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Powering the future: Germany's Wasserstoffstrategie in the transition to climate neutrality – case study on green hydrogen for the chemical industry

Valentin Benedikt Seithümmer, * Julia Valentina Lutz, Samuel Jaro Kaufmann, Haripriya Chinnaraj, Paul Rößner * and Kai Peter Birke

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This article provides a comprehensive insight into Germany's transition to climate neutrality, bringing together the political framework of Germany's Climate Protection Act (CPA), the funding strategy of its key pillar, namely the "Wasserstoffstrategie" and the technical dimensions for non-technical stakeholders through a case study of Germany's largest current hydrogen user, the chemical industry. Increasing complexity of our modern economy and society and a lack of clarity in reporting contribute to misleading conclusions and can facilitate polarised views. To overcome that gap, we aim to draw a clear picture of these complex scientific topics and make them also accessible to non-technical stakeholders. This paper reviews Germany's climate policy, emphasizing the federal constitutional court's pivotal role. By calculating prospective GHG-reduction paths for Germany, we illuminate the gap between aspirational targets and practical strategies, emphasizing the need to translate global targets into actionable national plans. Taking the crucial, often-overlooked CO_2-budget into account, potential shortcomings are revealed, even when annual emission goals are met by Germany. Shifting focus of this paper to the German hydrogen strategy, a core part of the Climate Protection Program, we reveal a strong emphasis on international collaboration. This involves a global hydrogen ramp-up and facilitation of hydrogen imports, offering trade opportunities but also introducing dependencies and potential price increases. A scale estimation case study on green hydrogen production for the German chemical industry underscores the rationale behind prioritising imports over domestic production. Calculating a demand of 7840 windmills (78.37 TW h) that require 168 000 football pitches (7000 m^2 per pitch) of space, it provides easy to grasp insights into the necessary actions for a climate neutral Germany. This perspective frames Germany's climate goals, the Wasserstoffstrategie, and the technical scale of implementing renewables by conducting a case study on green hydrogen. Hereby, it highlights the magnitude of the climate problem and the immense scale of solutions required for a sustainable technical transition in a clear and sound manner.

1 Introduction

While facing rising costs for human and environmental health as well as enormous economic cost due to climate change, the global CO_2 emissions in 2023 are rising.[1,2] The nature of this crisis is that states around the globe are equally affected, regardless of territorial borders and political alignments. This fact led to a legally binding agreement in the Paris Climate Agreement of 2015, which is globally effective.[3] All 195 participating countries have committed under international law to develop a "Nationally Determined Contribution" (NDC) and concrete steps for its implementation. The NDC allows the countries to self-determine its greenhouse gas (GHG) strategy, the way of implementation and to adjust the roadmap with its goals along the time. Because of the maximum space of action, all countries can align with the Paris Agreement, despite varying ambitions to achieve individual goals. The "Meeting of the Parties" reviews the Paris Agreement's implementation every five years to assess joint progress and long-term objectives, known as the 'global inventory'. But even in the latest United Nations (UN) secretary report[4] on GHG savings determined in NDCs of each participating country, it is stated that GHG emissions are still expected to increase until 2030.[3,5] A gap

Institute for Photovoltaics, Electrical Energy Storage Systems, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany.
E-mail: valentin.seithuemmer@ipv.uni-stuttgart.de, paul.roessner@ipv.uni-stuttgart.de; Tel: +49 711 685-67186, +49 711 685-67166

in ambition and results is apparent. In Germany, the translation of the Paris Agreement is manifested in the Climate Protection Act (CPA), while Germany wants to take a global pioneer role. The CPA aims towards a climate neutrality in Germany by 2045, which is to be achieved in several steps and measures like the German "Wasserstoffstrategie".[6] Beside the insights into the German climate politics, the role of the constitutional court is highlighted, which serves as a model for the separation of powers between the judiciary and the legislature, and ensures Germany technical progress. Different GHG emission reduction pathways are prospectively outlined to depict the often-unseen CO_2-budget to framing the urgency and scale of emissions reductions needed, providing a clear and quantifiable target for policymakers to develop strategies that are both ambitious and achievable. This indicates the challenges ahead and reveals that achieving Germanys contribution for the 1.5 °C target seems unlikely.

Further, the German Hydrogen Strategy as a core pillar of the CPA is analysed regarding its potential as well as the political focus. The case study on green hydrogen production for the German chemical industry provides technical dimensions based on calculated electrical energy and spatial requirements, avoiding abstract representations. This viewpoint is supposed to give an easy to grasp overview of Germanys climate policy and what it takes to use hydrogen to achieve these goals.

2 Insights

2.1 The role of the German constitutional court for the Climate Protection Act and its implementation

The German government enacted the federal CPA[6] on December 12, 2019, in which the national climate protection targets (Section 3 of the CPA) are anchored. These provide for a gradual reduction of GHG emissions of 65% by 2030 and of 88% by 2040 compared to the reference year 1990 (Fig. 1). Net carbon neutrality has to be achieved by 2045 and negative GHG emissions by 2050. By the time the CPA came into effect in 2020, GHG emissions had already been reduced by approximately 36.5%. This is partly due to effects of deindustrialising the German Democratic Republic

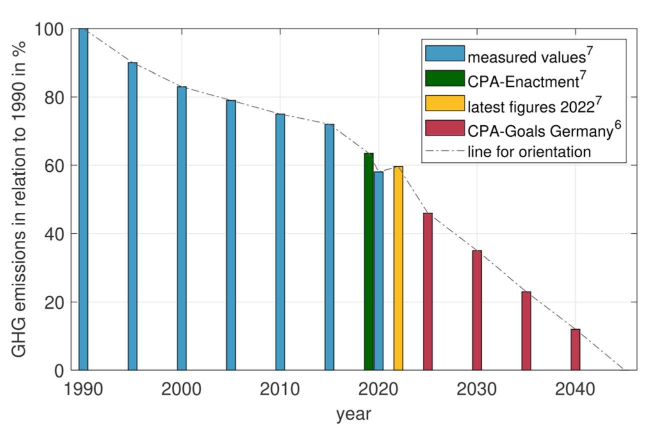

Fig. 1 GHG savings and goals of Germany compared to the reference year 1990.[6,7]

after the German reunion. That raises the question: How ambitious are these targets? Can the linear CO_2 reduction make a significant contribution to mitigating climate change?

In the current valid version of the CPA (date 01.07.2024), annual savings targets are set for the individual sectors of energy, industry, buildings, transport & traffic, agriculture and waste & other until 2030 (Table 1).

As of now, it remains uncertain in which sectors and with what amounts of CO_2-equivalent the German government intends to achieve the climate targets from the year 2030 onwards (Table 2), as there is no cross-sectoral classification available yet.[6]

In this respect, constitutional complaints submitted to the Federal Constitutional Court were partially approved on March 24, 2021. The Senate states: "The First Senate of the Federal Constitutional Court held that the provisions of the Federal Climate Change Act (CPA) of 12 December 2019 (Bundes-Klimaschutzgesetz – KSG) governing national climate targets and the annual emission amounts allowed until 2030 are incompatible with fundamental rights insofar as they lack sufficient specifications for further emission reductions from 2031 onwards".[8]

Hence, the Senate states that to achieve the Paris Agreement and limit global warming to 2 °C compared to pre-industrial levels, the proposed reduction path will irreversibly shift the burden of emission reductions to the years after 2030. "These future obligations to reduce emissions have an impact on practically every type of freedom because virtually all aspects of human life still involve the emission of greenhouse gases and are thus potentially threatened by drastic restrictions after 2030."[8] Therefore, it is stated that the liberty rights of the complainants, in particular for the young ones, are violated due to their freedom being restricted by later stricter measures to meet the post-2030 targets. In response to the ruling of the Constitutional Court, the CPA is under revision.

2.2 The Climate Protection Act – German goals and the update of 2024

In 2024, an update of the CPA by the Federal Ministry for Economic Affairs and Climate Action passed the German parliament, introducing several significant changes. First, the specified CO_2 reduction path for the years 2031 to 2040 set to be determined in 2024 and for the years 2041 to 2045 in 2034. Specific programs to achieve the overall cross-sectoral targets set out in the CPA are anchored in the Climate Protection Program 2023, dated 4th October 2023.[9,10] Further, the federal government is using the revision to exclude the sector-based savings and instead focus on overall GHG emissions of Germany, while leaving the figures unchanged (Table 3). The savings by sectors (Table 1) is shifted from sectoral binding saving goals to monitoring purposes as Annex 2b to Section 5.[8,10]

In practice, this means that all sectors are considered integrally for the evaluation of GHG emissions. Should specific sectors fail to meet their targets, any shortfall in reductions can be offset by those sectors that are exceeding their targets. This implies that if a sector exceeds its initial savings target, the

Table 1 Specified annual emission volumes [Mio. tons CO_2 equivalent] according the CPA[6] from Annex 2b (to Section 5 Para 1 Sentence 2 and 3)

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Energy sector	280		257								108
Industry	186	182	177	172	165	157	149	140	132	125	118
Buildings	118	113	108	102	97	92	87	82	77	72	67
Transport & traffic	150	145	139	134	128	123	117	112	105	96	85
Agriculture	70	68	67	66	65	63	62	61	59	57	56
Waste industry & other	9	9	8	8	7	7	6	6	5	5	4

Table 2 Overall reduction goals from 2030 on, from ref. 6. Annex 3 to Section 4

Year	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Annual reduction targets compared with 1990 [%]	67	70	72	74	77	79	81	83	86	88

Table 3 Summed annual emission volumes for the year 2020 to 2030 in the passed update of May 2024, from ref. 9. Annex 2a (to Section 4 Sentence 2)

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Summed annual emission [Mio. tons CO_2 equivalent]	813	786	756	720	682	643	604	565	523	482	438

overall savings might not necessarily rise, given that other sectors are allowed to offset this surplus by emitting additional CO_2. The government arguing for the changes by a facilitated focus on the greatest potential for savings as well as that climate targets can be achieved in a socially fair and economically efficient manner.[10] The adjustment of the law was necessary on the part of the government, as it has become clear that not all sectors can maintain their savings potentials, and this is therefore not compatible with the original law. An example is the German energy sector, as well as the transport and traffic sectors, where annual GHG emissions have been rising since 2020, after a reduction presumably caused by the COVID-19 pandemic, resulting in a widening gap between the target and actual emissions.[7] The adjustment is under critical discussion in the German media as well as in expert circles and environmental protection associations.[11–13] For example, climate associations (including Greenpeace, WWF, BUND) under the leadership of the ''Klima-Allianz Deutschland e.V.'' have formulated a ''joint appeal on the CPA amendment against the weakening of the CPA''.[14]

To picture the ongoing european process: the latest update pertains to the judgment rendered by the European Court of Human Rights on April 9, 2024, in case ECHR 087 (2024), in favor of a Swiss senior citizens' organization. In the judgment,[15] it is stated: ''The Court found that the Swiss Confederation had failed to comply with its duties (''positive obligations'') under the Convention concerning climate change.''

This strengthens climate protection from a legal perspective, but a revision by the federal government has been announced. This judgment could potentially have a signaling effect, leading to advancements not only in pure GHG reduction pathways but also in advanced energy and in carbon capture and utilization/storage (CCU/CCS) solutions.

3 Analysis

3.1 Reassessing annual GHG policies for a safe climate future.

The recent UN Environment Program (UNEP) report[16] highlights a persistent ''emissions gap'' in climate change efforts. Despite advancements in climate policies and lower costs of low-carbon energy, the projected trajectory indicates a significant 2.7 °C warming by 2100, surpassing the stringent 1.5 °C target. Governments, despite cleaner energy becoming more affordable, are expected to double fossil fuel production by 2030, conflicting with the imperative to limit warming. The examination of emissions, considering both total and per-capita metrics, sheds light on varied contributions from nations. However, a limited number of countries have updated their NDCs under the Paris Agreement, questioning global commitment to climate goals. The report stresses the urgent need for substantial emissions reductions, advising caution against excessive reliance on unproven carbon dioxide removal technologies and emphasizing the critical importance of addressing the emissions gap for a sustainable future.

In the context of Germany's efforts to align with its 2030 climate target, the recent data from the country's environment agency ''Umweltbundesamt'' (UBA) reveals a modest reduction in GHG emissions in 2022.[7] However, this reduction, amounting to about 2% across all sectors, falls short of steering Germany toward its 2030 goal. The annual reduction rate has to be tripled to 6% starting from 2023 onwards to meet the targets, as shown in our analysis.

Preliminary findings attribute the rise in emissions in the energy sector to increased coal use during the energy crisis due to disruptions in natural gas supplies prompted by Russia's war.[17] While emissions in the energy sector rose for the second consecutive year, industry emissions saw a notable drop of 10.4% (Fig. 2). This reduction, attributed to high energy prices and production cuts, prompts reflection on the need for transformative measures rather than mere reductions.[13] Germany, committed to achieving GHG neutrality by 2045, faces a critical juncture. The CPA outlines climate targets, including a 65% reduction by 2030. However, the data[7] in Fig. 1 already shows a reduction of 36.5% when the CPA came into force in 2020, signaling the need for accelerated efforts and raising the question of how ambitious these goals are.

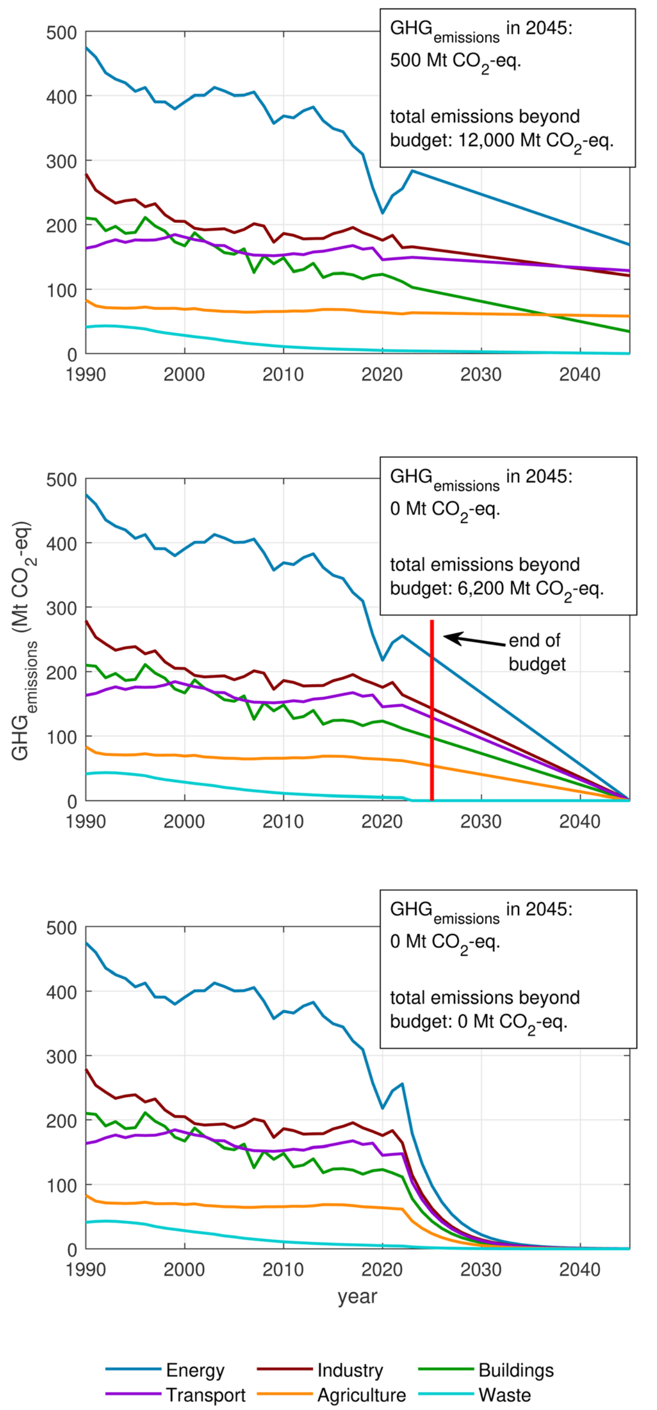

Fig. 2 Three scenarios for Germany's GHG reduction path towards climate neutrality. Top: Past-patterns-case. Middle: The linear 2045-net-zero-case. Bottom: Aspiring for 1.5 °C case.

3.2 Prospective scenarios for Germany's emission reduction path: Navigating the fictional 1.5 °C goal.

In charting Germany's course towards climate neutrality, we delve into three distinct scenarios, each offering a unique perspective on the country's emission reduction trajectory with a specific focus on the imperative of limiting global warming to 1.5 °C. The prospective calculations on reduction pathways illustrate the frequently overlooked CO_2-budget.

Calculated as an integral of CO_2 emissions over time, the budget incorporates the rate of CO_2 reduction. This reduction rate essentially represents the required pace of implementing measures by politics.

Methods

Scenario 1 (The past-patterns-case): calculated by a linear regression with the minimum square root deviation in the years 1990 to 2022 followed by linear extrapolation to the year 2045.

Scenario 2 (The 2045-net-zero-case): calculated by assuming a linear decline of GHG emissions in every sector to reach Net-Zero of GHG-emissions by 2045 in Germany.

Scenario 3 (The aspiring for 1.5 °C Case): Calculated with consideration of the CO_2-budget of 2000 Mt to achieve the 1.5 °C target with 67% certainty.[18] The associated reduction path has carried out by a parameter study of the function $f(x) = ae^{(bx-c)}$. The boundary conditions of the calculations are as follows: deviation of the integral to the CO_2-budget $<0.1\%$, $a = \mathrm{GHG}_{\mathrm{emissions,Germany}}(2022)$ of each sector and climate neutrality in 2045.

Scenario 1: the past-patterns-case as indicator for a future trajectory

GHG$_{\mathrm{Emissions}}$ in 2045: 500 Mt
Emissions beyond budget: 12 000 Mt

This scenario is based on historical GHG emission reductions since 1990, extrapolating a similar trend into the future with consistently declining average values. The inherent reduction rate from the pre-CPA era (1990–2022) would lead to a 60% decrease in annual GHG emissions by 2045. The calculated cumulative emissions from 2023 to 2045 would exceed Germany's UNEP budget by 12 000 Mt of CO_2 equivalent, while CO_2 emissions would still continue beyond 2045.

Scenario 2: the linear 2045-net-zero-case (Germanys CPA)

GHG$_{\mathrm{Emissions}}$ in 2045: 0 Mt
Emissions beyond budget: 6200 Mt

Aiming for net zero in 2045, this scenario assumes a straightforward linear decrease to zero emissions, not accounting for cumulative emissions along the journey. This scenario represents the current policy, which is focused on annual emission targets. It shows that these targets are not suited to contribute to the 1.5 °C goal, as the CO_2-budget is not considered in the German climate policies.

Scenario 3: the aspiring for 1.5 °C case

GHG$_{\mathrm{Emissions}}$ in 2045: 0 Mt
Emissions beyond budget: 0 Mt

In this scenario, Germany targets net zero in alignment with the 1.5 °C goal, tethered to a specific CO_2 budget of 2000 Mt. The steeper emission reduction path necessitates swift and comprehensive measures across sectors to achieve not just net zero but contribute significantly to global climate stability.

While striving for net zero is integral, it becomes apparent that a nuanced approach is vital. The scenarios illuminate the gap between aspirational targets and practical strategies, emphasizing the need to translate the global climate goal into actionable national plans. Critically, the focus shifts to the often-overlooked CO_2-budget, revealing potential overshoots even if annual emission goals according to the CPA are met.

Connecting the global and national perspectives, it's crucial to acknowledge that the estimated 2.7 °C global warming, as per UNEP, underscores the urgency of surpassing current policy efforts. Germany, as a significant economic player, must not merely assume a per capita share but should embrace a pioneering role. Given its higher-than-average emissions per capita and the economic influence, Germany holds the potential to lead by example, leveraging its engineering expertise to drive clean tech solutions and solidify its position in globally emerging green markets. Quantifying the urgency, the projected 2.7 °C global warming demands attention. Beyond the global implications, Germany's own economic interests align with robust climate action. With a heavy reliance on global export markets, the repercussions of climate change are set to impact not only environmental but also economic stability.

Germany's climate policies and global trends reveal a concerning reliance on tracking annual GHG emissions. While suitable for short-term goals, this approach, as seen in current policies, poses risks, steering towards a dangerous trajectory, as the UNEP's projection of a 2.7 °C global warming highlights. The UNEP report describes the inadequacy of focusing solely on annual emissions, failing to align with the aim of limiting global warming and accepting planetary ailment and severe economic consequences.[1,16] Relying on annual targets may mask the cumulative impact of emissions and neglect the profound consequences of accumulating emissions over time.

In light of these insights, the need to recalibrate climate strategies becomes evident. Robust climate action has to be based on a comprehensive approach, taking overall emissions and their underlying processes and infrastructure into account. Only through a holistic, forward-thinking strategy can we truly navigate the dangers that lie ahead, steering the course towards a safe and sustainable climate future.

3.3 German-hydrogen-strategy – a cross-sectoral pillar in the climate protection program

In June 2020, the German Federal Ministry for Economic Affairs and Climate Action (BMWK) published ''Die Nationale Wasserstoffstrategy''[19] (National Hydrogen Strategy), which is considered as the core pillar of the CPA. This strategy is intended to ensure the security of supply of the future energy sector while at the same time ensuring economic efficiency and environmental compatibility. The central goal here is the ''market ramp-up'' of hydrogen technologies to create a global market and competitiveness against fossil fuels. With a strong ''Heimatmarkt'' (German domestic market) of hydrogen production and application, global responsibility and a pioneering position should be taken. In 2023, the German government reaffirmed its intention by updating the hydrogen strategy. According to the conformation letter of the hydrogen strategy the eleven flagship projects are financed with an amount of 18.7bn € (20.6bn US$). An overview of currently running hydrogen projects and cooperation relationships with the respective funding volumes and durations is shown in Table 4.[20]

The conversion of the energy sector to hydrogen through renewable energies is based on the current strong dependence of energy supply on fossil fuels. As a result of the war in eastern Europe and the resulting sanctions against Russia, Germany's largest gas supplier so far, Russia, has also been cut off.[21] Another reason why Germany requires storage solutions is due to the substantial fluctuations in the two primary sources of renewable energy production, namely photovoltaic and wind power.[22] Additionally, Germany lacks adequate natural capacities for storage, such as those required for pumped storage power plants.[23,24] At the same time, however, the demand for green hydrogen currently exceeds the quantities that can be provided by renewable energies. In 2030, a hydrogen demand of about 100 TW h ± 10% is expected for Germany, while the production volume of 14 TW h in 2030 (28 TW h in 2040) is targeted.[19] This explains why a large part of the subsidies includes investments in feasibility studies for green hydrogen import cooperation (Table 4). For the investments considered here, the ''import-associated projects'' have a share of 64%, which corresponds to 12.06bn € (13.28bn US$).

The new import routes and partnerships will shift existing dependencies. The hydrogen strategy explicitly refers to the use of existing partnerships, but the large-scale funding volumes for future hydrogen cooperation projects bypass OPEC and further former energy suppliers such as Russia (ref. 19, Table 4). The prerequisite for new energy partnerships is a high potential of renewable energy. Since the number of partner countries is potentially limited and the political focus of the hydrogen partnerships has changed, points such as geographical distance are of secondary importance. For instance, significant investment has been made in the Australian Hydro Cooperation. This spans the greatest distance between two points on Earth. This leads to the fact that the transport price is a significant part of the total cost. Raab *et al.* have shown that the share of hydrogen costs attributable to transportation (Australia to Japan) is already between 22% and 38%.[25] The share of cost for German import from Australia would be consequently higher.

Due to the increasing grouping of the world order, as well as the recently outlined risk of pandemics, wars and thereby endangered global supply chains, Germany moves with its hydrogen strategy in the field of tension between economic efficiency, political reliability, ethical position with regard to civil rights and energy security with the highest possible degree of self-sufficiency.

The use cases of hydrogen across various sectors are diverse and entail a range of prerequisites. Utilizing green hydrogen

Table 4 Compilation of the Flagship Projects according to the progress report of the German "Wasserstoffstrategie".[20] ‡-marked investment volumes are import related

	Project	Key focus	Period	Volume Mio US$
1	Important Projects of Common European Interest H_2	Promotion of the value chain of green hydrogen, in particular production, infrastructure, use in transport, industry and heating (EU cooperation required)	2021–2027	12 100‡
2	Support program "Klimaschutzdifferenzverträge"	Subsidies for energy-intensive industries	2022–2031	605
3	General promotion concept for renewable fuels	Development of electricity-based fuels and advanced biofuels; production, market ramp-up	2021-open	1650
4	Funding programme for decarbonization in industry	Supports of energy-intensive industry (*e.g.* steel, cement) from research to large-scale application to avoid process emissions	2021–2024	3300
5	Hydrogen lead projects	Call for funding "Hydrogen-Republic-Germany – ideas competition"	2021–2025	814
6	Field laboratories of the energy transition	Transfer of research results into practice	2019–2024	660
7	Hydrogen Innovation and Technology Centre	Establishing development environments, especially for companies	2021–2024	319
8	HySupply	German-Australian feasibility study on hydrogen from renewable energies	2020–2022	2‡
9	Implementation: German-Moroccan hydrogen alliance	Construction of a green-H2-production plant (100 MW electrolysis), research platform development and facilitation of the supply chain	2021–2025	98‡
10	Promotion of green hydrogen in Brazil and South Africa	Establishment and development of a green hydrogen economy in Brazil and South Africa	2021–2023	81‡
11	H2Global	Acceleration of supply and demand markets for green hydrogen and PtX products (EU, Globally)	2022–2033	990‡

serves as one option in sectors where no viable alternative, such as direct electrification, exists, and where the requirement for additional infrastructure is minimal. Our attention turns to the German chemical industry, because the material use of hydrogen as a feedstock chemical is unavoidable. As this industry currently relies on hydrogen derived from fossil fuels, adopting green hydrogen serves as a seamless, drop-in solution to markedly curtail GHG emissions.

4 Case study – what does it take to future proof the German chemical industry using green hydrogen?

In 2022, Germany's total hydrogen consumption reached 1737 kt, with 85% (1481 kt) utilized by the chemical industry (refining, ammonia and methanol synthesis, and other chemicals), while mobility, e-fuels, steel, and power generation collectively accounted for less than 0.2% (2.5 kt).[26] Germany's utilization of green hydrogen currently (2022) stands at a modest 0.4%.[26,27] The utilization of hydrogen as a feedstock in the chemical sector is inherent and therefore unavoidable for this industry. Particularly in this sector, the provision of green hydrogen can offer a prompt alternative to the currently CO_2-emitting grey hydrogen, contributing to climate protection without requiring significant infrastructure adjustments. However, what scale does this seemingly straightforward step encompass?

This case study aims to provide a technical scale perspective. Specifically, the theoretical amount of electrical energy required to supply the German chemical industry with green hydrogen as a feedstock chemical, *e.g.* for synthesis processes, are calculated. Subsequently, we identify the necessary quantity of wind power plants to drive electrolysers to meet the current hydrogen demand and compare it with the current expansion rate of wind energy installations in Germany. By quantifying the land-side demand for these wind power plants, this study establishes a benchmark relevant for non-technical stakeholders.

Technical specification

Market-ready systems as basis for calculations

Maximum electrolyser power is 2 MW (H-TEC SYSTEMS Hydrogen Cube System, HCS-PEM); average electricity consumption is 53 kW h per kg H_2;[28] electrolysers operating time is 4000 hours of full load per year.[19] Maximum rotor power of the wind turbine is 5.56 MW (Enercon E-160 EP5 E3); the estimated average annual electricity yield at average German locations is 10 GW h.[29]

Given the specified prerequisites (box "Technical specifications"), this energy demand analysis determines that 9860 hydrogen production plants are needed to meet the hydrogen demand of the German chemical industry in 2022. This corresponds to an annual electricity demand of 78.37 TW h.

In order to cover the electricity required for the green hydrogen, renewable energy plants are needed. In the further course, reference is made to the technology of wind power. Taking into account the above assumptions (box "Technical specifications"), at least 7840 wind turbines are needed to supply the chemical industry in Germany with green hydrogen. Given 15 ha per wind turbine by the German Environment Agency,[30] the required area of the wind turbines (1175 km^2) corresponds to 168 000 football pitches (7000 m^2 per pitch) or 1.3 times the area of the German capital Berlin.

In 2023, 778 new onshore wind turbines with a total capacity of 3.85 TW h were installed in Germany.[31] If the current expansion rate of 3.85 TW h per year were to continue in Germany and be solely used for green hydrogen production,

Table 5 Results of the case study to supply the German chemical industry with green hydrogen

Annual electricity demand [TW h]	Number of required 2-MW-electrolysers	Number of required 5.56-MW-wind-turbines
78.37	9860	7840

it would require an additional 15 years to reach the calculated energy demand of 78.37 TW h (Table 5). However, it is noteworthy that these fictional newly installed wind turbines alone would only be sufficient for decarbonising the hydrogen supply for the German chemical industry and would not support other sectors in achieving climate goals.

The depicted scale of effort to substitute gray hydrogen with green hydrogen in the chemical sector, namely, the immense need for renewable energy installations to meet the additional electricity demand (78.37 TW h), a substantial land requirement (1175 km^2), and a relatively slow expansion rate of renewable energy (3.85 TW h of wind power in 2023), along with the investment and operation of approximately 9860 new electrolyzers, highlights that this seemingly simple solution involves significant political and technical challenges.

5 Conclusions

This article provides a comprehensive overview of Germany's transition to climate neutrality, combining the political framework of Germany's CPA, the implementation strategy of its key pillar, namely the ''Wasserstoffstrategie'' and the technical scale of efforts for green hydrogen production through a case study of Germany's largest current hydrogen user, the chemical industry. By elucidating these complex topics and their interfaces, we aim to provide a comprehensive and accessible overview that fosters dialogue between academia, politics, and industry. This, in turn, will help guide countries toward a robust and sustainable future.

Successful constitutional complaints by German citizens led to adjustments in German Climate Protection Act, ensuring more specific annual GHG emission savings from 2030 onward. The decision was justified with threatened liberty of the young population due to the necessity of more restrictions in the future to reach the 2045 goal. This demonstrates a functioning separation of powers between the judiciary and the legislature, positioning Germany as a potential global role model in the transition to climate neutrality. Despite Germany's 2% reduction in 2022 emissions, falling short of the 2030 target, the UNEP report reveals a persistent emissions gap, projecting a 2.7 °C warming by 2100. Three scenarios for Germany's emission reduction path reveal a gap between aspirational targets and practical strategies. A focus on annual emissions in climate policies steers towards an overshoot beyond the critical 1.5 °C threshold. A more comprehensive strategy considering the CO_2 budget is vital for robust climate action and aligning policies with a habitable planet. Through the analysis of three calculated scenarios, the alignment between German political strategy and the available CO_2 budget has underscored the necessity for stronger comprehensive measures. These measures may entail not only CO_2 reduction but also the advancement of energy utilization transitions, alongside the implementation of CCS and CCU technologies.

The findings of our German hydrogen strategy analysis underscore the governments commitment to hydrogen as a sustainable energy source. In the transition towards climate neutrality, the market ramp-up of hydrogen technologies emerges as the crucial and appropriate pathway for Germany. Given the delayed expansion of renewable energies and the resultant shortage in renewable energy capacities, the strategy gears towards collaborative imports with Western partners. In view of the transport costs for H_2 and new dependencies, the very strong focus on imports must be viewed with scepticism for the energy price level and thus for Germany as a business location.

Reflecting on the case-study with its calculated land side demand (1175 km^2) considering specifically wind as renewable energy source to electrify the hydrogen production of the German chemical industry, a comprehensive understanding of the scale of effort and its renewable power plants could be conveyed to technical and non-technical stakeholders as research institutions, companies, municipalities and politicians. With an annual electricity demand of 78.37 TW h which corresponds to 7840 windmills (each 5.56 MW) in Germany, the electrification for green hydrogen production (bulk chemical) in the German chemical sector seems currently too far ahead. The enormous technical demands for producing green hydrogen, combined with its current minimal share of 0.4% in the chemical industry, justify the focus of the Wasserstoffstrategie on imports. Moreover, these demands are a result of the absence of fundamental political decisions in the past and contributed to the anticipated exhaustion of Germany's CO_2 budget by 2025.

Bringing together the three examined levels (political framework, governmental investment strategy, and technical requirements), for Germany's energy transition a multidisciplinary approach is essential, encompassing not only CO_2 reduction but also net-negative technologies such as CCS and CCU and electrification of processes. This paper demonstrates the urgent need for establishing the framework for 'no-regret' measures, which are necessary under any future scenario. This includes the rapid expansion of renewable energy and the development of domestic hydrogen production capacities, as domestic production will still fall short of meeting demand even with accelerated expansion.

Author contributions

Valentin Benedikt Seithümmer: concept and writing, data acquisition, analysis and calculations; Julia Valentina Lutz: case study and calculation, review; Samuel Jaro Kaufmann: data verification and review; Haripriya Chinnaraj: graphics and review; Paul Rößner: concept, analysis and calculation, writing and review; Kai Peter Birke: review, funding and infrastructure; note during the preparation of this work the authors used AI in order to facilitate coding for data visualisation and linguistic optimisation. After using this tool, the authors reviewed and edited the content as needed and take full responsibility.

Data availability

All data used are available from the sources referenced in the text. Specific details regarding the data and the applied filters can be found in the respective cited references.

Conflicts of interest

There are no conflicts to declare.

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