Energy transition within 1.5°C

A disruptive approach to 100% decarbonisation of the global energy system by 2050

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Summary

Decarbonisation of the global energy system is one of the big challenges society faces today. The Paris Agreement, adopted in 2015, states that efforts should be pursued to limit the temperature increase to 1.5°C above pre-industrial levels. This is a tightening of earlier agreements that put the limit at 2°C. The question Ecofys, a Navigant company, will explore in this paper is: What does such increased ambition mean for the global energy system?

The temperature effect of CO_2 emissions is not primarily determined by the level of emissions in a future year; rather, it is by the cumulative amount of emissions, or the carbon budget. To stay within the carbon budget, global emissions need to be reduced—and fast. If society keeps on emitting CO_2 at the current pace, the carbon budget to limit the temperature increase to 1.5°C will be exceeded in one or two decades. Because of this, Ecofys explored what a fast energy system transformation could look like.

The Ecofys team developed its scenario against a background of increasing population, with a growing demand for energy services like space heating and cooling, transportation, and materials production. We constructed this scenario so that maximum feasibility is achieved, giving preference to options that have high social and political acceptability.

Our decarbonisation scenario includes several critical levers to constrain emissions:

- Ongoing efforts to deliver all energy services in an efficient way
- Electrifying energy consumption, especially for buildings and transportation
- Fast penetration of wind and solar in the electricity sector
- Adopting a range of other renewable energy technologies, from solar heat to electricity-based hydrogen
- Bioenergy as a fuel source for the manufacturing industry and specific transportation needs and a role for carbon capture and storage (CCS) in specific sectors

As result of strong energy efficiency improvements, it is possible to bring global energy use below current levels to 435 EJ, a large contrast to business as usual growth to over 800 EJ. While the total primary energy supply in the scenario is decreasing slightly, electricity demand is expected to almost triple. Ecofys estimates that all this energy can be supplied from zero-carbon or low carbon energy sources.

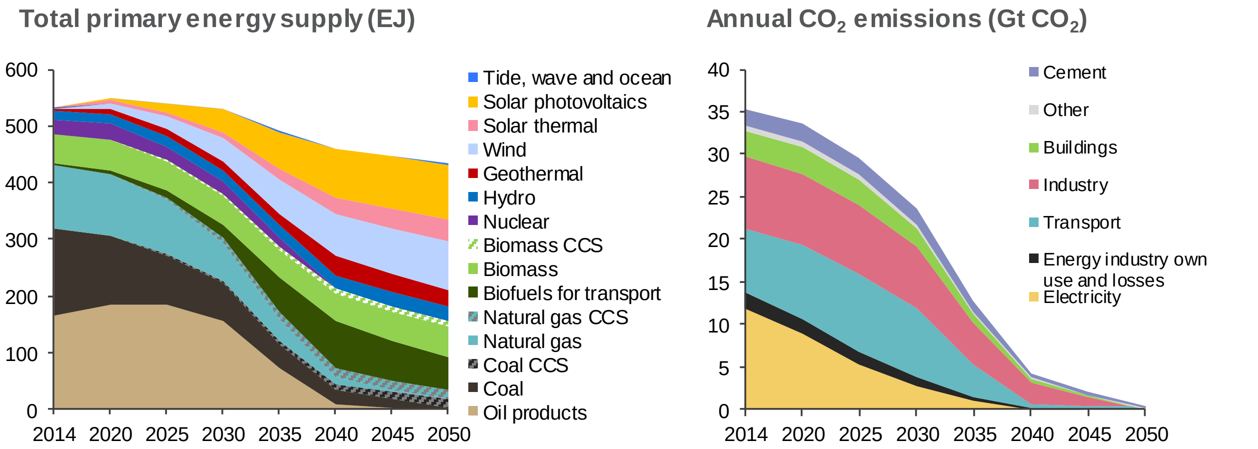

Figure 1. Global total primary energy supply and annual CO_2 emissions in our decarbonisation scenario

Despite the global energy system's rapid reduction of CO_2 emissions in our disruptive decarbonisation scenario, cumulative CO_2 emissions beyond 2014 are calculated to be 680 billion tonnes, likely exceeding the carbon budget. However, combined with options such as afforestation and agricultural carbon sequestration, it looks possible to stay within a carbon budget compatible with a maximum temperature increase of 1.5°C.

Fast global action is needed, and the way we live, produce, consume, and dispose of products and services needs to be redesigned, especially if society wants to reduce dependence on future technologies that enable negative emissions. An energy system transformation as set out here is feasible but highly disruptive. While it is based on technologies that are already available, it will have a high impact on all players in the energy system because of far-reaching electrification and the increased use of bioenergy. Existing businesses will need to be completely reoriented and new business lines developed to cope with the energy technology requirements of the future.

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1 Introduction

The outcomes of the 2015 Paris climate negotiations were a surprise to many. On top of limiting temperature rise below 2°C in this century, an even more ambitious intention was formulated to pursue efforts to stay within 1.5°C.[1] This half degree temperature difference results in a substantial reduction of the effects of climate change.[2,3] Furthermore, a lower temperature reduces the risks of positive feedback loops considerably, which could accelerate global warming even more.[4]

This target requires rapid decarbonisation of the global energy system. The estimated carbon budget for a 50% chance of remaining below 1.5°C is 200-800 Gt CO_2 as of 2016. If society keeps emitting CO_2 at the current pace, the carbon budget will be exceeded in one or two decades.[5] The outcomes of integrated assessment models (IAM) demonstrate that least-cost pathways that reach this target would first exceed the carbon budget significantly and subsequently deploy negative emissions on a large scale in the second half of this century.

However, there are several reasons to challenge this proposed trajectory. First, it is questionable whether this is actually the least-cost path. The experience curve of renewable energy technologies and storage options is much steeper than previously assumed and electricity from solar and wind is expected to be cheaper than coal in the near future.[6,7] On the other hand, development of carbon capture and storage (CCS), which is widely applied in IAM scenarios, is behind schedule.[8] Second, there are more fundamental arguments to decarbonise as soon as possible rather than compensating in the future. Scientists are concerned about the uncertainty of the effect and undesirable side effects of negative emissions.[9,10,11] On top of that, there is a significant risk of temperature overshoot if emissions are not reduced quickly. Finally, the question can be raised whether it is ethical to shift the responsibility

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[1] UNFCCC, "Historic Paris Agreement on Climate Change: 195 Nations Set Path to Keep Temperature Rise Well Below 2 Degrees Celsius," 12 December 2015. Available at http://newsroom.unfccc.int/unfccc-newsroom/finale-cop21/.

[2] Knutti, Rogelj, Sedláček & Fischer, "A scientific critique of the two-degree climate change target," *Nature Geoscience* 9 (2015): 13–18.

[3] Schleussner et al., "Differential climate impacts for policy-relevant limits to global warming: the case of 1.5," *Earth System Dynamics* 7 (2016): 327–351.

[4] Chadburn et al., "An observation-based constraint on permafrost loss as a function of global warming," *Nature Climate Change* 7 (2017): 340–344.

[5] According to Carbon Brief analyses based on IPCC data (http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf), the carbon budget for a 50% chance of remaining below 1.5°C is 312 Gt CO_2 as of 2017. Current annual emissions are around 40 Gt CO_2, resulting in 7-8 years of carbon budget at 2016 emissions. For a 66% chance of remaining below 1.5°C these figures are respectively 162 Gt CO2 as of 2017, corresponding to 4 years of carbon budget at 2016 emissions. Analysis available at https://www.carbonbrief.org/analysis-four-years-left-one-point-five-carbon-budget. Goodwin et al. report ranges from 715-750 Gt CO_2 as of 2017 for a 66% chance, indicating the large uncertainty in the available carbon budget. Goodwin et al., "Pathways to 1.5 °C and 2 °C warming based on observational and geological constraints," *Nature Geoscience* 11 (2018): 102-107. Available at: https://www.nature.com/articles/s41561-017-0054-8.

[6] Creutzig et al., "The underestimated potential of solar energy to mitigate climate change," *Nature Energy* 2 (2017): 17143.

[7] Kittner, Lill, & Kammen, "Energy storage deployment and innovation for the clean energy transition," *Nature Energy* 2 (2017): 17125.

[8] Peters et al., "Key indicators to track current progress and future ambition of the Paris Agreement," 2017.

[9] Anderson & Peters, "The trouble with negative emissions," *Science* 354 (2016): 182–183.

[10] Kartha & Dooley, "The risks of relying on tomorrow's 'negative emissions' to guide today's mitigation action." SEI, 2016. Available at https://www.sei-international.org/mediamanager/documents/Publications/Climate/SEI-WP-2016-08-Negative-emissions.pdf.

[11] Vaughan & Gough, "Expert assessment concludes negative emissions scenarios may not deliver," *Environmental Research Letters* 11 (2016): 95003.

of climate change mitigation (again) to future generations.[9] Nevertheless, utilising negative emissions is probably unavoidable given the current annual emissions from fossil fuels and cement production of over 35 Gt CO_2.[5,12,13,14]

In response to this discussion, Ecofys developed a backcasting scenario in which the global energy system is decarbonised as soon as reasonably possible, thereby reducing the required negative emissions to stay within 1.5ºC. The team constructed its scenario in such a way that maximum feasibility is achieved by giving preference to proven technologies with acceptable costs (techno-economic perspective). These technologies are accepted by society and can count on political support (socio-political perspective).[15]

2 Socio-economic projections

The socio-economic growth projections in our decarbonisation scenario are based on the shared socio-economic pathways developed by the climate modelling community to ensure consistency in modelling practice. Out of five different pathways, a medium growth scenario for GDP and population is used.[16] In this scenario, world population increases by 27% up to 9.2 billion in 2050. The global GDP triples between 2014 and 2050. Main relative growth is expected to occur in Asia and Africa.

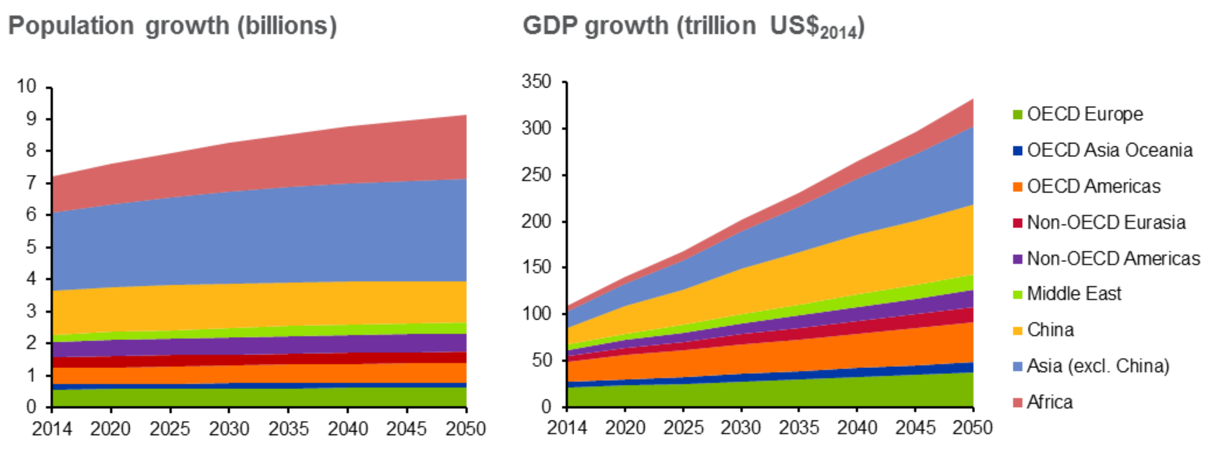

Figure 2. Assumed population and GDP growth in our decarbonisation scenario

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[12] IEA, *World Energy Outlook 2016*, 2016. Available for purchase at: http://www.iea.org/weo/.

[13] Lackner, "The promise of negative emissions," *Science* 354 (2016): 714.

[14] Van Vuuren et al., "The role of negative CO2 emissions for reaching 2 °C—insights from integrated assessment modelling," *Climate Change* 118 (2013): 15–27.

[15] The concept of the socio-political merit order is further described in Blok et al, 2018. The socio-political merit order – Developing energy strategies that can be rapidly deployed. Available at: https://www.ecofys.com/en/publications/the-socio-political-merit-order/.

[16] Riahi et al., "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview." *Global Environmental Change* 42 (2017): 153–168.

Demand for energy services is expected to grow until 2050

Demand for energy services is expected to increase considerably between 2014 and 2050 due to economic and population growth. The future demand for energy services is estimated based on analyses of the relation between GDP and activity. Literature was used whenever available to validate the outcomes.[17]

Industry. Seven key materials covering 53% of the energy consumption in the industrial sector, are investigated in detail. Because of economic and population growth, demand for basic materials increases. The expected production growth rates for these materials range from 14% to 178%. The production growth of cement is modest because of an expected decrease in China.[18] The largest relative growth is expected in methanol production, yet the associated energy consumption is small relative to the other materials (1% of total).

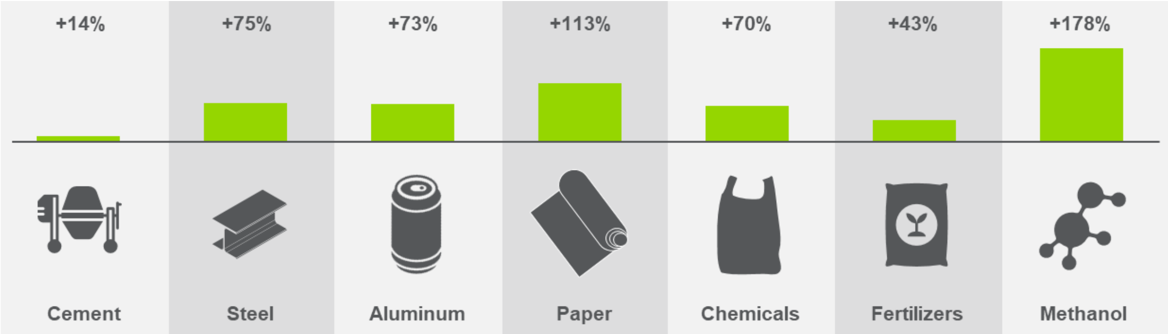

Figure 3. Expected demand development in the industry sector in our decarbonisation scenario

Transport. Significant demand growth is expected for almost all transport modes. While air transport is expected to increase dramatically, it is not alone: transport demand for passenger cars and freight road may triple as well. Activity in bus and light road transport is expected to keep pace with population size.

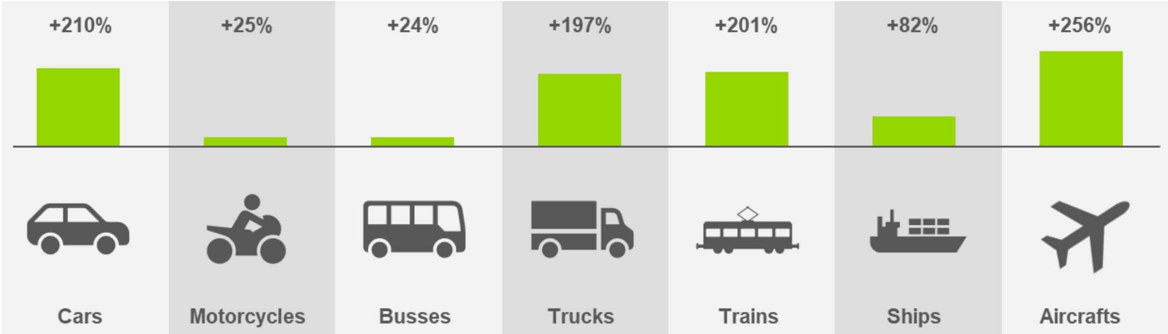

Figure 4. Expected demand development in the transport sector in our decarbonisation scenario

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[17] The demand projections are described in detail in Van Exter, *A Hitchhiker's Guide to Energy Transition Within 1.5°C: Backcasting Scenario for 100% Decarbonization of the Global Energy System by 2050*, 2017. Available at https://repository.tudelft.nl/islandora/object/uuid%3Aa0df8a13-e477-4f44-817b-def39496d679.

[18] Van Ruijven et al., "Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries," *Resources, Conservation and Recycling* 112 (2016): 15–36.

Buildings. The expected growth rates fluctuate considerably across different building functions. While demand for space heating, hot water, lighting, and cooling is expected to keep pace with economic and population growth, a much higher demand growth is expected for space cooling. As GDP per capita increases in many warm regions, the use of air conditioners could increase significantly.

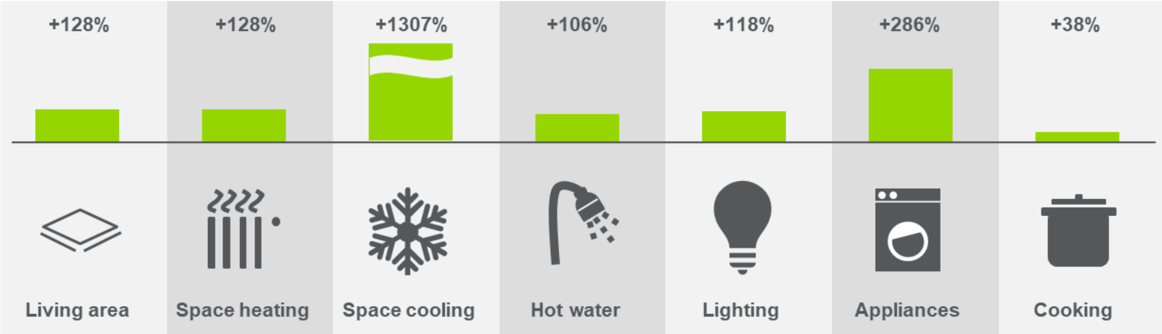

Figure 5. Expected demand development in the building sector in our decarbonisation scenario

3 Transition in the energy system

To reduce emissions, efficiency improvements and technology switches are required throughout the whole economy. The following presents an overview of the expected developments in the industry, transport, and buildings sectors in our decarbonisation scenario.

Industry. Estimated energy efficiency improvements between 2014 and 2050 range from 4% to 50% for the different production processes. In the aluminium industry few improvements are feasible, while there is abundant opportunity to increase the energy performance in non-energy intensive industries.[19,20] In terms of changes towards low carbon production technologies, producing aluminium, iron, and steel from secondary scrap is maximised to 50% because of ongoing stock accumulation. For the remaining primary production of iron, steel, and aluminium, CCS technology is applied, but hydrogen direct reduction (hydrogen-DR) can also play an important role in steel making by 2050. For primary aluminium production, a small share of the energy is provided by high temperature solar thermal.

In the chemical industry, biomass can replace oil products as carbon feedstocks. Ammonia can be produced with hydrogen derived from electrolysis rather than steam reforming. Subsequently, negative emissions can be realised for cement production and the paper, pulp, and print industry where biomass combustion is combined with carbon capture and storage technology (BECCS). Most of these technologies are in an early stage of market penetration and are expected to deploy slowly after 2020. Partial electrification is assumed in the other industries because most of these processes only require low temperatures.

[19] UNIDO, *Global Industrial Energy Efficiency Benchmarking An Energy Policy Tool,* 2010.

[20] Worrell & Carreon, *Energy demand for materials in an international context,* 2017.

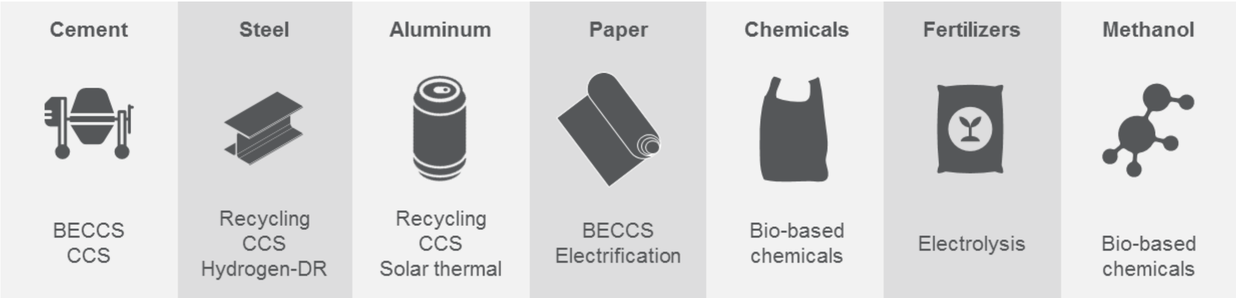

Figure 6. Overview of the low carbon technologies used for each material in industry

Transport. In the transport sector, most efficiency improvements are expected for ships (50%), aircrafts (42%), and passenger vehicles (24% to 47%). For road transport, which currently covers 77% of the total energy consumption in the transport sector, the near phase out of internal combustion engines after 2030 will result in a significant transition to electric and fuel cell vehicles. This transition also applies to freight road and busses, made possible by recent improvements in battery capacity and hydrogen storage.[21] Rail transport is currently powered with diesel and electricity. Current diesel trains are expected to be replaced with electric alternatives by 2050 or will be powered with biodiesel. For air and shipping transport, biofuel was the only viable alternative found. By 2040 the total demand for liquid fuels in transport is assumed to be met by biofuels to bridge the transition towards electric and hydrogen powered transport. The application of biofuels before 2050 results in peak demand for biomass, which can and has to be produced sustainably.

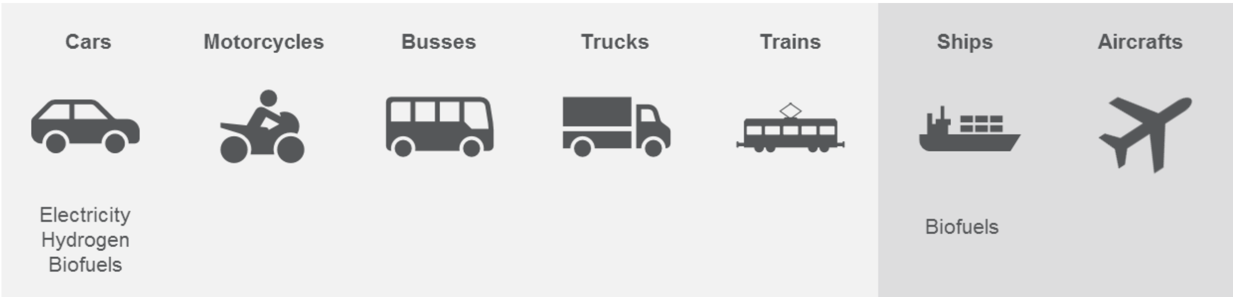

Figure 7. Overview of the low carbon technologies used for road, rail, shipping, and air transport

Buildings. To reduce emissions from the buildings sector, several strategies reinforce each other. An important measure is improving the thermal performance of buildings. This strategy could potentially reduce the heating and cooling demand between 35% and 70% by 2050. The application of natural gas, currently the most used fossil fuel in buildings, are expected to be phased out and replaced with electric alternatives. The application of highly efficient technologies such as heat pumps and LED lighting reduces the energy demand considerably. Furthermore, efficiency improvement of appliances should further curb the energy demand. Because of increasing welfare, using biomass for cooking is expected to decrease in developing regions.

[21] IEA, *Energy Technology Perspectives 2017*, 2017. Available at: http://www.iea.org/etp/.

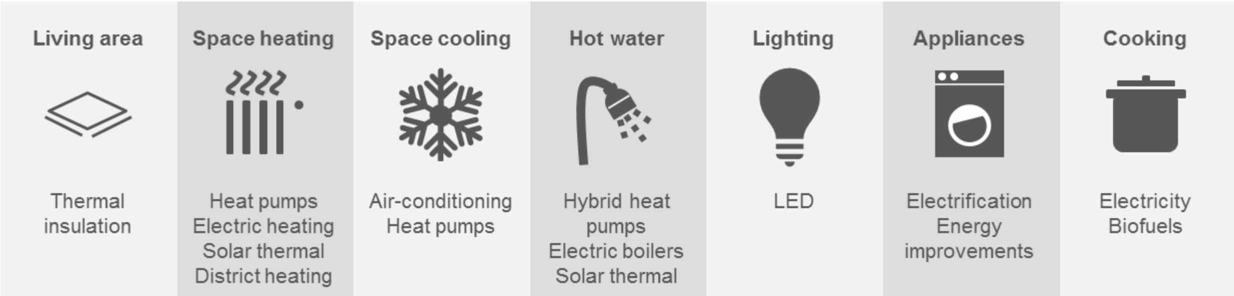

Figure 8. Overview of the low carbon technologies used for different functions in buildings

4 Renewable electricity production

As more and more energy sectors depend on electricity, renewable electricity production becomes vital. Wind turbines and solar PV currently produce 3.9% and 1.3% of global electricity production. However, their annual growth rates are high and recent studies found this growth is not likely to decline in the near future.[6,7,22] The spectacular cost reductions that were realised and the significant potential make wind and solar the most important future energy sources. Their high growth rates make a fast transition in the power sector possible: in our decarbonisation scenario, 100% of the electricity is generated by renewable sources by 2040. In our decarbonisation scenario, over 70% of global final electricity demand in 2050 is supplied by wind turbines and solar PV.

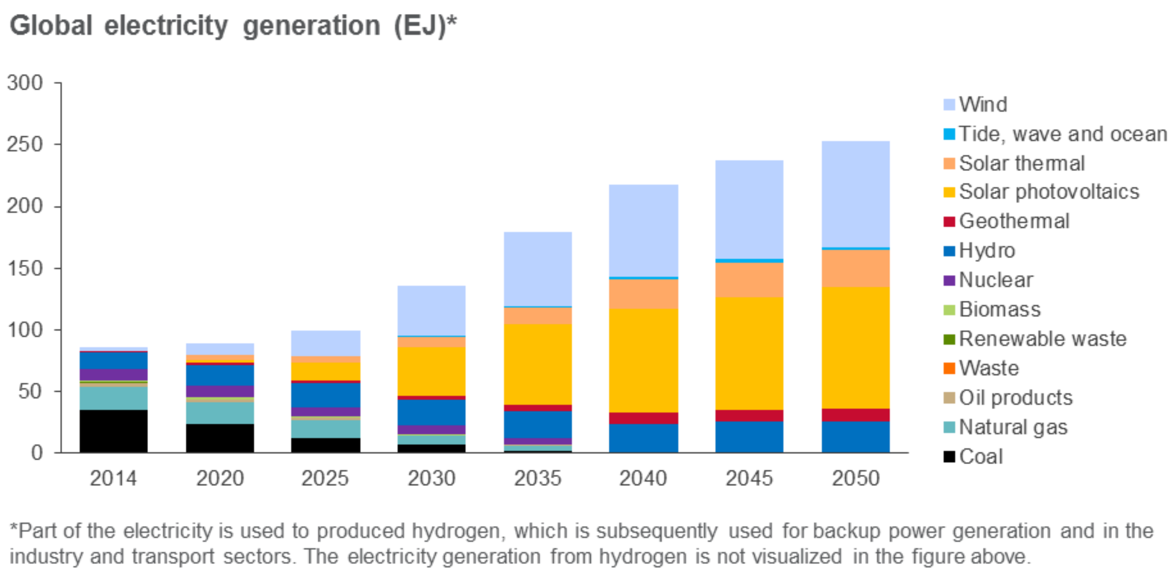

Figure 9. Projected global electricity demand developments in our decarbonisation scenario

[22] Napp, Gambhir, Steiner & Hawkes, *Expect the Unexpected: The Disruptive Power of Low-carbon Technology*, 2017. Available at http://www.carbontracker.org/wp-content/uploads/2017/02/Expect-the-Unexpected_CTI_Imperial.pdf.

An important disadvantage of wind turbines and solar PV is that it is a supply driven source rather than a demand driven source. The share of these intermittent renewables in the scenario is within the allowable maximum range found in literature.[23,24,25] Yet, flexibility options are needed. These options include demand response, grid expansion, power to gas, power to heat, and battery storage.[26,27,28,29,30,31,32] In our decarbonisation scenario, 56 EJ of renewable electricity is used to produce hydrogen. The hydrogen is subsequently used in the transport (15 EJ) and industry (12 EJ) sectors and for backup power generation (15 EJ). About 3% of the final global electricity demand is produced from hydrogen made from excess renewable electricity (power to power).

5 Total primary energy supply

The expected economic and population growth, assumed efficiency improvements, and technology switches result in a significant transition of the energy system to realise a net decarbonisation by 2050 (Figure 10). While demand for energy services increases strongly over time, the efficiency improvements and use of more efficient technologies enable a decrease in total primary energy supply to 442 EJ (-8%). This results in a relatively low total primary energy consumption compared to most other low carbon scenarios. In a business as usual scenario energy demand could even increase to about 800 EJ by 2050.[33]

In 2014, oil, coal, and natural gas provided 78% of the world's energy. In our decarbonisation scenario, this change rapidly after 2030 as biomass and renewable electricity sources become dominant. Looking at the global primary energy supply in 2050, wind, biomass, and PV have become the major sources of energy and are responsible for 70% of the total supply.

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[23] Klaus, Vollmer, Werner, Lehmann, & Müschen, *Energy target 2050: 100% renewable electricity supply*, 2010. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050_kurz.pdf.

[24] Ram et al, *Global Energy System based on 100% Renewable Energy – Power Sector,* Study by Lappeenranta University of Technology and Energy Watch Group, 2017. Available at: http://energywatchgroup.org/wp-content/uploads/2017/11/Full-Study-100-Renewable-Energy-Worldwide-Power-Sector.pdf.

[25] Ueckerdt et al., "Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model." *Energy Economics* 64 (2017): 665-684.

[26] Kavadias, Apostolou, & Kaldelis, "Modelling and optimisation of a hydrogen-based energy storage system in an autonomous electrical network," *Applied Energy.* 2017.

[27] Oldenbroek, Verhoef & Van Wijk, "Fuel cell electric vehicle as a power plant: Fully renewable integrated transport and energy system design and analysis for smart city areas," *International Journal of Hydrogen Energy* 42 (2017): 8166–8196.

[28] Diouf & Pode, "Potential of lithium-ion batteries in renewable energy," *Renewable Energy* 76 (2015): 375–380.

[29] Mwasilu, Justo, Kim, Do & Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renewable & Sustainable Energy Reviews* 34 (2014): 501–516.

[30] Arteconi, Hewitt & Polonara, "Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems," *Applied Thermal Engineering* 51 (2013): 155–165.

[31] Sternberg & Bardow, "Power-to-What? – Environmental assessment of energy storage systems," *Energy & Environmental Science* 8 (2015): 389–400.

[32] Lund, Lindgren, Mikkola, & Salpakari, "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renewable & Sustainable Energy Reviews* 45 (2015): 785–807.

[33] Extrapolation of the IEA World Energy Outlook 2017 New Policy Scenario towards 2050 results in a global total primary energy demand of 820 EJ. The IEA Energy Technology Perspectives 2017 Reference Technology Scenario reports a global total primary energy demand of 769 EJ.

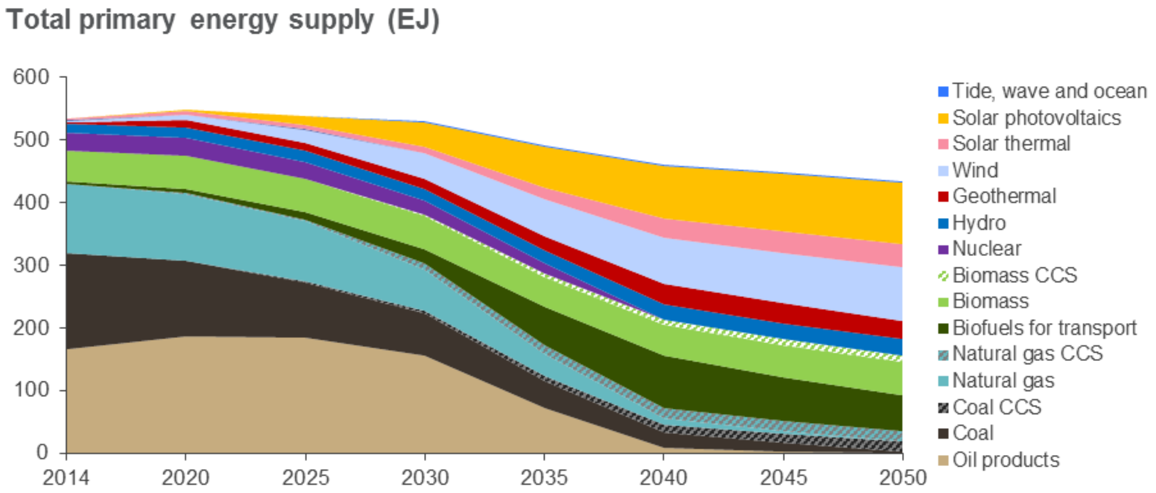

Figure 10. Total primary energy supply developments in our decarbonisation scenario

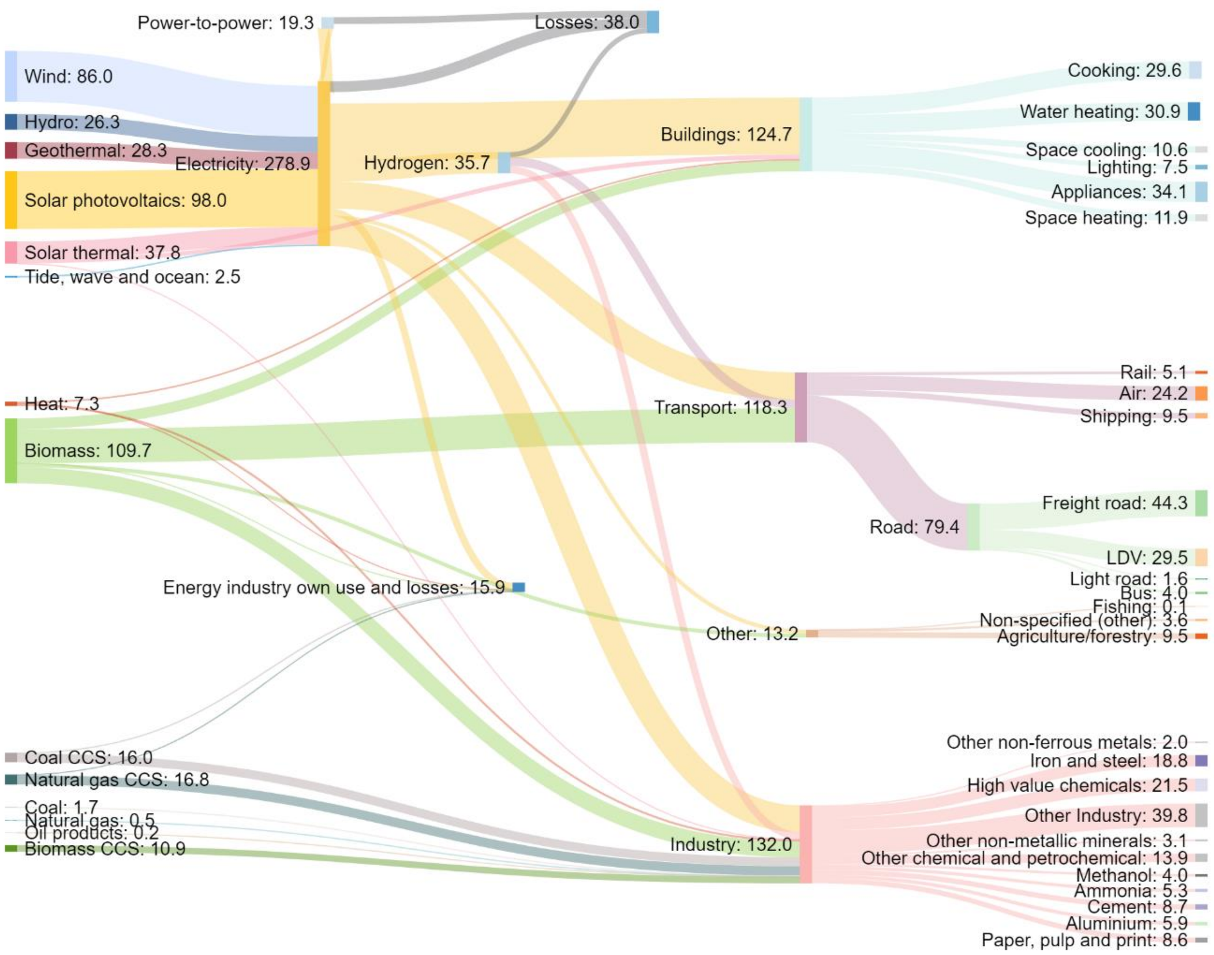

Figure 11. Flow diagram of the global energy system (EJ) in 2050 in our decarbonisation scenario

The future energy system is characterised as follows (Figure 11):

- Electricity, biofuels, biomass, and hydrogen are the main energy carriers used for energy services in the buildings, transport, and industry sectors.
- Electricity is fully produced from renewable energy sources (solar PV, wind, geothermal, hydro, and solar thermal) and becomes the backbone of the energy system.
- Hydrogen is produced using renewable electricity and is used in the transport and industry sectors and in the power system to provide flexibility to match supply and demand with the high shares of volatile renewable energy sources.
- Biofuels are primarily used in in the transport sector. Biomass is used in the buildings sector, primarily for cooking (18 EJ), and in the industry sector for both energetic (38 EJ) and non-energetic feedstock (20 EJ) purposes. Part of the biomass use in industry is combined with CCS (BECCS).
- Fossil fuels like coal and natural gas combined with CCS are primarily used in the industry sectors.

6 Cumulative emissions

In total, 680 Gt CO_2 is emitted between 2014 and 2050, of which more than half is emitted in the first decade (Figure 12). The energy transition results in a fast reduction of emissions from fossil fuels and industry, while annual emissions from the electricity sector decrease almost linearly over time.[34]

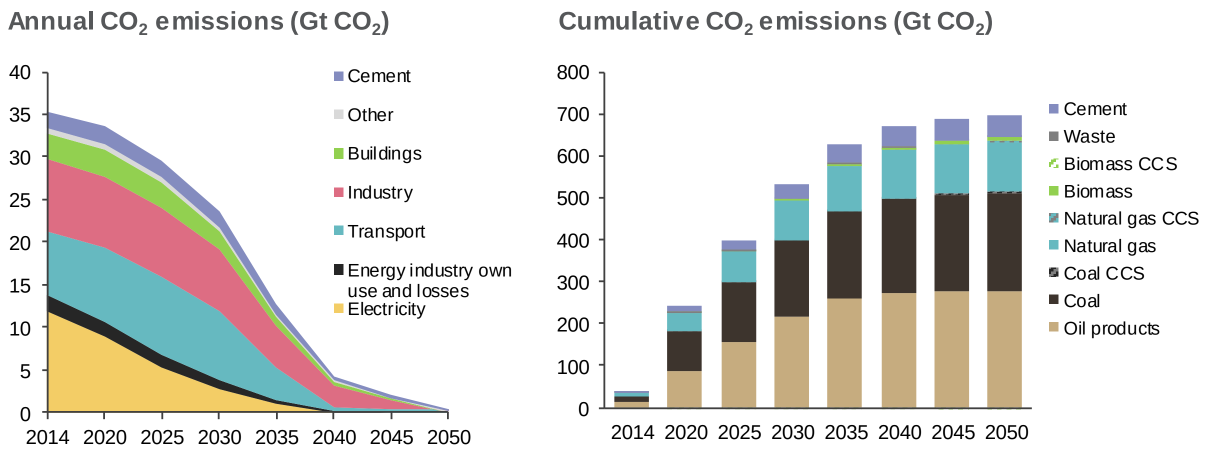

Figure 12. Left: annual CO_2 emissions per sector. Right: cumulative emissions per energy carrier

[34] According to Carbon Brief analyses, the carbon budget for a 50% change of remaining below 1.5°C is 433 Gt CO_2 as of 2014. This means that with cumulative emissions of 700 Gt CO_2, the carbon budget is exceeded by 267 Gt CO_2. For a 66% change of remaining below 1.5°C the carbon budget is exceeded by 417 Gt CO_2.

As electricity demand increases significantly, renewable electricity production is key for strong decarbonisation. In our decarbonisation scenario, fossil-based electricity is phased out by 2040. This accelerated decarbonisation of the power sector saves a cumulative 93 Gt CO_2 compared to reaching 100% renewable electricity by 2050 (Figure 13).

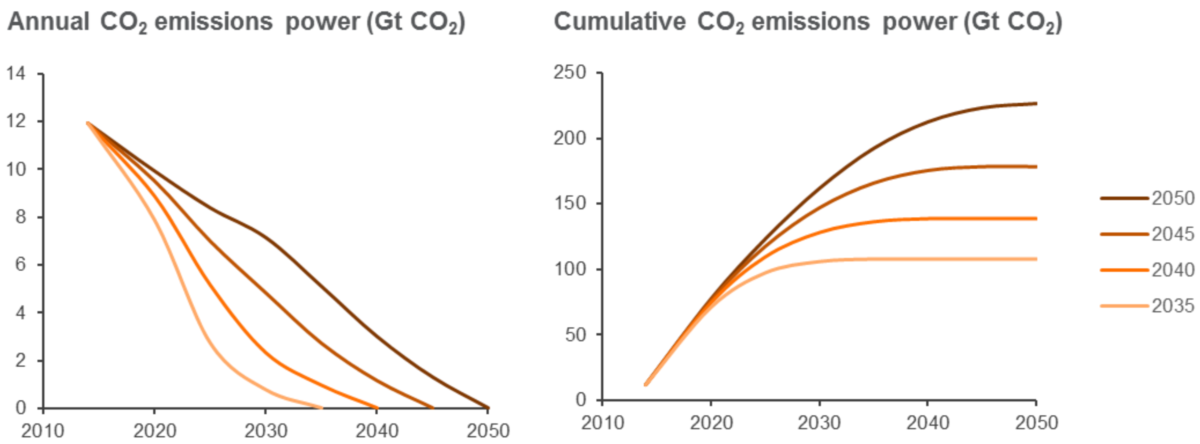

Figure 13. Annual and cumulative emissions from electricity production for various fossil-based electricity phaseout years

For the transport sector, a slight growth in CO_2 emissions is expected after which a steep decline takes place due to the phase out of internal combustion engines from 2030 onwards. In the remaining sectors, there is a more gradual decrease in annual emissions. Process emissions from cement (around 2 Gt CO_2 per year) decrease when CCS technology is installed.

Regardless of the rapid decarbonisation, the 1.5°C carbon budget is most likely still exceeded. For example, a remaining carbon budget of 400 GtCO_2 as of 2016 would require additional negative emissions of around 4 Gt per year for the remainder of the century, such as afforestation, reforestation, and soil carbon sequestration.[35,36] However, this is significantly less than most other low carbon scenarios.[37]

[35] UNEP, *The Emission Gap Report 2017*, 2017. Available at: https://www.unenvironment.org/resources/report/emissions-gap-report-2017-synthesis-report.

[36] Berg, “The positive side of negative emissions,” Navigant Research Blog (blog), Navigant Research, 15 February 2018. Available at: https://www.navigantresearch.com/blog/the-positive-side-of-negative-emissions.

[37] The cumulative emissions from fossil fuels and industry in the scenario described in *A Hitchhiker’s Guide to Energy Transition Within 1.5°C: Backcasting Scenario for 100% Decarbonization of the Global Energy System by 2050* by Van Exter are 61% lower than the average baseline scenarios and 25% lower than the average cumulative emissions in the low carbon scenarios from Riahi et al. (2017) and the IPCC AR5 (2014) low carbon scenarios with a chance of exceeding 1.5°C under 66%.

7 Conclusion

A steep decarbonisation pathway for the global energy transition is required to stay within 1.5°C. Fast global action is needed and the way we live, produce, consume, and dispose products and services will need to be redesigned to reduce dependence on future negative emissions.

Most of the required technologies are already available and developments in some sectors go so fast that transitions become cost-competitive. The scale up of technologies such as solar PV, wind turbines, electric vehicles, and heat pumps will be continuously unprecedented.

Electrifying energy services in buildings, transport, and industry will come with massive investment needs in electricity grids and require flexibility solution. Hydrogen produced from renewable energy could play a critical role from 2030 onwards, both in providing flexibility to electricity systems and as valuable energy carriers for the transport and industry sectors.

Biomass use will shift towards enabling decarbonisation of the transport sector and providing high temperature heat in industry to produce materials and chemicals. A strong increase in biomass demand in the steep decarbonisation pathway is unavoidable. Therefore, sustainable intensification of biomass production should be an integral part of climate policy. Sustainable production is essential on a planet with a growing population and welfare, and ecosystems already under pressure.

While the momentum for steep carbonisation is there, this paper shows that there is no time to lose. A global decarbonisation path should preferably be taken today rather than tomorrow to avoid spoiling society’s chances of staying within 1.5°C.

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