SCHOOL OF PUBLIC POLICY
CENTER FOR GLOBAL SUSTAINABILITY

STRATEGIES TO TRANSITION AWAY FROM RUSSIAN GAS AND DELIVER CLIMATE GOALS IN GERMANY

TECHNICAL APPENDIX

Center for Global Sustainability (CGS)
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1. Data and historical trends

Natural gas consumption in Germany has increased 9% over the past ten years. In 2021, households represented 32% of natural gas consumption, followed by the industrial sector (30%) (Figure S1). Electricity generation and district heating represented 23% of total consumption, while commercial and public services represented 14%. Other sectors, such as transportation, explain 1% of total natural gas consumption in the country.

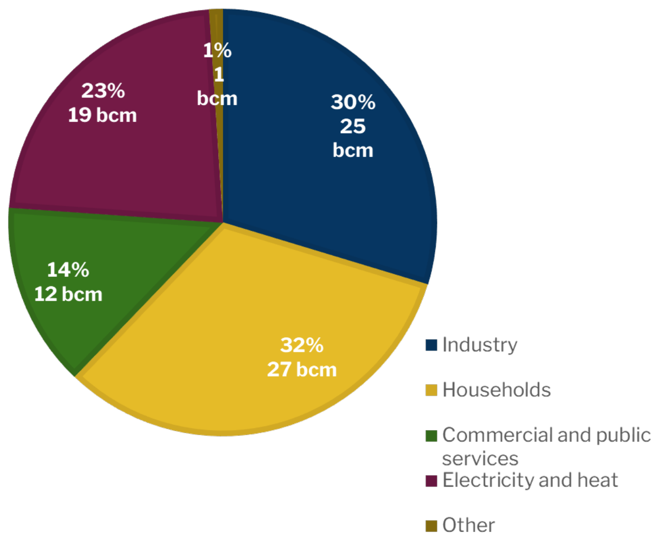


Figure S1. Gas consumption by sector in Germany (bcm), 2021[1]

The industry sector's use of natural gas has been stabilized over the past 10 years, and reached its highest level in 2017 (Figure S2). In general, the industrial sector accounted for about 30% of total Germany natural gas consumption, and natural gas was the source of about 35% of the industrial sector's total energy consumption in Germany.[2] And overall, the trend stays stable over the years, with an exception of the year 2014 when the share reached 34%. Within the industrial sector, chemical and petrochemical has the highest share of natural gas consumption, generally followed by food, beverage and tobacco, non-metallic minerals, and iron and steel.

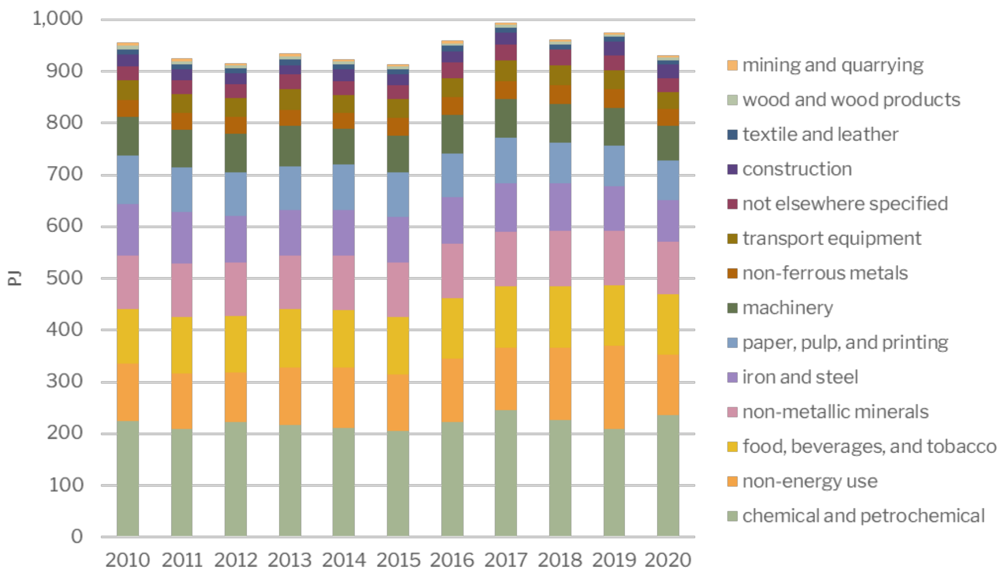


Figure S2. Historical gas consumption by industrial sector within Germany (PJ), 2010-2020[3]

The building sector's use of natural gas has been shifting over the past 10 years, but overall, has had an overall trend of slight decline. In the residential sector, which comprises most of the consumption in the building sector and thus drives the sector's trend, gas use for space heating has been fluctuating, though its overall trend is one of decline (Figure S3). Use of gas for residential hot water heating has been increasing at a rate of 1.83%, while remaining static for all other end uses. In the commercial sector, final consumption of natural gas has been fluctuating since 2010 for both hot water heating and space heating use (Figure S4).

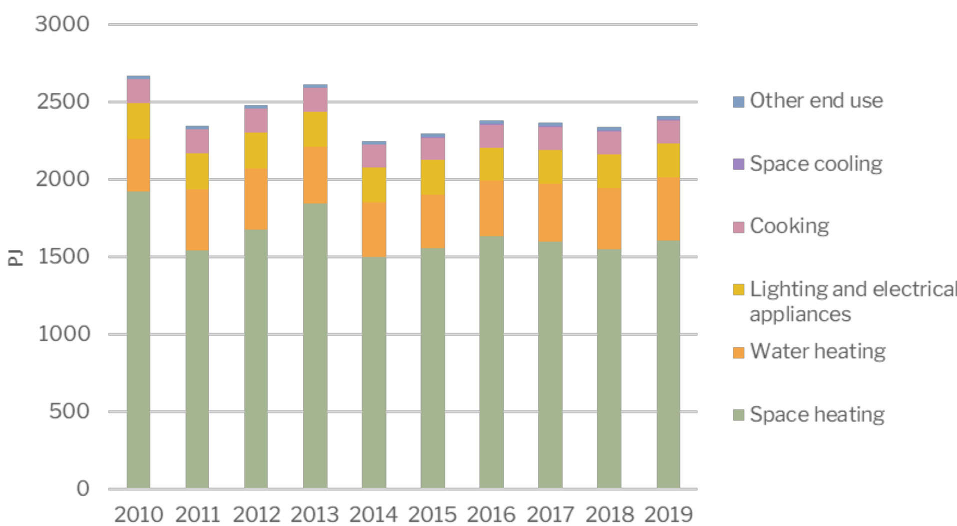


Figure S3. Historical gas consumption in residential buildings within Germany (PJ), 2010-2019[4]

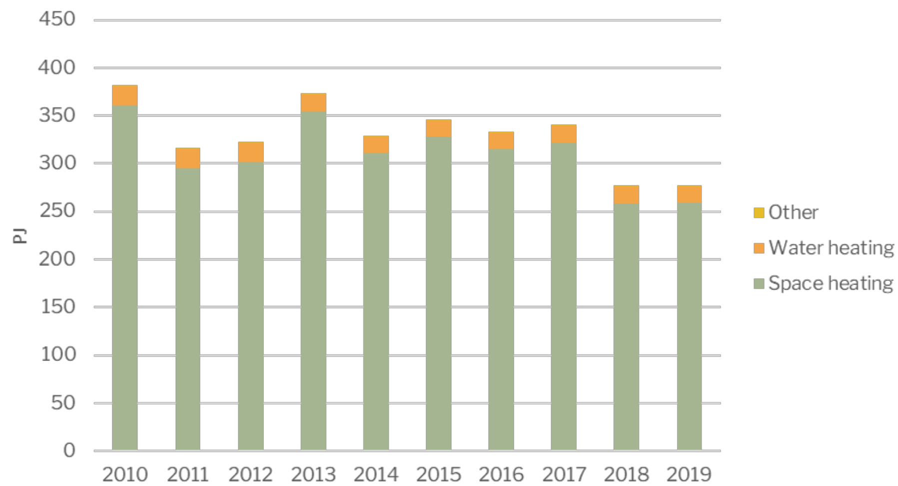
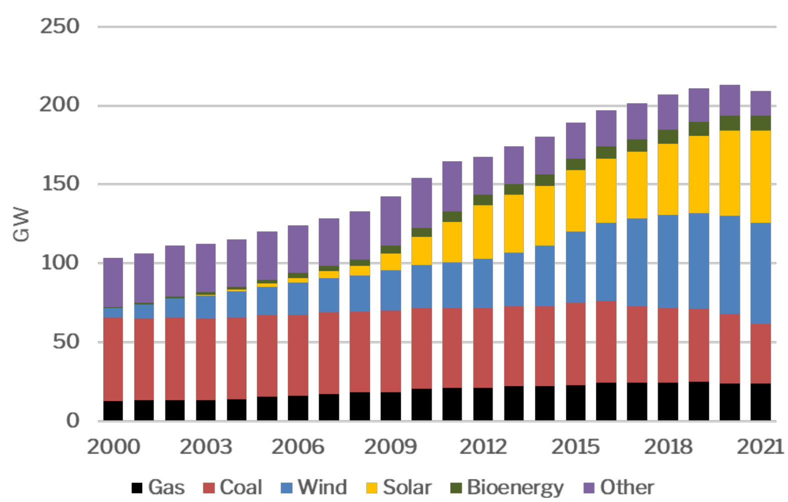


Figure S4. Historical gas consumption in commercial buildings within Germany (PJ), 2010-2019[5]

The use of natural gas in electricity and district heating has been variable over the past 10 years. From 2010 to 2014 the use of gas decreased for heating and electricity production 26%, while from 2015 to 2020, it had an upward trend, increasing 38%.[6] In the electricity sector, natural gas represented 11% of total installed capacity (Figure S5a) and 16% of total generation (Figure S5b) in 2021. The average annual growth rate of natural gas power generation was 1% from 2011 to 2021, while the natural gas installed capacity increased 12% over this period.[7] The use of coal and nuclear power for electricity production has decreased over the last ten years, being replaced largely by wind, solar and other renewable energy (RE) technologies, and by natural gas to a smaller scale. Natural gas represented 49% of total district heating in 2020. On average the share of gas in heating has remained stable over the last decade. In fact, the average annual growth rate of natural gas was -0.6% from 2011 to 2020. As in the case of electricity, the use of coal for heat production has decreased (-42%) in this period, being replaced mainly by renewable sources and biofuels.[8]

(a)



(b)

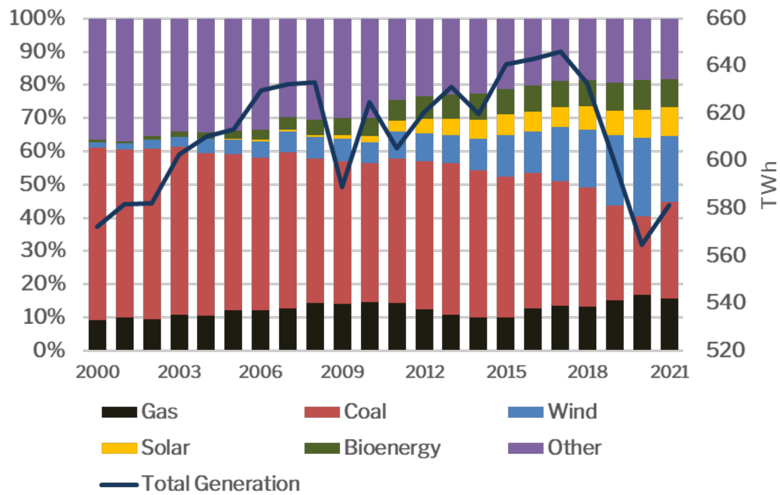


Figure S5. Historical data of electricity sector: (a) electricity installed capacity (GW); (b) electricity generation by technology (bars, %) and total electricity generation (line, TWh) (b), 2000-2021[9]

2. Scenarios for reducing gas demand across sectors

   a. Industry

The strategies to transition away from Russian gas in the industry include energy efficiency improvements, demand reductions, electrification, and switching gas to other low-carbon fuels, such as biomass and hydrogen. Meanwhile, it is apparent that the degree of potential transition away from gas varies according to different industrial processes. We select the top ten industrial sectors based on their final gas consumption and conduct scenarios based on specific industrial sectors. The total gas consumption of these ten industrial sectors listed below accounts for 95.71% of the entire sector in 2020. We utilize Eurostat as the primary data source, and additional data support from literature and reports.

EE measures

Energy efficiency (EE) has been one of the important strategies for industry to achieve a sustainable energy future. Energy-efficiency improvements in the industry covers a wide range of measures from generation, distribution to the overall system. It is generally considered to be a challenging task to fully capture the entire picture due to data limitation. Therefore, we adopted the values of a top-down approach from the European Commission study.[10] We assume a total improvement potential of 8.9 percentage points (medium demand reduction scenario) can be achieved by 2027 when compared to the efficiency level of the most current year, 2021. Our high demand reduction scenario uses an improvement potential of 12%, and low demand reduction scenario uses an improvement potential of 6%.

Demand reductions

Demand reductions covers a set of strategies that include material efficiency, and situations where customers reduce their consumption of final industrial products. Each industrial process presents different opportunities and potentials to lower material demand, which eventually leads to transit away from Russian gas. We collected and compiled the potentials of demand reductions for each key industrial sector from multiple sources, such as the Intergovernmental Panel on Climate Change (IPCC) report,[11] International Energy Agency (IEA), U.S. Energy Information Administration (EIA), etc. in Table S1.

Table S1. Demand reduction assumptions for three scenarios by industrial sectors

Industrial sector	Year (2020 to 2030)	Low Gas Reduction Scenario	Medium Gas Reduction Scenario	High Gas Reduction Scenario	Source
Chemical and petrochemical	6%	1.5%	3%	6%	IEA, 2021
Food, beverages and tobacco	40% (waste in the U.S., we can use demand reduction to save energy) (no year mentioned)	10%	20%	40%	IPCC, 2014
Non-metallic minerals	6%	1.5%	3%	6%	IEA, 2021
Iron and steel	7%	1.75%	3.5%	7%	IEA, 2021
Paper, pulp and printing	37%	9.25%	18.5%	37%	IPCC, 2014
Machinery	6%	1.5%	3%	6%	IEA, 2021
Non-ferrous metals	6%	1.5%	3%	6%	EIA, 2019
Transport equipment	15% drop from year 2020 to 2021	3.75%	7.5%	15%	Hertwich et al., 2019
Textile and leather	cloth demand dropped 30% from year 2020 to 2021	7.5%	15%	30%	Eurostat

Electrification

Electrification of fuel for industrial operations provides an effective way to transit away from combustion fuels, such as natural gas. However, the possibility of electrification differs significantly among different industrial sectors, given the different heat requirements for different industrial processes. We, therefore, assign each industrial sector with a heat temp, as low, medium, high, and very high, based on its requirement of heat temperature for production in Table S2.[12][13][14][15] We then set up the potential of electrification of fuel for each industrial sector based on the heat categories and variable technicalities today. Technically speaking, all energy required to generate heat for industrial processes up to approximately 1,000 degrees Celsius can be replaced by electricity using technology available today.[16] Therefore, we adopted the value from a Mckinsey report, and indicate that 50% of the gas consumed in the low and medium-heat-temperature industrial sectors can be electrified. For sectors listed as high and very high heat temperatures, limited potential is observed by 2030 in those industrial sectors. We only recommend electrification of fuel in the iron and steel sector.

Iron and steel sector. In EU, and Germany, blast furnace-basic Oxygen Furnace (BF-BOF) is mainly powered by coal, and electric arc furnace for direct reduced iron (EAF-DRI) is powered by natural gas.[17][18][19] Therefore, the strategy of electrification is switching EAF-DRI to EAF-scrap. And we assume 10% of the electrification in the medium demand reduction scenario, no electrification in the low demand reduction scenario, and 20% of the electrification in the high demand reduction scenario. Generally, electrically driven equipment is more energy efficient than the conventional option.[20] We use the coefficients of efficiency between technologies from the E3G report.[21]

Table S2. Heat temperatures for the top 1p industrial sectors

Industry sector (top 10)	Temperature	Heat Temperature
Chemical and petrochemical	above 1000°C	very high
Food, beverages, and tobacco	less than 100°C	low
Non-metallic minerals	above 1000°C	very high
Iron and steel	above 1000°C	very high
Paper, pulp, and printing	less than 100°C	low
Machinery	less than 100°C	low
Non-ferrous metals	165–345 °C	medium
Transport equipment	less than 100°C	low
Not elsewhere specified	less than 100°C	low
Textile and leather	less than 100°C	low

Fuel switching to biomass and hydrogen

In the iron and steel sector, the strategy of other fuel switching mainly relies on hydrogen. In Germany, natural gas is used to power EAF-DRI. Therefore, the switch will mainly focus on replacing EAF-DRI with hydrogen with DRI (H2-DRI). We use the coefficients of efficiency between technologies from the E3G report.[22] We assume that 20% of the rest of the gas will be replaced by hydrogen in this sector in the medium. No electrification in the low demand reduction scenario, and 50% of the electrification in the high demand reduction scenario. For sectors such as chemical and petrochemical, and non-metallic minerals, options for switching to other fuels include biomass (biomethane in particular) and hydrogen. We listed our assumptions in Table S3. Germany is estimated to have a potential of 100 TWh biomethane from sustainable sources by 2050.[23] Bioenergy usage in both non-metallic minerals and chemical and petrochemical sectors is about 17.6 TWh in 2020.[24] Therefore, the biomethane potential for Germany by 2027 will be about 37 TWh under an assumption of linear growth. Based on the assumption in Table S3, the total amount of biomethane needed under our medium and high demand reduction scenarios are 26 and 37 TWh, respectively. Therefore, the biomethane potential in Germany can meet the biomethane demand in our high demand reduction scenario by 2027.

Table S3. Fuel switching assumptions for three gas demand reduction scenarios by industrial sectors

Temperature	Sectors	Low Gas Reduction Scenario	Medium Gas Reduction Scenario	High Gas Reduction Scenario
High to very high temp sectors	Chemical and petrochemical	No	20% of rest of gas to biomass and hydrogen	50% of rest of gas to biomass and hydrogen
	Iron and steel	No	10% electrification 20% of rest of gas to hydrogen	20% electrification 50% of rest of gas to hydrogen
	Non-metallic minerals	No	20% of rest of gas to biomass	50% of rest of gas to biomass
Low temp sectors		30% electrification	50% electrification	80% electrification
Medium temp sectors		30% electrification	50% electrification	80% electrification

Figure S6 presents historical and projected gas demand for the industry sector for all three scenarios analyzed. These results reflect the assumptions from EE measures, demand reduction, electrification, and fuel switch presented before. Between 2021 and 2027, total gas consumption in industry declines by 80% under the high demand reduction scenario, by 43% under the medium demand reduction scenario, and by 21% under the low demand reduction scenario.

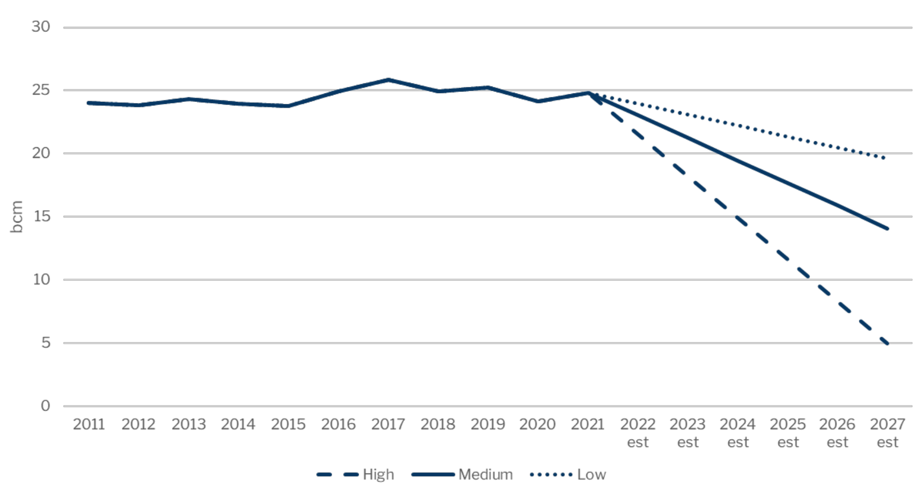


Figure S6. Historical and projected gas demand in industry under high, medium, and low gas demand reduction scenarios (bcm), 2011-2027

b. Buildings

Building Sector Data

The analysis of the building sector uses data from Eurostat on space heating and hot water heating use in the residential and commercial and public services sectors. Together, space heating and hot water heating make up 95% of total gas use in the residential sector,[25] and 49% in the commercial sector.[26,27]

All information for the building sector was gathered from Eurostat, which has data for the residential sector from 2010-2019, and commercial data from 2010-2020. The commercial sector data is not broken down into end uses, so to estimate the total final consumption for hot water heating and space heating, data from the Federal Ministry of Economics and Technology (BMWK) was used.[28] As that source contains data on end uses and final consumption, a breakdown of end uses was created by multiplying the fraction of total consumption composed of hot water heating or space heating by Eurostat's data on total consumption for the whole sector. The data from BMWK was also used to find the percentage of final consumption supplied by gas, heat pumps, and other fuels in hot water heating and space heating.

Calculations of potential gas reductions were split between these sectors and end uses, and for each a low ambition, medium ambition, and high demand reduction scenario were crafted. Gas reductions in these scenarios are brought about through heat pump deployment, assuming that heat pumps only replace gas use, and through reductions in total final consumption, brought about by behavior change, increasing energy efficiency, and increasing knowledge of energy use through tools like smart meters. Reductions in energy demand and increases in heat pump deployment were assumed to begin in July 2022, and progress through the end of 2027.

Electrification

For each sector and end use, it is assumed that heat pump use will increase. The analysis uses the Eurostat data or estimate based on Eurostat data for the addition of heat pumps in 2019 as the baseline for heat pump deployment levels. We then listed all the assumptions of heat pump adoptions for the low, medium, and high demand reduction scenario in Table S4. For this analysis, it is assumed that in the low demand reduction scenario, heat pump growth meets this previous baseline, while in the medium and high demand reduction scenarios, the previous baseline for growth is exceeded. Heat pumps directly replace gas at a ratio of 4.4:1, which accounts for the efficiency gains achieved by switching from a gas boiler with an efficiency of 88%[29] to an ambient air heat pump with a seasonal performance coefficient of 3.88.[30]

Table S4. Electrification assumptions for three gas demand reduction scenarios by building sector

Electrification					
Sector		Subsector	Low Gas Reduction Scenario	Medium Gas Reduction Scenario	High Gas Reduction Scenario
Residential	Heat pump	Space heating	3,326 TJ (2019 baseline growth rate)	6,652 TJ increase annually (2 X baseline)	9,978 TJ increase annually (3 X baseline)
	Heat pump	Hot water	329 TJ (2019 baseline growth rate)	658 TJ increase annually (2 X baseline)	987 TJ increase annually (3 X baseline)
Commercial	Heat pump	Space heating	229 TJ (2019 baseline growth rate)	457 TJ increase annually (2 X baseline)	686 TJ increase annually (3 X baseline)
	Heat pump	Hot water	28 TJ (2019 baseline growth rate)	55 TJ increase annually (2 X baseline)	83 TJ increase annually (3 X baseline)

Demand Management

Reductions in total final consumption also draw down gas use, as well as use of other fuels, as it is assumed that demand for all fuels/technologies reduces proportionate to their percentage of total consumption in 2021. For space heating, the low, medium, and high demand reduction scenarios all base demand reduction on smart meter installation and retrofits, while for the medium and high demand reduction scenarios in hot water heating reductions are based upon consumer behavior changes. For the low hot water heating scenario, however, historic trends are used to determine demand reduction. Commercial hot water demand reduction is calculated by finding the average annual change over the last 30 years. This rate of demand reduction is then applied annually, beginning halfway through 2022. The exception to this method is residential hot water heating; as use has been increasing over the past 10 years, it is assumed that under the low demand reduction scenario this growth stalls, and use remains static beginning in July 2022.

Demand Management: Space Heating

The reduction in space heating demand is achieved through building retrofits and smart meter installation. For the medium and high demand reduction scenarios, it is assumed that the retrofit rate will increase from its historic rate of 1% [31] to rates of 3% and 5%, with retrofits reducing space heating use by 24% for residential spaces and 31% for commercial buildings. This is done in order to achieve the European Commission goal of reducing energy consumption in heating and cooling by 18% compared to 2018 levels.[32] The amount that space heating would have to reduce by 2030 compared to 2015 levels was calculated, and the percentage of that reduction that would occur over 5 years was determined. In order to achieve that goal under a 5% retrofit rate, retrofits must achieve 24% energy reductions. Using this same framework, commercial building retrofits must achieve a 31% reduction in energy use. The rest of the reduction in space heating demand is attributed to increased use of smart meters. The rate of smart meter deployment for the medium residential scenario matches the previously unmet German goal of installing meters in 10% of the residential building stock annually,[33] while the commercial sector installs meters at a slightly lower rate of 7.5%. In all scenarios, use of smart meters results in space heating demand being cut by 15%.[34]

In the high demand reduction scenario, additional cuts to total final consumption are made through behavior change in residential and commercial space heating. For both sectors, over the course of the next 5.5 years, it is assumed that consumers will cut energy use in space heating to achieve 50% of the reduction seen between 2019-2020 during the beginning of the Covid-19 pandemic.

Demand Management: Hot Water Heating

Reduction in demand for hot water heating is achieved through changes in consumer behavior. Much of the demand reduction is achieved by adjusting boiler settings as listed in Table S5. It is assumed that users can achieve a maximum energy demand reduction of 8%[35] through these adjustments, and for the medium and high demand reduction scenarios, it is assumed that 75% and 100% of consumers, respectively, will make these changes over the course of 5.5 years. The rest of the demand reduction comes from decreased use of hot water, assuming that consumers change their behavior to reduce household and commercial hot water use. The demand reductions provided by both of these behavior adjustments are split over the next 5.5 years, from July 2022-December 2027.

Table S5. Demand management assumptions for three scenarios by building sector

Demand Management					
Sector		**Subsector**	**Low Gas Reduction Scenario**	**Medium Gas Reduction Scenario**	**High Gas Reduction Scenario**
Residential	Smart meters	Space heating	15% energy savings, 7.5% of houses annually	15% energy savings, 10% of houses annually	15% energy savings, 12.5% of houses annually
	Building retrofits	Space heating	1.6% retrofit rate, 24% energy reduction	5% retrofit rate, 24% energy reduction	8.3% retrofit rate, 24% energy reduction
	Demand Reduction	Space Heating	n/a	n/a	17,472 TJ (50% of reduction from 2019-2020)
	Demand reduction	Hot water	Demand remains stagnant at July 2022 levels	7.5% total, plus 75% of the population changes boiler settings	15% total, plus 100% of the population changes boiler settings

Commercial	Smart meters	Space heating	15% energy savings, 5% of buildings annually	15% energy savings, 7.5% of buildings annually	15% energy savings, 10% of houses annually
	Building retrofits	Space heating	1.6% retrofit rate, 31% energy reduction	5% retrofit rate, 48% energy reduction	8.3% retrofit rate, 31% energy reduction
	Demand Reduction	Space Heating	n/a	n/a	6,970 TJ (50% of reduction from 2019-2020)
	Demand reduction	Hot water	161 TJ (average of last 30 years' reduction)	7.5% total, plus 75% of the population changes boiler settings	15% total, plus 100% of the population changes boiler settings

Figure S7 presents historical and projected gas demand for the building sector for all three scenarios analyzed. These results reflect the assumptions from both electrification and demand reduction presented before. Between 2021 and 2027, total gas consumption in building declines by 39.5% under the high demand reduction scenario, by 22% under the medium demand reduction scenario, and by 7.5% under the low demand reduction scenario.

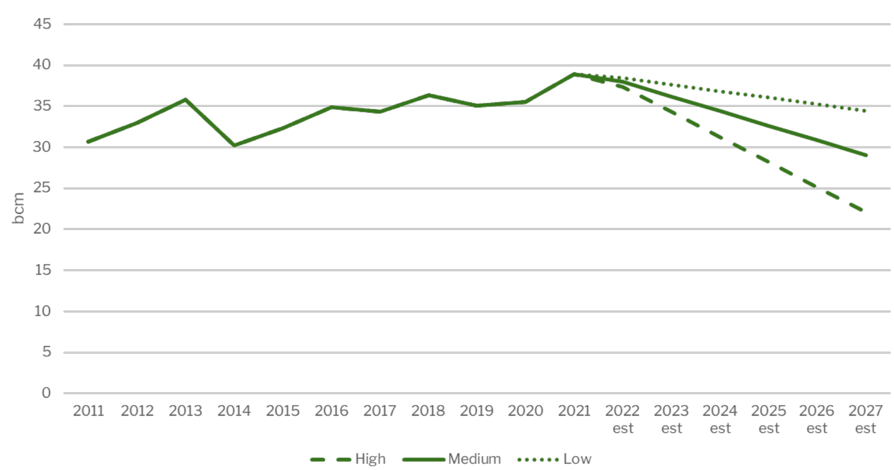


Figure S7. Historical and projected gas demand in buildings under low, medium, and high gas demand reduction scenarios (bcm), 2011-2027

c. Electricity and heat generation

Electricity and Heat Generation Sector Data

The analysis of the electricity and heating sector in this report uses data from Eurostat, Ember, Germany's Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (Bundesnetzagentur), Europe Beyond Coal, and Clean Energy Wire.

Eurstat's energy balance (2022) was used to gather historical information (2011-2020) about transformation input - electricity and heat generation - energy use, as well as gross electricity production classified by electricity-only and combined heat and power (CHP), and gross heat production classified by heat only and combined heat and power. For both the electricity and heating sectors, "main activity" and "autoproducer" information was included in the analysis.

Ember's Data Explorer tool was used to obtain updated information about Germany's annual electricity generation by source (2000-2021), monthly generation by source (2015-2022) and annual installed capacity by source (2000-2021). Bundesnetzagentur's power plants list was used to identify active gas, coal and biomass CHP power plants for 2020 and 2021, while the Renewable Energy Source Act (EEG) Report that compiles information about public energy tenders from 2017 to 2020 was used to structure the wind, solar, and biomass strategies.

Europe Beyond Coal database (May 2022)[36] was used to evaluate Germany's updated operational capacity, Germany's coal retirement plan, and to estimate the change in existing coal CHP utilization. Finally, the Clean Energy Wire report about Germany's Easter Package[37] (2022-2035) was used to establish the wind and solar additional capacity scenarios used to model natural gas phase out.

Demand Changes

Table S6 presents the electricity and district heating demand change from 2021 to 2027 for all demand reduction scenarios studied. These values reflect the expected demand for electricity and heating from industries and buildings, according to the analysis presented before, and the electricity demand expected from the transportation sector. In all scenarios, except the low demand reduction scenario, the efficiencies in electricity consumption from the industry, commercial and residential sectors offset the increasing demand from electric transportation in Germany.

For the transportation sector, we estimate the electrification rate based on government targets. For road service, in 2021, around 700,000 Plug-In vehicles (27% of new sales)[38] were sold in Germany. The share of EV in the new sales is expected to increase to 40-50% in 2025 in Germany, and 85% in 2040 in the entire EU.[39] The German government aims for at least 14 million EVs by 2030.[40] Therefore, in the low, medium, and high demand reduction scenarios, we assume 14 million, 15 million and 16 million EVs by 2030, respectively. For the rail service, we adopted 80% of electrification by 2030 for the medium demand reduction scenario based on Germany's "Electrification Plus" program. The low and high demand reduction scenario has 75% and 85% electrification rate by 2030, respectively.[41,42] As a result, electricity demand in transport will increase by 4.5 TWh, 4.9 TWh, and 5.4 TWh between 2021 and 2027 under the low, medium, and high gas demand reduction scenarios, respectively.

The demand for district heating is expected to decrease in industry and buildings, as energy efficiency is improved, and consumer behavior changes.

Table S6: Electricity and heat demand change from 2021 to 2027

	Low Gas Reduction Scenario	Medium Gas Reduction Scenario	High Gas Reduction Scenario
Electricity	5%	-58%	-61%
District Heating	-52%	-82%	-100%

Solar and wind deployment

In the high and medium demand reduction scenarios the additional wind and solar power listed in Table S7 is consistent with the Easter Package presented by the German government in April 2022.[43] Overall, the government intends to achieve a 100% carbon-free electricity production by 2035, while reaching 80% by 2030. For this, the government expects a total of 115 GW of onshore wind, 215 GW of solar, and 30 GW of offshore wind power by 2030. The low demand reduction scenario reflects for 2022 the expected wind and solar capacity to be installed in the country considering the results of the last wind and solar public tenders.[44] From 2023 to 2027, the wind and solar additional capacity considered is equal to the annual average new installed capacity of solar and wind power from 2016 to 2020.[45]

Table S7: Expected additional solar and wind power (GW)

	Low Gas Reduction Scenario			High and Medium Gas Reduction Scenarios		
	Solar	Wind	Total	Solar	Wind	Total
2022	1.2	4.4	5.6	7	3	10
2023	2.9	3.5	6.4	9	5	14
2024	2.9	3.5	6.4	13	8	21
2025	2.9	3.5	6.4	18	10	28
2026	2.9	3.5	6.4	22	10	32
2027	2.9	3.5	6.4	22	10	32

To estimate the energy provided from the new wind and solar power plants, a capacity factor was calculated for 2020, using the gross electricity production by source from Eurostat[46] and the country's installed capacity by source from Bundesnetzagentur's power plant list.[47]

Biomass CHP deployment

Expected additional biomass in all demand reduction scenarios was estimated using the results from the government auctions from 2017 to 2020.[48] The low demand reduction scenario in Table S8 considers the capacity that is expected to start operations in 2022, from 2024 to 2027. For 2022, the scenario considers half the capacity assigned in the auctions, while in 2023, considers all assigned capacity plus the capacity that is assumed missing in 2022. In the medium demand reduction scenario the expected capacity is equal to the low demand reduction scenario by two, while the high demand reduction scenario is equal to the low scenario by three. These values are consistent with Germany's energy policy and represent possible outcomes if more tenders take place in the future, to replace natural gas for electricity and heat production.

Table S8: Expected additional biomass power (MW)

	Low Gas Reduction Scenario	Medium Gas Reduction Scenario	High Gas Reduction Scenario
2022	31	61	92
2023	92	184	276
2024	61	123	184
2025	61	123	184
2026	61	123	184
2027	61	123	184

To estimate the energy available for district heating from biomass power plants, a heat/electricity ratio was calculated using Eurostat energy balance information.[49] For this, the gross heat production from combined heat and power bioenergy plants was divided by the gross electricity production from combined heat and power bioenergy plants, for 2020. This ratio was used to project the heat available from biomass plants, assuming all of them were CHP.

In addition, to estimate the energy provided from the new biomass power plants, a capacity factor was calculated for 2020, using the gross electricity production by source from Eurostat[50] and the country's installed capacity by source from the power plant list from the German Federal Network Agency.[51]

To make sure the needed biomass for the CHP plants can be obtained from sustainable feedstocks, we compare the biomass input under our scenarios to the estimated potential in Germany. According to IRENA, Germany has a biomass potential of 1.6 EJ - 2.3 EJ per year by 2030.[52] In the high demand reduction scenario, we expect the total biomass-based electricity and heat generation at 82.7 TWh by 2027. This is equivalent to 0.56 EJ of biomass input, within the potential that can be sustainably sourced in Germany.

Gas Demand in Electricity and Heat Generation

Figure S8 presents the expected gas demand for electricity and heat production for all the demand reduction scenarios analyzed. These results reflect the assumptions presented before as well as changes in existing coal CHP utilization. Under the high demand reduction scenario, natural gas is phased out in heating and electricity generation by 2023, while in the medium demand reduction scenario natural gas is phased out by 2025, and the low demand reduction scenario by 2027. Under the high demand reduction scenario gas consumption must decrease on average 69% annually between 2022 and 2023, in order to achieve total gas phase out in electricity and heat by the end of 2023. In the medium demand reduction scenario, gas demand should decrease on average 55% annually between 2022 and 2025 to phase out gas by 2025, while in the low demand reduction scenario gas demand should decrease on average 51% annually between 2022 and 2027.

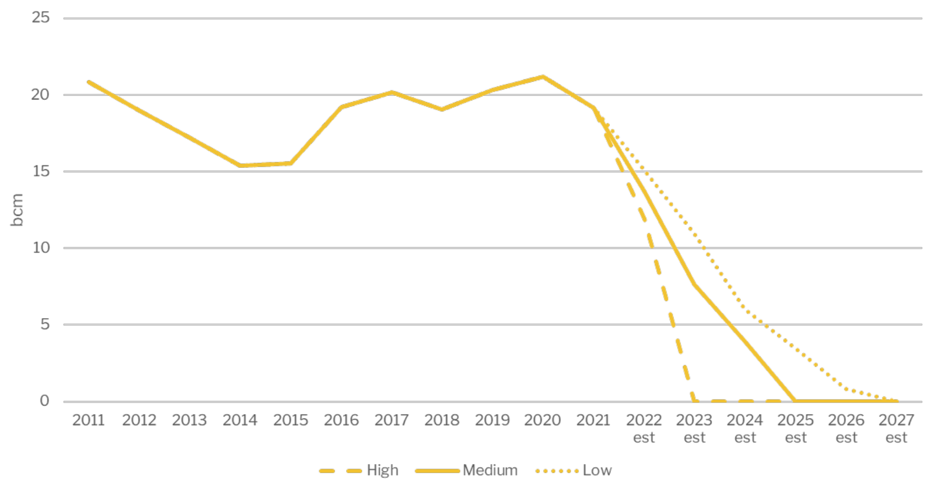


Figure S8. Historical and projected gas demand in electricity and heat generation under low, medium, and high gas demand reduction scenarios (bcm), 2011-2027

To estimate the use of coal CHP plants required to phase out natural gas in electricity and heating production in each demand reduction scenario, a dynamic model was applied. In it, additional operational hours for coal CHP plants were estimated considering the expected behavior of district heating and electricity demand, the additional wind, solar and biomass power capacity, and the timeline established for the reduction of natural gas. In all scenarios it was assumed that all the electricity and district heating demand reduction, as well as the introduction of new renewable capacity was first utilized to reduce or replace the electricity and heat produced with natural gas.

Once natural gas is removed from electricity and heat production, the lower demand for these services, as well as the remaining electricity and heat provided by the new renewable and biomass power plants, are used to reduce and replace the additional and existing coal power capacity required to remove natural gas. Table S9 presents the announced coal retirement in Germany for lignite and hard coal power plants, while Table S10 shows the expected coal retirement in the medium demand reduction scenario, in which 16,025 MW of hard coal plants and 4,600 MW of lignite plants can be phased out by 2027.

Table S9: Announced coal retirement in Germany[53]

	Hard coal					Lignite				
MW	CHP	Electricity only	Heat only	Captive	Total	CHP	Electricity only	Heat only	Captive	Total
Total open as of May 2022	15,404	3,935	169	260	19,768	13,244	6,173	85	201	19,703
Standby, deactivated, retrofitting	1,906	1,970			3,876	1,070	1,259			2,329
2022	2,092	380	78		2,550	1,419			128	1,547
2023	1,182				1,182	167				167
2024	150				150		340			340
2025					0	38				38
2026	294				294					0
2027					0					0
2028					0	2,770				2,770
2029	600				600	2,312				2,312
Not specified - before 2030	5,337		91	260	5,688	113		85	73	271
2030	100				100					0
2033							687			687
2034						980				980
2035						1,868				1,868
2038						2,507	3,887			6,394
Not specified - after 2030	3,743	1,585			5,328					0

Table S10: Coal retirement in Germany, medium demand reduction scenario

	Hard Coal					Lignite				
	CHP	Electricity only	Heat only	Captive	Total	CHP	Electricity only	Heat only	Captive	Total
2021	15,404	3,935	169	260	19,768	13,244	6,173	85	201	19,703
2022	13,498	1,965	169	260	15,892	12,174	4,914	85	201	17,374
2023	13,498	1,585			15,083	10,755	4,914			15,669
2024	13,498	1,585			15,083	10,588	4,914			15,502
2025	12,166	1,585			13,751	10,588	4,574			15,162
2026	3,743				3,743	10,550	4,574			15,124
2027						10,550	4,574			15,124
2028						10,550				10,550
2029						7,780				7,780
2030						5,355				5,355

3. Scenarios for increasing gas supply from other regions

As the second most important energy source, natural gas in Germany accounts for more than a quarter of Germany's primary energy use in 2021.[54] Meanwhile Germany is also one of the world's biggest natural gas importers, and imported around 95 percent of its gas consumption from multiple countries in 2020, such as Russia (66%), Norway (21%), Netherland (12%).

In terms of infrastructure, Germany has enough pipeline capacity to accept imports from other countries, but no has the infrastructure to receive liquefied natural gas (LNG) for now. Based on the data from Global Gas Infrastructure Tracker, Germany's pipeline capacity in operation is about 220 TJ, while 0 LNG capacity. Two proposed LNG projects are expected to start operating in 2025 (Brunsbüttel LNG Terminal) and 2026 (Stade LNG Terminal), respectively. [55]. Therefore, our scenarios for increasing supply from other regions are as follows:

Pipeline natural gas (PNG): PNG is constrained by the current infrastructure. In the short run, although Germany has enough pipelines to receive imported natural gas, the question really resides on the pipeline infrastructure of the exporting countries. Largest gas exporters, such as Nigeria, Algeria, Qatar, are lacking sufficient pipelines to connect to Germany. Therefore, only leave Norway and Netherlands in the short term.

Norway plans to open a significant number of new oil and gas fields over the next years and extraction will remain on a high level until at least 2030. "In March, production reached 316,7 million standard cubic meters per day, which is 6,3 percent above the original plans. It is also almost six percent higher than in the same month of 2021".[56] We adopted the value of 6% as the annual increase rate for the supply from Norway for all of our supply scenarios.

Liquefied natural gas (LNG): LNG provides an alternative channel for Germany to import natural gas from other countries, to cut their reliance on Russian gas. However, Germany, currently has no LNG terminals of its own, will have to rely on Floating LNG Hubs to import liquefied natural gas in the short run before the completion of their own LNG terminals. Our high supply scenario of LNG utilized the information available on the market. Therefore, between 2022 and 2024, Germany will import liquefied natural gas through the four signed contracts of renting floating terminals, 5 bcm per each contract.[57,58] Once the two LNG terminals complete in 2025 and 2026, Germany will gradually replace the floating LNG with LNG terminals.

In the low supply scenario, we exclude the option of renting floated LNG hubs to avoid locking into long-term constract, and all the LNG will be imported to Germany after the completion of the LNG terminals. We list the detailed plan of the low supply scenario in Table S13. We further visualize the low and high supply scenarios with the gas medium demand scenario in Figure S9. Our results show that Germany can feasibly and safely transition away from Russian gas by 2025 in the high supply scenario, and by 2027 in the low supply scenario.

In terms of the exports of LNG, we listed several potential candidates in Table S11:

- **United States:** US LNG exports to the EU reached 25.6 bcm in 2020.[59] Given that current German's share of total europe gas consumption is about 22%, we can assume at least 5.6

bcm of LNG can be exported to Germany. Additionally, 19 bcm of LNG was delivered to Europe in the first three months of 2022 from the US.[60] With a commitment of providing 50 bcm/year of additional US LNG until at least 2030, we are confident that the US LNG can play a major role in the short- and medium run in filling part of the neutral gas gap in Germany.

- **Qatar**: As the world's top natural gas exporter, and the largest exporter of liquefied natural gas (LNG) in the world.[61] Qatar serves as a good candidate to provide LNG to Germany. The German government signed a long-term contract with Qatar in March, 2022,[62] and with an expectation of importing LNG in 2024.[63]
- **Egypt**: Egypt is not connected to the EU by gas pipelines, its exports can only be in the form of LNG. It is technical and logically possible to import LNG from Egypt based on the LNG capacity listed in Table S12.
- **Nigeria**: Currently, one pipeline is under construction, and only goes to spain. So only LNG is possible for Germany based on the LNG infrastructure (Table S12).
- **Algeria**: Three main pipelines to the EU, but two connect to Spain, and one connects to Italy. Therefore, LNG is a better option from Algeria for Germany (Table S12).

Table S11. Potential importers for Germany

Country	Existing capacity in 2020	Potential to Germany (22%)
US	25.6	5.6
Qatar	30.2	6.6
Norway	4.1	0.9
Algeria	13.9	3.1
Nigeria	14.6	3.2
Egypt	20 (potential)	4.4

Table S12 LNG infrastructure status for Algeria, Egypt, and Nigeria

	Status	Country	Capacity	Capacity_TJ
1	Operating	Algeria	29.3	1,507,525
2	Retired	Algeria	7.8	400,774
3	Canceled	Egypt	5	256,906
4	Construction	Egypt	1.4	71,934
5	Idle	Egypt	4.2	215,801

6	Operating	Egypt	17.9	919,724
7	Canceled	Nigeria	32	1,644,199
8	Operating	Nigeria	22.2	1,140,663
9	Proposed	Nigeria	7.6	390,497
10	Shelved	Nigeria	5.7	292,873

Table S13. Assumptions for the low non-Russian gas supply scenario.

Year	Non-Russian supply needed (bcm)	New capacity (bcm)	Total additional capacity (bcm)	Import gap (bcm)	Infrastructure	Supply (low scenario)
2022	76	+1	29+1=30	46	Existing pipeline	Norway (1)
2023	66	0	30	36	Existing pipeline	Norway (1)
2024	59	0	30	29	Existing pipeline	Norway (1)
2025	51	+8	38	13	Brunsbüttel LNG Terminal	US (8)
2026	48	+6	44	4	Stade LNG Terminal	US (14)
2027	44	0	44	0	Stade LNG terminal	US (20)

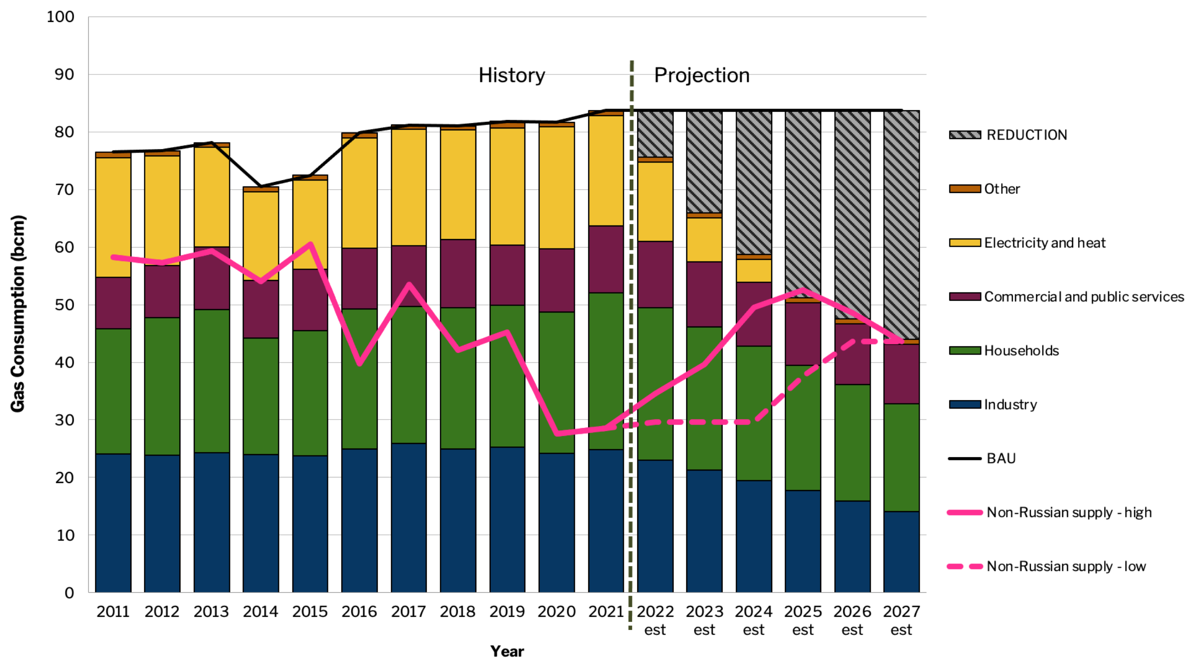


Figure S9. Historical and projected gas consumption by sector (bars) and non-Russian gas supply, the solid line shows the high non-Russian supply scenario used in the core analysis, and the dashed line shows the low non-Russian supply scenario explored as sensitivity. As a result, non-Russian gas supply under the low scenario meets demand (medium demand scenario) in 2027.

4. Results of high and low gas demand reduction scenarios

High and low demand reduction scenarios are explored as sensitivities, and specific assumptions are provided in the sections above. Here we present the combined results for these two scenarios. Under the high demand reduction scenario, total gas consumption declines from 84 bcm in 2021 to 28 bcm in 2027, or 67% (Figure S10). Non-Russian gas supply can meet the demand before 2024 with the same high supply assumptions as in the core analysis. Under the low demand reduction scenario, total gas consumption declines from 84 bcm in 2021 to 55 bcm in 2027, or 35% (Figure S11). Non-Russian gas supply cannot meet the demand by 2027 if all rented floating ships are returned as assumed in the core analysis.

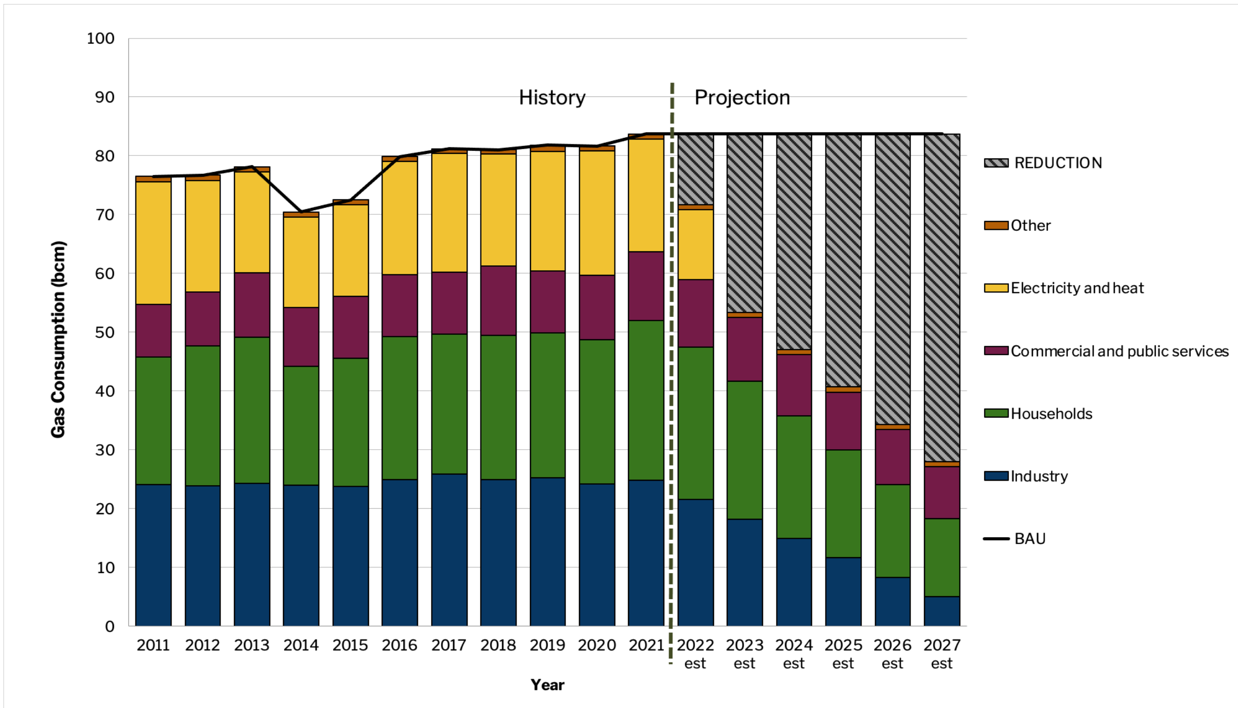


Figure S10. Historical and projected gas consumption by sector (bars) under the high gas demand reduction scenario

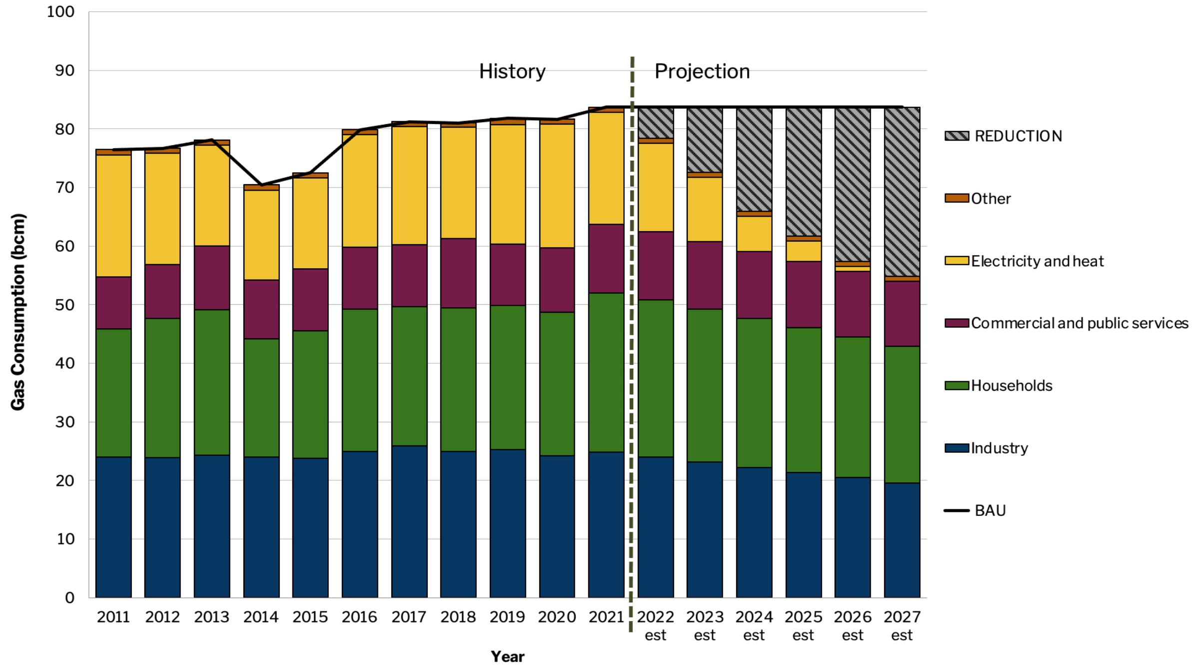


Figure S11. Historical and projected gas consumption by sector (bars) under the low gas demand reduction scenario

Figure S12 presents the range of gas consumption reductions between the high and low scenarios. Under the high demand reduction scenario, gas consumption in electricity and heat production is completely phased out by 2023, contributing to approximately 34% of the total gas reduction through 2027. Gas consumption in industry decreases by 20 bcm from 2021 to 2027, contributing to 36%, while gas consumption in buildings decreases by 16 bcm from 2021 to 2027, representing 25% of overall reductions.

Under the low demand reduction scenario, natural gas used for electricity and heat production is completely phased out by 2027, contributing to approximately 66% of the total gas reduction through 2027. Gas consumption in industry decreases by 5 bcm from 2021 to 2027, contributing to 18%, while gas consumption in buildings decreases by 4 bcm from 2021 to 2027, representing 14% of overall reductions.

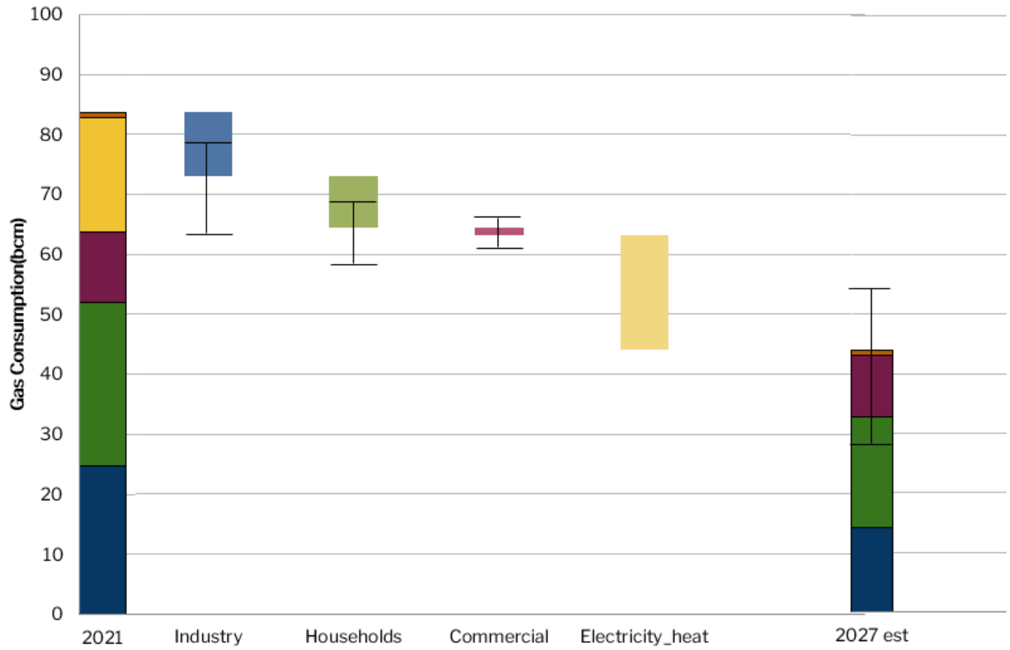


Figure S12. Range of gas consumption reductions from 2021 to 2027 by sector and strategies. Bottom of each bar shows the sectoral reduction under the medium gas reduction scenario, and the error bars show the sectoral reduction range under the high (bottom of error bar) and low (top of error bar) gas reduction scenarios; the 2027 bar on the right shows the estimated total gas consumption under the medium gas reduction scenario, and the error bar presents the range under the high (bottom of error bar) and low (top of error bar) gas reduction scenarios.

5. Comparison to 1.5°C pathways from GCAM

Using a global integrated assessment model (the Global Change Analysis Model, GCAM), we develop the pathway in line with EU (plus UK) net-zero greenhouse gas (GHG) emissions by 2050 and global 1.5°C. Overall GHG emissions decline by 13% in 2025 and 30% in 2030 from the 2020 levels under the 1.5°C trajectory (Figure S13). Energy CO2 emissions decline by 12% in 2025 and by 30% in 2030, where the electricity sector contributes to the largest reduction (by 457 MtCO2), followed by industry (with 159 MtCO2 reductions).

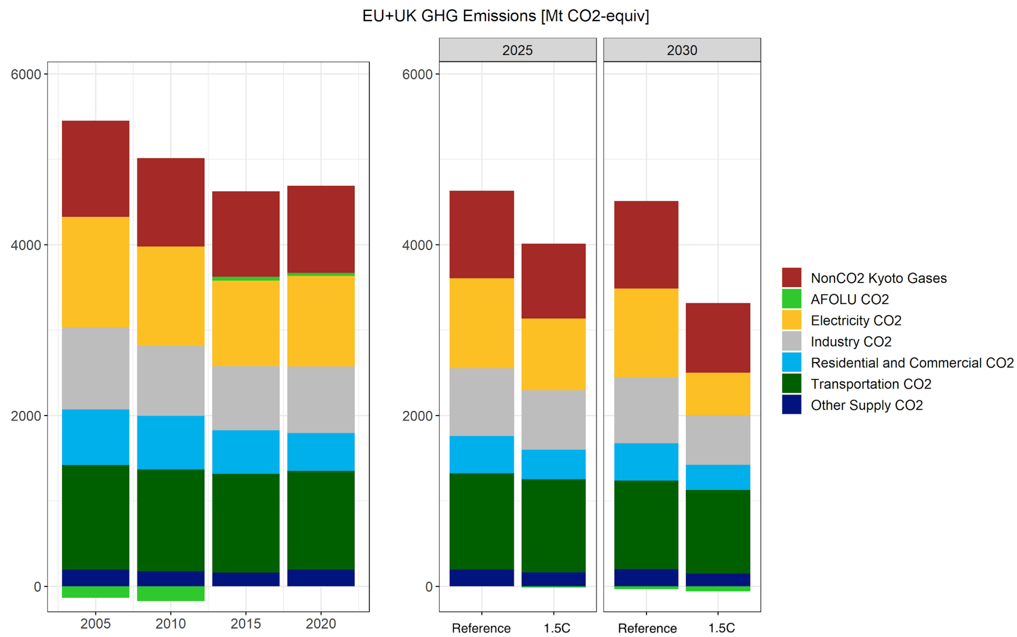


Figure S13. GHG emissions by sector for EU+UK under reference and 1.5°C trajectories from GCAM

The Global Change Assessment Model (GCAM, jgcri.github.io/gcam-doc/) is a global integrated assessment model that represents and links the world economy, energy, agriculture, land-use, water, and climate systems. It is designed to explore interactions between complex systems and gain insights about long-term trends. GCAM represents 32 geopolitical regions–including two EU regions[64] (EU-12 and EU-15)–and represents land use and agriculture in 384 land regions nested within 235 water basins. GCAM takes in assumptions about population growth and changes in labor productivity, along with representations of resources, technologies, and policies, and solves for the equilibrium prices and quantities of various energy, agricultural, water, and GHG emissions markets in each five-year period from 2010 (the calibration year) to 2100 at different spatial resolutions.

To model EU net-zero pathway, total GHG emissions for EU-12 and EU-15 are linearly constrained from 2020 to reach net zero by 2050. Other major economies with net-zero targets–including Canada, China, Japan, South Korea, Australia, the United States, etc.–are also constrained to account for the potential influence through global energy markets. A separate rest-of-the-world emissions constraint is implemented reaching net-zero CO2 emissions by 2050 to be in line with the global 1.5°C target.

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