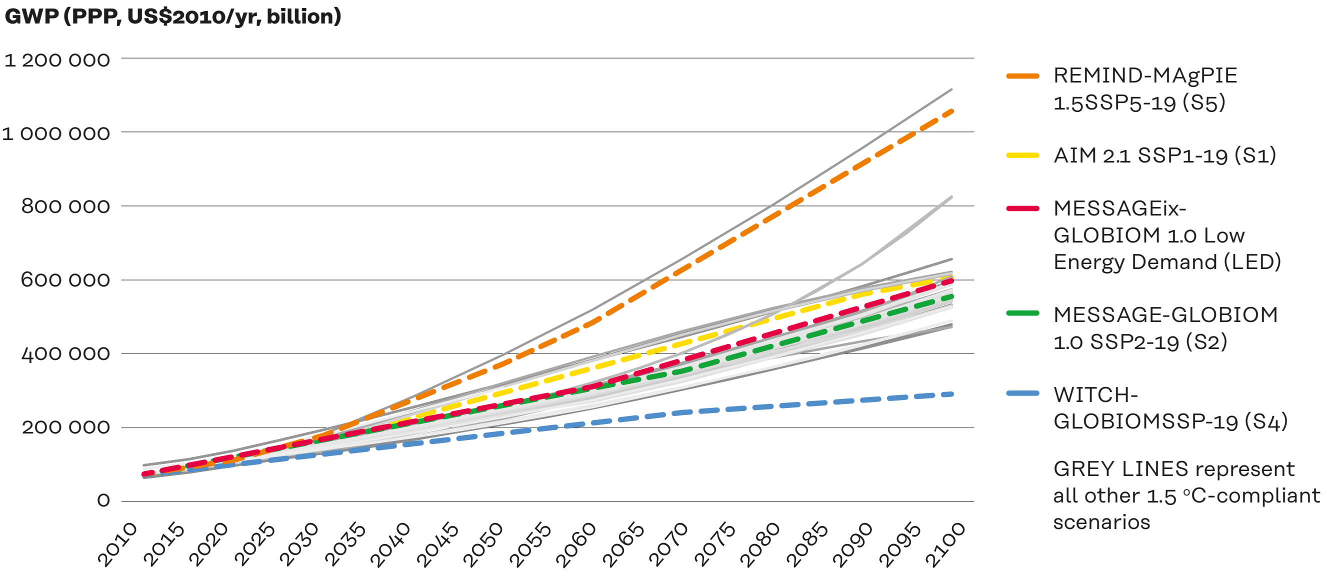
The following sections focus on the key mechanisms these pathways and underlying models employ to achieve decoupling at the global level under the SSPs. See the Technical Supplement for a more detailed discussion of the issues presented in these sections, including as they related to the modelling for the 1.5 °C-consistent decoupling scenarios in the EU's proposed strategy for carbon neutrality, "A Clean Planet for All: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy".

All the model runs producing 1.5 °C-consistent pathways require broad and deep transformations in the energy, industry, transport, buildings, agriculture, forestry and other land-use sectors. **Such pathways can be generated under a wide range of scenario assumptions, but assumptions around a lack of global co-operation (SSP3, SSP4), high population growth (SSP3), high inequality (SSP4), energy- and resource-intensive consumption and limitations around the ability to control land-use emissions (SSP5) are key impediments.**

Various such scenario assumptions converge in SSP3 to render it a particularly difficult scenario in which to achieve a feasible pathway to 1.5 °C. SSP3 assumes high population growth leading to high food and energy demand, regional rivalry hampering social and technological development, low rates of energy productivity improvement, low levels of natural land protection allowing for deforestation, a preference for non-renewable energy, and unsustainable consumption patterns. No modelling framework in Rogelj et al. (2018b) was able to create a feasible 1.5 °C-consistent pathway under SSP3.

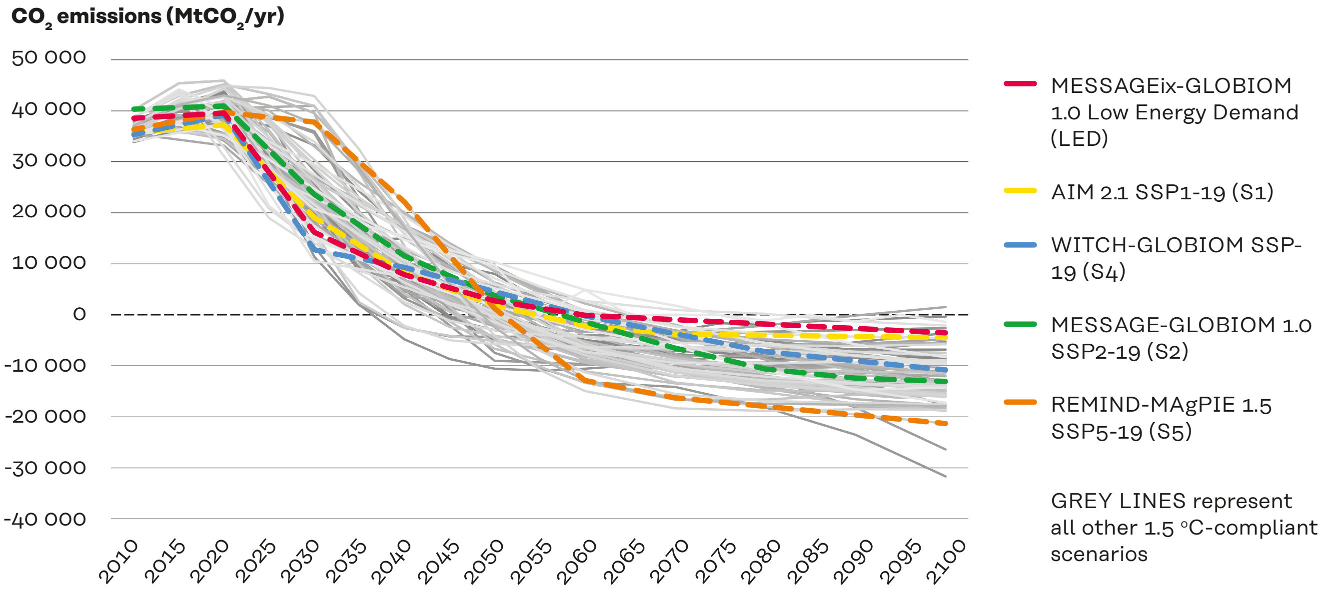
In the "baseline" scenarios of the studies, action to mitigate climate change is either absent or not increased beyond existing efforts, or emissions remain unconstrained. Of the five SSPs, the two most likely to project the lowest emissions trajectory in their baseline scenarios are SSP1 (high global co-operation and rates of technology development, with low population growth) and SSP4 (low GDP growth, high rates of technology development in affluent regions). The baseline scenarios developed by the modelling frameworks presented in Rogelj et al. (2018b) suggest it is possible to achieve absolute decoupling under these SSPs, even in the absence of active measures to mitigate climate change. However, this is only achieved after 2050, at CO_2 levels wholly incompatible with attaining a 1.5 °C limit by the end of the century.

Figure 12 a: Brief description of the impact on Gross World Product in five Shared Socio-economic Pathways (SSPs)



(data sources: Rogelj et al., 2018a; Huppmann et al., 2019) (Authors' note: grey lines represent the range of results produced by all other 1.5 °C-compliant scenarios reviewed by Rogelj et al. (2018a))

Figure 12 b: Brief description of the impact on CO_2 emissions in five Shared Socio-economic Pathways (SSPs)



(data source: Rogelj et al., 2018a; Huppmann et al., 2019) (Authors' note: grey lines represent the range of results produced by all other 1.5 oC-compliant scenarios reviewed by Rogelj et al. (2018a))

6.1 Economic output and structure

As described above, the GDP trajectories under each of the SSPs are inherent to their narratives. This accounts for the band of projected GDP trajectories presented in Figure 12.

Projections of GDP growth in economic models are either econometrically estimated or are the result of assumed increases in the productivity of labour or capital. Such productivity increases are a feature of economic development since the Industrial Revolution, and reflect factors such as technical, financial and organisational innovation, economies of scale and a shift towards a more knowledge-based economy (OECD, 2019b). Because there is no underlying reason why these drivers of GDP growth should be affected by policies to reduce CO_2 emissions, they are kept constant in both the baseline and 1.5 °C-consistent scenarios, allowing the models to estimate on a comparable basis the change in GDP resulting from emissions reduction. This change is largely driven by the difference in costs between low-carbon technologies and the fossil-fuel-based technologies that they replace. As the costs of low-carbon technologies have reduced in recent years, so has the cost of CO_2 reduction and the macroeconomic cost (reduction in GDP) of achieving it. As can be seen from Figure 12, none of the IPCC 1.5 °C-consistent scenarios come anywhere near suggesting that they will involve de-growth; i.e. an absolute reduction in GWP.

6.2 Energy demand and efficiency

Energy demand is a key determinant of CO_2 emissions, with improvements to the energy intensity of economies among the key distinguishing features of the different SSPs (Fricko et al., 2017). Energy demand and energy intensity are both inextricably linked to assumptions surrounding future socio-economic developments.[28] The 1.5 °C-consistent pathways encompass a reasonably wide range of developments regarding total primary energy consumption relative to 2010, although most pathways project only modest increases.

For the 1.5 °C-compliant SSP5 scenarios, such as S5 in Figure 12, energy demand increases dramatically, reflecting the high-growth, energy- and resource-intensive world represented by this narrative. In contrast, the S1 scenario, which uses the SSP1 narrative, projects the second-lowest of all 1.5 °C-consistent pathways in Figure 12. This is achieved mainly through increased take up of energy-efficiency measures and reduced transport service demand by households and industry, reduced consumer demand for manufactured goods and a reduction in the input of materials required for productive activities. These factors lead to rates of reductions in the energy intensity of the global economy that far exceed historic levels, and is only exceeded by the LED scenario, for which additional assumptions involving structural changes that avoid or shift passenger transport activity away from private cars towards other modes, such as

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[28] Such as GDP, population, demand for energy services in mobility, buildings and manufacturing, and the efficiency in satisfying these demands.

public transport, walking and cycling, are present.

Scenarios requiring or resulting in particularly low energy demand show many synergies with other system requirements. For example, if energy demand is reduced, so is the effort required to decarbonise what remains (Rogelj et al., 2018a).

6.3 Material demand and efficiency

Historically, economic growth has been coupled with an increase in the production and use of materials, which require energy to produce, with resulting CO_2 emissions. Reducing the material intensity of the economy through circular economy solutions such as developing materials and designing products and processes for a long life, reducing material losses during manufacturing and construction, more intensive use, reuse and recycling, can thus help to decouple economic growth from energy consumption and CO_2 emissions. This potential is particularly strong in sectors that produce intermediate goods that feed into a wide range of final products, such as the energy-intensive steel, cement and aluminium sectors. The IEA (2019) finds that relatively moderate increases in material efficiency can produce 30% of the CO_2 reduction required in these sectors by 2060 in a world in which the goals of the Paris Agreement are achieved,[29] with benefits extending through the value chain, such as reduced CO_2 emissions from lighter vehicles.

Increasing material and other resource efficiency is a pillar of the SSP1 narrative, and is also central to the LED scenario narrative, which aims to decrease aggregate material output by 20% between 2010 and 2050. So that although increased material efficiency is not explicitly represented in the modelling for this study, some of its effects are implicitly captured through the use of the SSP1 scenario as the starting point.

6.4 Use of low-carbon energy carriers and technology

Most models represent the supply side of the economy in much more detail than the demand side. However, there is substantial variation in the representation of different technologies and their characteristics (e.g. cost) in different modelling frameworks (Rogelj et al., 2018a), which – in combination with scenario design and implementation – may lead to substantial differences in projected mitigation pathways. Figure 13 shows the development of energy sources in the S1, S2, S4, S5 and LED scenarios that feature in Figure 12.

By around 2050 electricity generation is almost fully decarbonised in all 1.5 °C-consistent pathways reviewed by Rogelj et al. (2018a), with electrification the most important means for decarbonisation in all SSPs, and particularly for S1 and S4. Electrification is particularly extensive in transport through the use of electric vehicles, and in buildings with the use of heat pumps for heating. The deployment of renewables (particularly wind and solar) increases substantially and rapidly, and makes a major contribution to electricity generation by 2050 in most viable pathways, alongside a rapid reduction of unabated (i.e. with no carbon capture and storage – CCS) fossil-fuel use. Bioenergy, which may be used to produce electricity, liquid fuel, biogas and hydrogen, increases substantially over time in most pathways (ibid.). The use of CCS in the power sector varies substantially but is most prevalent in pathways with higher use of coal and gas, such as S5. CCS plays a major role in decarbonising industrial-sector

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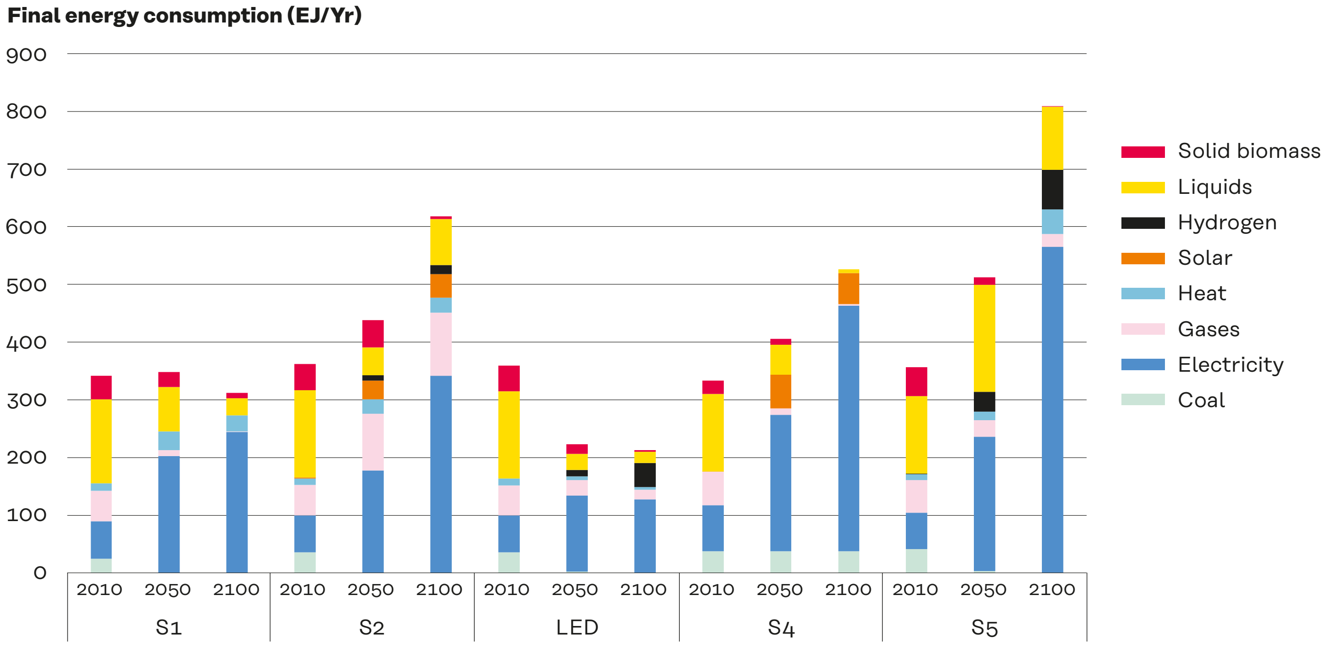
[29] In this case, the goals of the Paris Agreement are considered as met if the median temperature rise in 2100 is limited to 1.7-1.8 °C.

Figure 13: Global final energy consumption



(data sources: Rogelj et al., 2018a; Huppmann et al., 2019) (Authors' note: the figure shows final energy consumption for all end use sectors for all energy carriers, excluding transmission and distribution losses. "Gases" includes natural gas, biogas and coal-gas. "Heat" excludes direct geothermal and solar heating. "Solar" includes the direct use of solar energy from for example roof-top solar hot-water collectors. "Liquids" includes conventional and unconventional oil, biofuels, coal-to-liquids and gas-to-liquids. "Solid biomass" includes traditional and modern biomass (and excludes biogas and bioliquids))

process emissions, particularly in the cement, iron and steel industries (ibid.). CCS in the power sector is discussed below (except for bioenergy with CCS, which is discussed in the following sub-section).

6.5 Negative-emissions technologies

As illustrated in Figure 12, the vast majority of 1.5 °C-consistent pathways require the use of "negative-emissions" technologies or processes (i.e. those that remove CO_2 from the atmosphere), particularly after 2050, in order to generate net-negative overall emissions to remain below the required cumulative carbon budget to 2100.

The vast majority of 1.5 °C-consistent pathways employ BECCS. This uses biomass, which extracts CO_2 from the atmosphere as it grows, with CCS, which sequesters the CO_2 released from the biomass when it is combusted or refined. Biomass may be used to produce different kinds of energy, including electricity, biofuels, biogas and hydrogen. The deployment of BECCS varies significantly across the SSPs, particularly by 2100, as illustrated by the degree of negative emissions evident in Figure 12. This follows from the assumptions inherent in the narratives and their implementation in the models. An exception is the LED scenario, which is achieved explicitly without the deployment of CCS technologies of any description. This feat is also achieved only by the few other 1.5 °C-consistent scenarios with very low energy demand projections reviewed by Rogelj et al. (2018a).

An increasing demand for bioenergy (BECCS or otherwise) has potential implications for wider elements of sustainability, in particular land use, as discussed below. In addition, there is substantial uncertainty surrounding the technical and economic potential of BECCS in practice. As such, it is argued that BECCS should not be treated as a "silver bullet", and should increasingly be regarded as a potential contributor to a wider portfolio of mitigation options (ibid.).

Although many scenarios project substantial deployment of BECCS to achieve negative emissions, this is largely a function of BECCS being the primary method incorporated into models for achieving CO_2 removal from the atmosphere, apart from afforestation, which is discussed below. Other technologies, such as Direct Air Carbon Capture and Storage (DACCS, or just DAC), are rarely represented, and have similar if not greater levels of uncertainty surrounding their technological, economic and environmental potential and consequences.

6.6 Land use

The use of available land comes under pressure from different, competing demands in 1.5 °C-consistent pathways, including for agricultural products (influenced by population growth, but also dietary preferences and the efficiency of the food system and treatment of waste), demand for forest products for pulp and construction, demand for the production of biomass for energy production as discussed above, and for afforestation and reforestation – another negative-emission mitigation option. Land use is also a critical factor for biodiversity conservation or loss. In most 1.5 °C-consistent pathways, afforestation is scaled up by mid-century, facilitating net CO_2 neutrality by 2050 in most projections, while BECCS is usually more widely deployed to produce net-negative emissions in the second half of the century. This reflects the fact that afforestation is a negative-emission option that could have an impact before 2050, while BECCS is not projected to become widely available or cost-effective until later in the century (Rogelj et al., 2018a).

The production of biomass and the use of afforestation mainly occurs at the expense of agricultural land for food and feed production, although some biomass is projected to be grown on marginal land or supplied from residues and waste. However, the extent to which forest cover is projected to expand varies substantially. Reductions in agricultural land for food and feed production are usually compensated by intensification of agricultural and livestock production systems and changes in consumption patterns. Assumptions around activities related to land use may be a decisive factor in whether a 1.5 °C-consistent pathway may be feasibly produced by a modelling framework. For example, the SSP1 and LED narratives involve low consumption of energy and other resources, coupled with healthy diets, low meat consumption and food waste, and significant agricultural intensification. This implies a relatively small increase in the demand for land to produce bioenergy and for afforestation, which unlike BECCS is permitted in the LED scenario, with food demand met relatively comfortably. By contrast, the SSP5 narrative foresees less healthy diets with high levels of meat consumption and food waste, and a significant expansion of bioenergy crops to satisfy very high levels of BECCS, with resultant emissions from land use remaining high and difficult to offset elsewhere. High levels of natural habitat and biodiversity protection also prevent emissions from further land use change (ibid.).

6.7 Policy measures and implications

The Integrated Assessment Models (IAMs) implement or represent policy measures and their impacts using two primary approaches. The first is to place an emissions constraint on the model, either on cumulative emissions, or a maximum level of annual emissions in a given year, with the evolution in the "shadow price" of CO_2 emissions – the cost of reducing emissions by an additional tonne of CO_2 – produced as an output. This shadow price may be interpreted as the carbon price that would be required in order to achieve the other outputs the model generates under a given scenario (using other underlying assumptions in such models, discussed below). The second, opposite approach, is to introduce a carbon price into the model that then determines the cost-optimal configuration of the economy and resulting emissions.

Although much of the policy-related focus in modelling studies is on the role of carbon pricing in driving decarbonisation, other policy mechanisms may often be represented to different degrees. For example the LED scenario narrative assumes strict and tightening energy-efficiency standards for appliances and equipment globally, by assuming high rates of efficiency improvements in relevant technologies over time (Grubler et al., 2018).

The characteristics of individual models, particularly the range of technologies they include and their projected costs, are decisive in determining the carbon price as well as the profile of decarbonisation pathways. However, socio-economic and climate policy assumptions within the SSPs strongly influence the nature and economic implications of the projected pathways, regardless of the modelling framework employed. For example, delayed policy action and a lack of full global co-operation increases the total cost of mitigation and therefore the carbon price required to achieve it, as deeper efforts are required in later periods to counterbalance the lack of sufficient emissions mitigation in the nearer-term (Rogelj et al., 2018a).

Of the scenarios presented above, carbon prices in 2050 are in the range US$480-700/$tCO_2$ in S1, S2 and S5. At the extreme ends, S4 reaches an extremely high value of nearly US$3,000/$tCO_2$ by 2050, while LED reaches just US$160/$tCO_2$. By 2100, the carbon price in the LED scenario climbs to US$700/$tCO_2$, but to several thousand dollars per tonne of CO_2 in all other scenarios. Such prices compare to an actual global weighted average carbon price of just US$13.08/$tCO_2$, in early 2019, with a coverage of just over 13% of global anthropogenic emissions (or US$1.76/$tCO_2$, if all anthropogenic CO_2 emissions are considered) (Watts et al., 2019).

As illustrated by the particularly low carbon prices projected under the LED scenario, **moderating or reducing energy demand may play a substantial role in reducing the projected costs of mitigation.** The LED scenario projects supply-side investment costs at rates two to three times below most other 1.5 °C-consistent pathways (Grubler et al., 2018). However, the costs of many of the mechanisms that lead to a reduction in energy demand in the models are highly uncertain and often not included. That said, some options to increase energy efficiency and reduce demand may be cost-neutral or generate savings. These may include changes in preferences and behaviour, such as reductions in food waste, or the removal of barriers to the adoption of economically attractive energy-efficiency actions or investments.

6.8 Costs of mitigation

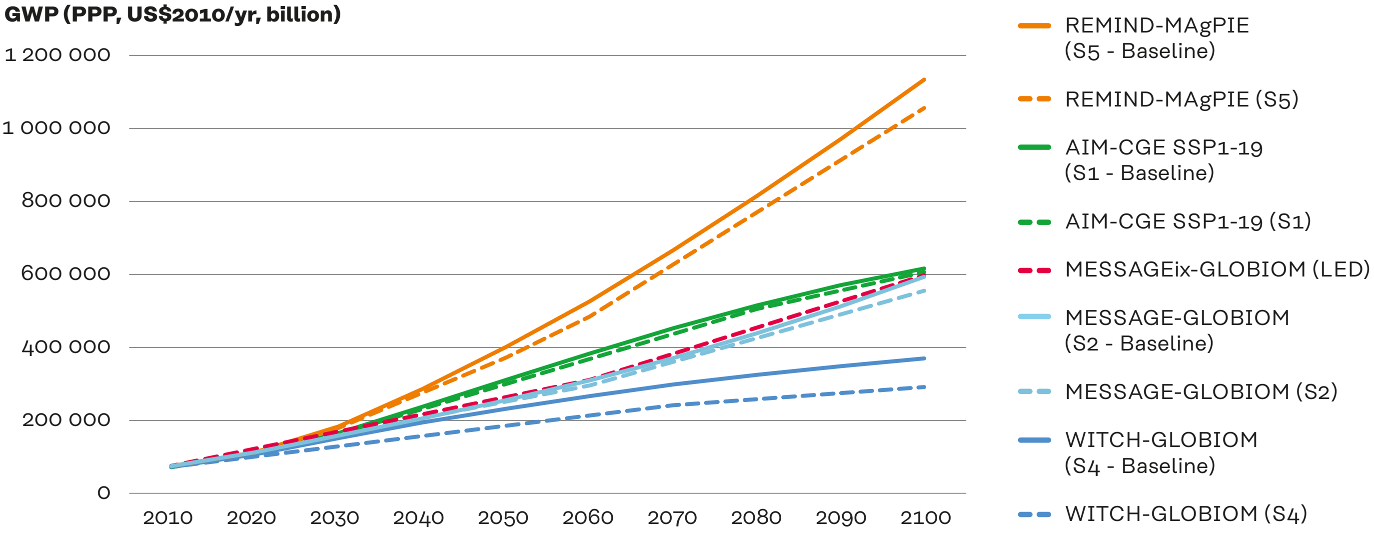
Figure 14 illustrates GWP projections for the S1 to S5 and LED scenarios. GWP loss is projected in each case compared to the baselines. It should be remembered that neither the baselines nor the scenarios take account of the potentially very substantial costs of unabated climate change, though these may be expected to be much higher in the baselines because of the higher levels of GHG emissions. It will be seen that, in all cases, economic growth remains positive, i.e. absolute decoupling is achieved in all the scenarios which achieve the 1.5 °C target. Carbon pricing may raise very substantial revenues and how these are returned to the economy may greatly influence the macroeconomic impact of climate policy measures. However, in all cases decarbonisation is achieved by 2100 in conjunction with an economy that is very much larger than in 2020. In the S1 and S2 scenarios, decarbonisation is achieved with relatively small reductions in GWP compared to the baseline.

A number of factors influence the decarbonisation pathways projected by the models. One of the most important is the uncertainty surrounding long-term trends and technology dynamics. For example, the cost trajectories, and, in some cases, the availability of key technologies, which are exogenous assumptions in most models, are likely to differ substantially from how such trajectories develop in reality. A more fundamental issue is the general difficulty of models and scenarios to reflect the dynamics of innovation and the potential for more wide-ranging transformational change, such as disruptive technologies that create new relationships between elements of the economy and energy system, and non-linear changes in human behaviour and preferences (Forster et al., 2018), which may substantially raise or reduce barriers to the reduction of CO_2 emissions in the long-term.

Another factor is the assumption within IAMs of idealised conditions within which policies may be introduced and operate. They typically assume that markets are frictionless and market failures are absent, and that mitigation actions are taken across the economy where and when they are most cost-effective across the assessment horizon. Governance issues such as institutional capacity and structures are also absent (Forster et al., 2018). Many models also consider the financial sector as a largely homogeneous source of low or zero-cost funds. However, in reality the financial sector is highly heterogeneous in terms of both actors and investment products and vehicles, offering rates of interest for financing that vary very substantially across sectors, technologies, countries and time. If such heterogeneity were more appropriately reflected in models, the capital-intensive nature of the investments required would mean the profile of projected cost-optimal decarbonisation pathways may be very different (Egli et al., 2019).

Such factors imply that under a regime in which carbon pricing is the principal instrument for driving decarbonisation, IAMs underestimate the potential cost of achieving the pathways they project.

Figure 14: Gross World Product projections – Baseline and 1.5 degree scenarios



(data sources: Rogelj et al., 2018a; Huppmann et al., 2019)

7 Scenario construction and modelling approach

Scenarios, such as the SSPs described above, are plausible and internally consistent projections of future events. They are not predictions or forecasts, but "thought experiments" as to how the future might turn out given certain assumptions and circumstances. Models are means of quantifying the outcomes of scenarios by specifying formal mathematical relationships between different variables. As has been seen with respect to the IPCC 1.5 °C report, scenarios and models have proved core tools for assessing long-term emission mitigation strategies and the vast majority of global, stringent decarbonisation scenarios demonstrate decoupling of GDP growth from emissions, as has been documented in Sections 3 and 4.

A key question is, what are the critical assumptions that need to be made in order to reach the scenario results shown in the literature, and how complete and permanent can the observed decoupling be while the economy continues to grow? The empirical observations and results from the modelling studies presented in Sections 3 and 4 provide a robust starting point for the analysis. **The objective of the scenarios to be modelled here is to investigate further the impacts on economic performance of different scenarios of ambitious emission reduction.** The key determinants of maintaining average global warming to below 1.5 °C are the availability and costs of energy efficiency and low-carbon **technologies**, the extent of **economic restructuring** away from resource-intensive activities and the **rate of transition** to zero or negative emissions.

Technology: As has been seen from the discussion of the scenarios above, technologies play a key role in reducing the carbon intensity of energy provision and can, through investments in more efficient technologies, also be used to reduce the volume of energy needed for a specific level of energy service. The widespread diffusion of novel, low-carbon technologies, however, requires cost reductions that are achieved through the uncertain processes of innovation, achievement of economies of scale, and learning by research and by doing. Improving energy efficiency can result in net positive economic benefits when cost-effective options are available for it. In addition to the technologies themselves, consumer behaviour and preferences are crucial, but highly uncertain, enablers of technology diffusion on the end-use side. Finally, reaching zero carbon requires either negative-emission technologies or full decarbonisation of all sectors, including those that are difficult to abate, and the cost and availability of the technology options in these sectors therefore play an important role. Key variables in scenarios are the assumptions made about these various developments and processes, in order to reach zero and negative carbon emissions. Some technologies may turn out to be more important than others, and some may be absolutely critical to achieving the 1.5 °C temperature target.

Changes in the structure and resource efficiency of the economy: Energy and industrial processes are major sources of carbon emissions and, as demonstrated for the UK in Section 2, changes in the structure of the economy in a less resource-intensive direction could help alleviate the pressures on technologies and behavioural change to deliver emissions reductions. But the nature and strength of the assumptions in this area are obviously important factors in scenarios, as well as their impacts in different regions across the world.

Ramping up of the mitigation efforts: Reaching emission levels consistent with 1.5 °C not only requires very deep emission reductions, but these also need to happen very rapidly. The technologies and infrastructures that would need to be replaced, however, are highly interconnected and many have long lifetimes – and the new alternatives tend to start with a higher initial cost than the costs of the incumbent technologies. Moreover, consumers are generally risk averse, which can further slow down the speed with which mitigation efforts can be ramped up. In light of this, scenario assumptions about the level of co-ordination, behavioural change and other barriers, to allow a rapid transition to the zero-carbon system, are important.

The purpose of the modelling in this project was to explore in detail the characteristics of energy system and other developments that would be necessary to meet two targets: global net-zero CO_2 emissions by 2050; and a maximum 1.5 °C global temperature increase by 2100. The scenarios modelled here consist of one central scenario and sensitivity runs[30] that stress-test the scenario in order to identify some of the most important assumptions needed to reach the required levels of decarbonisation. The sensitivity runs explore whether the targets can still be met if emissions reduction from phasing out coal or the ability to capture and store CO_2 is constrained, as described further below. The modelling also generates the economic results of imposing these global constraints on the world's economy, and for emissions and economic activity in the EU and in Finland.

Two energy system models and a macroeconomic model have been used for this exercise. The PRIMES energy system model deals with the national (Finland) and EU levels, while the TIAM-UCL energy system model is a global model. The computable general equilibrium (CGE) GEM-E3-FIT global macroeconomic model is used to assess the economic impacts at global, European and national levels. Some details about the models used in this project are given in the annex to this report and the Technical Supplement.

In brief, energy demands for the various subsectors and global regions in TIAM-UCL were derived from economic drivers supplied by GEM-E3 under SSP1 assumptions. Data on GHG emissions for EU member states using SSP1 assumptions was also supplied by PRIMES. Resulting detailed regional data from TIAM-UCL on electricity investment, capacity and generation, along with final energy consumption in the residential, commercial, industrial, transport and land-use sectors, were then used to generate improved economic growth predictions in GEM-E3. Further details on the modelling are given in the Technical Supplement.

The GEM-E3 CGE model has been used to quantify the economic implications of the central scenario within a dynamic socio-economic context. The key drivers of economic growth in the GEM-E3 model are technical progress, population growth and capital accumulation. The projection of population is not calculated by the model and outside sources are used (e.g. ILO population projections). The model calculates the investments needed to build the production capacity that optimises the firms' operation. Technical progress (total factor productivity) is partly introduced by the user of the model by using the expenditures on R&D and the learning-by-doing effects, and partly calculated by the model. The model's growth drivers have been calibrated to sources outside the model[31] and the energy system of the model

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[30] This is the term applied to a model run that varies just one assumption or parameter in order to gauge its influence on the model results.

[31] Non-EU GDP projections are based on the IMF "World Economic Outlook" (IMF, 2018) and the IEA/OECD "World Energy Outlook" (IEA, 2017). EU population projections follow the DG-ECFIN Ageing Report (EC, 2018; EUROPOP2019, 2019) and non-EU population projections are based on SSP1 (Samir and Lutz, 2017).

"What critical assumptions need to be made, and how complete and permanent can the observed decoupling be while the economy continues to grow?"

is calibrated to match the results of the energy system model, TIAM-UCL.

In interpreting the model results, it should always be borne in mind that, as noted above, SSPs and related model results are not forecasts, but quantified narratives that are internally consistent, plausible descriptions of how the world could develop. The quantifications are direct results of the assumptions made in the model parametrisation. Therefore, for example, the infeasibility (or feasibility) of reaching a specific target in the modelling should not be interpreted necessarily as a (technical, economic, etc.) infeasibility (or feasibility) in the real world. Finally, it is important to note that the modelling is focused on the energy and the economic systems and does not describe in detail a number of other systems (e.g. food production and land use more generally, water, material flows, ecosystems). What is more, while the temperature implication of a specific emission trajectory is an endogenous variable in the modelling framework, the impacts that changing temperature might have for the modelled system (or in the real world) and beyond are not accounted for.

7.1 Central decarbonisation scenario

The central decarbonisation scenario assumes ambitious and well-co-ordinated global climate policies that are compatible with a target of net-zero carbon emissions by 2050 and no more than 1.5 °C in 2100. For the central scenario, conditions broadly consistent with SSP1 ("Sustainability – Taking the green road") are assumed (O'Neill et al., 2017). This is the SSP narrative with the lowest challenges for carbon-emission reduction. This narrative includes an assumption of rapid technological development, lifestyle changes and strong policy support. This background narrative is combined with climate effort that is, on the global level, at least consistent with countries' Nationally Determined Contributions (NDCs) under the Paris Agreement on climate change, which focus on 2030, and involves further increases in ambition level after 2030. In the central scenario, all technology options are pursued, with different countries potentially focusing on different technologies. Also "exotic" technologies may be implemented in sectors for which other alternatives are scarce. The technology-specific details and regional economic trajectories are results from the models but are consistent with the aims set for this central scenario. The impacts of climate change are not considered – the stringent decarbonisation aim implies an assessment that inability to reach this target would have outcomes that are more costly than decarbonisation, or otherwise unacceptable.

In addition to SSP1 conditions, the central decarbonisation scenario assumes several climate targets. First, a net-zero CO_2 target is set for 2050, or for a period as soon as possible after that, if 2050 turns out not to be feasible. Second, global warming in 2100 is limited to 1.5 °C and a further net CO_2 budget of 420 $GtCO_2$ for the period 2020-2100 is set to align the scenario with IPCC's estimate of a 66% chance of limiting warming to 1.5 °C (IPCC, 2018) and to the ratio of mitigation efforts coming from CO_2 and other GHGs. Third, separate limits are set to reduce peak warming, if staying below 1.5 °C throughout the century is not feasible. GHG emissions for the EU up to 2070 under SSP1 assumptions supplied by the PRIMES energy system model are also included. Given the current technological immaturity of NETs, i.e. BECCS and DAC, an annual limit on their usage of 10 $GtCO_2$ is applied throughout, with a further limit on DAC specifically of 4 $GtCO_2$ p.a. CCS and BECCS are assumed to be available from 2030, and DAC from 2040. Limiting warming to 1.5 °C also requires a rapid shift away from coal. At the moment, however, coal features heavily in the energy systems of many countries. Therefore, its replacement by other energy sources may not be equally easy in all places (Jewell et al., 2019). In the USA, coal usage fell by an average of 5.4% p.a. between 2015 and 2018 (IEA, 2018b). The central scenario assumes that this 5.4% p.a. reduction in coal usage is the maximum feasible rate in other countries.

7.2 Sensitivity scenarios

The sensitivity runs are formulated to "stress-test" how results and conclusions may change as a function of changes in potentially critical input assumptions. These runs are informed by early results from the central decarbonisation scenario, focusing on technologies and dynamics that are important in it – and uncertain in reality. Variations in assumptions are thus adopted for the following elements:

1. In respect of technology deployment rates, the central decarbonisation scenario assumes that a regional coal phase-out rate up to 5.4% p.a. is feasible, as described above. The first sensitivity run assessed what the impact of a slower coal phase-out would be for the feasibility and costs of reaching the climate targets with the maximum decline rate for coal reduced to 2.7% p.a.
2. For the second sensitivity run, the focus is on capturing carbon and storing it. Carbon capture and storage technology can reduce the emission intensity of fossil fuel-based energy conversion (CCS) or, when applied to bioenergy, remove emissions from the atmosphere (BECCS). Direct air capture (DAC), in contrast, is not attached to a specific point source of emissions but captures carbon from ambient air. These technologies, especially BECCS and DAC, often hold a central role in ambitious long-term mitigation scenarios, as they allow hard-to-abate emissions to be compensated with increased use of technologies that remove CO_2 from the atmosphere. This is also the case in our central scenario. These technologies are, however, not fully mature and face a range of technological, regulatory and economic uncertainties that could well prevent their diffusion. As a consequence, our second sensitivity run assumes all CCS, BECCS and DAC technologies to be unavailable.
3. Our third sensitivity run combines the two previous sensitivities and assesses what a slower coal phase-out combined with a lack of CCS, BECCS and DAC does for the feasibility of reaching long-term climate targets.

As the assumptions in the sensitivity runs make it more difficult to reach the climate targets, the net-zero target is postponed as much as is necessitated by these assumptions. Similarly, the 1.5 °C and peak warming targets are relaxed, if necessary.

8 Results

8.1 Central decarbonisation scenario

The CO_2 emissions trajectory for the central decarbonisation scenario (hereafter the "central scenario") is shown in Figure 15. The results show that the model commences decarbonisation from 2020, and all sectors show rapid decarbonisation to meet the climate targets. The buildings, transport and land-use sectors are largely decarbonised by 2100 if not earlier, with slightly negative emissions from land use due to afforestation and carbon storage in soil. The rate of emission reductions for electricity and industry[32] is limited by their continued use of coal (with the coal phase-out limited to 5.4% p.a. as described above), though global emissions from electricity (and upstream processes) fall to around 1 $GtCO_2$ p.a. by 2100. The sector with the largest remaining CO_2 emissions in 2100 is industry, reflecting the challenge of mitigating emissions (including from cement manufacture) in this sector. Despite this fall in emissions, global temperatures are predicted to surpass the long-term 1.5 °C target, reaching a maximum of 1.87 °C in 2050. CCS, BECCS and DAC begin to remove and store emissions from 2030, and the global energy system is net-negative from 2055. This could not be achieved earlier due to limits on deployment rates of CCS, BECCS and DAC. BECCS and DAC deployment reaches 2.9 $GtCO_2$ p.a. and 4 $GtCO_2$ p.a. in 2100 respectively, with total offsetting emissions, including from agriculture, of around 10 $GtCO_2$ p.a.. This net-negative energy system brings the global temperature back to the 1.5 °C target by 2100. The total offset emissions for 2030-2100 from CCS, BECCS and DAC was 583 $GtCO_2$.

Primary energy consumption is shown in Figure 16. The challenging climate targets drive a rapid reduction in fossil-fuel usage, particularly for coal (though the coal phase-out rate was limited to 5.4% p.a.). Likewise, there is a rapid transition to renewable technologies (wind, solar and biomass). However, significant quantities of oil and natural gas are still in use in 2100, reflecting the challenge of mitigating emissions, largely in industry. There is also a sizeable dip in primary energy in the 2020-2050 time frame as stringent climate targets cause price-induced demand reductions and the roll-out of more efficient technologies. Primary energy rises later in the century with increased access to low-emission energy sources.

Electricity generation is shown in Figure 17. Electricity generation is predicted to rise rapidly up to 2100, driven by onshore and offshore wind and solar. Electricity generation from fossil fuels drops to very low levels. These results show that a rapid and substantial decarbonisation requires radical changes to electricity systems. Either a substantial reduction in demand is needed (e.g. through lifestyle changes, improved efficiency and increased circularity), or clean electricity generation (or usage of other low-emission energy sources) must increase rapidly.

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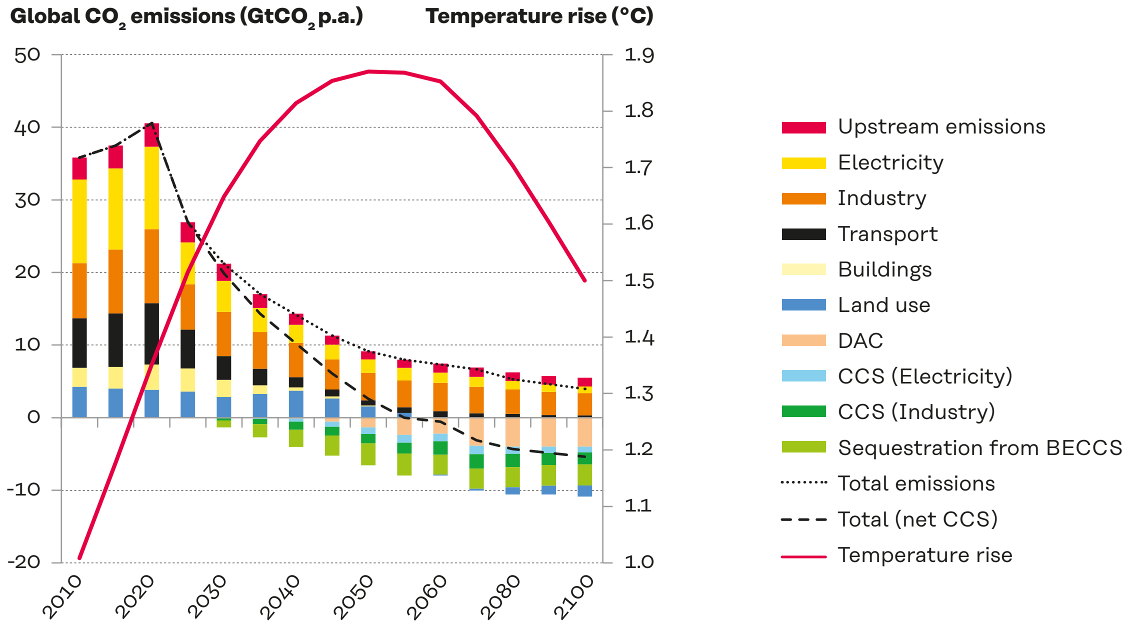
[32] The electricity sector includes emissions from power generation. Industry includes CO_2 emissions from the main industrial sectors (iron and steel, non-ferrous metals, non-metallic minerals, chemicals, pulp and paper, and other industry). The upstream sector includes CO_2 emissions from fuel extraction, processing and distribution. Transport includes emissions from cars, motorcycles, light vehicles, buses, trucks (commercial, medium and heavy), passenger and freight rail, domestic and international shipping, and domestic and international aviation. Buildings includes emissions in residential and commercial buildings (i.e. heating, cooling, hot water, cooking, lighting and appliances). Land use includes CO_2 emissions from farming, deforestation, afforestation, etc.

Figure 15: CO_2 emissions trajectory (central scenario)



(Authors' note: see footnote 20 for a detailed description of the content of the different sectors)

Figure 16: Primary energy (central scenario)

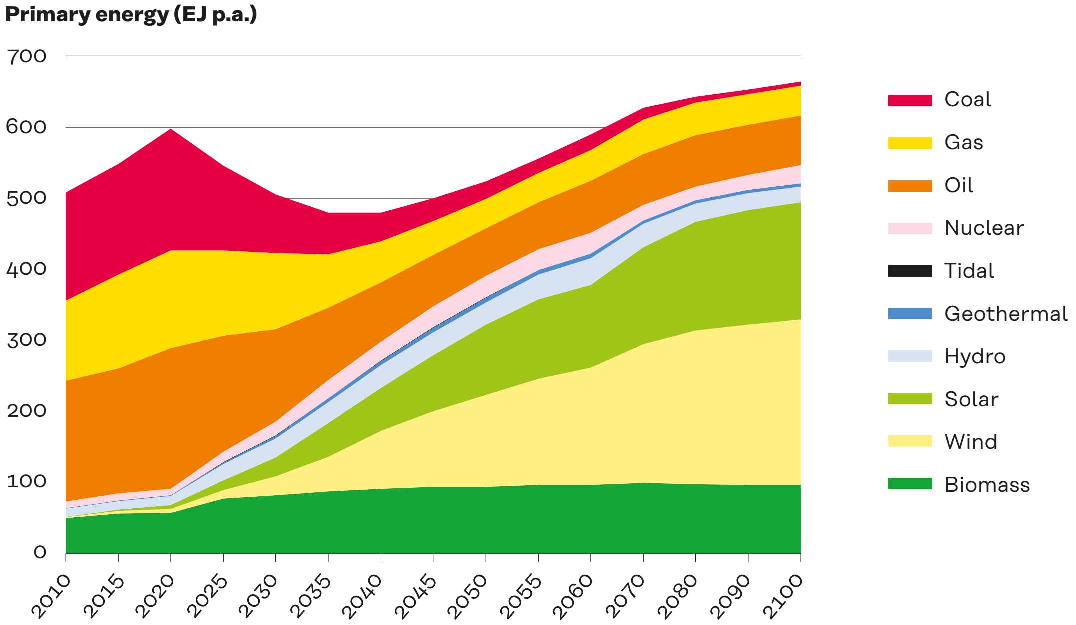
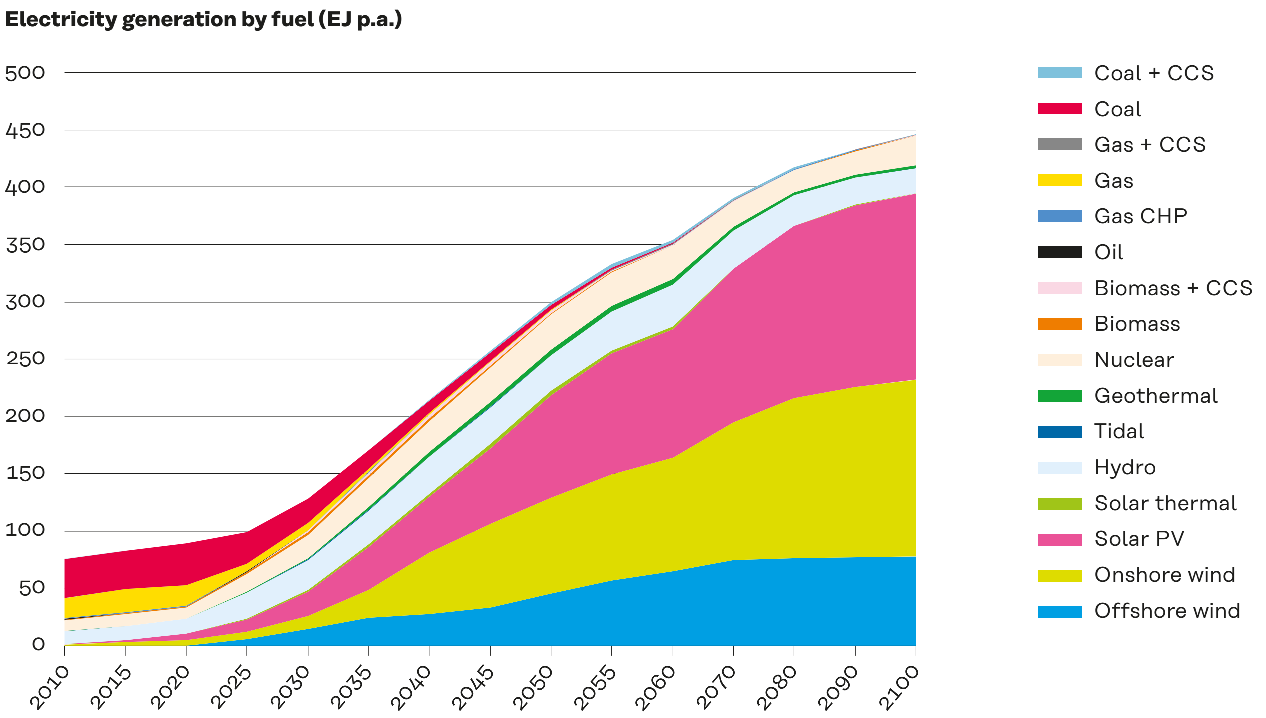


Figure 17: Electricity generation (central scenario)



Consumption in the residential and commercial buildings sector is shown in Figure 18. Natural gas and Liquefied Petroleum Gas (LPG) are largely phased out by 2050, with electricity becoming the dominant energy source for heating, followed by biomass. Overall energy consumption in the building sector rises slightly by 2100.

Energy consumption in transport is shown in Figure 19. Fossil fuels including petrol, diesel and heavy fuel oil are largely removed by 2050. A significant part of the transport sector is electrified. However, hydrogen also plays a substantial role, particularly for trucks and shipping (less so for bus, car and rail). Use of bio jet-kerosene in aviation (45% in 2050, increasing to 69% in 2100) helps to reduce aviation emissions, though fossil fuel-derived kerosene is also used.

Energy consumption in industry is shown in Figure 20. There is a rapid reduction in coal usage to meet the challenging climate targets (though this phase-out was limited to 5.4% p.a.). These targets also cause a dip in energy consumption between 2020 and 2050, although consumption rises again towards 2100 due to the growth in demand and the availability of offsetting technologies. Electricity is the primary low-emission energy source available for the industrial sector and its use rises rapidly towards 2100, with a smaller role for biofuels. However, there is still significant consumption of oil and natural gas in 2100, particularly in the chemicals sector, reflecting the challenge of reducing emissions in some parts of the industry sector.

Economically, the clean energy transition is a capital-intensive process through which low value-added products (fuels) are substituted by high value-added machinery and construction (wind turbines, PV panels, energy-efficient appliances and machines). Fossil-fuel sectors decline, fuel import bills shrink but at the same time domestic investment expenditures increase. This process develops in a dynamic framework where

Figure 18: Energy consumption in buildings sector (central scenario)

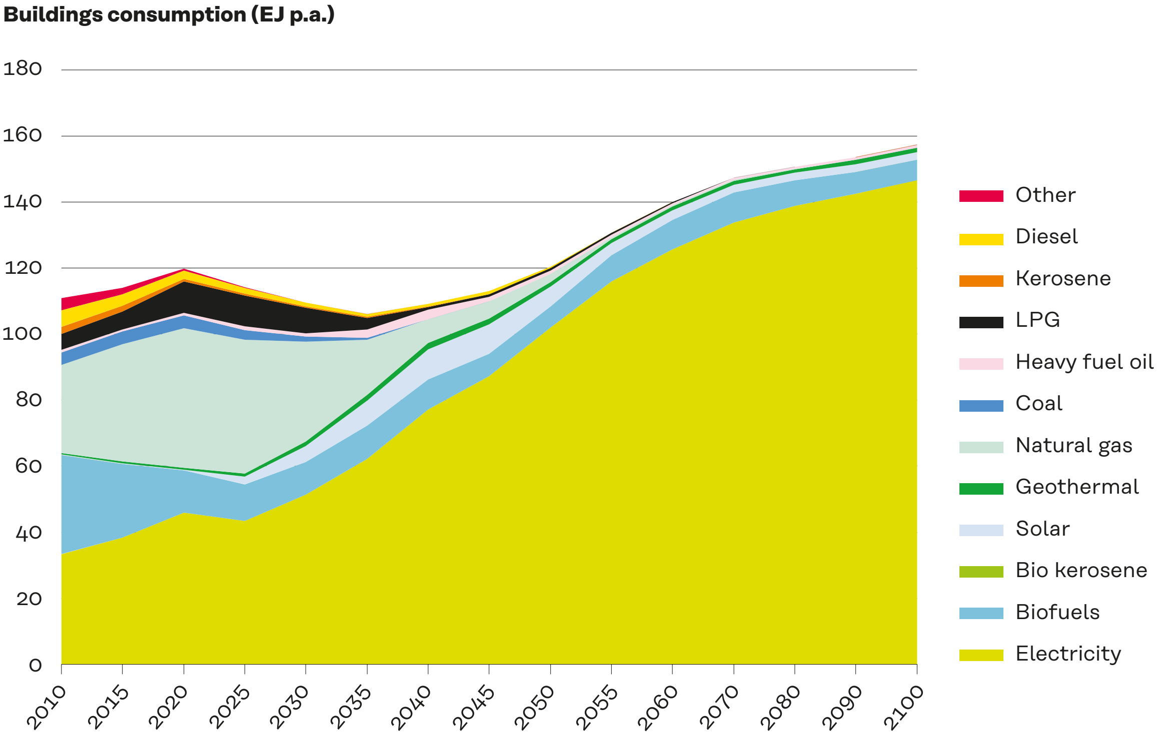
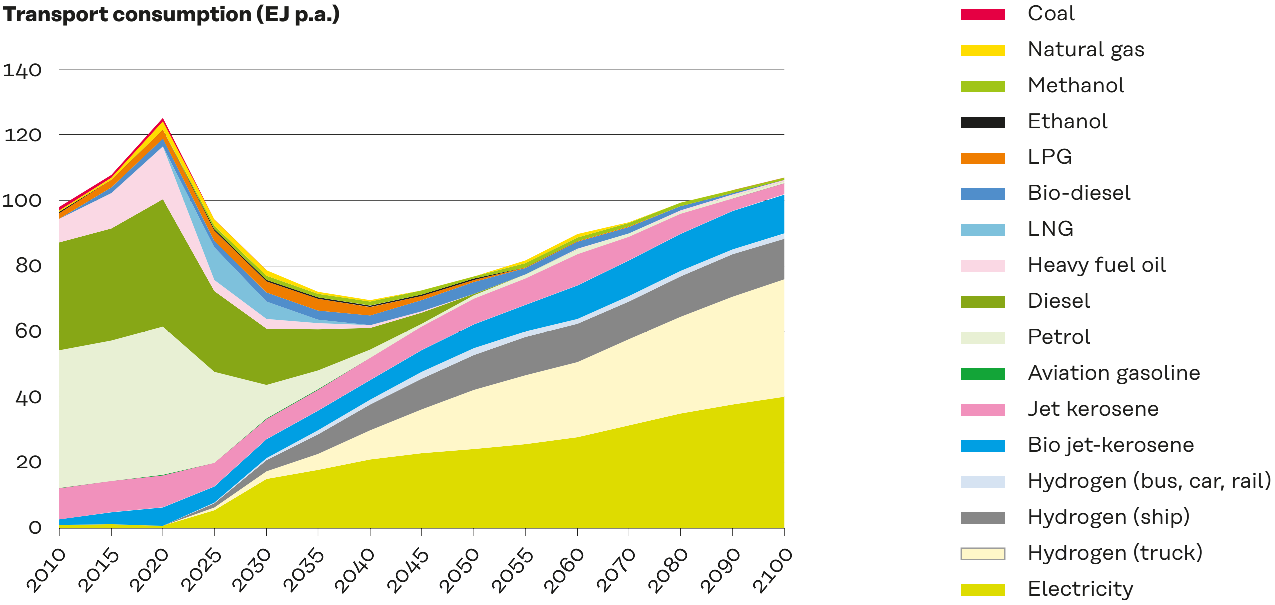


Figure 19: Energy consumption in transport sector (central scenario)

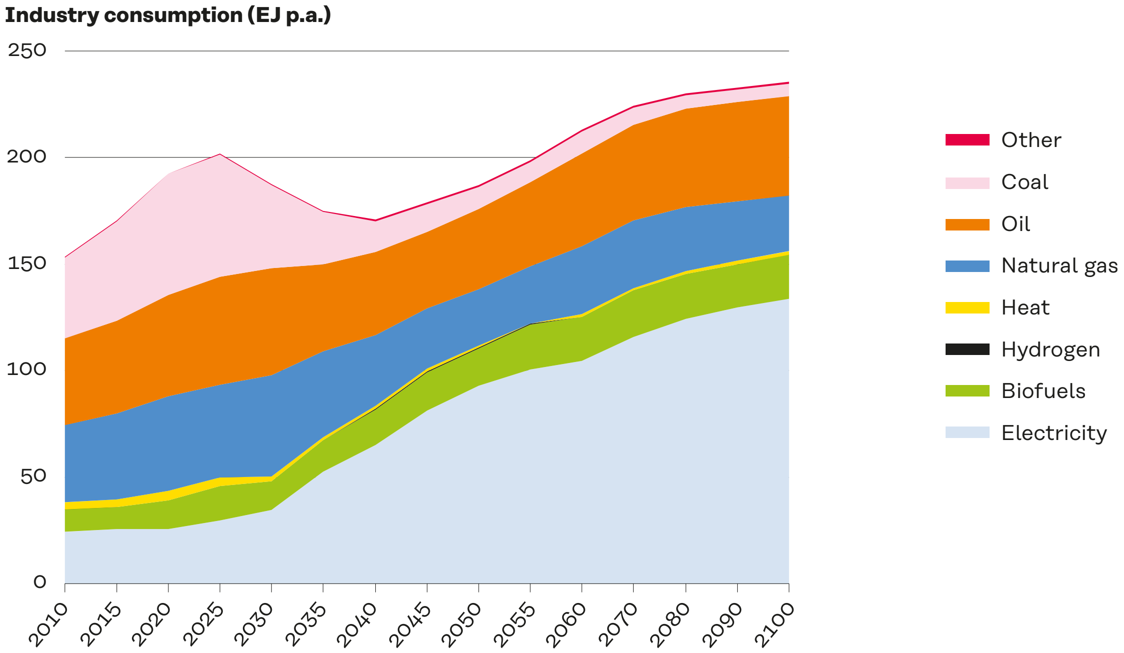


prices, technical progress, population, labour productivity, production structures, consumer preferences and habits evolve requiring different and new types of labour skills, infrastructure and materials.

These developments in a CGE model will tend to reduce economic growth if: 1) the low-carbon technologies are significantly more expensive over their lifetime than the fossil-fuel technologies they replace; 2) the development and installation of low-carbon technologies causes technical progress to slow and total factor productivity to fall; 3) the higher investment in low-carbon technologies "crowds out"[33] more productive investments in other technologies and/or raises interest rates. In respect of 1), low-carbon technologies are currently broadly competitive with fossil fuels except in some industry and transport sectors (e.g. steel, aviation), although technical progress with these technologies may be expected to make them cheaper by 2050. In respect of 2), it seems unlikely that low-carbon technological development will reduce overall rates of technical change, and it may even increase it. In respect of 3), whether or not "crowding out" occurs will depend on the macroeconomic circumstances at the time. Modelling "full crowding out" will give the maximum negative impact on GDP growth.

Figure 21 shows that economic growth after 2020 declines from 3.5% p.a. to just over 1% p.a. However, this decline is mainly due to the stabilisation of the human population over this period. Per capita GWP growth just about halves over these 80 years as the growth of investment slows, largely after 2040. The average annual growth rate of Gross World Product (GWP) over the period 2020-2100 consistent with an energy system that achieves 1.5 °C in 2100 is 1.76%

Figure 20: Energy consumption in industry (central scenario)



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[33] In CGE models there is a strict closure or balance between savings and investment, which means that investments compete for a finite amount of financial resources (determined by savings). The implication of this constraint is that investments in certain projects may "crowd out" investments in other projects in order to ensure financing (e.g. if additional investments are required to decarbonise the energy system then investments in other parts of the economy will have to be cancelled in order to free up financial resources). Relaxation of this closure is possible allowing for a temporary imbalance between investments and savings.

with full crowding out. Please see Figure 22 and note the increasingly compressed scale, for the periods 2015-20, 2020-30, 2030-50 and 2050-2100. These results mean that the global economy in 2100 is nearly four-and-a-half times its size in 2015. Even though its rate of growth declines, investment increases its share in GWP from ~23% in 2015 to 26% in 2100, as a result of the capital-intensive character of the energy system transformation process. This mainly takes place at the expense of private consumption that falls from 59% to 51%.

Figure 21: Decomposition of Gross World Product's annual growth rate to its key drivers

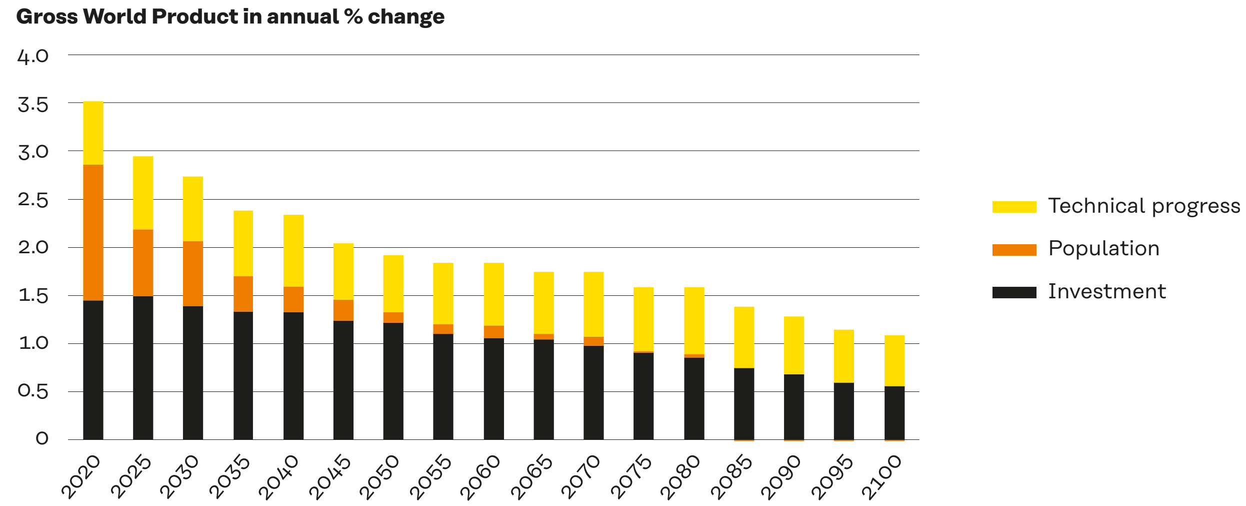


Figure 22: Annual Gross World Product (GWP), growth rate and components

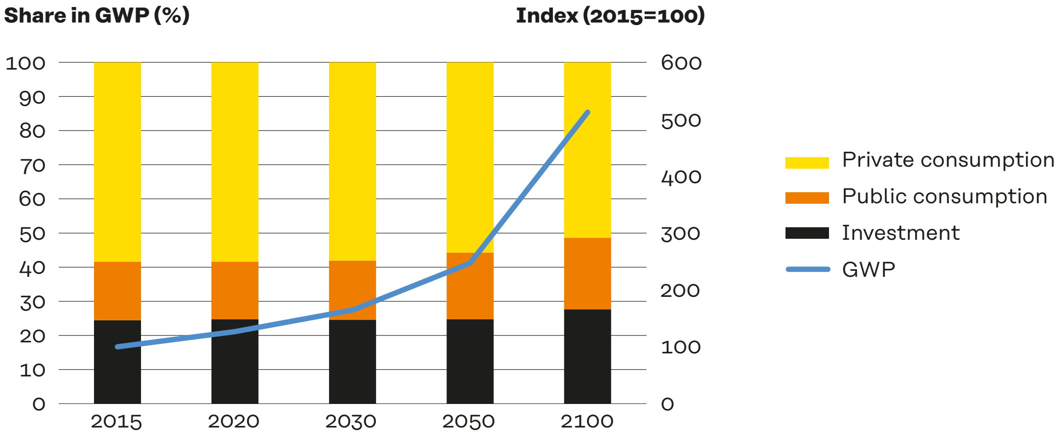
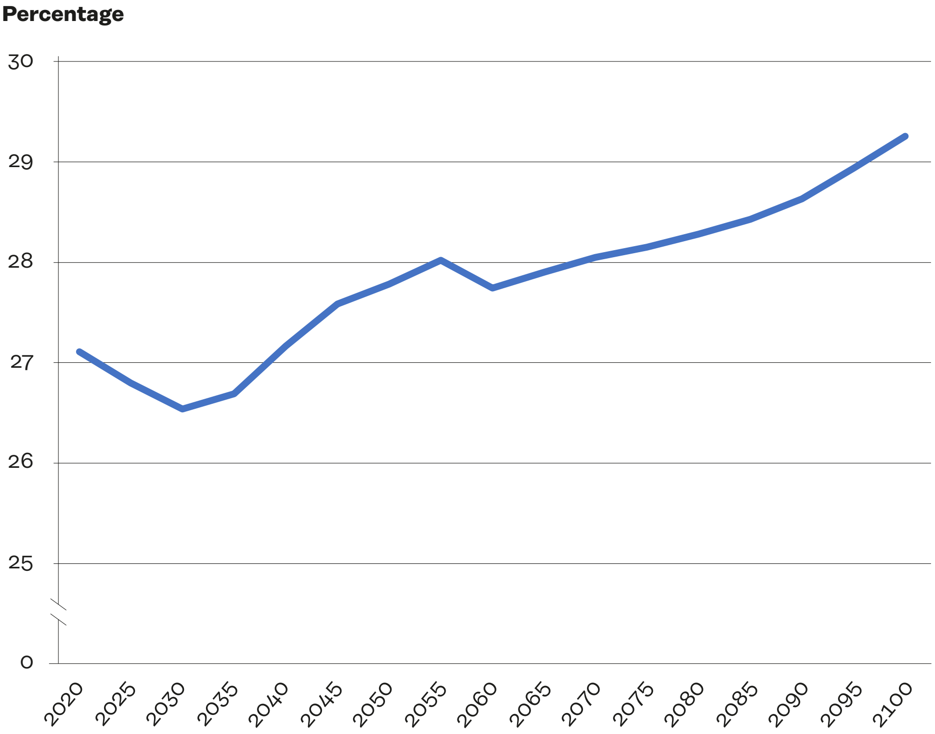


Figure 23: Trade openness[34]



The model suggests that trade openness or integration increases over time as trade grows faster than GDP (Figure 23). Trade openness means that firms are exposed to considerable international competition and any changes in their production costs affect their economic performance.

From a regional growth perspective, China presents the highest GDP growth rate and becomes the biggest economy by 2100, followed by the EU and USA (Figure 24). China becomes a significant supplier of equipment and services required to decarbonise the energy system. India also grows significantly over the projection period. In the EU, an ageing population and slow population growth have a negative impact on the overall growth potential.

The projection on the sectoral production mix in the entire world is provided in Table 2. Agriculture increases as it provides feedstock for the first-generation biomass. Services increase their share as the economy dematerialises. Construction, which is an essential sector both for energy-efficiency (EE) projects and the formation of capital goods, steadily increases its share in total value added over time, as do sectors producing renewable energy and EE equipment. Transport services increase their share benefited by electrification and world integration. The contribution of energy in total production depends on two key drivers: 1) in the short term, the demand for fuels and electricity is reduced as a result of the implementation of energy-efficiency projects; and 2) in the long term, the electrification of the economy (e.g. through electric cars) increases the contribution of the power generation sector and further reduces the importance of fossil fuels.

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[34] (Imports + Exports) / GDP.

Figure 24: Regional share in world income in 2100

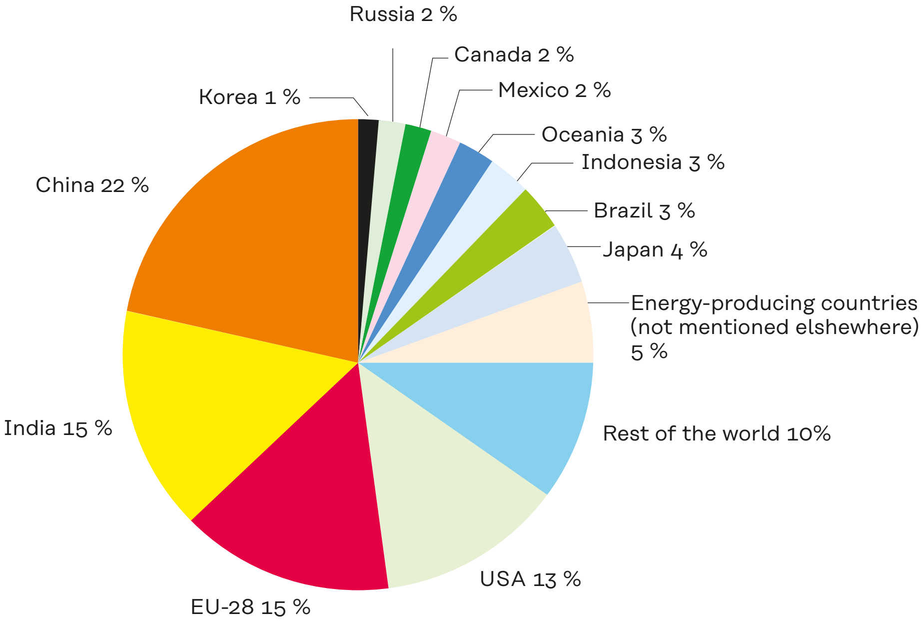

Table 2: World sectoral production

Sector (share in %)	**2011**	**2050**	**2100**
Agriculture	3.4	5.1	5.4
Energy (fuels and power generation)	7.5	5.4	5.9
Energy-intensive	12.9	10.7	8.5
Other industries	18.6	17.7	15.1
Transport	5.3	5.3	5.3
Construction	7.4	9.5	12.5
R&D	0.8	0.7	0.6
Services	43.8	43.8	45.0
Renewable energy (RES) and energy-efficiency (EE) equipment	0.2	1.7	1.7
Total (%)	**100**	**100**	**100**

8.1.1 Economic results for the EU and Finland

The economic performance of the EU-27 (plus the UK) is driven both by the world economic growth (demand for EU products) and by factors affecting the EU internal market. R&D expenditures and technical progress, an ageing population, expansion of production capacity towards clean energy technologies, dematerialisation and the ambitious climate and energy policies shape the pattern of EU economic growth. The EU economy grows by an average of 1.2% per year over the 2010-2100 period (Figure 25). The key feature of this long-term sustained economic growth is the transition to a more capital-intensive structure. The surplus in the balance of trade is constant throughout the projection period, implying that EU competitiveness is maintained.

Essentially over time there is a shift of value added from industry to services, despite an increase of industrial products regarding RES equipment. There is also an increase in construction activity that is correlated with the installation of RES. Over the 2015-2100 period the industry share is reduced by ~5.5% and services increase by ~4%. This result, where a significant share of the value added comes from services as opposed to industry, is in line with recent megatrends and in particular those of digitalisation and automation. The services sector provides the innovation and blueprints that are the high value-added component of the value chain. This shift in value added has direct implications for the labour skill requirements (although small in magnitude). The implications for the labour market can be separated into two effects:

1. A shift from low-skilled to high-skilled workers: automation and increasing labour productivity tend to decrease the requirements of low-skilled labour.
2. A shift within the skilled labour group: the higher share of services indicates increased demand for clerks/managers and analysts. Although both effects are visible, they are small in magnitude.

From a sectoral perspective the structure of the EU economy becomes more services-oriented and energy-efficient (Table 3). The share of agriculture remains relatively constant over time with a slight increase in the long term (after 2050), indicating the importance of the sector in supplying feedstock for biofuels and biomass. The production of RES and EE equipment increases over time to support the transformation of the energy

Figure 25: Economic growth in the EU-27 (+ the UK)

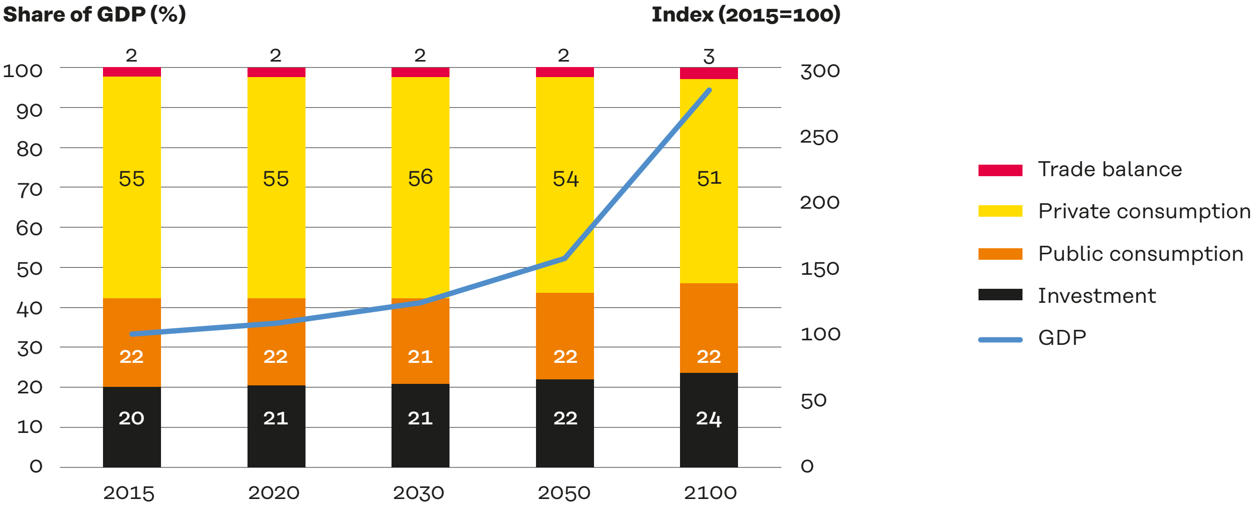

Table 3: Sectoral production in the EU-27 (+ the UK)

Sector (share in %)	**2011**	**2050**	**2100**
Agriculture	1.8	1.7	2.0
Energy	4.7	3.9	4.0
Energy-intensive	11.0	9.9	6.6
Other industries	15.3	11.1	7.7
Transport	5.6	6.6	7.1
Construction	7.4	9.8	12.8
R&D	1.2	1.2	1.2
Services	52.8	53.7	56.7
RES and EE equipment	0.1	2.1	1.9
Total (%)	**100**	**100**	**100**

system. The share of construction, which is a key sector contributing to gross fixed capital formation, increases steadily in the economy following the steady increase of investments.

The ageing of the population and low population growth rates reduce labour supply over time. At the same time, the increase in services and the deployment of RES, which are both labour-intensive sectors, increase labour demand. As a result, the unemployment rate constantly decreases over time, reaching the natural rate of unemployment towards the end of the study period, as shown in Figure 26.

The Finnish economy is projected by the GEM-E3 model to grow at a 1.4% annual growth rate on average over the 2010-2100 period (Figure 27). The growth path is characterised by increasing the production capacity of the economy over time through an accumulation of investments. However, private consumption still dominates the contribution to the GDP while the share of investments increases steadily. The balance of trade is assumed to make a constant contribution to GDP growth as it is virtually balanced over the whole projection period.

Finland continues to be a services-oriented economy with the share of services increasing to almost 50% by 2100. The general pattern of growth of the Finnish economy follows that of the average EU economy. However, there are two distinctive differences from the EU average production mix.

1. The contribution of clean energy technologies to total value added is small throughout the simulation period indicating that other countries (EU and non-EU) are expected to be key suppliers of these technologies. The market for clean energy technologies is dominated by countries that are characterised by capacities to achieve economies of scale, are close to the technological frontier, have low production costs, competitive wages for skilled labour and have accumulated significant R&D spending[35] on these technologies.
2. Increasing the share of investment in GDP over time is directly linked to the increased demand for construction, which has a considerable share in the long term (the second most important sector in terms of value added).

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[35] The GEM-E3 model projects that the key countries/suppliers of clean energy technologies will be: electric cars (USA, Germany, China), batteries (S. Korea, Japan), PV (China), wind (Germany, Denmark, China), biofuels (USA, Brazil).

Figure 26: Unemployment rate in the EU-27 (+ the UK)

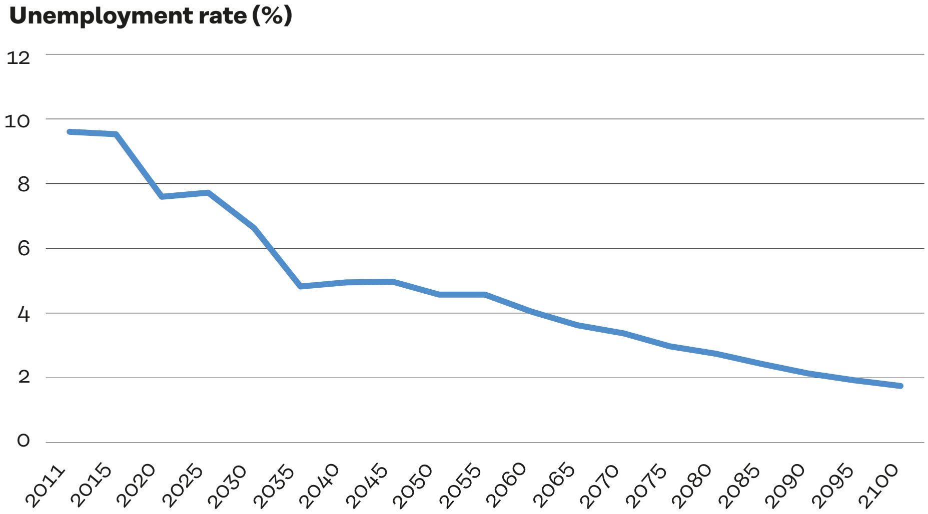


Figure 27: Economic growth in Finland

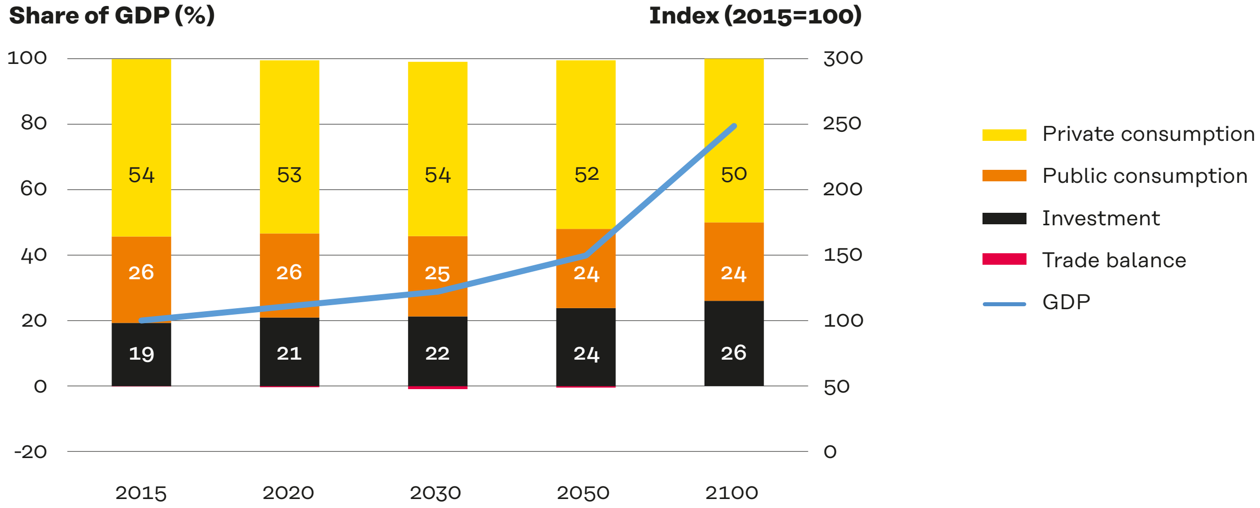


Table 4: Sectoral production in Finland

Sector (share in %)	2011	2050	2100
Agriculture	2.5	2.9	3.0
Energy	5.1	5.7	6.1
Energy-intensive	14.0	14.3	10.1
Other industries	15.6	10.1	8.3
Transport	5.9	6.3	6.4
Construction	8.4	11.9	14.9
R&D	0.8	0.8	0.7
Services	47.6	47.4	49.8
RES and EE equipment	0.1	0.7	0.5
Total	**100**	**100**	**100**

The results presented above do not include the impacts that the adoption of a circular economy would have on energy, emissions and economic activity. Detailed modelling of the circular economy implications of the effort to decarbonise the energy system would require bottom-up representations of numerous production processes. This goes beyond the scope of this study.[36]

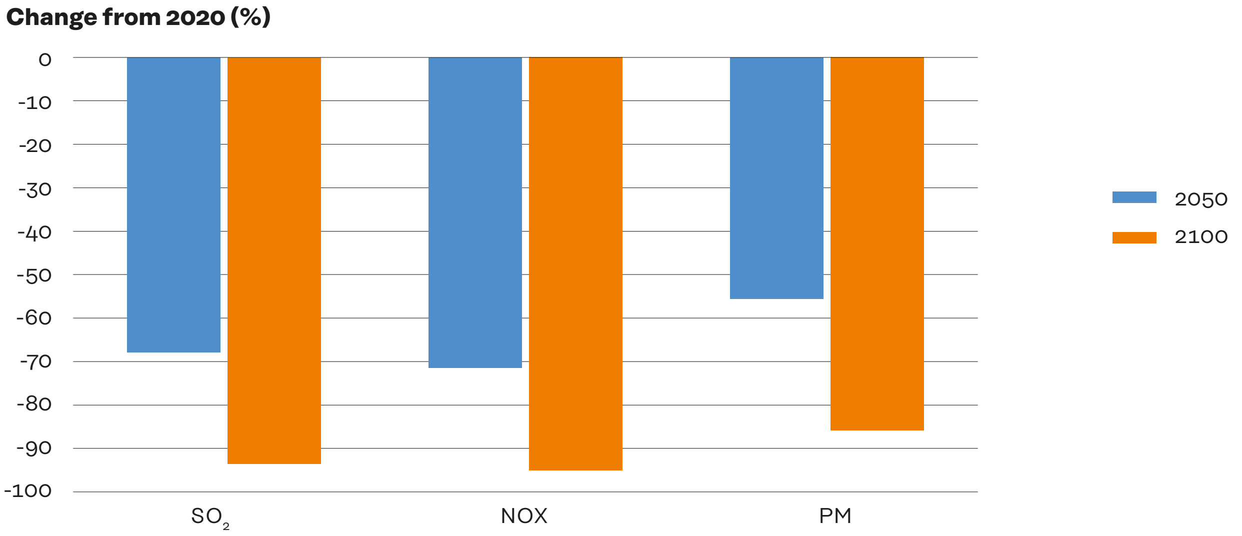
The radical reduction of CO_2 emissions has co-benefits in terms of reducing pollutants. Our analysis only considers ambient air pollution, as our modelling does not capture the relevant dynamics of indoor air pollution, e.g. traditional fireplaces, which however hugely contribute to air pollution-related premature deaths, particularly in developing countries (Landrigan et al., 2018). The study considers several air pollutants, including particulate matter (PM2.5), SO_2 and NO_x, from anthropogenic emission sources.

Recent literature suggests that there are significant co-benefits from climate action related to improved air quality (European Commission, 2017). Our estimations show that the large-scale reduction of GHG emissions achieved in the central scenario is associated with lower emissions and concentrations of air pollutants, in particular fine particles with a diameter of 2.5μm or less (PM2.5), nitrogen dioxide (NO_x) and SO_2. These pollutants have significant adverse effects on human health and can cause respiratory and cardiovascular diseases, among others, and are at the root of premature deaths.

Ambitious energy and climate policies in the central scenario drive a profound energy system transformation as indicated previously, based on reduced energy consumption and a shift towards less polluting fuels and energy forms. The low-carbon transition results in strong reductions of air pollutants; air pollutants are found to decline by about 70% by 2050 relative to 2015 levels. The largest reductions are registered for SO_2 and NO_x, driven by the extensive decline in the use of coal and oil products, resulting in strong benefits for air quality and human health.

Our analysis confirms that strong climate action would have important co-benefits through a large reduction of air pollutants (Figure 28); however, more spatially detailed assessment is required as air pollution highly depends on sub-national, geographical

Figure 28: EU air pollutant emissions in the central scenario over the period 2015-2100



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[36] Please see Annex 2 for further discussion of the circular economy.

specificities, for example as the air quality limits are regularly exceeded in large cities, urban settlements and industrial zones.

8.2 Sensitivity scenarios

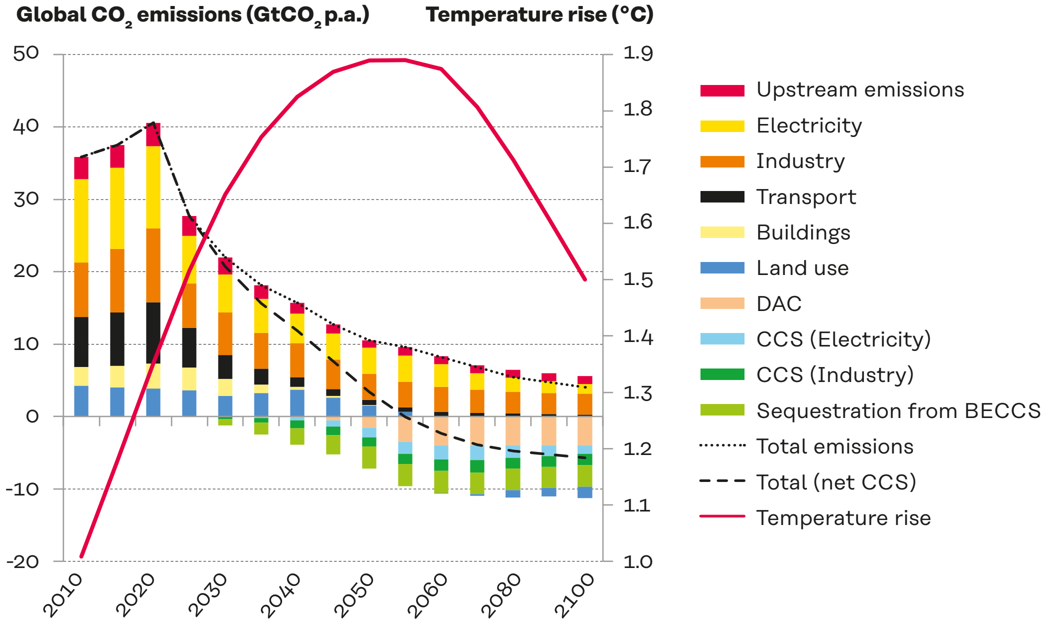
8.2.1 Slow coal phase-out

A rapid phase-out of coal will help decarbonise the energy system. However, there is likely to be a limit to how fast coal can be removed on a global level. The central scenario assumes this will be limited to 5.4% p.a. This first sensitivity run considers a situation where a coal phase-out rate of only half of this (2.7% p.a.) could be achieved. All other assumptions, including the 10 $GtCO_2$ p.a. limit on DAC and BECCS, remain the same. The resulting emissions pathway is shown in Figure 29. A slower reduction in emissions is observed, with gross CO_2 emissions (before CCS) of 10.6 Gt CO_2 p.a. in 2050 (vs 9.1 $GtCO_2$ p.a. for the central scenario). Net-zero emissions are still achieved from 2055 onwards. This slower reduction in emissions does lead to a higher peak temperature of 1.89 °C. However, increased usage of emission capture and storage means that the temperature reverts to 1.5 °C by 2100. The total offset emissions for the 2030-2100 period from CCS, BECCS and DAC is 638 $GtCO_2$, i.e. an increase of 9.4% over the central scenario. These results indicate that a slower coal phase-out rate increases the expected peak temperature and increases emission capture and removal requirements by around 10% in order to reach the long-term 1.5 °C temperature target. Given the uncertainty in the temperature reduction from CO_2 removal, this makes achievement of the 1.5 °C target more uncertain than in the central scenario.

8.2.2 No CCS or NETs

This sensitivity run considers the situation where the unproven technologies of CCS, BECCS and DAC are unavailable and unable to contribute to meeting the Paris targets. For this sensitivity the 420 $GtCO_2$ carbon budget and net-zero CO_2 emission date were removed, so that the mitigation efforts were

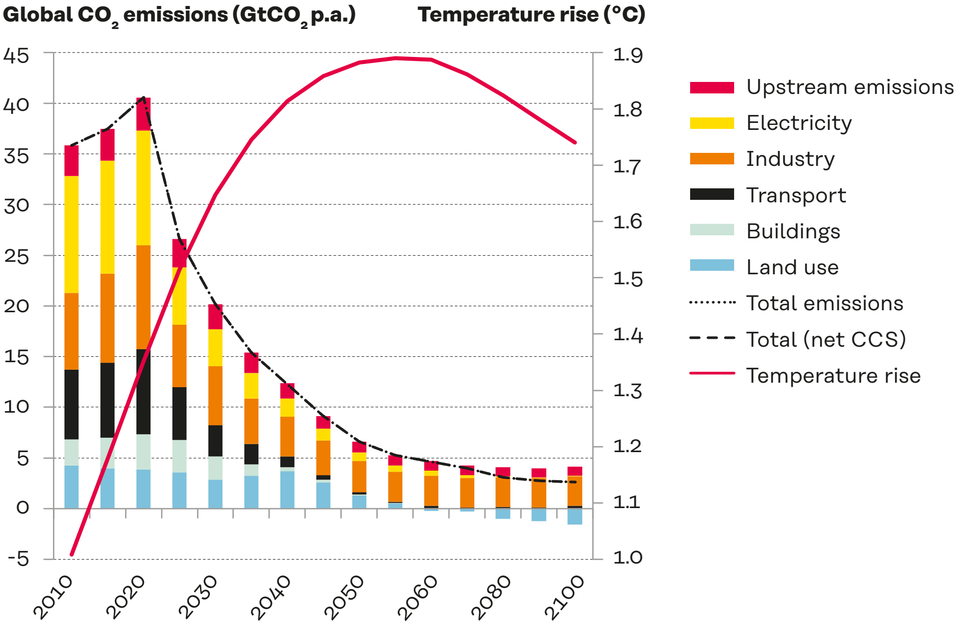
Figure 29: CO_2 emissions trajectory (slow coal phase-out)



driven by the temperature targets. The resulting emissions pathway (using the same coal phase-out limit in the central scenario of 5.4% p.a.) is shown in Figure 30. The results indicate that no net-zero CO_2 emissions date occurs, as there are emissions remaining in some sectors (particularly industry), and no technologies available to offset these, apart from a small amount of negative emissions due to changes in land use, such as more forests. Overall emissions from 2020 to 2100 increase from 420 $GtCO_2$ in the central and slower coal phase-out scenarios to 840 $GtCO_2$. The peak temperature increases to 1.89 °C compared to 1.87 °C in the central scenario. However, the main difference is that, without CCS, BECCS and DAC to offset emissions, the rate of temperature reduction in the latter half of the century due to natural absorption processes is much slower than in the central scenario (Figure 15).[37] This means the 1.5 °C temperature target in 2100 can no longer be reached, with the temperature falling to 1.74 °C instead. However, this is still well below 2 °C, and hence potentially compliant with the Paris goals. This result indicates that, without resorting to CCS or NETs but with a substantial global coal phase-out effort, the 1.5 °C long-term target can no longer be reached, but temperature can still be kept well below 2 °C in 2100.

A variation of this sensitivity was performed where the substantial coal phase-out rate of 5.4% p.a. does not occur, but a slower rate of 2.7% p.a. does instead. The resulting emissions trajectory is shown in Figure 31. The slower coal phase-out increases total emissions in 2050 from 6.6 $GtCO_2$ p.a. to 7.8 $GtCO_2$ p.a. The peak temperature increases to 1.92 °C, and the final temperature in 2100 increases to 1.79 °C. Net emissions from 2020-2100 are 913 $GtCO_2$, i.e. 8.7% more than in the faster coal phase-out case. Hence a slower coal phase-out effort combined with a lack of access to CCS, BECCS and DAC lead to more CO_2 emissions and a higher peak temperature. The

Figure 30: CO_2 emissions trajectory (no CCS or NETs)



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[37] The fact that the temperature falls even with net positive emissions indicates that natural absorption processes (e.g. the oceans) are extracting more carbon from the atmosphere than is being emitted to it.

long-term temperature can remain below 2 °C in 2100, but not get close to 1.5 °C. A summary of the main results is shown in Table 5.

8.3 Socio-economic implications of sensitivity scenarios

Regarding the economic performance in the sensitivity scenarios, the rate of coal phase-out is more important than the option to use negative-emission technologies. Figure 32 presents the impact on Gross World Product (GWP) and employment of the three sensitivity scenarios. Slow coal phase-out has a negative impact on GWP (compared to the central scenario) throughout the simulation period and in particular in the period up to 2050. Non-removal of coal in the early periods of decarbonisation means that other more expensive options have to be used in order to reduce CO_2 emissions, hence the energy system becomes more expensive with direct repercussions on households' disposable income and firms' competitiveness. After 2050 the capital costs of energy technologies decrease, while coal phase-out and the negative impact on the economic activity starts to diminish. The impact on employment largely follows the impact on overall economic growth. In terms of annual growth rates the cumulative impact is negligible. That is, in the central scenario, GWP grows at an average annual rate of 1.761% over the 2020-2050 period, whereas in the worst-performing scenario economically (coal phase-out 2.7%), GWP grows at an annual rate of 1.759% over the same period.

Figure 31: CO_2 emissions trajectory (no CCS or NETs, and slow coal phase-out)

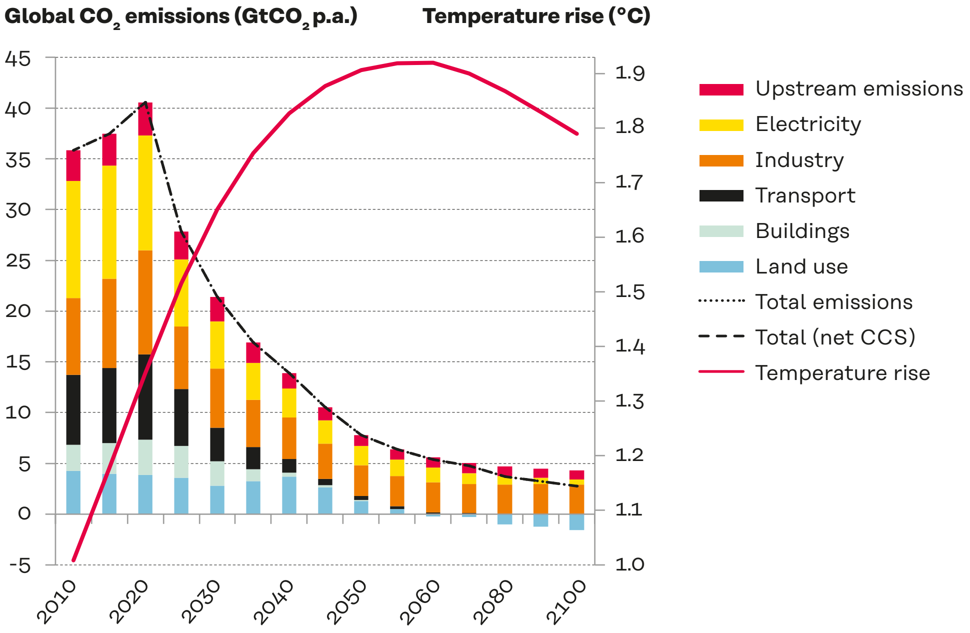


Table 5: Sensitivity results

	Central Scenario	**Slow coal phase-out**	**No CCS or NETs**	
Coal phase-out rate	5.4% p.a.	2.7% p.a.	5.4% p.a.	2.7% p.a.
Net-zero date	2055	2055	-	-
Offset emissions from CCS, BECCS and DAC (2020-2100)	583 $GtCO_2$	638 $GtCO_2$	0 $GtCO_2$	0 $GtCO_2$
Peak temperature	1.87 °C	1.89 °C	1.89 °C	1.92 °C
Final temperature (by 2100)	1.5 °C	1.5 °C	1.74 °C	1.79 °C

Figure 32 a: Impact on Gross World Product of alternative coal phase-out rates

% changes from Central Scenario

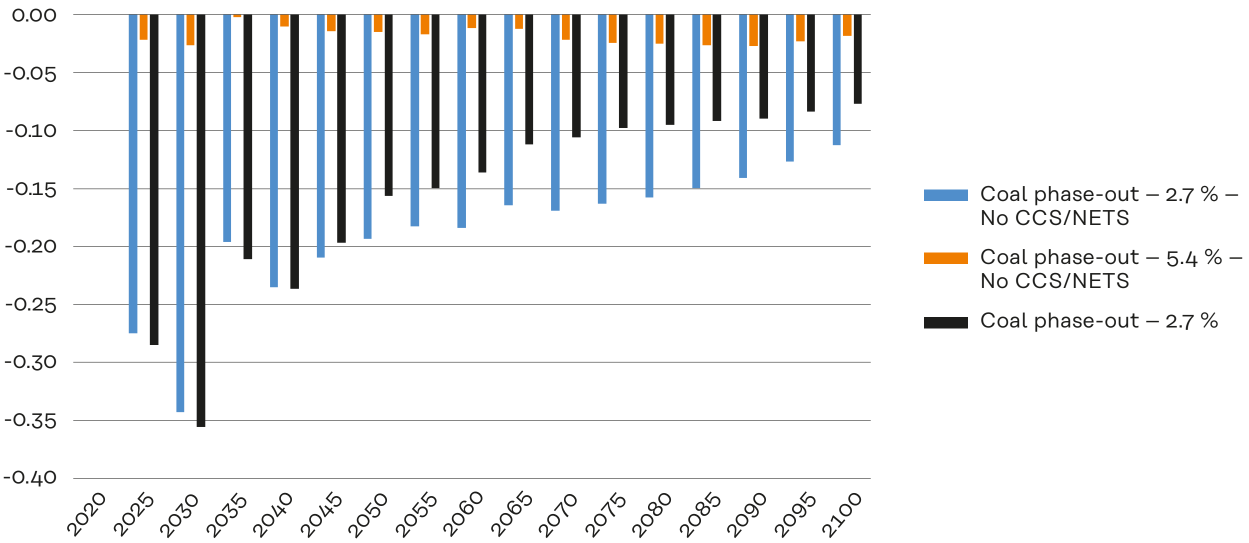
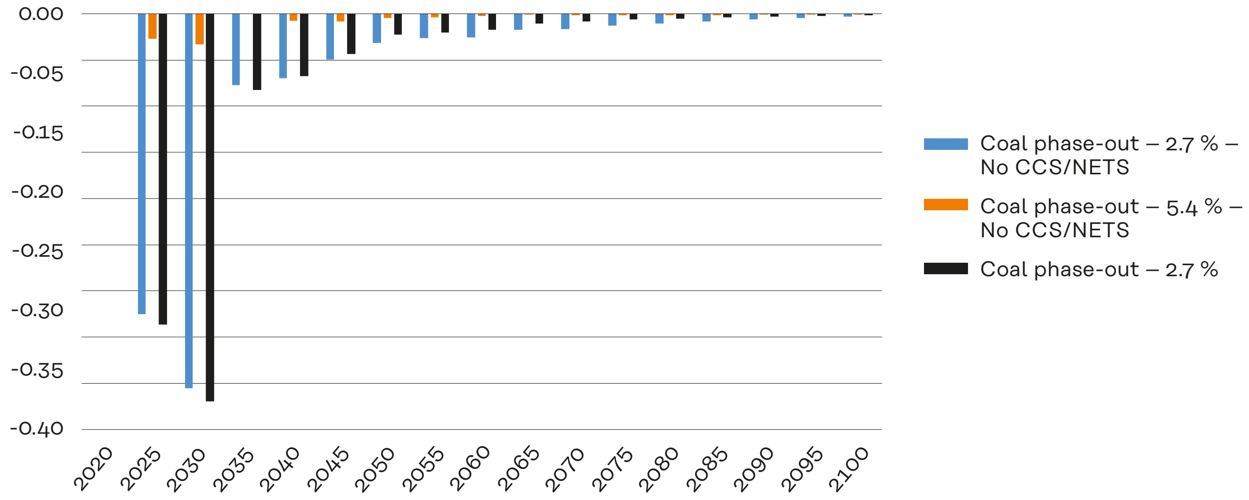


Figure 32 b: Impact on employment of alternative coal phase-out rates

% changes from Central Scenario



9 Discussion and policy implications

The results of this study may be summarised as follows.

The energy system modelling has made it clear that it is technically feasible for the world to reach net-zero CO_2 emissions around the middle of the century and limit the global average temperature increase to 1.5 °C by 2100 (although not without overshooting that temperature between 2050 and 2100). The conditions for this to be achieved include a rapid phase-out of the use of coal (especially in power generation) and the substantial development and use of negative-emissions technologies (NETs). If a rapid coal phase-out is not possible, then the temperature overshoot is slightly greater, even with greater use of NETs. On the other hand, if NETs are not available then the 1.5 °C by 2100 target is not achieved, even with a rapid coal phase-out. If the coal phase-out is slow *and* NETs are not available, both the temperature overshoot and the 2100 temperature are even higher (but both stay below 2 °C) (see Table 5).

The results from the economic model suggest that with the central decarbonisation scenario global economic output (GWP) continues to grow throughout the century (at an average rate of 1.76%). This may be slower than the rate of economic growth in the absence of both decarbonisation and climate change – but climate change is already occurring and generating significant costs. In the absence of decarbonisation these costs may be expected to increase substantially, though uncertainties do not yet permit their robust inclusion in macroeconomic models. Nowhere does the modelling undertaken for this study, or elsewhere, suggest that achieving the targets in the Paris Agreement requires the global economy to *shrink* from current levels (sometimes called "degrowth").

To understand this, it is important to appreciate what drives economic growth. As noted above, the three drivers are population growth, investment and technical progress. Leaving population growth aside, growth in GWP per head is driven by investment and technical progress. With regard to investment, it is apparent from the discussion above that decarbonisation will require huge investment in low-carbon technologies. Some of this will substitute other investment; some of it will substitute consumption. Substituting consumption will not affect economic output.[38] The modelling results above suggest that even with full substitution for other investment (full "crowding out"), economic growth continues. The reason is not hard to appreciate: low-carbon technologies are now broadly competitive with fossil fuels for electricity generation, so the additional investment for the same power output is not large, renewable energy is plentiful and electricity can substitute most other energy sources.

With regard to technical progress, this increases economic output in three ways: new resources are exploited; people learn how to do things better, thereby increasing their productivity; and new goods and services are invented and provided. Recent years have shown that low-carbon technologies have enormous potential in all these areas. Rather than constraining economic growth, it seems increasingly likely that the push for decarbonisation will create a new

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[38] Economic output (GDP) = Consumption + Investment + Government spending + (Exports – Imports).

industrial momentum, with new industries that are cheaper, more efficient and more productive replacing older technologies, as they have done in previous cycles since the Industrial Revolution. The difference this time is that the new technologies are much cleaner environmentally as well.

However, **the realisation of this benign narrative depends on public policy**. Progress in achieving decoupling between economic growth and CO_2 emissions, in countries where decoupling has been evident, has been for the most part the result of active, ambitious policy decisions and actions (as described in Section 3). The most striking example of this is the use of subsidies to drive the rapid growth in renewable energy (particularly solar PV) over the past two decades. This, in turn, has led to the cost of renewables falling precipitously (as learning takes place and through economies of scale), such that solar PV and offshore wind now represent – without subsidies – the cheapest source of new power generation for two thirds of the global population (with new solar PV competitive with the cost of operating existing coal power stations in China) (BNEF, 2020).

To achieve a target of 1.5 °C in 2100, policy and policymakers around the world must take a leading role in directing and accelerating the rapid, deep transformation across the energy system as described in Section 7. The breadth and ambition of this policy must match the enormous scale of the challenge, and be introduced with urgency, if the widespread benefits it would bring are to be secured.

Even though an increasing number of countries are stating their ambition to achieve net-zero emissions by 2050, very few have presented road maps to achieve this target, and those that have been presented have been judged to be largely insufficient (UNEP, 2019; Climate Action Tracker, 2020).

There is no general prescription for what specific policies should be adopted in a specific country or at a specific time. Each country has a different set of natural resources, economic capabilities, societal and institutional structures, and policy and political environment. However, there are a core set of principles that may be followed to guide successful policy development for decoupling, which may apply regardless of specific circumstances.[39]

9.1 Policy strategies

Setting clear, high-level policy objectives, substantiated with specific targets and principal plans to achieve them, can play a fundamental role in aligning the expectations and actions of the multitude of different actors in the energy system and economy towards a common objective. Although the Paris Agreement sets the common global objective of maintaining the increase in global average temperatures to "well below 2 °C … [and to pursue] efforts to limit the increase to 1.5 °C", the "bottom-up" nature of the agreement, in which parties submit their "nationally determined contributions" (NDCs), means it does not institute clear plans for achieving it. Formulating and articulating such plans fall under the remit of governments; most often national, but also supranational (e.g. the EU) and local (regional and city).

9.2 The need for "policy mixes"

Overarching strategies must be implemented using specific policy "instruments". Experience has shown that to be truly effective in encouraging decarbonisation across the economy, different instruments must be

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[39] The following discussion is based substantially on insights provided by Rogge and Reichardt (2016) and Grubb et al. (2014).

combined to create a "policy mix", with each instrument adding complementary characteristics that other instruments do not or cannot provide. Although the specific design and combination of instruments to be effective is highly context-specific, they must be drawn from across the following three "pillars" if they are to influence the decisions and actions of those across the economy that operate on a range of different scales and time frames.

Overview of the policy landscape in the EU

In November 2018, the European Commission published "A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy", setting a target of net-zero EU emissions by 2050, and describing seven strategic "building blocks" for joint action to achieve it. This target was subsequently endorsed by both the European Council and European Parliament, and now sits at the heart of the "European Green Deal", presented by the commission as a new "European growth strategy" to make the EU's economy more sustainable, with an explicit objective of decoupling economic growth from resource use, and a proposal for a new European Climate Law to make the politically agreed target of net-zero emissions by 2050 a legal commitment. It contains a road map of key actions to achieve its goals across a range of policy areas (stretching beyond climate to all areas of environmental sustainability), including those under the direct competence of EU institutions, and those requiring action by member states.

The European Union has committed to reducing its greenhouse gas emissions by 40% compared to 1990 levels up to the year 2030. This target is now being updated. The European Commission presented its plan to reduce net EU greenhouse gas emissions by at least 55% by 2030 (European Commission, 2020a). In order to achieve this goal EU, the climate policy framework, including the EU Emissions Trading Scheme (EU ETS) and the Effort Sharing Regulation (ESR), need to be revised.

All EU member states are required to submit National Long-Term Strategies outlining how they intend to achieve decarbonisation in line with EU objectives. The first strategies, covering the period to at least 2050, were required for submission to the commission by January 2020. As of June 2020 many countries had yet to submit these strategies. The new tighter targets recently adopted by the EU will require an update to many of those that have been submitted.

The EU ETS has operated since 2005 and places a carbon price on EU emissions from the electricity and industrial sectors (responsible for approximately 45% of the bloc's GHG emissions).[40] As a tradable permit system, the carbon price it imposes varies based on permit supply and demand. The price has varied substantially since it was introduced, but it steadily increased from a €5-10/tCO_2 experienced between late 2011 and mid-2017, to stabilise at around €25/tCO_2 throughout 2019. The reduction in demand for electricity and industrial output resulting from the COVID-19 pandemic appeared to begin to reverse this trend, although since mid-April 2020 prices have remained above €25/tCO_2.

The current target for the EU ETS is to achieve a GHG reduction of 43% below 2005 levels by 2030. According to the commission, the role of the EU ETS needs to be strengthened. For example, a study by Sitra found that an EU-wide overall GHG target of 55-60% below 1990 levels by 2030 requires a reduction of the emissions covered by the EU ETS of 61-65% below 2005 levels (Graichen et al., 2019).

For the ESR sectors (agriculture, waste, transport and buildings) the current target is a 30% emissions reduction by 2030 compared to 2005 levels. Member states have national targets under this regulation. The current target for Finland is a 39% reduction by 2030 (European Commission, 2019) . Although the ESR sectors are mainly regulated by national policies, there are also important regulations applied across the EU as a whole, such as vehicle emissions standards. It is expected that these will be strengthened to align them with the increased climate ambition.

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[40] This also includes intra-EU aviation.

9.2.1 Correcting economic incentives

The first pillar requires instruments that make low-carbon, energy-efficient investment and actions economically attractive. The most direct method of achieving this is to internalise the market "externality" that the impacts of CO_2 emissions represent and place a price on CO_2 emissions. Carbon prices are most often introduced through two broad types of instrument; a tax, levied per tonne of CO_2 emitted from a given activity, or a "cap-and-trade" system, in which a cap is placed on the total volume of emissions permissible, with permits then issued for each tonne of CO_2 under the cap. The entities covered by the system must then hold sufficient permits to cover their emissions, with a price created through a market for trading these permits between entities that have different abilities and face different costs to reduce their emissions. Both instruments have been widely used across the world. As of April 2020, around 16% of global GHG emissions were subject to a carbon price, with few of the 58 active carbon-pricing instruments imposing a price of more than €20/tCO_2 (World Bank, 2020).

Carbon pricing has been introduced in various forms across the world, and the evidence suggests it is effective at reducing CO_2 emissions (Best et al., 2020) largely through encouraging increasing efficiency in the use of fossil fuels, and in fuel "switching" from CO_2-intensive to less CO_2-intensive fossil fuels, such as the widespread switch from coal to gas in electricity generation in Europe in the years following the introduction of the EU ETS (Laing et al., 2013).

However, in order to drive the transition to the extent (and at the pace) required, much higher carbon prices will be required, across a much higher proportion of the energy system. This would have the dual effect of incentivising the use of low-carbon energy sources and promoting the more efficient use of energy overall (particularly in the short term, as most energy use is from high-carbon sources). Such "price-induced" efficiency is a core feature of the decarbonisation pathways described above – although altering economic incentives to achieve this is only part of the picture, as discussed in the following sub-sections.

Significant carbon taxes would also raise substantial revenues, which could be used in a variety of ways. An approach often called an "environmental tax reform" (ETR) involves reducing other taxes, particularly those on employment, in order to increase the demand for labour. The revenues could also be used to increase the incentives for the deployment of energy-efficient and low-carbon technologies, or simply go into the general government budget.

A common concern for industry and policymakers in jurisdictions considering introducing stringent carbon pricing is the risk that businesses – particularly those in energy-intensive sectors such as manufacturing – will "offshore" their activities to countries that do not impose stringent carbon pricing, to minimise their cost of doing business, while failing to reduce the volume of global CO_2 emissions. As a result, carbon-pricing instruments often contain mechanisms to prevent such "carbon leakage".

Little evidence suggests that carbon leakage has thus far occurred. Although this may be in part due to such measures, at the relatively low level of carbon taxes applied to businesses so far, it is likely that carbon leakage would have been limited in their absence due to a multitude of other considerations for businesses, such as labour productivity, the exchange rate and political risks, and infrastructure quality and transport costs (Naegele and Zaklan, 2019). Such mechanisms often therefore remove the economic incentive to minimise CO_2 emissions, to no real benefit.

However, with a rapidly rising carbon price – particularly if applied unevenly across the world – the risk of carbon leakage is likely to grow. Alternative mechanisms may be employed to help guard against this risk, but

"Although providing the appropriate economic incentives is key to achieving deep decarbonisation, it is not sufficient."

which maintain the incentive for energy-intensive industries to reduce their emissions. One key example is "revenue recycling", where the revenue raised from carbon pricing is used to reduce the cost of (or subsidise) positive activities, such as with an ETR, described above. Another key example is a Border Carbon Adjustment (BCA), which aims to effectively remove the incentive to relocate production. BCAs are discussed further in the Technical Supplement.

On the opposite side of the coin to carbon pricing is the provision of subsidies for the production and consumption of fossil fuels, which totalled US$478 billion in 2019 (OECD, 2020). These subsidies are often introduced to moderate energy costs for low-income consumers. However, as energy consumption tends to increase with income, most of the subsidy accrues to the wealthiest in society (Arze del Granado et al., 2010). At the same time, they incentivise the further consumption of fossil fuels.

Although various commitments to reduce and remove subsidies for fossil fuels have been announced in recent years, particularly in high-income countries, there has been little progress. However, the advent of record-low energy prices following the reduction in energy demand resulting from actions to tackle the COVID-19 pandemic presents a historic opportunity. Removing subsidy mechanisms when market prices are so low (and are likely to remain so for the foreseeable future) minimises the practical impact and political consequences and allows resources to be channelled to encourage more positive activates (e.g. strategic investment for low-carbon development, as discussed below).

9.2.2 Regulatory standards and engagement

Although providing the appropriate economic incentives is key to achieving deep decarbonisation, it is not sufficient. It has long been recognised that a large energy-efficiency "gap" exists – there appears to be a much greater level of energy consumption (and associated CO_2 emissions) than the level that would appear to be economically rational, given existing energy prices and related economic incentives. Various reasons exist for this, but the principal explanation is the fact that people and organisations usually do not compute and weigh the full balance of cost and benefits of each and every decision taken to produce an "optimal" outcome. As such, simply increasing energy (or carbon) prices would not achieve the increase in energy efficiency that deep decarbonisation scenarios, including those presented in Section 7, suggest is required. The second pillar of policy requires the use of regulatory standards and instruments to inform, educate and engage businesses and citizens, and to encourage action where economic incentives cannot or do not sufficiently deliver.

Regulatory standards, such as bans on or requirements for certain products, activities or levels of performance, are widely used around the world. Key examples include maximum CO_2 and air pollution regulations for vehicles, minimum energy performance standards for energy-using products and building regulations that set minimum requirements on energy efficiency and the provision of renewable energy. Such instruments have been highly effective at achieving their objectives where economic instruments are difficult to implement or fail to deliver their objectives alone. The examples above, which are largely performance standards that increase in stringency over time, have been supplemented by plans for outright bans; particularly on generating electricity from coal, including in the UK from the mid-2020s and Finland from 2029, and on the sale of new fossil-fuelled cars, such as in Norway from 2025, and several other countries and jurisdictions from 2030 onwards.

Such instruments may also address situations in which economic incentives are misaligned. For example, building tenants are commonly liable to pay energy bills, and thus are incentivised to invest to improve the energy efficiency of the building. However, it is often only the landlord, who does not pay the energy bills and therefore is not incentivised to invest in reducing them, that is empowered to do so. This is a substantial problem in countries with a large domestic rental sector, and which regulations – such as requiring minimum energy standards for rented buildings – may address.

In some cases, opportunities to reduce energy consumption and associated costs are forgone due to a simple lack of awareness about these opportunities and how to seize them. Instruments such as labelling for energy-efficient products, energy audits for organisations and public information campaigns can help overcome this and encourage organisations and citizens to take advantage of cost-effective opportunities for energy efficiency, reducing energy consumption and associated CO_2 emissions, as well as unproductive expenditure on energy, freeing resources that may be spent elsewhere and contributing positively to economic growth.

9.2.3 Strategic investment

Although the prospect of securing a market advantage provides a substantial incentive for organisations to innovate to develop, introduce and adopt new products and services, often the innovation that results is incremental, with investment in more fundamental innovation entailing high levels of risk. Developing more radical innovation often requires the involvement of the public sector, which is often able to provide greater resources and is willing to tolerate higher levels of risk. Although many of the technologies required to deliver the transition to a net-zero energy system are known (with many, such as several renewable energy technologies, developed through public financing), some remain uncertain or unproven – such as CCS, BECCS and DAC. Other as-yet-unknown technologies may also be developed through publicly funded research, allowing some elements of the system to be decarbonised more quickly or at lower cost, or with greater benefit.

Various international initiatives exist to focus public finance on research and development (R&D) for low-carbon technologies, such as the Mission Innovation initiative (a coalition of 24 countries plus the European Commission launched in 2015 that aims to accelerate clean energy innovation, in part through a doubling of public R&D funding (Mission Innovation, 2020)), and the EU’s "Horizon Europe" research and innovation programme starting in 2021, which will devote at least 35% of its €100 billion budget to addressing climate-related objectives (European Commission, 2020b).

Beyond R&D, public investment is also often crucial in allowing new technologies to come to market and achieve widespread adoption. This may be through directly subsidising technologies that are not yet cost-effective compared with the incumbent, such as immature renewable technologies or low-carbon vehicles (until such technologies develop and achieve sufficient scale that they become competitive or even cheaper than the incumbent), or through investing in enabling infrastructure, such as an electric vehicle charging network or in redesigning the urban form to facilitate the greater use of public transport, walking and cycling.

The scale of the public investment required around the world to stimulate economies following the economic consequences of the COVID-19 pandemic allows an unprecedented opportunity to accelerate the low-carbon transition and take advantage of the economic opportunities it offers.

"The four most important characteristics of the policy mix are consistency, coherence, credibility and comprehensiveness."

In their Sustainable Recovery Plan, the International Energy Agency (IEA) estimates that if channelled towards low-carbon technologies, industries and infrastructures, a global stimulus investment of US$1 trillion per year between 2021 and 2023 (about 0.7% of GDP[41]) would reduce emissions from the global energy system by over 10%, boost economic growth by an average of 1.1 percentage points per year and save or create 9 million jobs per year, by the end of the plan (alongside a range of other benefits, such as a 5% reduction in local air pollutant emissions, extending clean cooking technologies to 420 million people and enabling electricity access to a 270 million people) (IEA, 2020).

9.2.4 Policy mix characteristics

Regardless of the overarching objective and ambition of policy objectives, targets and strategies, and the specific combination of the policy instruments employed to achieve them, policy mixes must exhibit four interrelated characteristics if they are to be effective.

The first characteristic is **consistency** between policy strategies and policy instruments. At the least, they must be free of contradictions or conflicts that could prevent the achievement of the desired outcome. Ideally, however, they should be complementary and mutually reinforcing, such that the whole becomes greater than the sum of its parts. This applies both within and between levels of governance (e.g. EU and member state-level policy), and within and between different policy domains (e.g. transport and buildings). Consistency is made substantially more likely if the second characteristic – **coherence** – is evident. This refers particularly to coherence in the processes of developing, implementing and monitoring policy strategies and instruments, which can be achieved in part through policy co-ordination and integration across government departments (again, both within and between levels of governance, to avoid "siloisation" of policymaking). The third characteristic is **credibility**, the extent to which the policy mix is sufficiently reliable to base long-term investment and decision-making upon. This is influenced by a range of factors in addition to consistency and coherence, including political commitment, the strength of the rule of law, the delegation of responsibilities to independent agencies and a rule-based approach to determine when, if and how key elements of policy instruments or policy mixes may be amended. The fourth and final characteristic is **comprehensiveness**, capturing the extent to which the policy mix addresses all barriers that would otherwise prevent the policy objectives being achieved, including the appropriate use of policy instruments from all three pillars of policy, and whether the policy mix sufficiently considers secondary effects, such as the risk of carbon leakage.

However, these characteristics are extremely difficult to achieve, particularly when the policy strategy and associated policy mix must drive deep systemic change across all sectors of the economy and society. In the same way that there is no prescription for the specific policy that should be adopted, there is no single approach for making sure the policy mix exhibits these characteristics. Working towards achieving them will be to a substantial degree a process

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[41] Driven by public investment but including the private finance it would mobilise.

" Governments must make sure that their policymaking processes are open to learning from the successes and failures, and to making the changes that are required."

of learning from successes and failures, both in the country or region itself, or from others. Governments must make sure that their policymaking processes are open to learning these lessons, and to making the changes that are required. In many cases this will require substantial institutional capacity that, in low-income countries in particular, may not currently exist. Global co-operation, through funding and platforms for technical assistance and capacity building, would be one approach to addressing this problem.

9.2.5 Global co-operation

The scenarios presented in Section 7 are based on the narrative elements of SSP1, which at its heart assumes effective global co-operation to achieve decarbonisation. The Paris Agreement lays the foundations for such co-operation, although key elements of the architecture to facilitate it have yet to be agreed; specifically, those around Article 6 of the agreement on carbon markets and other forms of international co-operation.

Article 6 contains three potential mechanisms for advancing global co-operation; two related to different options for emissions trading, and one for "non-market"-based approaches to international co-operation (i.e. where no trade is involved). Supporters of these mechanisms argue that they will allow for greater ambition and a more rapid, cost-effective transition, however there is wide-ranging disagreement about how these mechanisms would work in practice. These issues are discussed further in the Technical Supplement.

10 Conclusions and policy recommendations

This study has explored the broad conditions for achieving net-zero CO_2 emissions by 2050 and limiting global average temperature increases from global warming to 1.5 °C by 2100, and whether this can be combined with economic growth. The conclusions from the modelling suggest that this is technically feasible, although it is now very unlikely that average global temperatures can be prevented from rising above 1.5 °C between 2050 and 2100. However, they may be kept below 2 °C during that period.

However, for the net-zero and 1.5 °C targets to be achieved, a number of non-trivial developments must all occur: greatly increased energy efficiency; enormous investment in renewable energy technologies, mostly from the private sector; rapid phase-out of the use of coal in power generation; and substantial deployment of effective carbon capture, storage and removal technologies. Conclusions about these topics will be briefly discussed in turn.

Increased energy efficiency

Reducing the energy demand by increasing the efficiency of energy use comes through as a major means of making the targets less difficult to achieve, as they reduce the quantity of low-carbon energy that needs to be supplied. Where energy-efficiency measures are lower cost than energy supply, they will also reduce the overall cost of reaching the targets. Major efficiency gains are available by replacing vehicles with internal combustion engines with electric vehicles, through district heating (where appropriate) and through the installation of heat pumps. In many countries building fabrics can be made more energy-efficient, and there are many opportunities in industry.

Increased renewable electricity

Substituting renewable electricity for fossil-fuel generation (especially coal) and for liquid fossil fuels in transport (through electric vehicles), for fossil-fuel-fired home heating (through heat pumps) and for many industrial processes **requires an enormous expansion in renewables technologies, which in turn needs huge investment**. Much of this investment will need to come from the private sector. There is no shortage of money for this investment, but the renewables projects will need to satisfy the usual risk/return criteria for the private sector in order for the investment to be made.

Coal phase-out

Coal must be removed from power generation as soon as possible (even if initially it is replaced by gas rather than renewables), and replacements developed to reduce its use in the rest of the energy system as well. The modelling above shows that this greatly reduces the reliance on NETs in achieving the targets. The key test of China's very recent (and most welcome) commitment to net-zero emissions by 2060 will be how fast it closes existing coal-fired power stations and whether it cancels many of the coal-fired power stations that are still projected to be built there.

NETs must be developed and deployed at scale

At present this is probably the most challenging recommendation. Governments have so far been resistant to providing the large necessary investments to prove the technology at the scale required, and the private sector cannot justify carbon capture and storage (CCS) at current carbon prices either. Land-use considerations place serious limits on the possible use of BECCS, and DAC technologies are at a very early stage of development and expensive. A way through these barriers still needs to be found if these technologies are to deliver the emissions reductions projected by the models.

Other considerations

While these are the four main conclusions from the modelling, there are a number of other issues that are both important and uncertain as far as getting to net zero is concerned. These include the following.

1. The need for innovation and deployment at scale for low-carbon industrial processes to replace current high-carbon practices (e.g. in steel and cement manufacture), and for some high-carbon products (e.g. cement and plastics) to be replaced by low-carbon substitutes.
2. The need for global afforestation and massive carbon capture in soils, as opposed to continuing carbon release through deforestation in the Amazon and elsewhere, the release of methane through the melting of permafrost and agricultural practices that deplete soil carbon.
3. Clarification of the role of hydrogen. There are currently functioning real-life examples of the use of hydrogen fuel cells or combustion in ships, trains, buses, lorries, cars and homes, and under development for aircraft. Most of the hydrogen produced for these uses comes from natural gas and (without CCS) is not low-carbon. But with enough renewable electricity, zero-carbon hydrogen could be produced at scale, although the costs of electrolysers would have to come down considerably for this to be attractive economically.
4. The shift to a circular economy. Substantial quantities of energy are used to extract and process raw materials. In many instances, much less energy is used to repurpose those materials back into the economy at the end of products' lives. Seeking to achieve this raises complex questions of incentives, responsibility and logistics. But these will need to be addressed by policy if the current trend of soaring primary material extraction, and its associated energy use, is to be changed.

The importance of public policy

None of this will come about without strong, consistent, coherent, credible and comprehensive public policy, applied over decades. Countries will apply these policies in different ways to suit their different contexts, but, to be effective, it is likely that their "policy mixes" will need to include rising carbon prices, regulations on building energy efficiency and internal combustion engines, rapid phase-out of coal use, policies to move towards a circular economy, and innovation policy to take new technologies rapidly from demonstration through large-scale deployment, as has happened with solar PV and offshore wind, and is now happening with batteries. At the same time, policy will need to encourage low-carbon behaviours in areas such as diet and tourism, and to ensure that electricity grids are able to absorb and operate securely with almost 100% (intermittent) renewable power. There are working examples of most of these policies in different countries. But no country has yet put them together into a convincing strategy for 2050 and 2100.

The economic implications

A major motivation of this study was to unpack and explain the processes at work in "decoupling" economic growth from carbon emissions and energy and material use. As has been seen, **the modelling in both this project and the many studies reviewed by the IPCC provide no basis at all for thinking that decarbonisation will require "degrowth" (i.e. the economy getting smaller from today's level), in either rich or emerging and developing economies.** This is not surprising when the underlying drivers of economic growth are understood.

As explained above, economic growth results from processes of investment and technical progress. These include discovery of new resources, turning non-resources into resources (e.g. sunlight and wind into electricity), making products, processes and organisations more efficient, and the development of new products and services. All these factors are manifestly present in decarbonisation.

In the process of decarbonisation, two other factors might serve to reduce economic growth: 1) if the cost of low-carbon energy sources was significantly higher than that of the fossil fuels they are replacing; and 2) if the process of decarbonisation resulted in large parts of the capital stock suddenly becoming obsolete before it had recovered the investment in it and before new investment could replace it. In respect of low-carbon energy sources, in the past they were substantially more expensive than fossil fuels, and that may have been the reason why early studies of decarbonisation showed significant reductions in economic output (GDP) from baseline projections (although none showed degrowth or negative growth from then-current levels). But low-carbon energy sources are demonstrably not generally more expensive now. In many parts of the world renewable electricity is now the cheapest source available. So there is no likely reduction in growth levels from that source.

With regard to the existing capital stock, the great majority of this will need to be refreshed or replaced anyway over the 30 years to 2050. The key priority here is that this replacement is carried out in a way that is both consistent with and promotes net-zero emissions in 2050. Decarbonisation will be very expensive if investment now goes into high-carbon assets that have to be prematurely scrapped. But this is a circumstance resulting from a failure of governance or foresight that is entirely avoidable.

In conclusion, the evidence of this study, and of the IPCC work we have consulted, suggests that net-zero emissions in 2050 and a maximum 1.5 °C average global temperature increase in 2100 are technologically feasible, although probably not without some temperature overshoot in the period 2050-2100. Moreover, it is highly uncertain whether such decarbonisation would even lead to a reduction in the economic growth rates that would otherwise occur. It is highly likely that any such reduction would be small – 1% of GDP was the estimate of the UK's Committee on Climate Change when it recommended the net-zero target to the UK Government. This would be a tiny insurance premium to avoid the worst effects of climate change. However, it will only come about with a "4C" (consistent, coherent, credible and comprehensive) government policy. The absence of such a policy now will make decarbonisation more expensive and put the achievement of the targets in doubt.

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ANNEX 1

The energy system and macroeconomic models: PRIMES, TIAM-UCL, GEM-E3

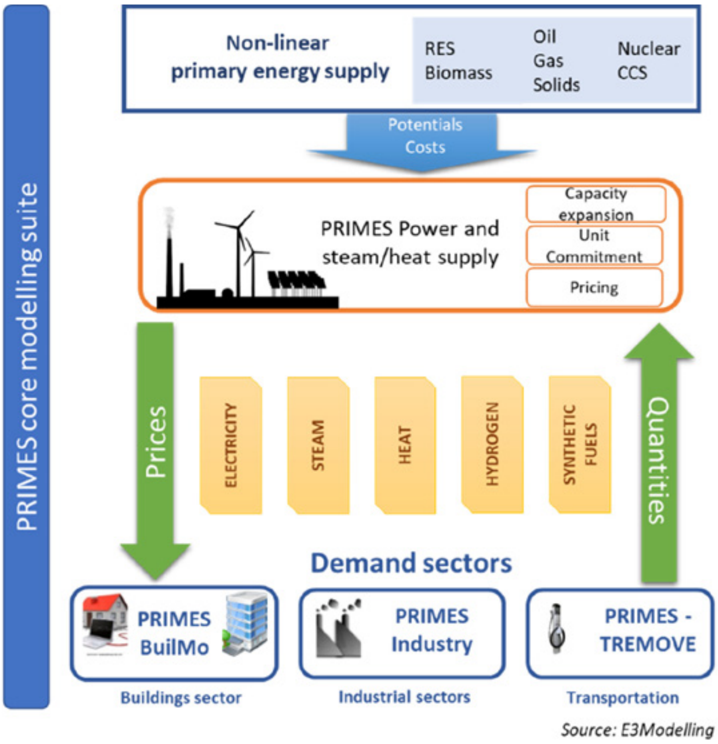
Two energy system models and a macroeconomic model have been used for this project to assess the feasibility and sensitivity of limiting global warming to 1.5 degrees with positive GDP growth. The PRIMES energy system model will deal with the national (Finland) and EU level, while the TIAM-UCL energy system model is a global model. The GEM-E3-FIT macroeconomic model is used to assess the economic impacts.

PRIMES energy system model

The PRIMES (Price-Induced Market Equilibrium System) is a large-scale applied energy system model that provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions (see Figure 33). The distinctive feature of PRIMES is the combination of behavioural modelling (following a microeconomic foundation) with engineering aspects, covering all energy sectors and markets. The model has a detailed representation of instruments of policy impact assessment related to energy markets and climate, including market drivers, standards and targets by sector or overall. It handles multiple policy objectives, such as GHG emissions reductions, energy efficiency and renewable energy targets, and provides pan-European simulation of internal markets for electricity and gas.

PRIMES offers the ability to handle market distortions, barriers to rational decisions, behaviours and market co-ordination issues and it has full accounting of capital and operating costs (CAPEX and OPEX) and investment on infrastructure needs. The model covers the horizon up to 2070 in five-year interval periods and includes all member states of the EU-28 individually as well as 10 other European countries.
PRIMES is designed to analyse complex interactions within the energy system in a multiple agent-multiple markets framework. Decisions by agents are formulated based on microeconomic foundations (utility maximisation, cost minimisation and market equilibrium), embedding engineering constraints and explicit representation of technologies and their age; optionally perfect or imperfect foresight for the modelling of investment in all sectors. PRIMES is well placed to simulate long-term transformations for long-term (rather than short-term) transitions and includes non-linear formulation of potentials by type (resources, sites, acceptability, etc.) and technology learning.

Figure 33: Diagram of the PRIMES model[42]



TIAM-UCL energy system model

This study uses a global energy systems model, TIAM-UCL, to describe the development of the global energy system and the related emissions. The representation in the model covers the full energy system from primary resources (oil, gas, coal, nuclear, biomass and various renewables) through their conversion (e.g. electricity production), transport and distribution, and eventual use to meet energy demands across a range of economic sectors (various demands, e.g. in the transport, residential and industrial sectors). The model keeps track of emissions throughout the system, allocating them to the processes that are responsible for them (e.g. combustion in power plants, internal combustion engines in cars) and also includes a rudimentary representation of the emissions emerging from non-energy sectors. Technology choice in the model is driven by least-cost optimisation across the full time horizon of the model (until 2100) and future energy demands, which are price elastic, are projected based on a number of projected drivers (e.g. GDP, population, number of households) (Figure 34).

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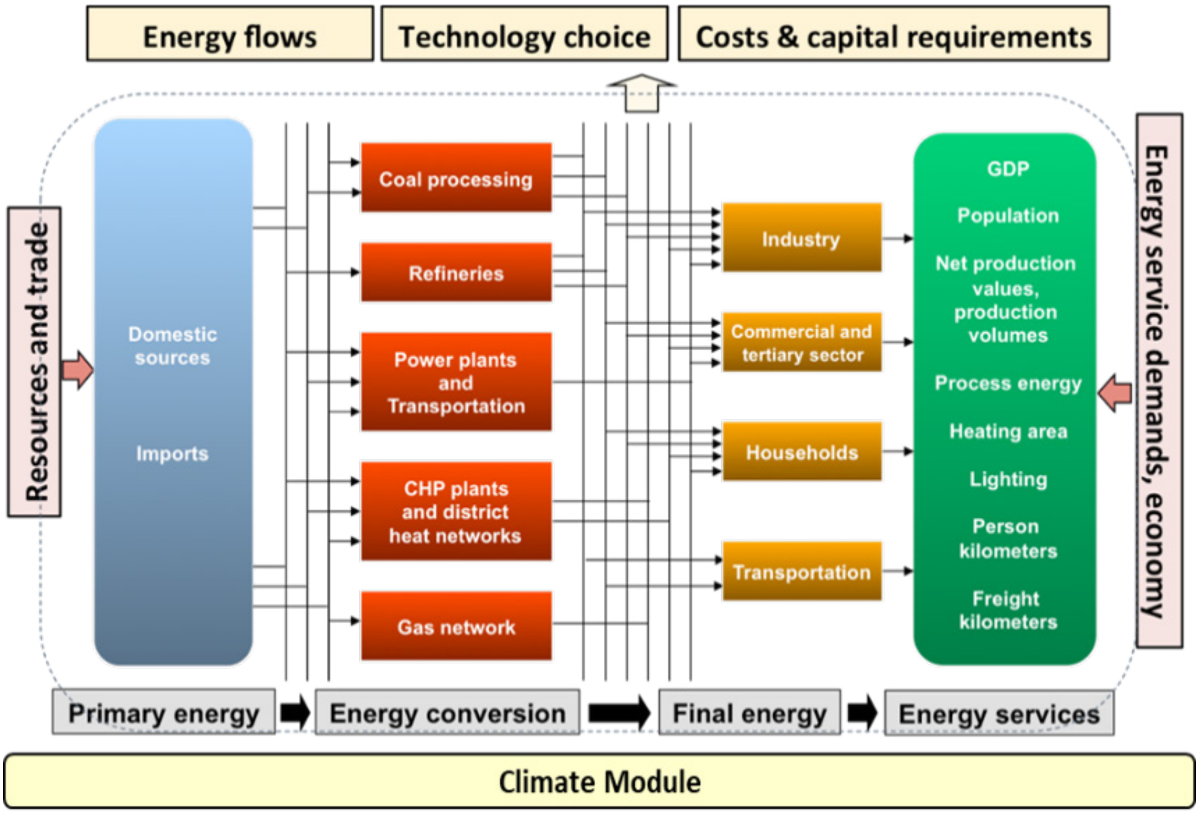
[42] Further information about the PRIMES model can be found here: https://e3modelling.com/modelling-tools/primes/.

Figure 34: The TIAM-UCL global energy system model[43]



Macroeconomic modelling and analysis: GEM-E3-FIT

To analyse the macroeconomic impacts in a quantitative manner, a computable general equilibrium (CGE) model will be used: GEM-E3-FIT will undertake the analyses of the macroeconomic impacts at a global, regional (EU) and national level. The macroeconomic model models the same scenarios as the energy system models.

GEM-E3-FIT, the main components of which are shown in Figure 35, is an advanced and detailed CGE model that enhances the standard version of GEM-E3 in the following aspects:

- it represents the financial sector explicitly
- it represents policy-induced technical change and innovation-induced growth by two-factor learning curves (learning by doing and learning by research) associated with knowledge spill-over matrices based on patent citations data
- it represents household decisions on education that affect human capital, and links human capital with the creation of knowledge and the ability to absorb knowledge spill-overs
- it has an explicit representation of infrastructure

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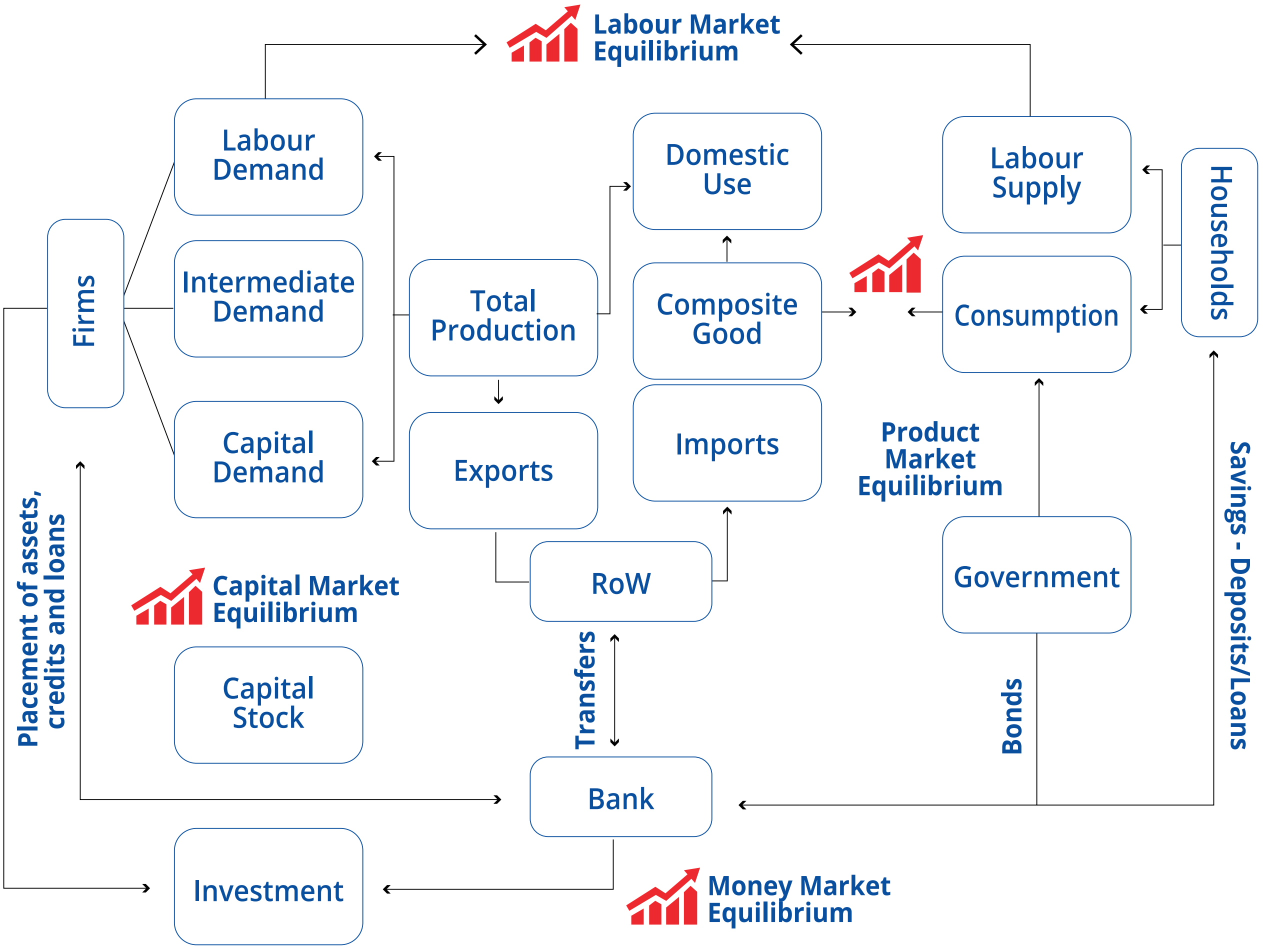
[43] More information about the model can be found here: www.iamcdocumentation.eu/index.php/Model_Documentation_-_TIAM-UCL.

- it provides built-in options for Monte Carlo simulations to perform sensitivity analysis
- it includes a detailed representation of transport (freight and passenger by mode)
- it includes a discrete representation of sectors producing clean energy technologies (wind, PV, CCS, electric vehicles, biofuels, batteries, insulating materials)
- it has a high degree of sectoral (economy is disaggregated into 53 productive sectors) and regional resolution (46 countries/regions are represented), and it has a new calibration of energy volumes that combine in a consistent way data from energy balances and input-output tables
- it has detailed data on energy subsidies globally based on an IEA dataset
- it accounts for the number of firms by economic activity and calculates the profitability rates of each activity.

Figure 35: Diagram of GEM-E3-FIT (Capros et al., 2017)[44]



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[44] Available at: https://e3modelling.com/modelling-tools/gem-e3/.

ANNEX 2

The circular economy – what is it and how could it help with decoupling?

Text provided by Sitra

Our present economy is based on overusing the natural resources of our planet. This not only destroys habitats around the world but accelerates climate change as well. At present, less than 10% of the materials produced are recycled back to use. In our everyday life we are surrounded by various mixed hybrid and composite materials that contain bio-based materials, different kinds of metals and plastics. In addition, many of these materials are still produced in an ecologically unsustainable way. Current industrial production uses non-renewable natural resources without making the necessary decisions at the beginning of their life cycle on how to retrieve these materials and return them to the production loop after their initial use, and as a result they end up losing their value. In addition, the manufacturing phase of many products mainly involves the use of energy from fossil fuel sources, such as oil and coal.

The EU Commission’s new Circular Economy Action Plan, which, as an integral part of the European Green Deal, aims to support substantial greenhouse gas emissions reductions by 2030, contributes to achieving climate neutrality in 2050 and decoupling economic growth from resource use. Optimising the circular use of resources throughout the economy is key for minimising the environmental impacts of the EU economy.

The challenge in the transition towards a circular economy faced by the world’s economies is to find ways to integrate the paths of environmental sustainability and economic growth with the profitability of companies.

In the transition towards a circular economy there is need for new solutions in every phase of the life cycle. Improved industrial processes, product design, recyclability of materials and new business models are important elements of a circular economy. Eco-design and a life-cycle approach provide the keys to success.

There are various definitions for the term "circular economy". In this report, the circular economy refers to an economic model that does not focus on producing more and more goods, but instead promotes consumption based on using services – sharing, renting, and recycling – instead of owning. Materials are ultimately not destroyed but are used to make new products over and over again (Finnish Innovation Fund Sitra, 2020).

The OECD (2019a) identifies five business models that can support a transition towards a more circular and resource-efficient economy:

1. Circular supply models that replace primary materials inputs with bio-based, renewable or recovered materials.
2. Resource recovery models that focus on producing secondary materials from waste streams.
3. Product life extension models that aim at increasing the lifespan of a product by enhancing its durability.
4. Sharing models that share underused consumer goods and assets (e.g. housing or vehicles) through co-ownership or co-access mechanisms.

5. Product service systems (PSS) that focus on selling a service rather than the product itself.

The circular economy business models can reduce not only material extraction rates but also the negative environmental externalities associated with extraction and processing, including GHG emissions and biodiversity losses. Around 50% of all industrial CO_2 emissions come from the production and processing of five materials, namely steel, cement, paper, plastic, and aluminium – most of which have secondary equivalents that are much less energy-intensive to produce (McCarthy et al., 2018). The Finnish Innovation Fund Sitra estimates that a more circular economy can cut emissions from heavy industry by 296 million tonnes of CO_2 per year by 2050, out of 530 Mt in total (Material Economics, 2018). Recycling materials could also contribute to energy savings. For example, producing aluminium from scrap results in a 90 to 95% reduction in energy use (Gardner, 2017). Additionally, the extraction and processing of materials, fuels and food make up more than 90% of biodiversity loss and water stress globally (IRP, 2019).

Circular economy models can also reduce countries' exposure to resource supply risks and foster remanufacturing, employment and GDP growth by saving costs and developing new economic activities. In other words, a transition to a circular economy could make the decoupling of GHG emissions from GDP growth easier, but also enable required material use decoupling from GDP.

Circular economy skills and knowledge are needed in different areas in both the public and private sectors – in chemistry, legislation, business activities, behavioural sciences, construction and food production. Education will play a key role in the transition from the linear economy to a circular economy. New circular business models require new skills as well. There are already industry-specific skills gaps. To overcome these challenges, a just transition mechanism is needed to up- and reskill workers and support research and innovation to promote circular economy solutions and business.

Modelling of all the five circular economy business models would require a detailed representation of the raw materials, value chains and production process of products. This is not possible in the scope of the modelling methods used in this study. See Section 8 for more details.

ANNEX 3

Overview of the policy landscape in Finland

Text provided by Sitra

In 2019, the new Government Programme announced that Finland will become climate-neutral by 2035 – a substantial increase in ambition from the previous target of an 80% emission reduction from 1990 levels by 2050. This target was set by the 2015 Climate Change Act, which also requires a medium-term climate change policy plan to outline an action programme towards achieving the goals of the act to be published for each new electoral term. A new energy and climate strategy is being prepared as well as a new medium-term climate change policy plan, expected to be published in 2021. It will include actions required until 2030 to place Finland on track for the revised target for 2035. The Climate Change Act will also be revised to enshrine this target into law (Ministry of the Environment, 2020).

Finland was the first country in the world to introduce a carbon tax in 1990, which now covers 36% of all Finland's GHG emissions across the transport, building and industry sectors, with a price of US$58-68/$tCO_2$, depending on the fuel. Finland is also part of the European Union Emissions Trading System (EU ETS) and the system covers approximately 45% of Finnish GHG emissions. The largest untaxed source of GHG emissions in Finland is biomass.

While the carbon tax is in principle the same for all energy forms, the Finnish national carbon-pricing system has included discounts and exemptions to guard against the risk of "carbon leakage" similar to many other countries. For example, the Finnish carbon tax does not apply to fuel use for combined heat and power (CHP) units and coal and natural gas used as a raw material, while free allowances are given to many industries under the EU ETS. Such discounts and exemptions effectively reduce the influence of the carbon price. In addition, carbon prices are often counteracted by (tax) subsidies for fossil-fuel consumption. In Finland such subsidies are represented primarily by discounts on the standard energy tax provided for various fuels used in energy-intensive industries and agriculture, and on diesel used in transport, light fuel oil used in mobile machinery and peat used for heating (OECD, 2019c).

Finland is planning a new environmental tax reform (ETR) as part of the policies to reduce GHG emissions in line with the carbon-neutrality target of 2035 (Government Programme, 2019). Historically Finland has gradually increased emission taxes and lowered income and corporate taxation since 1997, although none of these kinds of tax changes have been explicitly called environmental tax reform. The coming reform plans to include comprehensive energy and transport tax reforms together with tax changes to support the circular economy. In addition to planned increases in carbon taxes, the ETR is expected to include some tax reductions (such as a reduction in the electricity tax on industrial sectors to support electrification) and increases in subsidies for low-carbon measures.

In addition to economic policy instruments, Finland has used and plans to use various standards and regulations to curb GHG emissions. For example, Finland has banned the use of coal from 2029 onwards and requires a 30% share of biofuels in transport sector fuels by 2030. Additional policies to support a circular economy have been drafted. However, as of November 2020, the plans and policy changes to guarantee reaching carbon neutrality by 2035 are still not complete.

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