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Future use of natural gas under tightening climate targets

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ABSTRACT

Natural gas has developed as a prominent energy source across the world over the last century. However, its use in the future will be constrained by evolving climate goals, and an optimal role for natural gas in a future 1.5 °C world is debated. We conduct a systematic review of the literature, and analysis of the Intergovernmental Panel on Climate Change SR1.5 scenarios to understand the role of natural gas in a 1.5 °C world. We also examine key factors that influence the use of gas such as Carbon Capture and Storage and Negative Emissions Technologies. We find that global gas use decreases more considerably under a 1.5 °C target than 2 °C with half of the 1.5 °C scenarios reducing gas use by at least ~35% by 2050 and ~70% by 2100 against 2019 consumption. We find there is no correlation between the level of Negative Emissions Technologies and the permitted gas use in Intergovernmental Panel on Climate Change scenarios, while there is a strong correlation between gas use and the deployment of Carbon Capture and Storage. Regionally, there are considerable ranges in gas use, with the Organisation for Economic Cooperation and Development & European Union seeing the greatest decrease in use and Asia increasing use until 2050. Notwithstanding this uncertainty, global natural gas use is likely to decrease in the coming decades in response to climate goals.

1. Introduction

Natural gas is the third most used fuel in the world, responsible for 22% of total primary energy use worldwide (BP, 2020). It is used for a plethora of reasons: It is cheap and abundant, with the boom of shale gas in the US aiding price decreases over the past decades (Hu et al., 2020). It has a high energy density and can be transported easily. It is flexible (Speirs et al., 2020), which, some proponents argue, complements intermittent renewable energy generation, through stand-by gas power plants (Insights, 2021; Ameli et al., 2020). It is also lower in air pollutants, and can be used to displace coal generation where air quality is an issue (Yu et al., 2021). Finally, it has a lower carbon intensity than coal, and can be used to replace it in many applications (Wilson & Staffell, 2018; UNECE, 2019).

However, natural gas emits methane along its supply chain and releases carbon dioxide when burned (Balcombe et al., 2017). This causes it to have a large effect on global warming, including being responsible for 12% of total anthropogenic methane emissions (IEA,

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2020). Therefore, in order to meet climate targets, the unabated use of natural gas must be constrained, and supply chain methane emissions addressed. However, potential replacements for natural gas such as hydrogen and biomethane are not yet cheap enough or produced at sufficient scale (IEA, 2019). Moreover, the current energy system is very complex (i.e. interconnected with heavily invested infrastructure relied upon for affordable and secure energy supply) which makes rapid change problematic. There are also a multitude of stakeholders and interests and the need for a just transition that is cognizant of sustainable development goals that makes any major energy transition difficult. Therefore, it is likely that some quantity of natural gas will be used in the future energy system for years to come. It is also increasingly apparent that there are significant natural gas resources relative to atmospheric capacity to cope with the emissions from their combustion and associated methane supply chain emissions (Budinis et al., 2017, 2016).

The role that gas can play in the global energy system while maintaining emissions within the limits set by global climate change targets is complex and contested (McGlade et al., 2018; Mete, G.; Stern, 2021). The amount of natural gas, and other fossil fuels, that should remain unproduced, a concept known as unburnable carbon, has been subject to previous analyses (McGlade & Ekins, 2015; Sara Budinis et al., 2016). However, changing climate targets have modified the calculation of unburnable carbon, reducing the quantity of accessible fossil fuels relative to previous analyses based on older targets (Welsby et al., 2021).

The role for the remaining natural gas, judged to be within burnable limits, is subject to a number of assumptions regarding the future development of the energy economy. Many of these assumptions are characterised within global energy models, such as those used to map potential pathways to 1.5 °C global warming targets (Forster et al., 2018). The resulting analysis of these models provides one method for identifying the relative roles of different natural gas uses while remaining within emissions limits. However, there are many ways to meet global climate targets depending on assumptions, and there is therefore uncertainty as to the future energy mix. Moreover, this analysis will explore why gas use decreases or increases and what is used to replace it in future energy scenarios. Studies examining the best use of other energy sources such as biomass within climate targets have been previously conducted, illuminating the way forward for optimal use of the resource (Woolf et al., 2016; Codina Gironès et al., 2017; Hoefnagels et al., 2017; Slade et al., 2010).

This paper presents results of a systematic review of the available evidence around future natural gas use, utilising the IPCC 1.5 °C scenarios (Daniel Huppmann et al., 2019), and literature surrounding the best uses of natural gas to bring clarity to the debate. This paper focusses on the outcomes of whole system energy models and the scenarios investigated in the 1.5 °C Special Report (SR1.5) analysis. The extent to which considerations of political economy, sustainable development goals or other economic, social and demographic issues influence natural gas use is largely confined to the considerations within the SR1.5 scenarios. This paper explores the findings of the review, the consensus of the evidence on where natural gas fits in 1.5 °C energy scenarios, how this changes between global regions, and what are the most important variables defining these regional differences.

2. Methodology

2.1. Systematic review

This paper summarises some of the key findings from a systematic review that uses an adapted methodology created by the Technology and Policy Assessment (TPA) group, part of the UK Energy Research Centre (UKERC) and refined by the SGI for its White Paper Series (TPA, 2023; SGI, 2023). The methodology uses systematic and well-defined search procedures to document the evidence review, providing clarity, transparency, replicability and robustness to the analysis. An external expert advisory panel was appointed with a broad range of perspectives to consult on the initial framing and specification of the review procedure, as well as providing additional comments throughout the course of the project as the analysis emerged. The research outputs were reviewed by the expert panel prior to publication.

2.2. Regions

We examined each region within the SR1.5 database. This is aggregated to 5 regions, detailed in the SI.

- OECD and Europe;
- Latin America and the Caribbean;
- Asia;
- Middle East and Africa (ME & Africa); and
- Eastern Europe and Former Soviet Union (EE & FSU) (Daniel Huppmann et al., 2019);

We also examined the literature from countries within these regions to garner further information where available. These studies were predominantly from, the EU, USA, UK, China, India and Latin America.

2.3. Climate models

In 2014 the IPCC collated several climate models in the Assessment Report 5 (AR5) database to examine scenarios that were compatible with 2 °C warming. The next iteration of this database, AR6, was launched in 2022 but was not available at the time of writing. The 1.5 °C Special Report, and accompanying database of scenario outputs, was published to support climate target development in advance of the release of AR6, generating scenarios meeting the 1.5 °C target as well as the 2 °C target. The 100 s of scenarios created represent different potential future energy systems with varying levels of gas use.

We examined the data from all scenarios that met a 1.5 °C warming target by 2100 (high overshoot, low overshoot and below 1.5 °C). All data was examined from 2020 until 2100. This allowed us to plot the correlation between different factors that may affect natural gas use, such as replacement fuels, Carbon Capture and Storage (CCS) and Negative Emission Technologies (NETs).

2.4. *Natural gas use within climate targets*

To meet current climate targets there is a calculable amount of carbon that can be emitted; a global carbon budget. From this total carbon budget we can estimate the optimal or 'best use' of natural gas fitting within this budget using energy system models as described above. The global carbon budget is uncertain, and subject to several factors including environmental tipping points, climate sensitivity and the feasible quantity of negative emissions technologies (NETs). However, we must define the term 'best use', starting with why we want to find what best use is, before exploring the consequences of interpretations of the term, and how we define it.

2.4.1. *How to estimate optimal use of natural gas within climate targets*

Here we focus on the outputs of energy system models and their assessment of optimal use of natural gas (i.e. what is the least-cost way to use natural gas within emissions targets). However, there are many different criteria that could be optimised for when estimating future natural gas use.

Optimal use of natural gas can be defined through optimisation for specific criterion or criteria. There are many different criteria that can factor e.g. the sustainable development goals, of which climate is only one criterion. Adding each layer of optimisation criteria further complicates the question. Fig. 1 shows an illustration of potential optimisation criteria, within a carbon use consistent with 1.5 °C alongside their potential outcomes. Separate optimisation criteria, highlighted around the outside of the illustration, may be combined in a multicriteria optimisation (in the centre) necessitating some compromised outcome that may not reflect the outcomes of any of the single criterion optimisations. This is not an exhaustive list. However, it is meant to be a representation of how the selection of criteria can change the outcome. IPCC scenarios use modelling approaches to combine economic energy system models and climate targets to address two of these criteria simultaneously.

2.5. *Analysis*

2.5.1. *Correlation between variables*

Simply averaging across every scenario in SR1.5 to understand the future trends in gas use would be a simplification which neglects the variations seen in each scenario. Therefore, we examine the relationships across all scenarios by plotting scatter graphs of key energy vectors change in consumption rates against the change in consumption rates for natural gas in each region. The correlation (R squared or R) values, which quantify the extent to which change in one variable is linked to change in another are calculated. From this we examine how the growth of a technology or energy alternative may affect the final use of gas.

2.5.2. *Data visualisation*

The data presented in this paper shows significant variation across scenarios. This variation is a function of the differing modelling

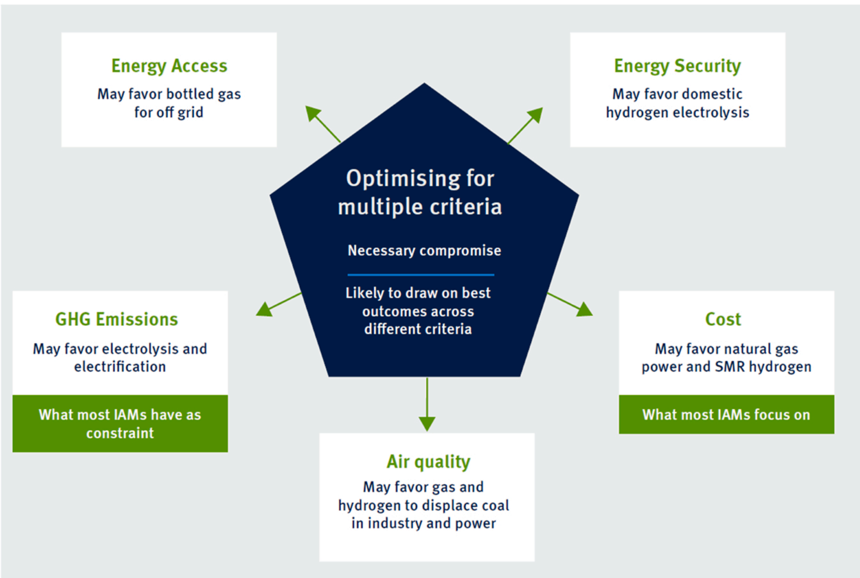


Fig. 1. Illustrative figure showing different optimisation criteria.

approaches, assumptions and scenarios. This variation is represented here in two ways.

In the first, where data is represented for a specific moment in time (e.g. 2050) a 'violin plot' is used (explained in more detail in the SI). This plot is very similar to a 'box and whisker' plot. Each specific scenario is represented by a circle and the density of scenarios in an area is represented by the width of the violin. This allows for information about the distribution of scenarios to be presented clearly. In this plot the mean is represented by a straight line, the median is defined by a white circle, the interquartile range is represented by a grey box and the lower and upper adjacent values are the grey line. Outliers are all points outside of this range.

The second is a 2d histogram where each scenario is plotted on a figure where the x axis displays the year and the y axis the quantity of natural gas use. Summing over all the scenarios and smoothing the data can more clearly show the trends across several scenarios.

3. Results and discussion

3.1. Global natural gas use

Globally natural gas use trends down between 2020 and 2100 (Fig. 2). However, there is a large range of scenarios with some seeing increases to 2050 before modest declines to 2100. The majority however envisage a rapid decrease in natural gas use until 2050, after which there is a slower decrease or maintaining of natural gas between 0 and 100 EJ/year to 2100.

Comparing the differences in natural gas use between 1.5 °C and 2 °C scenarios (Fig. 3) we see that 2 °C permits natural gas use considerably higher than 2019 use whereas 1.5 °C has most scenarios below 2019 use in 2050. By 2100 both 2 °C and 1.5 °C have lower natural gas use than in 2019 with 2 °C having a far greater range with some scenarios permitting over 200 EJ/year. However, most scenarios permit natural gas use in the range of 0–100 EJ/year with half of the IPCC 1.5 °C scenarios reducing natural gas use by at least ~35% by 2050 and by ~70% by 2100 against total natural gas use in 2019. The broad trend from this comparison is that moving from a 2 °C climate target to a 1.5 °C target constrains the future role of natural gas in most scenarios. However, the significant range of outcomes does allow for a future where natural gas continues to play a significant role in the energy system, particularly to 2050. This is in broad agreement with the IEA's net zero scenarios where gas use decreases to 2050, however at a manageable pace of an average of 3% per year (IEA, 2021). Within this decrease there is a significant shift to abated gas use. Abated gas use increases to over 50 EJ in 2050, with the majority of this being used in the energy production sector. This is also seen in the SR1.5 scenarios (Section 3.3).

Comparing these future levels of natural gas use to the total natural gas reserves and resources (Fig. 4) we see it is likely that natural gas use under 1.5 °C scenarios needs to be constrained below what is estimated to exist, even when compared to 2 °C scenarios. Under many scenarios this means leaving easy to access, economically attractive fuel in the ground.

3.2. Does future natural gas use depend on NETs?

Arguments are often made that cite the high use of NETs as unrealistic, and as an enabler of fossil fuels such as natural gas. To assess this, we examined the carbon captured by NETs against the carbon emitted by natural gas cumulatively from 2020 to 2100 in scenarios that meet a 1.5 °C warming. Fig. 5 presents this comparison. The figure is ordered by lowest to highest natural gas emissions scenario, showing that the quantity of emissions captured by NETs in this comparison appears to be largely independent of emissions from natural gas, with an R squared value of 0.0235. This could be due to the huge emissions across all sectors, independent of gas use that must be accounted for the reach a 1.5 °C target.

When we look at the 10 scenarios with the lowest NET dependence compared to the 10 scenarios with the highest NET use we see

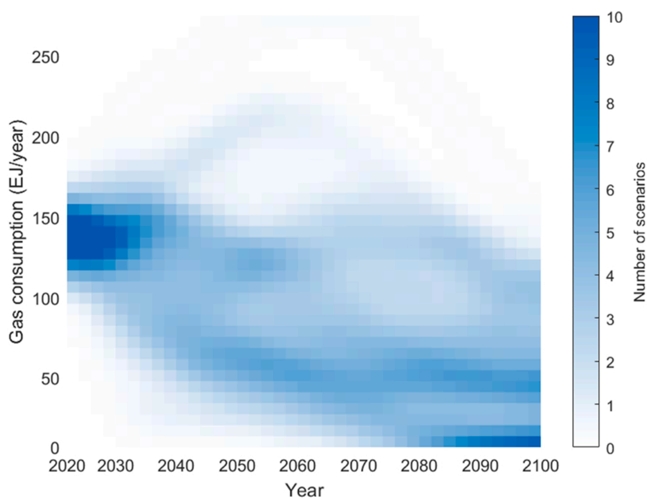


Fig. 2. Total worldwide primary energy natural gas consumption in scenarios that meet 1.5 °C from SR1.5.

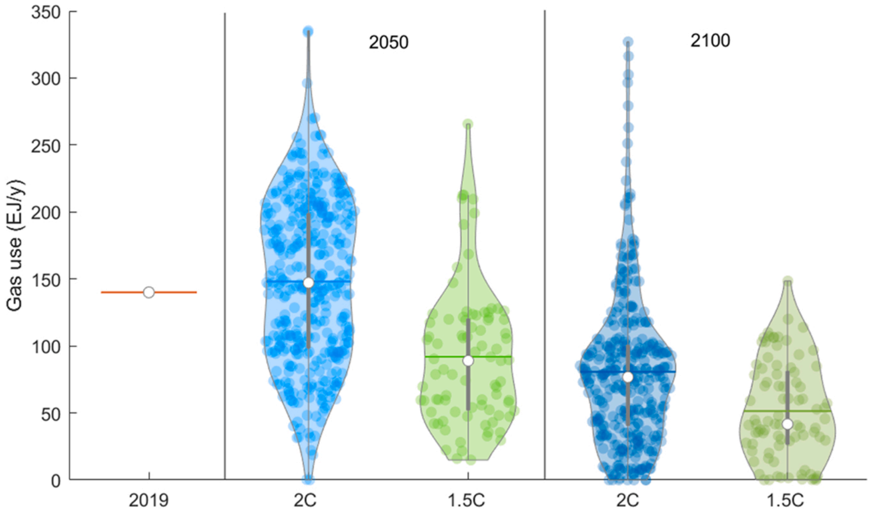


Fig. 3. Natural gas in primary energy in global whole energy system scenarios that meet a 1.5 °C warming target.

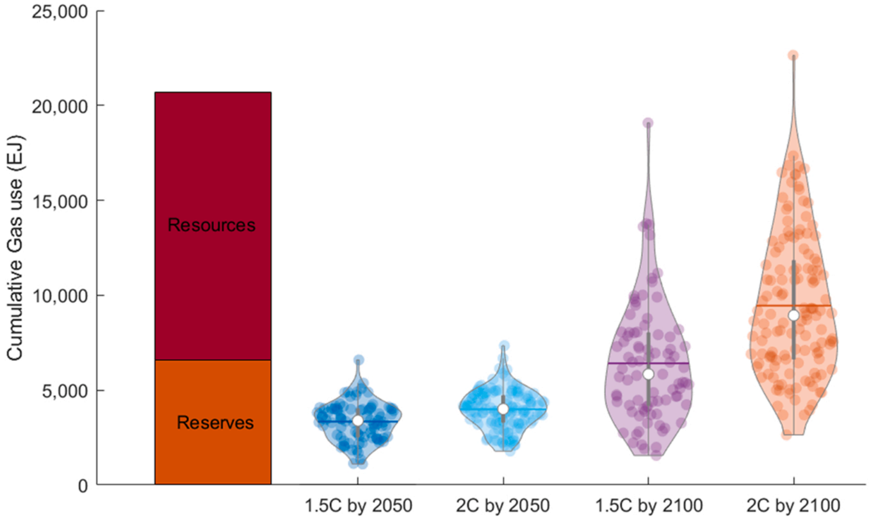


Fig. 4. Total natural gas use in 1.5 °C and 2 °C scenarios in SR 1.5 against total gas reserves and resources **Reserves are estimated volumes of natural gas anticipated to be commercially recoverable from known accumulations from a given date forward, under existing economic conditions, by established operating practices, and under current government regulations. Resources are generally accepted to be all those estimated quantities of natural gas contained in the subsurface, as well as those quantities already produced. Sometimes called "Petroleum-in-place" or "Resource Base". Definition from Society of Petroleum Engineers (SPE).*

that gas use is on average 85.8 EJ/y compared to 84.6 EJ/y, while NET use is 4.8 times higher. This again shows the very high NET use is not particularly sensitive to levels of gas use. From this analysis we can conclude that the level of NET use in a scenario is driven by factors other than natural gas use and that NETs are not used as an enabler for natural gas use. However, given a constrained carbon budget, one additional $MtCO_2$ from natural gas use would inevitably lead to a commensurate removal of carbon via NETs or elsewhere.

3.3. Dependence on CCS

The relationship between abated natural gas use and total natural gas use in future energy systems is important. First, to understand whether the total quantity of natural gas changes with increasing CCS use. Second, to understand the implications of CCS struggling to develop sufficiently quickly. To gather evidence for these two questions total primary energy natural gas use against total abated natural gas use from 2020 to 2100 is presented in Fig. 6a. This shows a clear trend of increasing total natural gas use with increasing abated gas use. Therefore, in order to meet climate goals with natural gas still remaining in the system CCS is crucial. Moreover, as the outcome of CCS deployment today is uncertain, investments may be made in gas infrastructure that locks in natural gas use without the

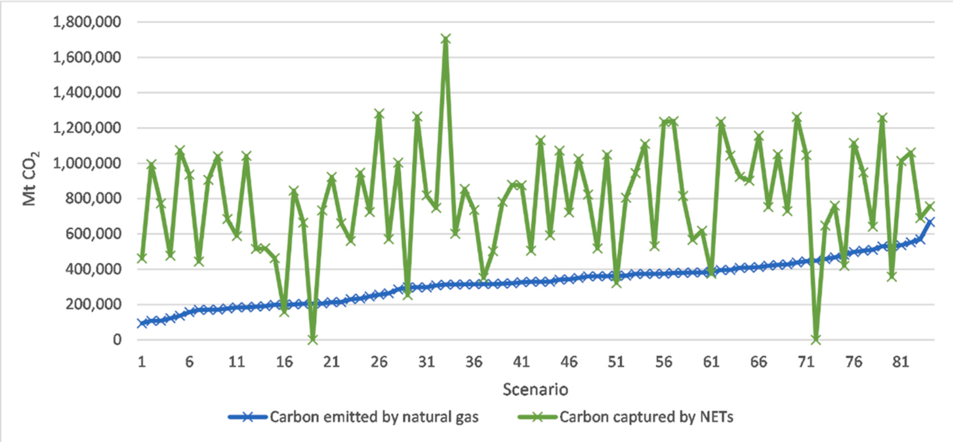


Fig. 5. Emissions from natural gas use against emissions captured by negative emissions technologies (NET) in scenarios that meet the 1.5 °C target
Note: Scenarios ordered along x axis by emissions from natural gas use. Includes 1% methane leak rate with a GWP of 37, and 50 $MtCO_2$ per EJ gas from the combustion of gas (EIA, 2021). An 80% capture rate is assumed for the gas with CCS. The specific scenarios underlying the data in Fig. 6 are presented in the Supplementary Material.

CCS system to abate it or strands these assets where their use is restricted. Should such a scenario occur, alternative energy vectors may be required to meet any supply deficit. Additionally, biomethane and hydrogen may be able to utilise the existing natural gas infrastructure and recoup some of the losses.

The role of natural gas for electricity generation without CCS while dominant currently, decreases significantly in next 30 years. Conversely, the role of natural gas electricity generation with CCS increases steadily until 2050, with most scenarios reaching at least ~8EJ/y, or 70% of gas electricity generation in 2050 (Fig. 6b). Scenarios tend to agree that natural gas power generation with CCS decreases from 2050 to 2100. However, the range of scenarios is far broader than the scenarios without CCS, suggesting more uncertainty or variation across scenarios.

3.4. Regional natural gas use

Fig. 7 shows the variance in yearly natural gas use in 2020, 2050 and 2100 for all of the examined regions. First we see that all regions other than Asia show a general trend of reducing natural gas use until 2100. The main differences between the regions are not whether natural gas decreases, rather how rapidly it does. In Asia, scenarios show flat or slightly increasing natural gas use between 2020 and 2050, before reducing natural gas use significantly to 2100. The most significant reduction in natural gas use is found in the OECD and EU countries, where natural gas use in at least half of the scenarios reduces from over 50 EJ/y in 2020 to approximately 30 EJ/y in 2050 and approximately 15 EJ/y in 2100. This decrease seems far more plausible in light of the war in Ukraine and the move away from gas across Europe. In all regions there are a limited number of scenarios that see an increase in natural gas use between 2020 and 2050 reflecting the uncertainty in the optimal uses of natural gas in each region. However, these scenarios run against the grain and the overwhelming likelihood is a decrease in natural gas use of varying degrees in each region.

The data in Fig. 7 can also be examined in the form of a 2d histogram (Fig. 8). This shows the uncertainty and pathways to reach different levels of natural gas use. These scenarios show four main trends:

1. Natural gas use in the OECD + EU and Eastern Europe & Former Soviet Union countries does not increase by any significant amount in any scenario which is likely due to the very high starting values.
2. Both Asia, ME & Africa and Latin America have some scope to increase their total natural gas consumption while remaining within 1.5 °C. However even here many scenarios predict a decrease in total natural gas use.
3. There is not much consensus on what the optimal quantity of natural gas use is across the scenarios.
4. The main difference between regions is in how fast natural gas use decreases, not whether it decreases.

Moreover, there is disagreement in the literature on how to justly undertake the energy transition. In many countries such as in Africa, clean growth without widening the poverty gap is very desirable. Therefore in many regions it is logical to reduce gas in specific areas, while increasing in others (Bugaje et al., 2022). This highlights the local variability within the optimal use of gas. However, Kemfert et al. (2022) believes expanding natural gas would put the energy transition at risk. This further confirms the disagreement within the literature that is seen within the scenarios. Therefore, nuance is required, any broad analysis done here shows the trends, but does not contain the exact answers for individual countries.

3.4.1. Regionally comparing to AR6 scenarios

While this work does not focus on the AR6 scenarios, as they were released after the time of analysis. Some comparisons are useful

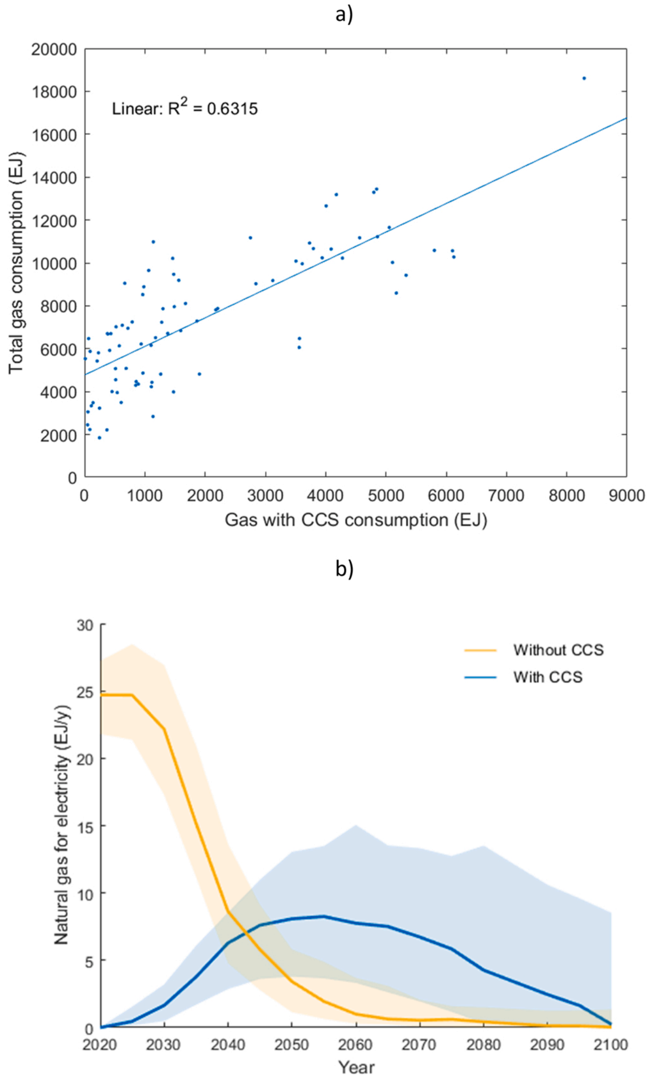


Fig. 6. a) Total cumulative gas use against cumulative gas use with CCS from 2020 to 2100. b) Secondary energy gas use for electricity with and without CCS. The central line is the median, the shaded areas represent the 25th and 75th percentiles.

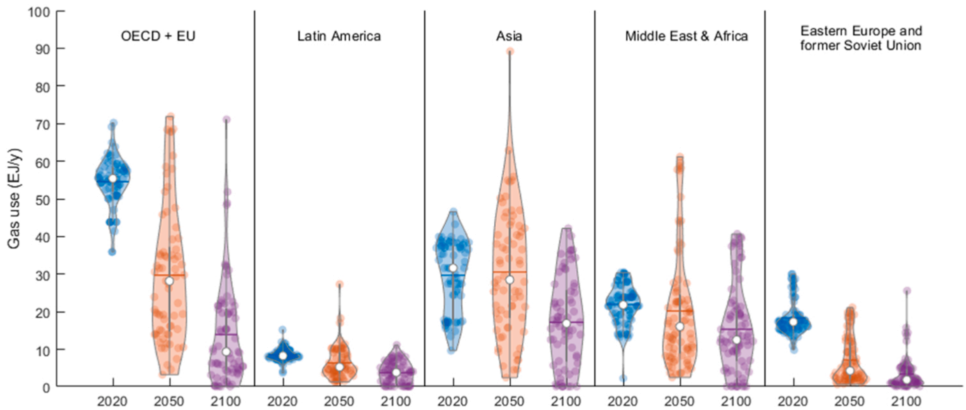
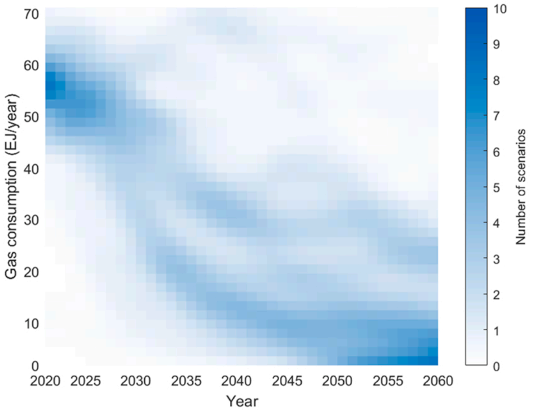
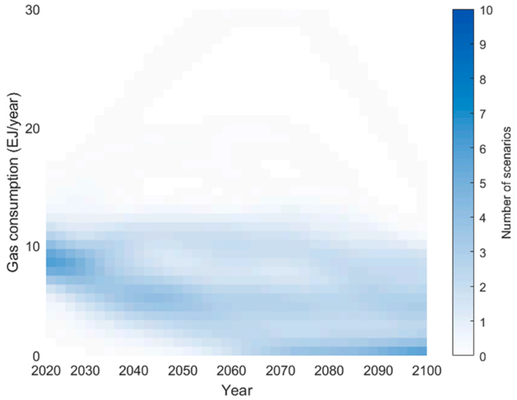


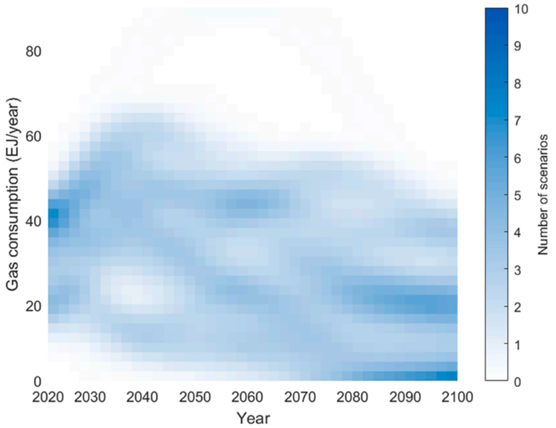
Fig. 7. Regional distribution of primary gas use in 2050 and 2100 in the five regions used in the scenarios modelled for the 1.5 °C special report.



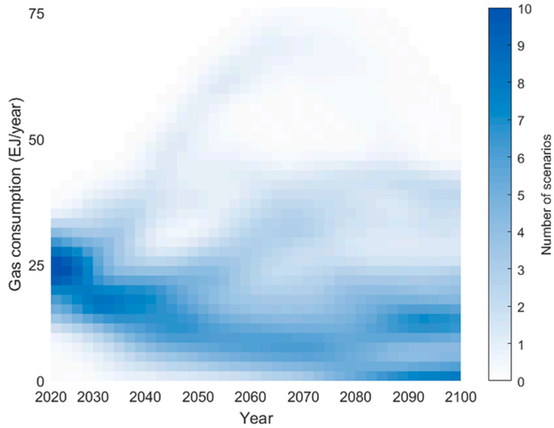
a) *Natural gas use in the OECD + EU*



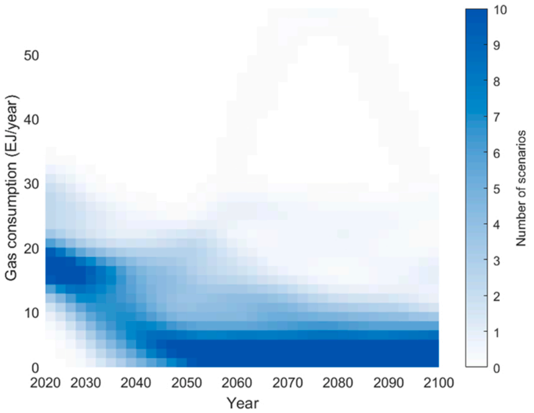
b) Natural gas use in Latin America



c) Natural gas use in Asia



d) Natural gas use in the Middle East and Africa



e) Natural gas use in Eastern Europe and the Former Soviet Union

Fig. 8. The future gas consumption in all scenarios that meet 1.5 °C warming across each SR1.5 region.

due to the AR6 scenarios being broken down into countries. From the AR6 scenarios we can see that the analysis does not change. In order to meet 1.5 °C targets gas use has to significantly drop in each region. However, there is uncertainty in the route, particularly in the India and China regions. With gas use in China increasing to a peak in 2040 and gradually decreasing until 2090 in most scenarios, but in others gas use never rises and remains steady. In India, gas use increases more modestly to 20 EJ/year in 2040 and stays level in most scenarios until 2100, however some scenarios allow for large increases in gas use post 2050. This uncertainty underpins the large possibility of ways to reach 1.5 °C while using gas in certain countries.

In large gas producing countries such as the US gas use decreases in all scenarios, however there is a range of possibilities over the speed of decrease, with most scenarios seeing rapid declines until 2050 and almost no gas use in 2100. However, others see a bounce back post 2050 to gas use at levels close to the current day. Russia sees gas use at steady levels until 2030, where it drops and remains low to 2100.

This comparison to AR6 scenarios supports the findings of this paper and the SR1.5 scenarios. That there is still uncertainty in how much gas use must decrease by, and when. But that there must be a decrease. Moreover, it demonstrates that within Asia countries such as India and China have scope to increase gas use up to 2050, and replace less green fuels in the process.

3.4.2. What replaces natural gas

We examined the relationship between the change in natural gas use and various key energy vectors. This was achieved by plotting scatter graphs of the change in consumption rate for each year, for each region to calculate an R squared value, as explained in Section 2.5. This indicates which energy vector appears to replace natural gas in each region. Fig. 9 shows these R squared values. Renewable power increases across all regions, but not necessarily to replace natural gas in the energy system, as the increases often outstrip the decreases in natural gas use. The correlation between renewables growth and gas use reduction appears most profound in the OECD + EU regions where natural gas is reduced at a much greater rate. Solar power has potential in the Middle East and Africa to replace natural gas, but wind and hydrogen show no correlation with natural gas use.

3.4.3. Sectoral breakdown

We examined the changes in consumption of natural gas, hydrogen and electricity in each sector against the changes in total energy use in that sector from the SR1.5 database. The linear correlation coefficients (r) for this analysis are shown in Fig. 10. It must be noted that natural gas is not separated out from biogas and coal-gas in the sectoral breakdowns, so this analysis includes them, though their effect will likely be minimal across the regions, although local deviations from this will be possible.

The relationship between total energy consumption and natural gas use in the residential sector shows no strong correlation in any region meaning that natural gas use in this sector is not driven by total energy requirements. The main source of energy increases in the residential sector in all regions is electricity, meaning heat pumps, electric stoves and heaters play a role in future energy systems. Hydrogen shows some correlation in Latin America and Asia as a fuel source for the residential sector, helping to drive increased energy demand. This correlation is not seen in the OECD + EU regions where hydrogen use does increase, but total energy use can either decrease or increase with no correlation to the total hydrogen quantity used.

In the literature the OECD + EU subregions examined appear to agree on the need to remove natural gas from the residential sector. In the EU the decline of natural gas alongside increasing hydrogen consumption is seen in the sector (Peters et al., 2020; Terlouw et al., 2019). Similarly in the US, electrification of heating and cooling is seen as a potential way to decarbonise domestic energy use (Wu & Skye, 2021). In India, residential gas consumption is very low, and heating is of lesser concern than in the OECD. A major challenge is the desired growth of natural gas for cooking, which could replace traditional biomass as a cleaner and easier fuel (Kumar et al., 2020). There are therefore likely to be increases in natural gas use for this reason, which is reflected in the mean increases up to 2050 then declining to 2100 when electrification will become more available. In an analysis by Jiang et al. (2018) it is estimated that natural gas use in China will increase in the urban residential area up until 2030, where it will see sharp declines, when replaced by electricity and reduction in consumption.

Natural gas shows some negative correlation to energy use in the industrial sector for the OECD + EU, meaning natural gas becomes

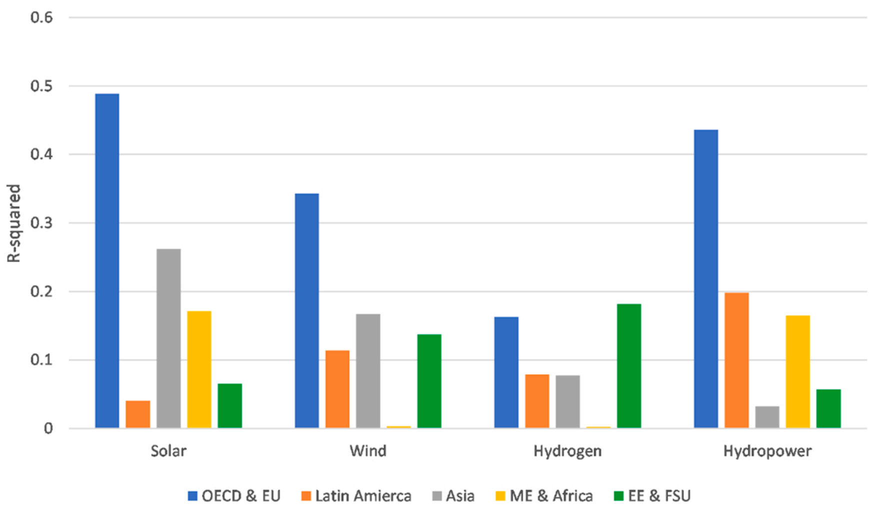


Fig. 9. R – squared value for different energy vectors change in consumption vs change in gas consumption from 2020 to 2100.

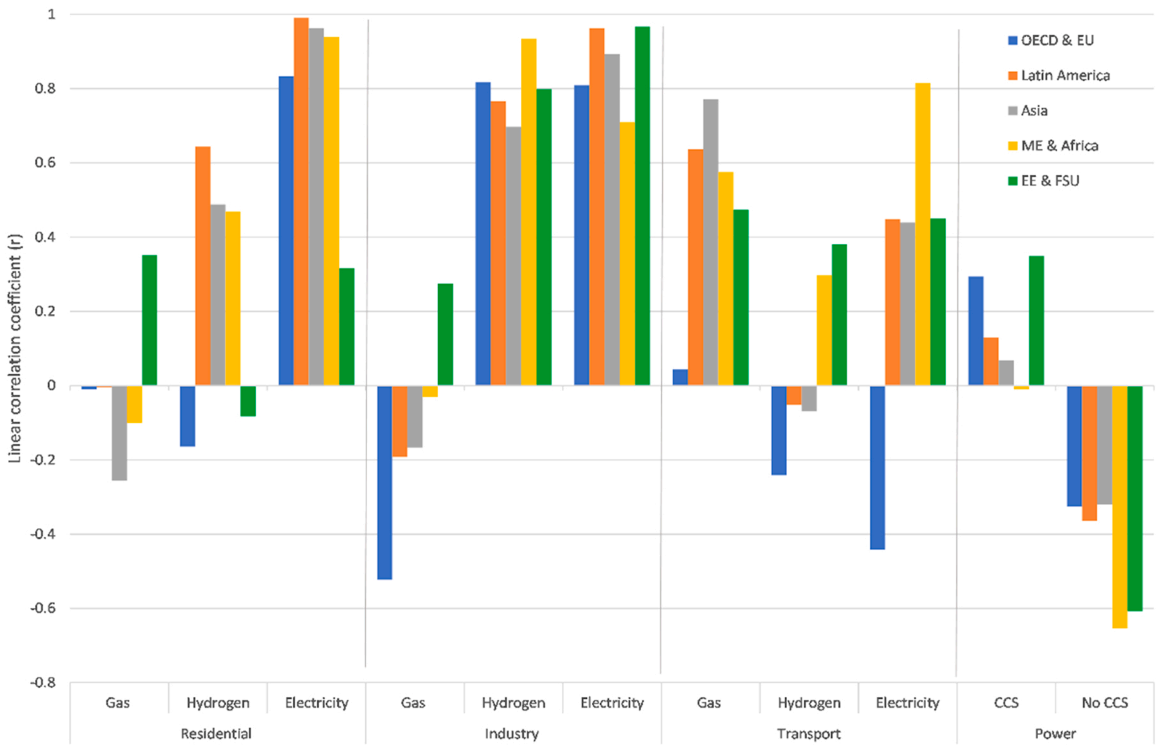


Fig. 10. Linear correlation coefficient value between the total change in energy use and change in different energy sources in each SR1.5 region and sector from 1.5 °C SR1.5 scenarios from 2020 to 2100.

decoupled from the industrial sector and is replaced by hydrogen and electricity, shown by their high correlation. The energy consumption increases in Asia and Latin America are fuelled by both hydrogen and electricity, with electricity responsible for the most significant gains.

The literature on natural gas use in industry regionally aggregated under 1.5 °C futures is sparse. Bødal et al. (2020) found that in Texas hydrogen produced via SMR can be cost optimal for industry under a high demand scenario, but under a high carbon price scenarios renewable energy electrolysis is favoured, which would be more likely in a 1.5 °C world. In the EU Capros et al. (2019) finds industry can become carbon neutral by 2050 through electrification and hydrogen use. This is in agreement with the scenarios that energy reduction combined with switching to hydrogen and electricity in the pre-2050 period is key. In China, fuel switching away from fossil fuels to cleaner sources combined with significant reductions in energy use will help to meet the 1.5 °C target within the industrial sector (Duan et al., 2021). However, India has a large energy requirement for industry that will likely continue to growth (Bataille, 2020). In the steel industry, of which China is the world's largest producer, India the 2nd and Brazil the 9th a combination of blue hydrogen, carbon neutral biomass, electrification and CCS offer the most effective solutions for carbon reductions (Fan & Friedmann, 2021).

In the scenarios where natural gas for transport increases it is correlated to increased energy use in Latin America and Asia. This is not seen in the OECD + EU, which shows little correlation. It is also clear that when natural gas for transport increases beyond a small amount it is responsible for the majority of energy in the sector, meaning it plays almost an all or nothing role. There is very little correlation seen between hydrogen use and total energy use. However, this can be partly explained by the inconsistent outcomes on total energy use in the transport sector. Thus, hydrogen increases even when total energy use decreases, highlighting its importance in the sector. Electricity use in the sector also increases regardless of the total energy use.

From the literature we see that in India a 1.5 °C scenario is shown to decrease the overall transport energy requirements, leading to significant reduction in oil use. However, with this it also reduces the total quantity of natural gas used for transport compared to business as usual (Dhar et al., 2018). Hydrogen use is significant in the 1.5 °C scenario examined. Arioli et al. (2020) estimates the use of natural gas for freight and passenger transport in India and Brazil to be low, but non-zero moving into 2050, something reflected in the majority of scenarios. The use of hydrogen in both regions is also expected to be very low with electrification and hybrid diesel engines being widespread instead. In China, Pan et al. (2018) find transport emissions under 1.5 °C are expected to peak in 2035 before rapidly decreasing by 2060. Natural gas has a role in heavy freight transport but it is a small percentage of the total energy use. Electrification and biogas have the largest impact on removing oil, and the role of hydrogen increases from 2040 to be the third largest fuel.

Within Europe there is appetite for hydrogen vehicles as a decarbonisation option for transport (Capros et al., 2019; Logan et al., 2020). Overall, the evidence for the use of natural gas in transport across the regions is patchy and often contradictory. In many scenarios natural gas use does not take off. However, there is scope for large increases in natural gas use, which are well correlated to large increases in energy requirements for the sector. Therefore, the optimal use of natural gas in transport may be to track how energy use is evolving and use natural gas where hydrogen and electricity are not viable options. Fig. 11.

The future of unabated natural gas for power decreases in every region, with the largest drop seen in the OECD + EU. However, even within this general decreasing trend there is great uncertainty in the total quantity of natural gas used. Asia uses the most unabated natural gas for power by 2050 after significant decreases across the OECD + EU. However, these decreases are partly replaced with natural gas with CCS. There is a large range of abated gas use, particularly in the OECD + EU and Asia. In some scenarios the CCS gas use reaches as high as unabated gas use. Little to no correlation is seen between CCS use and total change in gas use for power in any region, meaning the changes in power consumption are decoupled from the growth of CCS. Moreover, there is some negative correlation between changing power consumption and the quantity of unabated natural gas used in the sector. This could be indicative of larger power requirements in high electrification scenarios which rely on high levels of renewable energy.

3.5. Future work

A number of avenues of future research might further contribute to the assessment of the future role of natural gas in global energy systems. First, the data analysed here was the most up-to-date scenario data available from the IPCC at the time of writing. However, the scenarios from Working Group III of the AR6 report are now available. A similar analysis of new scenario data will provide insight into any changes in the role of natural gas in the future and what may be driving those changes. Key issues such as the role of global socioeconomic and demographic changes in the future are more prominently included in AR6 using Shared Socioeconomic Pathways scenarios. This is a key issue for future natural gas use that might lend greater insight if examined further in the future. The extent to which Sustainable Development Goals may provide slightly different influences on natural gas use in the future and provide different modelled outcomes to climate change optimised scenarios is also a key area for future research.

Another critical area for further study is the extent to which changes in assumptions on technologies, infrastructures and their emissions may influence the use of natural gas in the future. These assumptions may include:

- The emissions of methane and CO2 from the natural gas supply chain;
- The cost, development time and emissions assumptions surrounding CCS technologies and infrastructure; and
- The extent, cost, emissions and development time of NETs in future energy scenarios.
- The extent to which a changing in understanding of tipping points could affect the level of CO_2 permitted in each climate target.

4. Conclusions

Global natural gas use is likely to decline in the future as climate targets are pursued, with half of the IPCC SR1.5 scenarios that meet 1.5 °C reducing natural gas use by at least ~35% by 2050 and by ~70% by 2100 against total natural gas use in 2019. This is in comparison to total primary energy increasing by at least 30% in the majority of 1.5 °C scenarios assessed by 2100. This reduces the role of natural gas in total primary energy from 23% in 2019 to 15% in 2050 and 5% in 2100. However, the range of outcomes is broad, with some extreme scenarios seeing increases in natural gas use by 2050 and a return to current natural gas demand by 2100. Conversely, some scenarios see natural gas use decrease 7–9-fold by 2050 and to almost completely 0 by 2100.

The use of natural gas in future energy systems has no correlation to the use of NETs. Meaning increasing the quantity of NETs does not increase the quantity of natural gas observed. Conversely, this does not mean reducing the quantity of natural gas will reduce the quantity of NETs required as there are many other driving factors for NETs independent of natural gas use.

Natural gas use is strongly dependent on the development of CCS. Increasing the availability of CCS permits greater gas use within climate targets. This is clear in power generation where most scenarios agree 70% of natural gas electricity generation in 2050 is fitted with CCS.

Across different regions and sectors of the energy system different stories emerge. Natural gas use drops rapidly in the OECD & EU and Eastern Europe & Former Soviet Union regions across all sectors in the majority of scenarios. Reduction in energy consumption, development of hydrogen, CCS and renewable electricity with electrification of end-uses are necessary to do this. Latin America and the Middle East & Africa maintain or slightly decrease natural gas use across all sectors. Electrification is necessary to fill the growing energy requirements in all sectors. Within Asia there are many routes to meet climate targets, including increasing natural gas use, particularly in the residential and industrial sectors. Natural gas for power may also increase, or reduce only slightly, but this comes at the expense of sharp declines in coal use. Overall, in each region there is divergence mostly over the extent of decrease in natural gas use, rather than whether a decrease occurs.

The best use of natural gas globally and regionally is a complex and contested question. We have shown it depends on the prevailing conditions such as the emergence of enabling technologies (CCS) and the uptake of renewables and hydrogen. While a surprisingly large quantity of natural gas is permissible in 1.5 °C futures the current level of natural gas is not possible. Rapid, deep and sustained reductions in natural gas consumption are likely to be required if climate targets are to be met.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

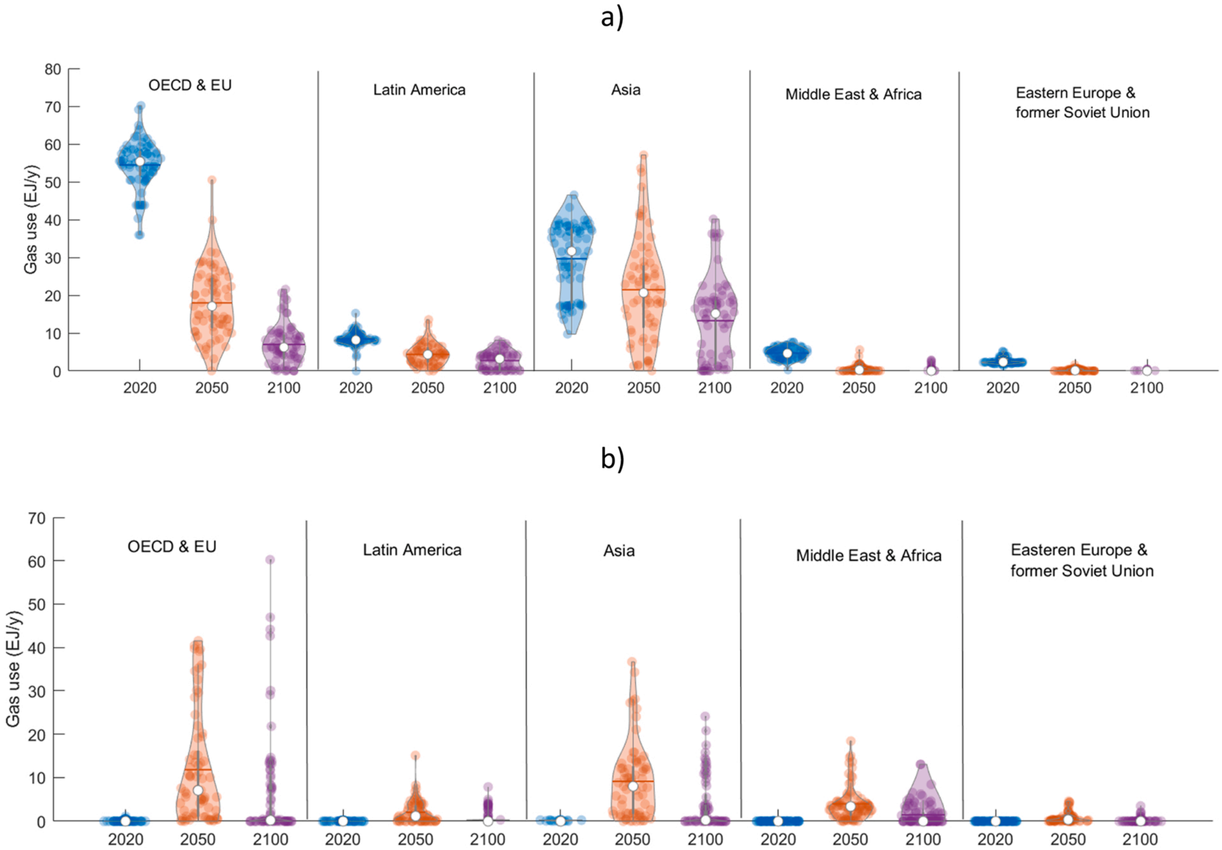


Fig. 11. Violin plot of gas use for power a) without CCS b) with CCS.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.futures.2023.103158.

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