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Net-Zero CO_2 Germany—A Retrospect From the Year 2050

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Key Points:

- The net-zero system shows that for countries like Germany, avoiding CO_2 emissions was the largest contribution to achieve net-zero CO_2
- With the three strategies of emissions avoidance, reduction, and removal, Germany has achieved its net-zero CO_2 goal for the first time
- In addition, to natural sink enhancement carbon dioxide removal (CDR) options, technological CDR measures combined with geological CO_2 storage were necessary to reach net-zero CO_2

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Germany 2050: For the first time Germany reached a balance between its sources of anthropogenic CO_2 to the atmosphere and newly created anthropogenic sinks. This backcasting study presents a fictional future in which this goal was achieved by avoiding (~645 Mt CO_2), reducing (~50 Mt CO_2) and removing (~60 Mt CO_2) carbon emissions. This meant substantial transformation of the energy system, increasing energy efficiency, sector coupling, and electrification, energy storage solutions including synthetic energy carriers, sector-specific solutions for industry, transport, and agriculture, as well as natural-sink enhancement and technological carbon dioxide options. All of the above was necessary to achieve a net-zero CO_2 system for Germany by 2050.

Plain Language Summary Here a net-zero-2050 Germany is envisioned by combining analysis from an energy-system model with insights into approaches that allow for a higher carbon circularity in the German system, and first results from assessments of national carbon dioxide removal potentials. A back-casting perspective is applied on how net-zero Germany could look like in 2050. We are looking back from 2050, and analyzing how Germany for the first time reached a balance between its sources of CO_2 to the atmosphere and the anthropogenic sinks created. This would consider full decarbonization in the entire energy sector and being entirely emission-free by 2050 within three priorities identified as being the most useful strategies for achieving net-zero: (a) Avoiding- (b) Reducing- (c) Removing emissions. This work is a collaboration of interdisciplinary scientists with the Net-Zero-2050 cluster of the Helmholtz Climate Initiative HI-CAM.

1. Introduction

Let's take a look at a possible future Germany that has reached its net-zero CO_2 emissions goal by 2050. What are the measures that have contributed to reaching this net-zero system? And what kind of implementation efforts are associated with this portfolio of measures?

In this perspective, we outline how a carbon-neutral system for Germany in 2050 could look like, following three strategies of avoiding, reducing, and removing CO_2 emissions. We envision a net-zero-2050 Germany by combining analysis from an energy system model with insights into approaches that allow for a higher carbon circularity in the German system, and first results from assessments of national carbon dioxide removal (CDR) potentials.

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This work is a collaboration of interdisciplinary scientists with the Net-Zero-2050 cluster of the Helmholtz Climate Initiative (HI-CAM, 2021; Net-Zero-2050, 2021).

While previous studies illustrated several forward-looking pathways for Germany on how to reach a climate-neutral or greenhouse-gas neutral Germany by 2050 (e.g., Duscha et al., 2019; Günther et al., 2019; Prognos et al., 2020), here we assume a possible, but still hypothetical, net-zero carbon future and look back on how this goal was achieved. This unique perspective allows us to take a novel, goal-oriented view on the challenge of net-zero CO_2 emissions in Germany and accordingly enables discussions on how we (as a society) would like to achieve such a goal. This study brings together the different aspects needed to achieve net-zero CO_2 across the energy, industry, agriculture, and transport sectors and provides the first expert estimates of German CDR potentials based on the most recent literature. Distinct from previous studies, we here include options of large-scale CDR in the form of technological CDR—like bioenergy combined with carbon capture and storage as well as direct air carbon capture and storage (DACCS)—and natural carbon sinks enhancement—like soil carbon management, reforestation, peatland rewetting, and seagrass restoration.

This study concentrates on CO_2 rather than CO_2-equivalent emissions, following the scientific reasoning of (net) zero CO_2 targets based on the transient climate response to cumulative CO_2 emissions (Matthews et al., 2009; Rogelj et al., 2018). We also make sure to exclude any existing natural carbon sinks like existing forests, but concentrate on the potential of anthropogenic enhancement of carbon sinks, again following the best scientific evidence (Matthews et al., 2009; Rogelj et al., 2018). While this study takes into account the feasibility of CDR options with regard to possible scale of implementation within Germany and discusses implementation obstacles, we are not aiming to design a most cost-effective CDR implementation scenario. The summary of the article includes an overview of the net-zero CO_2 system for Germany in 2050, illustrating the contributions of each single measure to reaching this goal.

With this study, we aim to highlight the potentials of net-zero options for Germany as an example case, the associated implementation efforts needed for such a possible net-zero CO_2 system as well as possible obstacles that need to be overcome. The epistemic value of this piece is the transparency of the underlying and often disregarded assumptions of future visions of net-zero.

2. An Envisioned Net-Zero Germany in 2050

Germany 2050: For the first time Germany reached a balance between its sources of anthropogenic CO_2 to the atmosphere and anthropogenic sinks created. Germany therefore is now in line with the target set by the UNFCCC back in 2015 (Paris Agreement, 2015). This target had been put into EU law in the early 2020s (Council of the European Union, 2020).

Back in the early 2020s, there were heated debates on how rapidly Germany should decrease its emissions. Climate movements argued that industrialized countries like Germany need to take their global responsibility and ensure a just transition for all, while big fossil fuel companies argued for a longer transitioning time and compensation for stranded investments in the fossil economy (cf. e.g., Bals, 2018; FFF, 2021; France 24, 2019; ITUC, 2020; Wehrmann, 2021). This challenge of finding a balance of phasing out fossil fuels, for example, by increasing the price on carbon, without placing too much of a burden on workers within the fossil economy (Baber, 2019; Jetten et al., 2020), initially caused delays in climate action. Finally, in 2021 the political climate within Germany changed, making it impossible to further delay ambitious climate action and catalyzing the necessary system transformation (BMU, 2021).

Due to this delayed action, Germany's emitted carbon budget now, in 2050, is above what some consider Germany's fair share of emissions in terms of distribution per equal-per-capita approach or the scientific advice from for example, the Helmholtz Climate Initiative, which proposed a budget of 6.9 Gt CO_2 from 2021 onward (Mengis et al., 2020).

2.1. But How Does Our Carbon-Neutral Society Look Like Today Compared to 2020?

Since 2020 we have seen a 5% decrease in German population while economic growth has continued along the long-term trends as projected back in 2020 (e.g., Kemmler et al., 2020; StBA, 2017). With 79 million inhabitants, Germany today generates about a third more gross domestic product (GDP real) compared to 2020. The decline in population has not been able to compensate for the trend toward single households, with the result that a rather constant living space and number of households have to be supplied with heat. However, by continuing an ambitious thermal insulation strategy and by high thermal standards for new buildings, the energy demand of buildings could be strongly reduced. The shift toward a service-oriented society has continued at the expense of industry and the primary sectors, for which production accordingly remains close to their 2020 levels. Furthermore, the upward economic trend has also led to an increase in freight transport. However, a reverse trend has been initiated for individual automobile transport, through a series of measures, such as improved public transport, car sharing, biking, and walking, as well as parking management in cities.

Germany finally achieved net-zero CO_2 by pursuing three major strategies: (a) avoiding emissions by replacing fossil fuel-based energy production with renewable energy (RE), but also increasing energy efficiency and extending energy storage systems; (b) reducing emissions from hard-to-abate sectors, such as the chemical, steel or cement industry, the transport sector, and agriculture—here, sector-specific efforts were undertaken to reduce remaining emissions; and finally (c) compensating residual emissions by removing CO_2 from the system—so-called CDR measures have been put in place, which range from natural carbon sink enhancement to creating anthropogenic sinks by technological carbon capture and permanent storage (see box 1 for more info).

The linear economy that we had followed until 2020, took fossil energy carriers to produce goods, and generate energy and heat. The resulting CO_2 got dumped into the atmosphere (see yellow arrows in Figure 1). Considering that over 85% of CO_2 emissions back in 2020 were caused by energy provision (see Figure 4), a net-zero carbon economy significantly depended on the reduction of energy demand and the substitution of fossil fuels and materials through renewables ("avoid"), the reduction of CO_2 emissions within sectors where avoidance was not possible, as well as the re-use of remaining CO_2 emissions in circular carbon approaches ("reduce"), and the deposition of CO_2 in carbon storage sites to compensate for any remaining positive emissions ("remove") (Paris Agreement, 2015).

New technologies allowed us to change the linear approach into a circular one and even remove CO_2 from the atmosphere: DACCS combines technologies that first capture CO_2 from the ambient air through chemical processes with carbon dioxide absorbing materials, and purify and concentrate this CO_2 to sequester it in geological storage sites (producing negative emissions; e.g., HI-CAM, 2020). However, all these processes are energy intensive and put an additional strain on the energy system, thus they are effective if supplied by RE (HI-CAM, 2020).

In the case of direct air carbon capture and use, the captured CO_2 is converted into hydrocarbon fuels and materials with the help of H_2 and RE (e.g., Dittmeyer, et al., 2019). These fuels and materials can be used as substitutes for fossil carbon materials and fuels in industrial processes and even the aviation sector, thereby reducing emissions in sectors for which emissions are otherwise hard to abate (e.g., Airbus, 2020; Billig et al., 2019; Dittmeyer, et al., 2019).

Bioenergy and Carbon Capture and Storage (BECCS) is the process which combines generation of energy (e.g., electricity, heat, biofuels) from biomass with capturing and storing of the otherwise emitted CO_2 in geological storage sites (e.g., Furre et al., 2019; Gluyas & Bagudu, 2020; Knopf & May, 2017; Porthos, 2019; Swennenhuis, et al., 2020). Since the carbon in the biomass is taken out of the atmosphere by the plant during their growth and then actively removed from the system through permanent storage, negative emissions are achieved.

In addition, we can manage or restore natural systems that allow us to reduce CO_2 emissions from those systems or even enhance natural carbon sinks on land and the ocean. For example, by restoring drained peatlands through rewetting, CO_2 emissions from these soils are avoided (e.g., Leifeld et al., 2019; Tanneberger et al., 2021). Changing our agricultural practices increases organic and inorganic soil carbon content (e.g., Al-Kaisi & Yin, 2005; Dold et al., 2017, 2019; Haddaway et al., 2017; Kell 2011; Sanderman, 2012; Trost et al., 2013; Verma et al., 2005; Wei et al., 2021; Zornoza et al., 2016). And lastly, we can get the ocean to take up more carbon, by restoring or protecting seagrass meadows, allowing for their expansion (e.g, Alongi, 2018; Eriander, et al., 2016; Greiner, et al., 2013; Infantes et al., 2016; Infantes & Moksnes, 2018; Moksnes et al., 2018; Postlethwaite et al., 2018; Prentice et al., 2020).

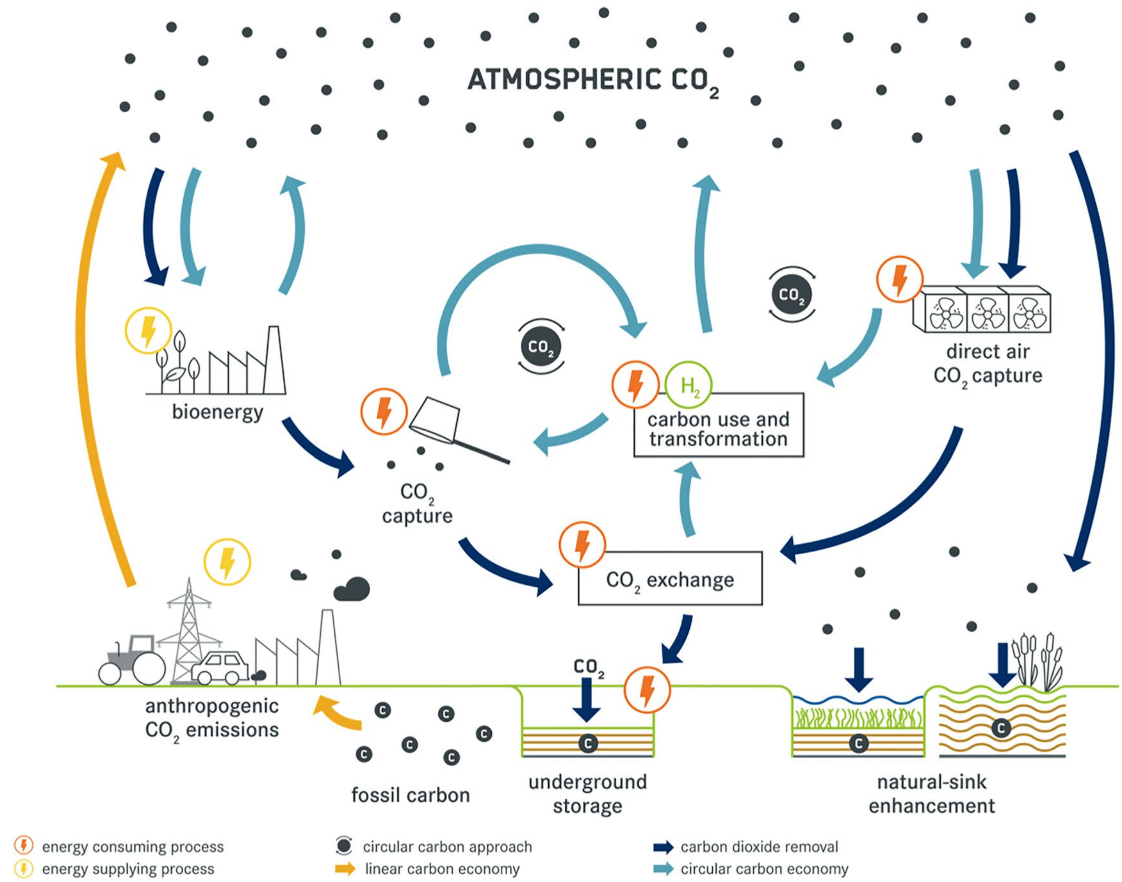

Figure 1. Illustration of historical linear carbon economy burning fossil carbon (yellow arrows), and novel approaches allowing for a more circular carbon economy (light blue arrows) and carbon dioxide removal measures (dark blue arrows) (source: Helmholtz Climate Initiative//Tanja Hildebrandt).

3. Avoiding CO_2 Emissions

Looking back from the year 2050, the most cost-effective strategy of reaching net-zero CO_2 was avoiding emissions from major emitters by transforming toward a more sustainable energy supply. The energy sector, which was the main emitter of CO_2 emissions from the combustion of fossil fuels, managed to curb most of its annual 660 Mt CO_2 emissions from back in 2019 through massive transformation efforts. For that the energy system focused on three pillars: (a) reducing energy consumption, (b) electrification of heat, power, and transport supply, tapping the potential of sector coupling, and (c) supplying the necessary green hydrogen and hydrocarbons as renewable commodities and for long term energy storage.

3.1. Reduction of Energy Demand Through Higher Energy Efficiency

Societal changes in Germany have led to a successful decoupling of economic growth and energy demand. Behavioral changes, avoiding rebound effects, and a more efficient energy use, were key to reduce the overall energy demand. For example, the ambitious strategy to substantially improve thermal insulation of the building stock and to introduce high-end thermal standards for new buildings contributed to a final energy demand reduction of around 50% by 2050 (Fritz et al., 2019; Pregger et al., 2013; see Supporting Information for scenario comparison). Other measures range from increasing efficiency in heating and waste heat use in industry to applying more efficient and electrified power trains in transport. Eventually, large shares of the efficiency potentials were implemented, saving roughly a third of final consumption while maintaining equal energy services (see Figure 2). Shifting efficiency losses to the power supply was avoided by a simultaneous transition toward efficient and renewable power production.

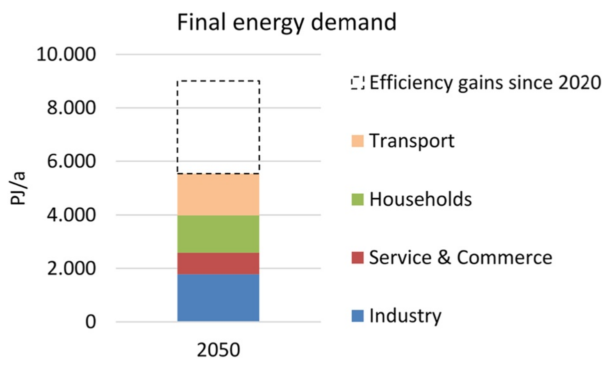

Figure 2. Final energy demand in 2050 and energy savings from efficiency measures relative to 2020 (own calculations based on Kemmler et al., 2020).

3.2. Transforming the Power, Heat and Transport Systems From Fossil to RE

Heat, power, and transport systems are now closely coupled to balance energy demand and supply. Thus, the energy system is now almost CO_2 free and relies mainly on renewable power produced by wind, solar, hydro, sustainable biomass, and geothermal energy (see Figure 3). Significant direct electrification of road and almost all rail transport has been achieved. Today, two-thirds of all passenger vehicles—more than 20 million—are electric. Freight transport and rail transport without catenaries relies now significantly on indirect electrification for example, via fuel cells. Massive retrofit investments in the heat sector have led to a fundamental transformation in residential buildings. 25% of residential heat is provided via heat grids (own calculations based on Fette et al., 2020; Kemmler et al., 2020; Zech et al., 2019). This integrates direct use of solar, geothermal, and biomass heat for base load with electricity via large seasonal heat storages (Fette et al., 2020). In combination with heat grids, large volume subsurface heat storage contributes to reducing energy demand in residential areas and in large office buildings by more than 50% compared to 2020. By 2050, the development of deep geothermal energy and biomass for district heating has multiplied and became an important pillar of heat supply. Large efficiency improvements were the precondition for increasing utilization of heat pumps. Electricity has become the backbone of heat supply in buildings, providing direct electric heating, but also hydrogen and synthetic gas, where a retrofit was not possible. Coupling both the heat and power sectors thus provides mutual benefits (see also Gea-Bermúdez et al., 2021; Jimenez-Navarro et al., 2020; Zech et al., 2019).

Due to the necessary sector coupling, electricity consumption has more than doubled in recent decades (BMWi, 2020a). The simultaneous decarbonization of electricity generation required a massive and accelerated expansion of photovoltaic (PV) and wind power plants beyond any records held before 2020. The increase in capacity (average of 10 GW per year) for both PV and wind power plants lead to 240 GW of wind capacity and more than 370 GW of PV capacity in 2050. Additional infrastructure was key to balancing the now almost completely renewable power sector: grid expansion, battery storage, demand side management, and increased power exchange in the European Transmission System predominantly compensate for short-term fluctuations.

3.3. Green Hydrogen, Synthetic Energy Carriers and Biofuels for Energy Storage

Roughly half of the power system in Germany today is dedicated to the production of RE -based synthetic fuels—hydrogen, synthetic methane (CH_4), and liquid hydrocarbons (see "H_2, syngas, synfuels" category in Figure 3). Green hydrogen is predominantly produced by electrolysis of water. Hydrocarbon fuels (also called *electro-fuels*) are made of green hydrogen and CO_2 via so-called Power-to-Liquid processes (Agertet al., 2020; Kasten, 2020; Roeb et al., 2020).

The fluctuating and regionally unequally distributed RE supply within Germany, the regionally unequal provision of storage capacity as well as the necessary long-range transport of energy required an extensive and still continuing expansion of the power transmission grid by almost 90% relative to 2020 and the establishment of an infrastructure for the import, distribution and storage of synthetic fuels (see Supporting Information S1).

Given that Germany is geographically far from high solar irradiation areas, synthetic fuels are imported by already developed infrastructure (pipelines or commercial tankers) from North Africa and Middle East countries (Liebich et al., 2021). These fuels can be produced to a large extent by concentrated solar power which is coupled with thermochemical cycles or electricity generation and simultaneous water desalination (Olwig et al., 2012). For the import and trade of green hydrogen across the EU and its partners the certification "CertifHy" implemented by the EU was essential, since it enabled a wide-ranging trade of green molecules (Veum et al., 2019; White et al., 2021).

Today, most of the infrastructure that had been used for natural gas back in 2020 was transformed to transport and store hydrogen. Most of the hydrogen grid was ready for use when the so-called hydrogen backbone was completed in the year 2040 (Wang et al., 2020).

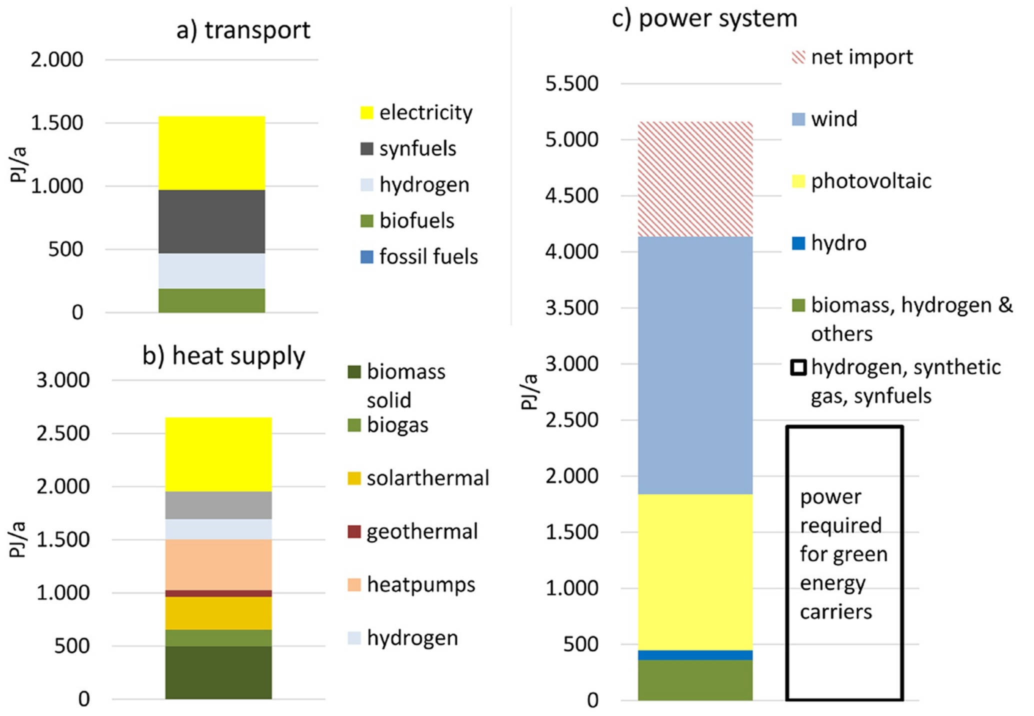

Figure 3. Supply structure power system, including electricity supply to heat and transport sectors in Germany in 2050 (own calculations based on Fette et al., 2020; Kemmler et al., 2020; Zech et al., 2019).

Next to lithium-ion batteries and pumped hydro storage, which cover for short-term variability, synthetic methane and hydrogen are mainly used for intermediate and long-term storage in caverns, in the northern and central parts of Germany. Former hydrocarbon reservoirs in the southern part of Germany and pressure tanks are now the backbone for energy.

4. Reducing CO_2 Emissions

Although Germany has reached the goal of an overall carbon neutral society, some CO_2 emissions remain even in 2050. The second strategy hence was to reduce emissions from all the sectors for which emissions are hard to abate, like industry, parts of the transport system, and agriculture. For each of those sectors, individual strategies were developed and implemented to reduce their CO_2 emissions as far as possible.

4.1. Solutions for Sectors With Hard-to-Abate Emissions - Industry and Transport

With the help of synthetic energy carriers like green hydrogen, synthetic methane, synthetic liquid hydrocarbons, and biofuels, emissions from otherwise unavoidable fuel demands could be reduced (IRENA, 2020; Sharmina et al., 2020). The necessary carbon for the production of synthetic fuels and gases now comes from remaining point source emitters, like cement or lime factories, for which inherent process-based emissions remain hard to abate (Plaza et al., 2020). Those facilities have been retro-fitted with CO_2 capture modules.

In many industrial applications, hydrogen could be directly implemented to substitute fossil fuels (e.g., coal, crude oil, or natural gas) either as energy carriers or as raw material. For primary steel production, the coke-based blast-furnace route has first been replaced by hydrogen-based direct reduction (Bhaskar et al., 2020) and lately also by electricity-based electrowinning (Fischedick et al., 2014). Given that renewable electricity is used, this enabled to reduce emissions of German steel production by about 82% relative to the 2020s (Harpprecht et al., in preparation).

Ammonia production underwent a similar transition. In 2020, hydrogen required for ammonia was produced from natural gas via steam-reforming (DECHEMA, 2017). Nowadays, 100% of hydrogen demand for ammonia production is supplied through water electrolysis, which makes it completely emission-free (Dittrich et al., 2020).

For cement plants, emissions could be reduced by 64% relative to 2019 through the transition to RE, a reduced clinker to cement ratio, and novel carbon capture technologies (see Supporting Informationfor details). All newly built plants are now equipped with carbon capture technologies of oxyfuel (Schneider, 2019; Voldsund et al., 2019) and LEILAC (Low Emissions Intensity Lime & Cement; Hills et al., 2017; LEILAC, 2017). To substantially reduce process-based emissions, cement, and lime production sites needed to be linked to the CO_2 grid to permanently store 8.8 Mt CO_2 each year.

Synthetic liquid hydrocarbons like gasoline, diesel, kerosene, methanol, or dimethyl ether not only supply the chemical industry (e.g., for polymer production), but also serve as a complementary solution in the transportation sector (for heavy freight, maritime transport, and aviation; Millinger et al., 2021). Electrified private and public transportation are now part of zero-emission city concepts. The bulk of rural transportation is also electrified with larger ranges of electric vehicles and an improved charging stations infrastructure. In addition, public transportation in rural areas now relies mainly on demand responsive transport services (Sörensen et al., 2021). Nevertheless, mobile applications which cannot store energy in batteries (e.g., aviation, navigation, rail, and heavy duty), became users of green hydrogen or green fuels (Ehrenberger et al., 2021). Today, one-third of all passenger vehicles rely on hydrogen and biofuels, aircrafts for short and medium distances have been operated with hydrogen since the year 2035 (Airbus, 2020). In the same way, long-range cargo logistics transport still relies on carbon-based fuels.

4.2. Solutions for Sectors With Hard-to-Abate Emissions - Agricultural and Organic Soils

4.2.1. Agricultural Soils

Today, farmers extensively apply techniques such as the state-of-the-art fertilizer, tillage, and irrigation scheme in Germany. Organic fertilizers (OF) are now preferred over mineral fertilizers, because the latter have a larger carbon footprint, and the former return organic material back to the soil (Hasler et al., 2017). OF are applied on soils with highest carbon storage potential or traditionally low OF application, such as crop production areas in East Germany (Don et al., 2018; Lal et al., 2015). Thereby, farmers actively avoid CO_2 emissions by preserving the carbon stock in the soils. Furthermore, biochar is applied to the soils to increase the amount of recalcitrant carbon (Bai et al., 2019; Smith, 2016). Where mineral fertilizer application is still required, acidifying nitrogen fertilizers are avoided or nitrification inhibitors are applied to allow continued carbonate weathering (Elrys et al., 2020; Liebig et al., 2018; Robertson, 2014). Precision farming with high-resolution soil maps support the effective distribution of fertilizer, so that they are now applied in optimized amounts and period of time. OF pelleting supports precision farming (Delin et al., 2018; Liu et al., 2017; Romano et al., 2014). Where applicable, conservation tillage was introduced to reduce CO_2 emissions from the topsoil (Bai et al., 2019; Baker et al., 2007; Dold et al., 2019; Haddaway et al., 2017). Frequency, tillage depth, and tillage method were improved, and turning tillage with the mouldboard plow was avoided (Al-Kaisi & Yin, 2005). Regulated deficit irrigation and drip irrigation reduced CO_2 emissions, because microbial activity is reduced under dry soil conditions, and carbonate weathering is accelerated (Sanderman, 2012; Trost et al., 2013; Wei et al., 2021; Zornoza et al., 2016). The use of carbonate-enriched irrigation water is avoided to reduce CO_2 release from irrigation water (Sanderman, 2012; Verma et al., 2005). These changes in agricultural and land management practices reduced CO_2 emissions by around 1.9 Mt CO_2 annually in Germany relative to the 2020s.

4.2.2. Peatland Rewetting

Back in the early 2020s, more than 98% of the organic soils (about 1.8 Mha) were drained mainly for agricultural use (Tanneberger et al., 2021; Trepel et al., 2017). Therefore, already in the late 20th century, efforts to raise the water table of peatlands to the surface were undertaken to avoid oxidation and the consequent CO_2 release to the atmosphere (Joosten et al., 2017). Since 2020 about 50,000 ha of German peatlands were set to be gradually rewetted each year (Abel et al., 2019).

The net annual CO_2 fluxes in peatland ecosystems are strongly dependent on their management, and land use (Leifeld et al., 2019; Petrescu et al., 2015). New sustainable management approaches, like the implementation of paludicultures following the rewetting were applied to selected drained peatlands, allowing for continued utilization of these areas for agriculture and forestry (Joosten et al., 2017). These management options were essential to turn our peatland ecosystems from a source of CO_2 to a sink.

Rewetted peatlands today prevent about 15 Mt of CO_2 emissions from previous agriculturally used areas (Buendia et al.et al., 2019), and even enable permanent carbon sequestration of 2.7 Mt CO_2 per year (see Supporting Information), in addition to advocating other co-benefits like biodiversity, water quality, and filtering out nutrients.

5. Removing CO_2

Despite all efforts to avoid and reduce CO_2 emissions, net-zero-2050 CO_2 emissions in Germany could only be reached because the remaining gross positive emissions released into the atmosphere are compensated by gross negative emission achieved by CDR. Two main strategies were followed to achieve negative emissions: (a) the enhancement of natural carbon sinks by restoring natural ecosystems across land and coastal sea and (b) the implementation of negative emission technologies combined with permanent carbon storage facilities. While the former provided additional benefits for biodiversity and ecosystem services and avoided substantial amounts of future emissions from ecosystem deterioration the latter mainly served as a necessary means to achieve net-zero CO_2 emissions.

5.1. Natural Sink Enhancement

5.1.1. Agricultural Practices to Increase Organic Top-Soil Carbon

Today, in 2050, agricultural soils function as areas of CDR by increasing biomass production and hence increased CO_2 uptake during carboxylation in the photosynthetic process of crops. Accordingly, soils are enriched with soil organic carbon over time, taking up additional CO_2 until a new carbon equilibrium is reached. The effectiveness of soil for CDR is quantified as the ratio of carbon build-up and carbon inputs (Wiesmeier et al., 2020).

The challenge of the first approach was to intensify crop production for securing food security, while reducing CO_2 emissions from agriculture and land-use (Bai et al., 2019; Lal, 2019; Taylor et al., 2016). Crop production systems that act as carbon sinks or carbon neutral are now used: For example, growers transitioned to improve crop rotations from C3 to C4 crops, which typically have higher net ecosystem production than C3 crops (Dold et al., 2017). For the 2020–2050 period measures to improve crop rotations stored additional 97 Mt CO_2 in the soils. In addition to that, crop residues in the field were increased by preferring crop varieties with deep and dense root systems (Don et al., 2018; Kell, 2011). Cover crops with deep root system, high biomass production, and nitrogen-fixing symbiosis are now grown during the off-season of summer crops to prolong the period of photosynthetic carboxylation on the field (Bai et al., 2019; Don et al., 2018; Poeplau & Don, 2015), storing 44 Mt CO_2 in agricultural soils. Further, the use of agroforestry systems on 10% of the cropland increased soil carbon stocks by another 36 Mt CO_2. Finally, the successful intensification of agricultural practices freed low-yielding field patches to be converted to pasture and forest, as they have higher carbon sequestration rates per land unit (Don et al., 2018; Morgan et al., 2010). The conversion of 10% of low-yielding cropland to each pasture and forests increased the carbon stock by 38 Mt CO_2, and 41 Mt CO_2, respectively.

5.1.2. Seagrass Restoration and Recovery at the German Coast

To maximize their ability to sequester carbon, efforts to extend seagrass meadows area in Germany were implemented already during the 2020s. While active restoration was conducted in the Baltic Sea, seagrass meadows in the North Sea were left to regenerate naturally after measures (like peatland rewetting) were implemented to improve water quality, the main stressor back in the 2020s (Dolch et al., 2017). Seagrass meadows reach maturity and therefore their maximum carbon sequestration rates after approximately 18 yr (Eriander et al., 2016; Infantes et al., 2016; Infantes & Moksnes, 2018; Marbà et al., 2015; Moksnes et al., 2018). In contrast to land-based plants, the burial potential of seagrass meadows thereafter remains at this high level, the stock does not saturate.

Today, over 80% of this theoretically habitable available area has mature seagrass meadows along the German coast, that is an additional 306,400 ha and 9,780 ha along the Baltic and North Sea coast, respectively. The restored and now matured *Zostera marina*-dominated seagrass meadows in the Baltic Sea sequester carbon at a mature rate of 39.4 g C/m^2/yr (averaged from Greiner et al., 2013; Marbà et al., 2015; Prentice et al., 2020). The carbon sequestration in the North Sea is slightly less with 24 g C/m^2/yr for *Zostera noltei*-dominated meadows (averaged and adjusted from Alongi & Alongi, 2018; Postlethwaite et al., 2018; Prentice et al., 2020). Today, the total area of seagrass along the German coastlines (Baltic and North Sea) sequesters approximately up to 454 kt CO_2/yr.

5.2. Technological Carbon Dioxide Removal With Geological Carbon Storage

Bioenergy supported the energy transition in (a) providing flexible electricity to compensate for fluctuations coming from variable RE sources, such as wind and solar power, (b) renewable heat implementation, and (c) providing options for carbon capture and storage. Today, point source carbon capture at bioenergy power plants provides a bulk of the CO_2 that is transported to permanent storage sites, and therefore produces negative emissions. The main sources of biomass used for bioenergy generation are forestry and agricultural by-products and residues and organic waste which is predominantly generated within Germany (Billig et al., 2019; Thrän et al., 2020). Germany took advantage of its existing biogas plants system and supported retrofitting of biogas plants with CO_2 capture units. This process allowed an annual removal of 11.3 Mt of biogenic CO_2 from both biogas-fueled cogeneration plants (biogas CHP) as well as biomethane plants (Billig et al., 2019). A part of faded out coal-fired power plants was also converted to handle sustainable biomass sources as feedstock and retrofitted with carbon capture units (enervis, 2021; Wi, 2020b). They now serve as centralized sources of biogenic CO_2 for carbon removal providing roughly 16 Mt of biogenic CO_2 as a negative emissions source.

Another source of CO_2 for permanent carbon storage to achieve negative emissions are direct air capture facilities. These plants provide the option to produce concentrated CO_2 taken directly from the atmosphere. However, since this process is rather energy-intensive (mostly heat but also power), and therefore inefficient in low insolation areas like Germany, another solution was found: Today, almost every big office or retail building has an air carbon capture unit integrated in the heating, ventilation and air-conditioning (HVAC) system capturing a total of 17 Mt CO_2 (Dittmeyer et al., 2019; HI-CAM, 2020). The hotter summers caused an expansion in air conditioning needs for buildings, and this demand was used to retrofit existing HVAC-systems as well as install new HVAC-systems which are now included in the CO_2 transportation and storage system. In total, technological CDR now needs to remove ~50 Mt of CO_2 each year to be stored permanently on and off-shore.

CO_2 storage was a difficult topic in Germany back in 2020, but already in the mid-2020s, a number of successful off-shore initiatives had been started in the Dutch, Norwegian and British North Sea corridors, providing the possibility of permanent CO_2 storage in saline aquifers or depleted gas fields (Furre et al., 2019; Gluyas & Bagudu, 2020; Porthos, 2019; Swennenhuis et al., 2020). Back then, German CO_2 was transported across borders and stored in sites belonging to neighboring countries. Initially, the transport was done via ships on federal waterways to limit new infrastructural impact. As the safe and lucrative operation of these forerunner off-shore storage sites became apparent to the German public and policymakers, steps were taken to make use of the 3.8–23.9 Gt of storage capacity offered by the German North Sea subsurface (Knopf & May, 2017).

Transport to those storage sites today is provided by a cost-optimized pipeline network dedicated to CO_2 connected to decarbonized industrial clusters and collection hubs (IEA Energy Technology Perspectives, 2020; Yeates et al., 2020). While ensuring the delivery of decentral negative emissions from bioenergy and HVAC direct air carbon capture plants to an offshore storage site, this network also allowed for transporting emissions from hard-to-abate industry point sources toward synfuel production plants.

Beyond that, off-shore projects had strengthened the confidence in CO_2 storage technologies. Follow-up on-shore carbon storage projects were initiated within Germany, allowing underground storage of CO_2 in a temporary manner in a number of disused, geological storage sites. Established underground storage capacities in porous aquifers amount 20.4–115.3 Gt CO_2 (Knopf & May, 2017). Furthermore, favorable conditions for CO_2 mineralization in geothermal plants such as demonstrated in Iceland (Gislason & Oelkers, 2014) have been proven in Germany as well (Banks et al., 2021). Technological development in this field had gained momentum and, with the large-scale industrial development of deep geothermal energy, it now contributes to the permanent storage of CO_2 in Germany.

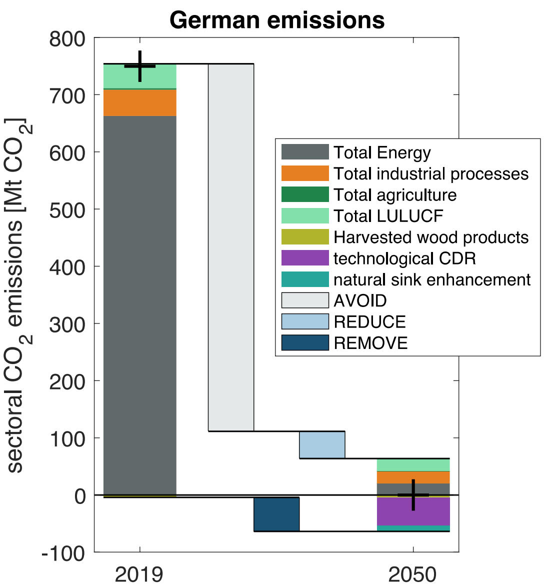

Figure 4. Comparison between CO_2 emission systems in 2019 and 2050. Including illustrations of avoided, reduced, and removed emissions that led to achieving net-zero by 2050. LULUCF, land-use, land-use change and forestry; CDR, carbon dioxide removal.

6. Summary - A Net-Zero CO_2 System in Germany

So, which are the measures that contributed to our current net-zero system, in 2050? Following the three strategies of emissions avoidance, reduction, and removal, Germany has achieved its net-zero CO_2 emissions goal for the first time this year (see Figure 4; see Supporting Information S1 for detailed information). This goal required a balance between anthropogenic sources and sinks, for which substantial efforts were undertaken: The increase in energy efficiency, electrification and sector coupling, and the introduction of synthetic energy carriers as green fuels and energy storage allowed us to avoid over 600 Mt of CO_2 emissions per year from previous fossil fuel combustion activities. Energy is now provided by over 95% RE, which avoids emissions in all energy consuming industries, including manufacturing, construction, and transport. But even as increasing efficiency reduced energy demand by almost 3,000 PJ per year, the demand for renewable synthetic energy carriers and negative emission technologies increased by about as much. Furthermore, synthetic energy carriers and changes in manufacturing practices reduced the remaining emissions from industrial processes by over 25 Mt CO_2 each year. Changes in agricultural practices and peatland-rewetting further reduced emissions from land use by about 20 Mt CO_2 per year. That means that today Germany still emits about 60 Mt of gross positive CO_2 emission.

The emissions come from remaining fuel combustion activities mainly waste combustion and industrial processes, as well as from land use and agricultural practices. Those remaining emissions are now compensated by gross negative emissions. Measures that enhance natural sinks like agricultural practices to increase organic top-soil carbon, reforestation of vacated agricultural areas, peatland rewetting, and seagrass restoration and recovery are able to take up almost 12 Mt CO_2 every year. This is in addition to a small amount of anthropogenic carbon sinks that had already existed back in 2020, like harvesting wood products. The remaining negative emissions are achieved through technological CDR measures combined with permanent carbon storage in German on-and off-shore sites. Bioenergy combined with carbon capture and storage contributes about 28 Mt CO_2 each year, decentralized HVAC implemented DACCS systems provide 17 Mt CO_2 each year.

The net-zero system shows clearly that for developed countries like Germany, avoiding CO_2 emissions was the largest contribution for achieving net-zero CO_2 emissions. The fact that over 85% of gross positive emissions back in 2019 were still emitted by fossil fuel combustion activities, shows the enormous potential of the transition to carbon-free energy sources. Beyond that any energy intensive technologies that allow for a higher carbon circularity or carbon removal in our current 2050 system, were only realizable because sufficient carbon-free energy is available.

Natural-sink enhancement CDR solutions usually experience a higher acceptability than technological measures in Germany (Bertram & Merk, 2020; Braun et al., 2018; Merk et al., 2019), also because of positive co-benefits like biodiversity and ecosystem restoration. And while they significantly contribute to removing CO_2 from the atmosphere today, they are not able to stem the whole burden left by hard-to-abate emissions by themselves. Accordingly, technological CDR measures including permanent carbon storage were required to achieve today's goal of net-zero CO_2 emission in Germany. This is in direct contrast to the climate policy back in the 2020s, which exclusively referred to natural sink enhancement for negative emissions (BMU, 2012).

7. Outlook - Obstacles That Need to Be Overcome for a Net-Zero CO_2 in Germany by 2050

In this backward-looking story, we imagined how a possible future Germany could look like, that achieved its net-zero CO_2 emissions goal in the year 2050. Our fictional future focuses strongly on technological achievements rather than rapid societal transformations based on behavioral changes at the individual and collective level (e.g., animal husbandry, consumption, travel), or far-reaching international compensation (Anderson et al., 2020; Kuhnhenn et al., 2020; Larkin et al., 2018; Paterson, 2020; Van Vuuren et al., 2018). Instead, we include ambitious transformations in the energy and industry sectors, in infrastructure for RE carriers as well as substantial changes in land-use and agricultural practices including peatland rewetting, as measures to reduce our gross positive CO_2 emissions by over 90%.

However, Germany does not currently have any unmanaged areas. Next to the area demand for the necessary and unprecedented increase in the volume of RE capacity and the substantial increase in the power grid that will have to be accommodated, any terrestrial CO_2 reduction and removal measure will have to be achieved by changing land-use practices and management options rather than applying them to unused land. This is especially true for balancing area demand for agriculture, peatland rewetting, top-soil carbon enhancement, and reforestation (Boysen, Lucht, & Gerten, 2017; Boysen, Lucht, Gerten, Heck, et al., 2017), limiting the overall carbon removal potential by natural-sink enhancement for Germany to about 12 Mt CO_2 per year. In contrast to what is envisioned in the German Climate law, as well as in its Nouvella (BMU, 2021; Bundesministerium der Justiz und für Verbraucherschutz, 2019), nature-based solutions alone are not enough to compensate for the remaining positive emissions. In order to achieve net-zero, we include estimates for HVAC systems (which put an additional strain on the energy system) and existing biomass power plants to be equipped with carbon capture systems for permanent carbon storage.

Removal potential is, however, merely one side of the story. CDR options currently face a number of obstacles, including infrastructure needs, missing economic incentives as well as problematic public perception (Benrath et al., 2020; Schumann et al., 2014). Similar to the transformation needed for RE carriers, CDR with geological carbon storage would need an infrastructure for transporting and storing CO_2. For large-scale CO_2 transport over land, pipeline networks are known to be the most economical solution. All while minimizing the infrastructure impact by adhering to pre-existing gas pipeline layouts (Yeates et al., 2021), the CO_2 network could also be seen as an opportunity to dynamize less-industrialized Federal states. As such, proximity to a CO_2 pipeline route would become synonymous with net-zero industrial development. And while once built the infrastructure would be cost-efficient, the largest obstacle would be the initial investment. Paired with the substantial energy cost, the same is true for retro-fitting HVAC systems with DAC systems, and the retrofitting of existing bioenergy plants with carbon capture systems, which brings us to another obstacle for CDR options in general.

The European emissions trading system does not currently create incentives for removing CO_2 from the atmosphere (Daggash & Mac Dowell, 2019). A revision of the EU-wide CO_2 trading system to include CDR measures will be a challenge as CDR measures have different time spans of retention and bear diverse risks of unintended re-emission (Lomax et al., 2015) while the ETS creates a uniform price signal. Regulations not only need to reward the removal of CO_2 emissions but also to financially penalize their intended and unintended re-emission to generate an efficient market outcome. To account for such differences, complementary technology-specific policy instruments (either market-based or regulatory instruments) could be implemented to correct for market distortions and create a level playing field for the competition between the different mitigation measures (Lehmann et al., 2020). However, in order to pay attention to the financial limitations of public households, carbon pricing should constitute the main driver for a cost-effective achievement of net-zero CO_2 emissions in Germany allowing limiting state subsidization to remaining market distortions (Lehmann et al., 2020).

Finally, all net-zero options discussed in this article, including repurposing of areas within Germany infrastructure expansion, changed agricultural practices, and carbon storage, need public support. Ensuring a just transition out of the fossil economy that accounts for trade-offs and an equitable sharing of costs, seem to be critical in order to avoid societal conflicts (e.g., Bals, 2018; Wehrmann, 2021). Research on social acceptance shows that rather than a lack of knowledge, resistance to technology development can be better understood by more overarching concerns such as basic value conflicts, perceived fairness, and failures of trust in governing institutions such as regulatory authorities and technical advice bodies (Markusson et al., 2020; Waller et al., 2020; Winickoff, 2017). A good example for this is the previously successful public outreach concept for the Ketzin pilot CO_2-storage project, where an open and transparent dialogue with all stakeholders was started from the very beginning (Martens et al., 2015). In another context, changes in mindsets and practices for farmers could be initiated by changes in the Common Agricultural Policy (CAP) of the EU. The CAP is currently undergoing a reform process. If set aside a large enough part of payments to farmers for eco-schemes that incentivize environmental and climate action, more farmers would apply management practices that reduce CO_2 emissions or even provide negative emissions (European Commission, 2019). Through the provision of comprehensive guiding materials (Lampkin et al., 2020), as well as an open discussion process involving all relevant stakeholders (e.g., BMEL, 2019) to effectively implement such eco-schemes, climate actions could play an important role in future farming management. In this way acceptance of negative emission technologies including permanent carbon storage could be achieved by expanding public debates to develop common ways forward, while responsibly assessing and governing such emerging net-zero technologies (Winickoff, 2017).

With this piece, we aim to foster political and societal debates on how we want to achieve net-zero CO_2 in Germany. Bold decisions need to be taken, be it for rapid societal transformations, far-reaching international compensation or investments into technological developments. Our vision for Germany in 2050 is *one* possible outcome. A different question is—do we describe a desirable net-zero-2050 future?

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data used for calculating CO_2 emissions from cement and steel by 2050 in the study are available at the Figshare repository via https://figshare.com/s/d6c12db8cb33939fe304. The study on two experimental rewetted peatland sites is based on datasets available at http://www.europe-fluxdata.eu/ (DE-Zrk & DE-Hte).

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