

## Reviewers' comments:

### Reviewer #1:

This paper presents pathways for the European energy system under different stringencies of climate targets and different constraints on the availability of Russian gas. The pathways provide policy implications and energy system developments which could reduce dependency on Russian gas, meaning it is of significant current interest to the broader energy community. In terms of originality, the authors compare the longer-term implications to current literature on the impact of reducing reliance on Russian gas from the European Commission and the IEA which largely focus on nearer-term pathways to 2030. The bulk of the literature has been on the shorter-term impact of reduced Russian imports and therefore a longer-term outlook of the potential impacts, particularly in combination with different climate policies, provides highly relevant insights. Of particular importance is that in the Paris-aligned 1.5oC scenario, the rapid reduction in gas demand provides a pathway for a) meeting the Paris goal of keeping temperatures to 1.5oC and mitigating some of the worst impacts of climate change, b) reducing dependence on fossil fuels and the corresponding volatility of internationally traded prices, c) increasing energy security, and d) moving early can reduce power system costs etc. in the longer term. More discussion that a gas bridge is incompatible with a Paris aligned scenario would be useful, particularly given the authors highlight that gas has been highlighted as a "transition fuel" by the EC.

The authors are to be commended on developing these scenarios and report in a short space of time. I believe with some revisions this paper can provide a useful and topical contribution to the literature around gas market uncertainties, geopolitics, and energy system decarbonisation.

However, in my opinion, several improvements could be made.

There is limited discussion on the supply-side around specific gas market and wider energy system uncertainties and dynamics:

\* Limited/no discussion on supply diversification. For example the ability to increase/decrease take-or-pay contracted gas from Central Asia, North Africa, Middle East, and spot LNG imports from North America and elsewhere. The point about lots of existing infrastructure (regasification) being concentrated in Southern European gas markets (e.g. Spain) is a very important one, but the discussion could really do with widening in the modelling (i.e. is additional regasification capacity out to 2050 built, and if so where and when, and what are the risks of these assets being stranded, particularly in a 1.5oC scenario). Additionally, domestic European gas production is not discussed at all, especially Norway, as the supply side of gas markets is largely overlooked;

#### Comment:

The discussion on supply diversification that you propose is relevant, which is why we have extended our analysis in this matter. Our initial submission considered the European gas supply in 2019 (4700 TWh), which includes 1) own production, 2) imports via gas

pipelines and 3) imports from shipping (LNG). It is true that limiting one of these three sources might increase deliverance of gas from the others. In our revised version, we allow additional LNG regasification terminals to be installed, enabling the imports from shipping to increase. Assuming an LNG price of 1.9 times the natural gas price [1], and a capacity cost of 70 EUR/kW [2], only a marginal difference is observed, compared to our results without additional LNG capacities.

When allowing the capacity of LNG regasification terminals to expand, enabling an increased import of LNG, new terminals are only installed in the 2C scenario, and then only used in the first 10 years. System cost is marginally reduced in the following years, despite terminals being stranded assets, because less, more-expensive coal power capacity needs to be deployed. The LNG terminal expansion is only cost-optimal in the 1.5C when coal price is quadrupled. Lastly, allowing LNG still entails a delayed coal phaseout.

The discussion on domestic gas sources is also relevant. However, the capacity of these sources is not expected to change significantly [3]. We added the following sentence to the introduction, explaining why we do not consider large expansion of internal gas production:

*“In contrast, we do not consider a large expansion of internal gas production, including gas fields in Norway, as these sources combined can only be expected to provide an extra 10bcm per year [20]”*

These findings are all included in the revised manuscript.

[1] Hampp, J., Düren, M., and Brown, T., “Import options for chemical energy carriers from renewable sources to Germany”, 2022, preprint, DOI: <https://doi.org/10.48550/arXiv.2107.01092>

[2] Lochner, S. and Bothe, D. “The development of natural gas supply costs to Europe, the United States and Japan in a globalizing gas market—Model-based analysis until 2030”. In: Energy Policy 37.4 (2009), pp. 1518–1528. ISSN: 0301-4215. DOI: <https://doi.org/10.1016/j.enpol.2008.12.012>. URL: <https://www.sciencedirect.com/science/article/pii/S030142150800756>

[3] IEA. *A 10-Point Plan to Reduce the European Union’s Reliance on Russian Natural Gas*. Tech. rep. 2022. URL: <https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas>.

\* If the focus is on the long-term, including different levels of European energy system decarbonisation, then there needs to be more discussion, at least in a supplementary document, on the assumptions being made around the growth/decline of different technologies, otherwise it is difficult for the reader to determine the feasibility of the

results:

o As with all IAMs, the speed at which different technologies are allowed to grow/decline are hugely important parameters and play a fundamental role in shaping the scenario outputs. The 2019-2030 growth rates for the deployment of solar PV are feasible in terms of historical European growth rates ( $\sim 20\%$  for solar between 2010 and 2017), however more data on assumptions around other technologies (including wind, e.g. offshore wind looks to be growing at about 30% per year between 2019 and 2030) would be useful.

Comment:

We agree that the growth-rates are very important assumptions, and our original manuscript was not very elaborate on this point. To elaborate on the assumptions made in the model, and to discuss the growth rates required the following section have been added to the Results and Discussion section of the manuscript. Furthermore, we have included two additional figures showing the growth rates of renewable capacities, and annual change in primary energy consumption (Supplementary Figure 2 and 3).

*“The PyPSA-Eur-Sec model used in this work does not constrain build-out rates of generation capacity. As there is significant uncertainty related to future build-out rates, we prefer not to limit the model in this way, allowing us to observe the preferred rates. Installation rate of renewables can be seen on Figure S3 and total annual change in primary energy consumption in Figure S2. It is clear that a transition of our energy supply requires significant build-out of renewable and heat-pump capacities. Results show installation rates of approximately 600 GW/a of wind and solar. These figures are naturally higher than any historical values [29]. However, this does not necessarily mean that achieving this transition is infeasible. As wind and solar costs decrease, demand and production capacity will increase since these technologies show already lower costs than fossil fuel-based generators in most world regions [30]. Such a fast transition will require ambitious policies implemented globally together with strategies that avoid regulatory bottlenecks and ensure public acceptance. Rather than focusing on the build-out required to attain the 1.5 °C and 2 °C scenarios, which has been extensively discussed previously [23], we instead focus on the impact of reducing reliance on gas.*

*Results show that limiting gas availability incentivizes early decarbonization of the energy supply. In both the 1.5 °C and 2 °C scenarios, this results in lower annual build-out rates as the transition is performed more gradually. The impact on growth rates caused by reduced availability of gas compared to the impact of climate ambition is, however, small.”*

General comments and suggestions to improve this work

The authors are to be commended on developing these scenarios and report in a short space of time. I believe with some revisions this paper can provide a useful and topical contribution to the literature around gas market uncertainties, geopolitics, and energy system decarbonisation.

\* Carbon budgets:

o Are the quoted numbers for 1.5oC (25.7 Gt) and 2oC (73.9 Gt) cumulative to 2050 or 2100?

Comment:

To clarify the following text have been added in the introduction of the manuscript in the section where the energy system model is introduced:

*"The available CO2 budgets are 25.7 and 73.9 Gt CO2 cumulative to 2050 for the 1.5 °C and 2 °C respectively [23]. Maximum CO2 emissions in every time step are determined based on the carbon budgets assuming an exponential decay and carbon neutrality by 2050."*

o Only one of the carbon budget choices is Paris aligned and is hugely challenging (and highly unlikely) without vast amounts of NETs or significant demand-side reductions (which the model cannot consider as far as I understand). An additional scenario exploring a Paris aligned carbon budget (e.g. 1.5 at 50% or 1.75 at 66%) would be useful.

Comment:

The manuscript have been submitted as a Report style article and not a full length research article, thus imposing a limit to the length of our manuscript. To keep the story clean we have chosen not to include additional scenarios as it would be hard to incorporate the additional analysis in the limited space. We do, nevertheless, agree that the discussion of alternative transition pathways is indeed important. In our manuscript we reference a previous paper [1] conducted by our research group where alternative transition paths have been studied in more detail.

*[1] Victoria, Marta, et al. "Early decarbonisation of the European energy system pays off." Nature communications 11.1 (2020): 1-9.*

\* What constraints are there on the growth and decline of different technologies?

o The gas consumption decline for the 1.5 degree looks to be ~ 18% per year (from 4700 TWh in 2019 to ~ 500 TWh in 2030) and there is no discussion around this. Without any discussion it is difficult to make a judgement on the validity/feasibility of this result.

o There is huge uncertainty around the deployment and decline of new and existing technologies but some discussion around, for example, historical rates of transitions would be useful to validate the results

o No discussion around constraints on fossil fuel production (e.g. growth and decline of natural gas production)

Comment:

As mentioned above, a section has been added discussing growth-rate assumptions and findings.

\* Especially the 1.5oC, but also the 2oC, will be sensitive to assumptions around the availability of biomass - whether this be a global total or an assumed European level with domestic production and imports (e.g. wood imports from North America) - these could be made clearer by explicitly stating what the biomass potential is in TWh

Comment:

The assumptions made on biomass potentials are indeed very important as they have huge impact on scenarios with high decarbonization. To clarify what specific biomass potentials have been used the following sentence have been added to the “Energy system model” section:

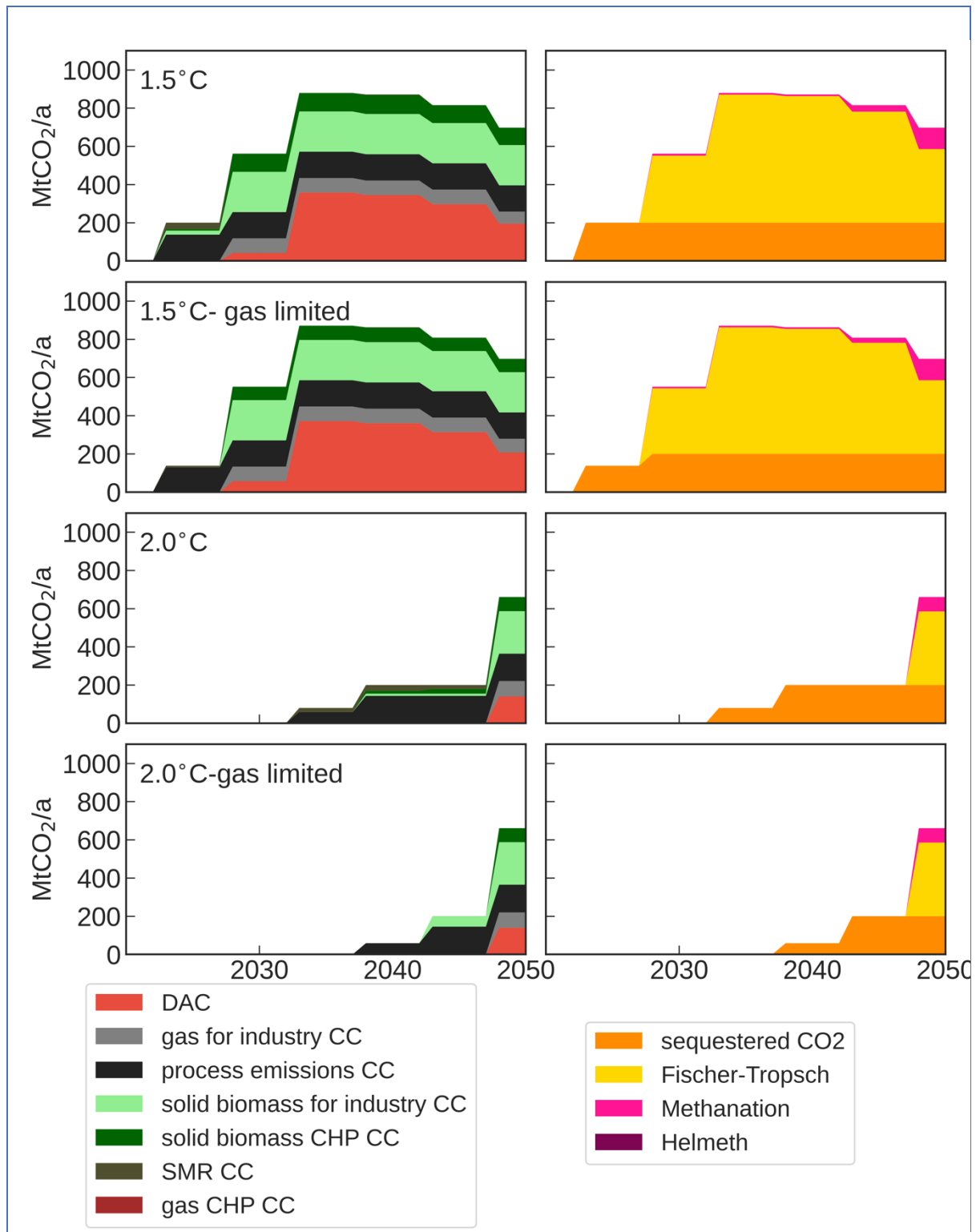
*“Conservative European potentials of 1185 TWh/a of solid biomass and 345 TWh/a of gas are assumed based on the ENSPRESO biomass database [3].”*

\* Option to use residual heat from industrial processes/power plants to heat solid sorbent solution in DAC processes - for transparency it would be good to have actual numbers in terms of capture (from negative emissions technologies (DAC and BECCS) and from conventional carbon capture and storage), i.e. what is the cumulative or annual capture in Gt CO<sub>2</sub> which keeps Europe within the prescribed carbon budgets

Comment:

To clearly show how DAC and BECCS technologies are utilized in the model, a supplementary figure was made (seen below) showing captured CO<sub>2</sub> and use of the captured CO<sub>2</sub>. In addition the following text have been added to the results section of the manuscript:

*“Carbon capture remains mostly unaffected by the gas limit and the additional CO<sub>2</sub> emitted by increased use of coal to produce electricity, Figure S12). Especially in the 2.0 °C scenario, additional emission from coal use is balanced by a corresponding increase in electricity generation from renewable sources and the use of more energy efficiency technologies such as heat pumps. For the 1.5 °C scenario, the model finds it cost-optimal to capture around 800 Mt/CO<sub>2</sub> annually. CO<sub>2</sub> is captured mostly from process emissions, biomass and gas used in the industry. The 1.5 °C-path also includes substantial direct air capture, Fig. S12. The potential for CO<sub>2</sub> sequestration in the model is limited to a conservative assumption of 200Mt/CO<sub>2</sub> (slightly above process emissions in the system).”*



\* The lack of demand side elasticities is also significant yet only mentioned once. In the IEA Net Zero Report and in many scenarios exploring net zero/1.5oC (e.g. IPCC Special Report on 1.5oC) the role of demand reduction is really significant, either through behavioural changes or demand elasticities due to the rising prices of energy service demands heavily reliant on fossil fuels with limited low cost technology alternatives such as aviation travel.

Comment:

It is true that a reduced demand for energy services could ease the consequence of a reduced supply of gas and, in general, it has a significant impact on emissions making it easier to comply with the CO<sub>2</sub> reduction scenarios. In our work, we have chosen to not include behavioral changes in the demand for energy services. This assumption is in line with our choice of analyzing a worst-case scenario where the reduced gas supply must be replaced by other means. In the text this choice has been made clearer by the following change:

*“Using the sector-coupled energy system optimization model PyPSA-Eur-Sec,<sup>9</sup> we perform myopic optimization in 5-year steps from 2025 to 2050 to investigate the long-term consequences of reduced gas availability in Europe. We present four scenarios for the transition of the European energy supply which have either an ambitious goal targeting a global temperature increase below 1.5 °C, or a more moderate goal targeting a temperature increase below 2 °C. The available CO<sub>2</sub> budgets are 25.7 and 73.9 Gt CO<sub>2</sub> cumulative to 2050 for the 1.5 °C and 2 °C respectively [23]. Maximum CO<sub>2</sub> emissions in every time step are determined based on the carbon budgets assuming an exponential decay and carbon neutrality by 2050. Using the two ambition levels, we define a reference scenario with an unbounded gas supply and a scenario where the gas supply is limited to today’s levels, minus the share of gas currently imported from Russia. The EU27+GB gas consumption in 2019 was 4700 TWh<sup>17</sup> of which 1600 TWh originated from Russian imports,<sup>18</sup> so we limit gas available to the system to 3100 TWh. The PyPSA-Eur-Sec model presented in [23], spanning 33 countries within the ENTSO-E, includes the electricity, heating, land transport, aviation, and shipping sectors, as well as the industry sector including feedstocks. Furthermore, detailed accounting for CO<sub>2</sub>-emissions, carbon capture, utilization and sequestration (CCUS) is implemented. The effect of building renovation is incorporated as exogenous efficiency improvements. Demand-side elasticity and short-term substitution elasticity are not considered in the model. Behavioral changes could ease the consequence of a reduced gas availability, in particular reduced demand for energy services that are directly coupled to the use of gas such as lowering the indoor temperature of households heated by gas boilers.*

*Constraining the gas availability to 3100 TWh while keeping the demand for energy services constant represents a worst case scenario where gas imports from Russia cannot be replaced by gas imports from other countries. The availability and cost of coal, lignite, and oil is assumed to remain unchanged in the base scenarios, but sensitivity to these parameters is discussed. In contrast to the natural gas pipeline supply, replacing Russian oil and coal in the short term is challenging, but existing shipping networks can more easily redirect a global supply with help from targeted policy such as the Trans-Atlantic Energy Pact between North America and Europe.<sup>24</sup> In the medium-to-long term, vast electrification of the transport sector is expected to relieve the pressure from a Russian oil shortage, while the global coal market would replace Russian coal, albeit at a higher cost.”*



Reviewer #2:

The presented manuscript discusses the implications of phasing-out Russian natural gas imports in Europe. The manuscript is relatively well-written and easy to follow. Obviously, the topic is timely. Given that the modeling framework is well-established and not novel, the added value of this work must reside in the application/case study, which I'll focus on in my review.

First, the premise that the EU won't be able to find alternatives for natural gas imports, whereas coal and oil imports will be entirely replaced by alternative suppliers, is odd. I would – at least – have expected a more detailed analysis to justify this claim, plus a sensitivity analysis w.r.t. the availability of alternatives.

Comment:

See the response to Reviewer 1 regarding the added sensitivity analysis studying increased LNG imports.

Second, as the EU needs to take action now, it is unfortunate that you don't provide more detail for the years 2022-2025, but rather focus on the medium- to long-term implications. The challenges (when it comes to facing out Russian gas, oil and coal) are manifesting them today and in the next few years.

Comment:

Short-term implications of a discontinuation in the delivery of natural gas from Russia is indeed very important. As indicated by the title of our manuscript we have chosen to focus on the medium- to long-term implications of reducing reliance on natural gas in the European energy system. Short-term implications have been extensively discussed in other works, therefore we chose to focus on medium- to long-term implications. In the manuscript we do, however, discuss short term implications in the section also titled "Short-term implications"

*"While this paper focuses on the medium- to long-term consequences of cessation of Russian gas on the European energy system, we briefly discuss the immediate short-term implications here. Groups such as the International Energy [20] and the European Commission [19] have proposed several strategies to go through the next winter in Europe without importing Russian gas. In summary, these plans propose: delaying nuclear phaseout, speeding-up solar and wind deployment to compensate for production of*



electricity, rapidly deploying heat pumps to substitute gas for heating, accelerating energy efficiency improvements in buildings and industry, encouraging a temporary thermostat adjustment by consumers, and increasing coal use [31,20]. While most measures would support the energy transition and help Europe reach its climate goals, increasing coal consumption would deplete Europe's available carbon budget even further. Some proposals point at increasing LNG imports; reopening internal gas fields, such as Groningen in the Netherlands [32]; or increasing biogas consumption in Denmark [33,19]. The European Commission expects that increased import of LNG combined with regasification can replace 50 bcm of the missing gas, equivalent to 485 TWh [19]. However, the existing LNG regasification terminals (mostly located in Spain) and intra-EU pipeline capacities, together with the small size of the global LNG market limit the potential of this strategy. As an indication of these limitations, the gas price in Europe reached 226 €/MWh in March 2022 (15 times higher than its average price in the period 2015-2021). The European Council also suggests that increased gas imports from countries other than Russia and increased domestic biogas production could supply an additional 18 bcm (175 TWh) of fossil/bio-gas [19].

Here we reference several works related to the short-term implications:

[19] European Commission. REPowerEU: Joint European action for more affordable, secure and sustainable energy.

Mar. 2022. URL: [https://ec.europa.eu/commission/presscorner/detail/en/ip\\_22\\_1511](https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511) (visited on 09/03/2022).

[20] IEA. A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas. Tech. rep. 2022. URL:

<https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-bruegel-natural-gas>.

[31] McWilliams, B., Sgaravatti, G., Tagliapietra, S., and Zachmann, G. Preparing for the first winter without Russian

gas. Tech. rep. 2022. URL: <https://www.bruegel.org/2022/02/preparing-for-the-first-winter-without-russian-gas/> (visited on 10/03/2022).

[32] Reuters. Dutch limit gas production at Groningen despite energy crisis. 2022. URL:

<https://www.reuters.com/article/netherlands-gas/dutch-limit-gas-production-at-groningen-despite-energy-crisis-idUKL2N2VH1A0>.

[33] Altinget. Ea Energianalyse: Sådan kan Danmark frigøre sig fra russisk gas. 2022. URL:

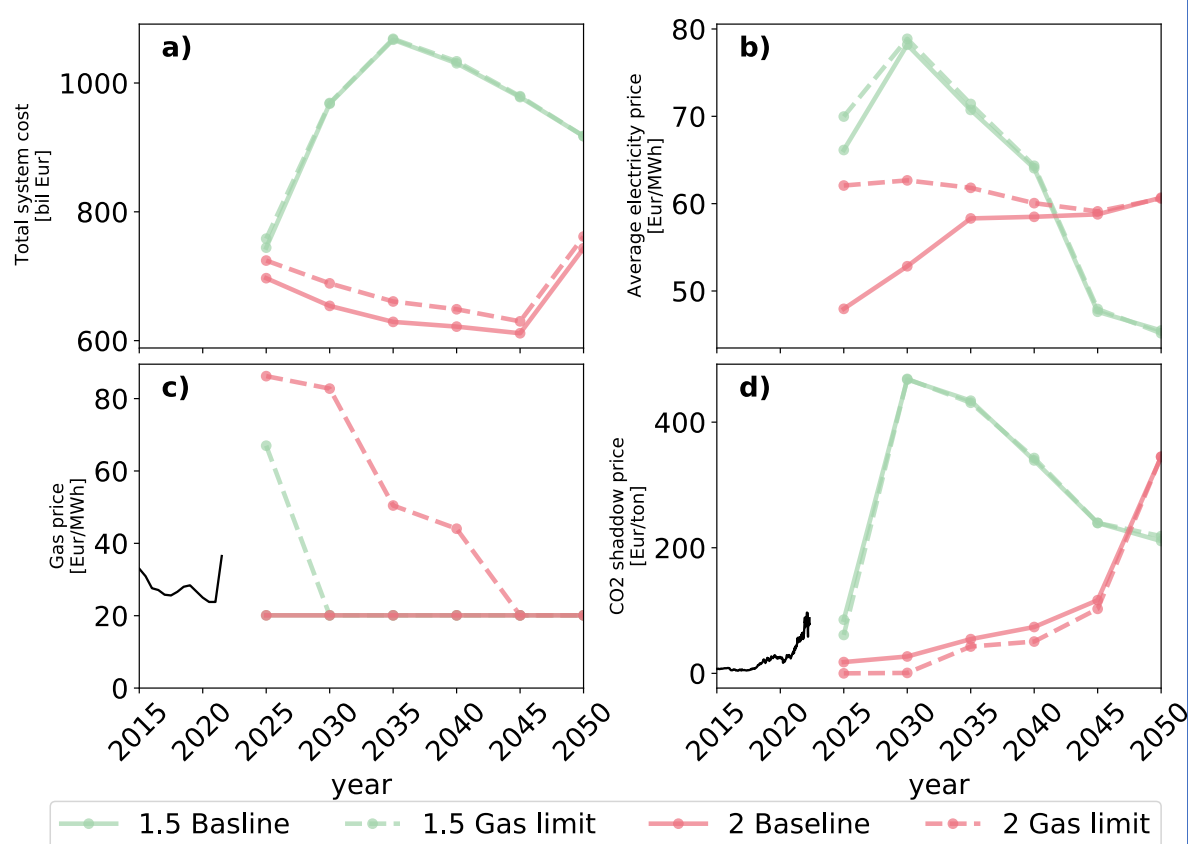
<https://www.altinget.dk/energi/artikel/ea-energianalyse-saadan-kan-danmark-frigoere-sig-fra-russisk-gas> (visited on 04/03/2022).

Third, the counterfactual 2°C scenario is, in my opinion irrelevant, as it is not in line with EU and MS policy. This is also evident from the numerical results, see e.g., the computed shadow price for CO<sub>2</sub> emissions, which is well below the emission allowance futures that are being traded in EU ETS. Similarly, it's a pity that the computed prices aren't compared to today's values.

Comment:

The climate ambition of the European Council is to reduce emissions to stay well below temperature increases of 2C. Thus, the 2C scenario serves as an upper bound for the ambitious set out by the European Commission, as “well below” can be interpreted in several ways.

Historic CO2 prices have been added to Figure 4, showing that model results on CO2 prices is in-line with historic developments. However, it should be noted here that the CO2 price in our model does not distinguish between ETS and non-ETS emission rights. Rather it describes the shadow price of reducing CO2 emissions across all sectors. Thus, we do not expect a 1:1 match with the EU ETS futures.



In conclusion, I have the impression the authors rushed through this analysis in order to be the first to come out with a study on this topic. In such an important matter, I would, however, recommend a more detailed, nuanced analysis.

Comment:

We believe that the topic of the paper is of immediate interest to both policymakers and the scientific community, which is why we have prioritized an unusual amount of

resources to the analysis. We are thankful for all the reviewer comments as you have helped us identify nuances that we did not include in the first revision.

Reviewer #3:

The authors model the difference in an European energy system, taking into account potential gas supply constraints to Europe. While the paper is of course very timely, I do not see that it generates sufficiently new insights into our understanding of the European energy system to warrant a publication in Joule.

In particular, the transition pathways with or without limiting gas are very similar, and the main difference is between the 1.5°C and 2°C pathway, which is an extensively studied topic – and is not addressed in depth in the paper.

Comment:

The central idea and timing of the paper is obviously sparked by the current conflict between Russia and most Western nations, but this is not the scientific motivation for writing the paper. Rather the scientific novelty of the paper is in the fact that natural gas is seen as a key transitional fossil fuel in numerous studies in the literature. This point of view was also recently implemented directly in the European policy when natural gas was included in the EU green taxonomy, further emphasizing its wide-spread acceptance. However, the current Russian-European energy crisis is shining a new light on the role of gas in the European transition by highlighting the uncertainties associated with EU's dependence on energy import. At the same time the carbon-equivalent emissions from gas over other fossil fuels is being heavily debated in the scientific literature, further challenging the role that gas can potentially play as a transitional fuel. Thus, the scientific motivation and novelty of the paper is to study how the decarbonization of the European energy system is affected if natural gas is limited in its ability to play a key role as a transitional fossil fuel. To the best of our knowledge no other study in the literature takes the point of view of a significantly reduced availability of natural gas and, thus, the insights gained from our study will advance the understanding of the European transition. Clearly, such insights are currently in high demand by both public, political and academic communities.

In the paper, the above reasons for conducting the study are highlighted in the introduction:

*"Fossil gas has been regarded as a key transition fuel that could help bridge the gap between the present day and a carbon neutral future. Though carbon-emitting, gas has the following advantages compared to other fossil fuels: gas power plants have lower capital costs,[1,2] lower CO<sub>2</sub>-equivalent emissions when burned,[3,4] and generators have quick ramp-up times.[1] The European Commission has even labeled gas activities as contributing to the green transition.[5] For these reasons, numerous studies of highly renewable energy systems keep gas as the only conventional form of power generation [6,7,8,9,10] or otherwise phase it out last.[11,12] However, as a fossil fuel, gas must still be eliminated during the transition. In addition, the savings of CO<sub>2</sub> equivalent emissions from gas over other fossil fuels may be overstated or non-existent due to leakage of methane during extraction, distribution, processing, and end use.[13] Nations must wean themselves off of gas by 2050 in order to comply with the Paris Agreement. For the EU, this is no easy task. In 2019, gas made up 21% of final energy consumption,[14] including 43% of residential use and 35% of industry energy use.[15,16] Gas in Europe is primarily imported, with 70% coming from outside of Europe<sup>14</sup> when counting Norwegian gas as internal production. The current energy supply in Europe has a particularly strong dependence on Russian imports. Out of the 398 bcm (3890 TWh) of gas imported by the European Union in 2019 (EU27 + GB),[17] 41%<sup>18</sup> had Russian origin (Fig. 1). On top of that, 27% and 47% of oil and coal imports in 2019 came from Russia."*

In addition, Figure 5 was added to more clearly identify the differences in the energy balance between the gas limited and baseline scenarios.

Furthermore, you do not provide any insights into how those systems may adapt apart from - to put it bluntly - "things are built quicker".

Comment:

Thank you for the “blunt” statement, which has motivated us to thoroughly revise the manuscript to highlight as many insights as possible. The major changes are listed below, but we have also made a number of minor changes to clarify how and why imposing gas scarcity changes the transition. E.g. in the conclusion of the paper.

We have elaborated on our discussion of results to further show how the system may adapt. A discussion of build-out rates have been added, supported by two additional supplementary figures on growth rates. Furthermore, discussion on distributional impacts have also been included supported by an additional panel in Figure 4(e), as seen below.

*“The PyPSA-Eur-Sec model used in this work does not constrain build-out rates of generation capacity. As there is significant uncertainty related to future build-out rates, we prefer not to limit the model in this way, allowing us to observe the preferred rates. Installation rate of renewables can be seen on Figure S3 and total annual change in primary energy consumption in Figure S2. It is clear that a transition of our energy supply requires significant build-out of renewable and heat-pump capacities. Results show installation rates of approximately 600 GW/a of wind and solar. These figures are naturally higher than any historical values [29]. However, this does not necessarily mean that achieving this transition is infeasible. As wind and solar costs decrease, demand and production capacity will increase since these technologies show already lower costs than fossil fuel-based generators in most world regions [30]. Such a fast transition will require ambitious policies implemented globally together with strategies that avoid regulatory bottlenecks and ensure public acceptance. Rather than focusing on the build-out required to attain the 1.5 °C and 2 °C scenarios, which has been extensively discussed previously [23], we instead focus on the impact of reducing reliance on gas.*

*Results show that limiting gas availability incentivizes early decarbonization of the energy supply. In both the 1.5 °C and 2 °C scenarios, this results in lower annual build-out rates as the transition is performed more gradually. The impact on growth rates caused by reduced availability of gas compared to the impact of climate ambition is, however, small.”*

Furthermore, the difference between the scenarios with and without gas limits are minor and not structurally explored in the paper to discover interesting features.

Comment:

As mentioned above, a major rewrite of the results section have been performed to ensure that the primary focus is placed on the impact of reducing gas availability and the impact of climate ambitions as secondary. The main purpose of the new Figure 5 is to uncover differences between gas-limited and baseline scenarios, and we do find new interesting features as discussed in the paper.

*“Highly renewable energy systems are challenged by dark doldrums (i.e., a week in winter in which solar and wind generation is low but electricity and heating demand is high)<sup>9,11</sup>. We investigate the system operation throughout the most critical week of the year in which gas consumption in the 2 °C gas-unlimited scenario is highest, Fig. 5. When unlimited, gas used in OCGT, CCGT, and CHP units is the main source of electricity besides the renewable production. In the gas-limited scenario, a much higher proportion of renewable energy is shown, as well as an increase in coal and biomass. Battery storage now appears in the balancing during night. For the heating supply, gas is clearly the predominant source in both the baseline and gas-limited scenarios. In the latter, a fraction of the gas use is replaced with heat pumps. In addition, biomass CHP plants are now on par with or even surpass the gas CHP plants, while they were not present in the baseline scenario.”*

Further detail have been added to the analysis studying the impact of limiting gas availability. Figure 4 have been updated with an additional panel highlighting the distributional impact, in terms of added costs, induced by a limit on gas availability. As mentioned, the results section have seen a major revision, in which the following text have been added:

*“The impact of gas scarcity on individual countries is shown in Figure 4e in terms of added system cost, related to reducing reliance on gas in 2030 for the 2C scenario. We observe that countries with a high availability of good wind resources, such as Denmark, Great Britain, and France, are investing heavily in wind power to compensate for the missing gas availability. In southern Europe and the Balkans a large increase in costs related to coal power is observed, indicating that gas is replaced by additional coal use. The cost increases shown on the figure are in absolute numbers. Analyzing the added costs relative to the size of the economies, the largest impacts are found in countries where the switch from gas to renewable is made. It is also worth noticing how the economic impact in countries such as Norway and Sweden is rather insignificant.”*

I still think the paper is a valuable contribution to the policy discussion, but you may have to find a different outlet than Joule for it. I however encourage the authors to work more extensively on their results and aim at a resubmission. I think there are e.g. very important distributional impacts from a limitation on gas supply, which you could explore which your model, as I understand that it allows to derive regional differences in impacts. Furthermore, as you are able to provide prices, you could assess in more detail winners and losers of such a change.

Comment:

It is correctly observed that our model does indeed contain spatially resolved information regarding the burden related to reducing reliance on natural gas. We have extended the analysis of our results to cover the distributional impacts of reducing reliance on natural

gas. Figure 4 have been expanded with an additional panel (e) showing spatial impacts on costs, and the following text have been added:

*“The impact of gas scarcity on individual countries is shown in Figure 4e by plotting the additional annual system cost when imposing the gas limit constraint in 2030 for the 2 °C scenario. Evenly across Europe, all countries increase investments in heat pumps to replace gas consumed to supply heat. We observe that countries with good wind resources, such as Denmark, Great Britain, and France increase investments in wind power to compensate for the missing gas availability. In Italy and the Balkan countries a large increase in costs related to coal power is observed, indicating that gas is replaced by additional coal use, Fig. 4. The cost increases shown in Fig. 4 are in absolute numbers. Analyzing the added costs relative to the size of the economies, the largest impacts are found in countries where gas is replaced by renewable energy Fig. S18. It is also worth noticing how the economic impact in countries such as Norway and Sweden is rather insignificant.”*

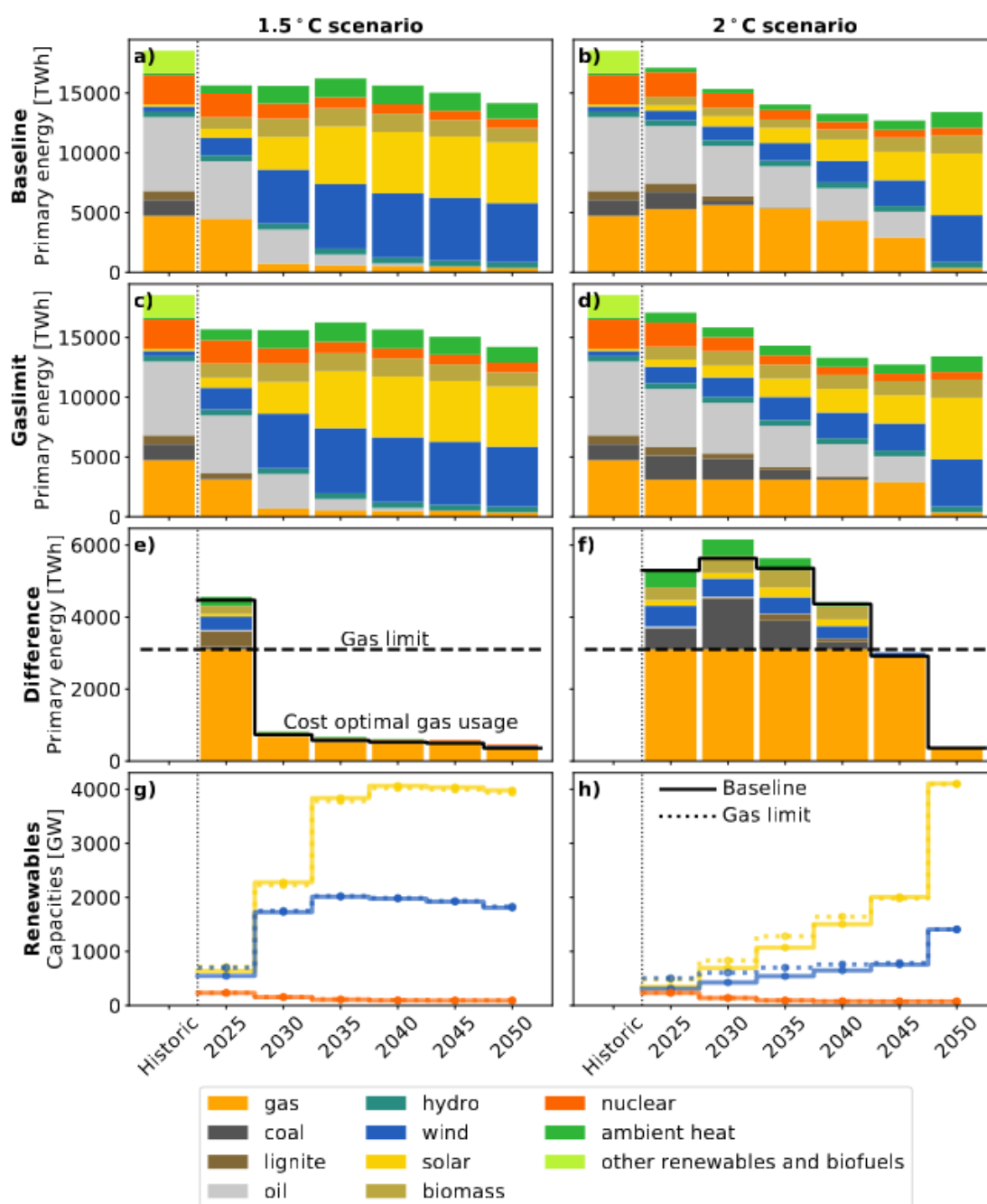
Some minor comments:

- Legend of Fig. 2 g), h): unclear how capacities differ between scenarios, i.e. which line belongs to which scenario (dashed/solid)?



Comment:

Figure 2 panel g), and h) have been updated to clarify what lines belongs to which scenarios. See the updated figure below:



**Fig. 2:** Primary energy consumption for scenarios 1.5 °C base (a), 2 °C base (b), 1.5 °C gas limited (c), and 2 °C gas limited (d). Ambient heat refers to the energy utilized by the heat pump, e.g. from the ground or air. Historical primary energy consumption for 2019 is shown in the first bar from Eurostat<sup>16</sup>. Gas consumption, and technologies substituting missing gas (the colored areas above the dashed line), are shown for the 1.5 °C (e) and 2 °C (f) scenarios. The amount of energy used to replace missing gas might be slightly higher/lower due to differences in the energy supply efficiency, e.g. the lower efficiency of coal power plants compared to gas turbines. Cumulative renewable capacities are shown in g) and h).

- "A marginal cost of 21.1 Eur/MWh for gas is assumed. The constraint on gas availability introduces a shadow price on gas, when demand is higher than supply. The gas price depicted in the figure is the sum of the marginal price and the shadow price."

I think there is an error in terminology.

(1) The term "marginal price" is unknown to me.

(2) The price of the resource is therefore marginal production cost + shadow rent.

Comment:

We agree that we should be more careful with our wording when discussing gas price in our paper. The wording of the mentioned section has been altered so it now reads:

*"In Figure 4c the reference gas prices for the modeled scenarios are shown. A cost of 21.1 EUR/MWh for gas is assumed, similar to the price observed before 2021. When binding, the constraint on gas availability introduces an additional shadow price on gas determined by the Lagrange multiplier associated with the gas limit constraint. In the 2 °C scenario, the constraint is binding until 2040. As a result, the total gas price initially increases to approximately 85 EUR/MWh after which it gradually drops to the base level in 2045. The 1.5 °C scenario, on the other hand, only experiences elevated gas prices in the first modeled period corresponding to 2025."*

- Please observe that apparently you do not have a full gas market model, as you do not include all gas consuming sectors directly in the model. Therefore, I am not sure how to interpret the prices. One would probably have to assume that somehow the amount of gas going to the modelled energy sectors is fixed by definition and that other sector adaptation processes will not affect the equilibrium price. This should at least be explicitly stated somewhere.

Comment:

The model does indeed cover all sectors consuming gas. This was not made clear in the manuscript. To clarify what sectors of the gas market that are covered by the model the following description has been added to the "Energy system model" section:

*"The model includes a representation of all the sectors consuming gas in Europe. This comprises gas for electricity production (using CCGT, OCGT and CHP units), gas for heating in CHP plants and individual gas boilers, as well as gas consumed in the industry for energy provision or as feedstock (including the production of H<sub>2</sub> via SMR with or without CC). Gas can have a fossil origin, be synthetically produced via the Sabatier reaction, or upgraded from biogas."*

In Figure 5, we now make a distinction between gas and biomass CHP to more clearly show where the gas is going.