Review of AVOID 2 report WPC6, March 2016, Version 1.0

[Note: responses to this review are given in red text beneath each point]

1. *Does the literature reviewed in the paper give an up to date and unbiased view of the literature? What is missing?*

    1.1. The literature reviewed is quite wide, but my impression is that there is some bias towards the literature which stresses the critical aspects of shale gas. Or maybe that it is a choice of the paper to give more space to the critical aspects highlighted by the selected literature.
    1.2. I highlight a few critical issues which I think are not adequately discussed or that would benefit from the consideration of further literature.

Specific concerns addressed in succeeding comments.

2. The important role given in the paper to the fugitive methane leakage from shale gas extraction, as it could lead to a substantial additional global warming. Correctly, the paper says that "*This study does not assess the costs of mitigation of this additional methane, since at the current time the measures to accurately monitor and mitigate fugitive methane emissions are not in place, as discussed in section 2. Nevertheless, it may be reasonably expected that in such an instance there would be additional costs to mitigation, either through such measures or through compensating additional mitigation in other sectors, which could increase the cost and negatively affect the feasibility of meeting the 2°C, and "well below 2°C", goals*". However:
3. according to a study of the Environmental Defense Fund (EDF), a 40% percent reduction in onshore methane emissions is projected to be achievable with existing technologies and techniques at a net total cost of less than $0.01/Mcf of gas produced
4. the IEA *Energy and Climate Change: World Energy Outlook Special Report 2015* identified oil and gas methane reductions as one of five key policies tools to secure a peak in global greenhouse-gas emissions by 2020; upstream oil and gas methane reductions could yield 15% of the reductions needed to deliver such an early peak in emissions, an amount similar to that which would be realised through incremental investments in renewables.
5. I think these kind of data and arguments, if not directly addressed in the quantitative analysis, should be at least included in the discussion

Re: 3-5 Thanks for these additional sources, references have been added in discussion. These sources highlight the importance of tackling methane leakage and possible strategies for targeting this. They don't eliminate the risk of high levels of methane leakage though, and we think don't reduce the importance of considering global temperature implications of high leakage rates. We have carefully caveated these higher leakage rate scenarios to show that they are only indicative of what would happen without sufficient mitigation of fugitive methane.

6. The report highlights several times the potential overestimation of shale gas resources:
7. I think it would be appropriate to mention that the study conducted by Advanced Resources International, Inc. (ARI) for the U.S. DOE's EIA evaluates the shale gas and shale oil resource in 26 regions, containing 41 individual countries; on one hand it is true that it has been criticized for some optimistic assessments (e.g. Marcellus), on the other hand it should be taken into account that it is not fully comprehensive of the global resources.

More detail on scope of ARI study has been added, and made explicit that McGlade combined this with others for global estimates.

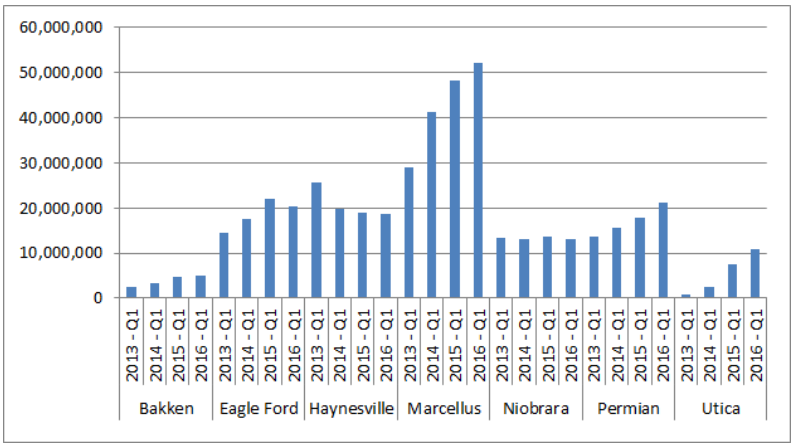
8. The report doesn't mention the study conducted in 2014 by the German Federal Institute for Geosciences and Natural Resources (BGR), maybe the latest one on the issue, which includes estimates which are very similar to the one included in ARI, i.e. about 200 Tcm of shale gas.

Thanks for this extra source. We have added a reference, but note that this study doesn't provide methodological details. The ARI study is cited, so it may well be similar because it is largely of the same origin.

9. The report mentions a study stating that "It has been suggested that the economic investment currently required to build a higher number of wells to replace declining supply from higher productivity wells is not being, and will not be, recuperated at current gas prices" (Hughes 2013):
10. For sure the current price conditions are now challenging for those contemplating new long-term investments in supply. However, it is also true what shown in the chart here below (my elaborations on EIA data) about the US Natural gas production, which kept increasing notwithstanding the very low price environment

10.1.1.1. US Natural gas production - main regions (Mcf)

10.1.1.2.



11. There is also a literature on some key strengths of shale gas, first of all the flexibility of its production and the short-term cycle of investments. A striking example of this flexibility is given by the behaviour of US gas production in 2014, when gas prices at Henry Hub reached the highest level since 2010, mainly driven by an extremely cold winter. The consequence was an impressive production response, as cumulative annual production additions totalled 25 bcm over the period. The magnitude of the supply-side response brought about by a small price increase (about USD 0.4/MBtu) is further evidence of the surprisingly high supply-side elasticity of the US gas industry (IEA, Medium-term Gas market report 2015).

Our report specifies that gas production in US has increased significantly with shale gas production (See Section 1.2). Whilst this elucidation of the elasticity of US shale gas production is certainly important, this particular aspect of the potential benefits of shale gas is beyond the originally intended scope of this paper, which focuses on the implications of shale gas extraction on the costs and feasibility of meeting stringent long term temperature goals. The implication that shale gas supply in the US has increased because of its favourable economics is also potentially valid, but here we address the issue of the economics of shale and how that impacts on its role in low-carbon scenarios through a consideration of a range of cost-supply curves for shale gas, drawing on the most robust publicly available extraction cost data that we've been able to find.

12. Is the analytical approach applied to build on the literature appropriate?

13. The tool used to assess the question, a global energy system model, is appropriate. Indeed similar tools are widely used to carry out these kind of analyses. Moreover, the TIAM model itself has been already used to assess the potential long-term impacts of shale gas.
14. However, I see some room for a better explanation of both some limitations of the model and of some of its key characteristics that can affect the outcome of the analysis:
15. Price formation in TIMES energy system models: TIMES has a limited capacity to represent price formation; in order to overcome this limit, I remember the original ETSAP-TIAM model included some exogenous assumptions to force an increase of oil and gas price; there was also a sort of implicit link between oil and gas prices. All this has a significant impact on the shadow prices of natural gas calculated by the model. As a key potential effect of a wider development of shale gas

could be a decrease of gas prices, this is an important point. I think it would be useful if the paper would include:

15.1. A few words on gas price formation in TIMES and in TIAM-Grantham in particular, explaining to what extent the model is able to capture this potential effect of shale gas.

15.2. Some description of the results produced by the model in terms of natural gas prices in the different regions, both at the beginning of the time horizon and in the long-term, under the different scenarios.

15.3. Once obtained an acceptable representation of the effects of an optimistic shale gas scenario on prices, it would be interesting to see if the current results of the paper would change substantially; maybe in that case the difference in system costs between an optimistic and a pessimistic shale gas scenario could be larger than now?

The model optimises for a minimum cost whole energy system, without considering detailed price formation dynamics. We are aware that some previous versions of TIAM have a variable operating cost mark-up to crudely simulate the mark-up that occurs in selling extracted reserves. This version of the model has no such mark-up as the analysis is focused on the resource cost of shale gas extraction, rather than the allocation of revenues to shale sellers and specific examination of price formation. Hence, the analysis is focused not on the metric of gas prices, but rather on the metrics of shale gas and conventional gas usage in different scenarios of their extraction cost, and the impacts this has on overall energy system and mitigation costs towards the 2 degrees C target. A note has been added to the description of TIAM (Box 1, Section 3: Methods) highlighting the reliance on extraction costs.

16. Demand response: I'm not sure I have understood correctly the model version that has been used in the study. Is it the non-elastic demand version? In any case, I think it would appropriate to mention that the potential development of shale gas is also linked to the gas demand elasticity to a potential price reduction (see previous bullet): Therefore, if this chain is not represented appropriately, the overall impact can be underestimated (no problem if this is a structural limitation of the tool used, but it's a point that should be mentioned).

This is the elastic version, so we believe these concerns don't apply. Added a note indicating the elastic version is used to methods section 3.

17. Reference scenario: all the impacts of shale gas are assessed by comparing the results of a set of different reference scenarios (each one having different assumptions on the cost curve of conventional/unconventional gas) as well as by comparing the reference scenarios with the corresponding 2C scenarios. I think it would be helpful for the reader to see the main results of the reference scenario, to be able to assess around which benchmark the analysis is built. I remember that the version of TIAM delivered to ETSAP users produced some debatable results under several aspects (e.g. total demand and trade). It is true that there is no way to assess "the quality" of a very long-term reference scenario (to 2100), still it would be useful to have the possibility to detect some peculiar features of the model, e.g. if the penetration of gas is already at high levels or not, the degree of competitiveness of nuclear, which can be an obstacle to the development of gas whatever its price, the actual development of renewables under the different scenarios, etc…

Absolute resource usage has been added in an appendix. Energy demand growth and resource mix is broadly in line with previous TIAM-Grantham runs included in previous AVOID2 analysis (WPC2a). Nuclear contributes relatively little to the energy mix (2-3% throughout reference and mitigation runs), and gas peaks in 2030 at around 30% of supply, and declines more rapidly in mitigation than reference scenarios. We have used this version of the ETSAP-TIAM model throughout the AVOIDing dangerous climate change programme. In this programme the model has been compared to other energy system models and not found to be a significant outlier. Overall the model outputs, in terms of mitigation costs, fossil fuel and non-fossil fuel demand patterns, and technology deployment patterns, are broadly speaking in line with other models integrated assessment models such as WITCH and MESSAGE.

18. Are the choices of scenario used in the analytical approach suitable to give a balanced view?

19. I think approach to use a range of scenarios based on different assumptions on the cost curve of conventional/unconventional gas is appropriate to address the uncertainty around the issue, without having to address the high complexity of a full uncertainty analysis.

Thanks.

20. I'm less convinced about the sort of sensitivity analyses:
    20.1. About the issue of the potential limited availability of funding for low carbon electricity, it is justified through the "possible diversion of public and private funding away from cleaner technologies, which might lead to their being developed and deployed more slowly, with possible implications both for the economy and the environment". I think this is true for the development of any kind of energy technology that is not in the basket of the low carbon technologies selected in the paper. That looks a bit arbitrary. It's not clear why this concept has been applied only to shale gas. Moreover, in the paper it is correctly said explicitly that the quantitative assumptions about the cost of capital financing rates (+1%, +10%) are "arbitrary choices". This lead the reader to wonder about the practical usefulness of these scenarios and of their results.

As noted in response to our other reviewer, this scenario is based on policy and mitigation effort being directed towards the support of shale gas rather than low-carbon energy technologies, and was part of the specified remit for this report, as agreed prior to model runs. Whilst it is possible that an increased shale gas uptake could impact other fuels, this was not specified in the original remit of the study, which is focused on how shale gas might affect / impact on low-carbon investment.

    20.2. I have similar perplexities about the scenarios on methane emissions, whose results receive a lot of attention in the paper ("could lead to additional global warming"…); they look arbitrary, because: a) as said above, they assume that no mitigation measure is taken, while the cost of mitigation could be low, b) if I understand correctly, the leakage rates are applied only to shale gas, while the methane emissions of the energy sector are related to activities linked to oil, gas, coal and bioenergy supply, and of the emissions from the oil and gas sector just under 60% come from upstream operations.

Re (a): the impact of a range of emissions rates is considered, and the higher rate indicates the importance to ensure adequate monitoring and emission-reducing challenges are overcome before widespread extraction, and to regulate effectively.

Re (b): the leakage rates are stated as additional leakage that occurs in shale gas compared to conventional gas, which is not mitigated through specific measures. It should be noted that the analysis is based on a cumulative 21st century level of CO_2 emissions from fossil fuel combustion and industrial process emissions of 1,340 $GtCO_2$ which earlier analysis in the AVOID programme has established as giving a 50% likelihood of limiting global temperature change to 2°C above pre-industrial levels. In arriving at this cumulative CO_2 level, account has been taken of the fugitive methane emissions from fossil fuel extraction and distribution, the mitigation measures to reduce / eliminate such emissions, and the costs of doing so. Full details are given in AVOID 2 reports WPC2a (http://www.avoid.uk.net/2015/11/assessing-the-challenges-of-global-long-term-mitigation-scenarios-c2a/) and WPC2b (http://www.avoid.uk.net/2015/11/the-contribution-of-non-co2-greenhouse-gas-mitigation-to-achieving-long-term-temperature-goals-c2b/). The experiment here thus represents a scenario whereby there is unexpected or unplanned methane leakage over and above that for conventional gas, such that it isn't mitigated. In reality it may well be monitored and mitigated, avoiding this leakage. The report therefore sets out the benefit, in climate terms, of doing this monitoring and mitigation, rather than implying that this level of leakage will occur. This is clarified in section 3: methods, as well as the relevant results sub-section

    20.3. The "dash for shale gas" scenarios can be more easily justified, I guess to represent a sort of political choice "in the name of energy security".

Glad to note the agreement with the "dash for gas" as a sensible scenario.

20.4. However, till now shale gas has been exploited only on the base of economic reasons, while it has been often opposed for socio-political considerations.

It doesn't seem that economic basis of shale extraction up to this point has been clear. Whilst it is clear that US gas production has increased, and prices have reduced, as a result of shale extraction, other analysts conclude that investment in shale gas are unlikely to be recuperated (eg. Hughes, cited, or leaked industry documents in NY times http://www.nytimes.com/interactive/us/natural-gas-drilling-down-documents-4.html). Socio-political considerations are certainly significant, and are briefly summarised in our introduction, but largely fall outside of the scope of this report.

21. I think it would be interesting if the analysis could include an assessment of the (potentially structural) impact of alternative shale gas developments on gas prices and through that on gas demand, either by running the elastic demand version of the model or by simply describing I more detail the effects of the scenarios already developed.

See response to point 12 on pricing. Absolute resource usage has been added in an appendix.

22. Are the assumptions of the approach clearly explained?

23. The reader would benefit from a more detailed description of some assumptions:

23.1. It is said that "the TIAM-Grantham model is calibrated to standard growth projections based on the "Shared Socio-Economic Pathways 2" (SSP 2) socio-economic assumptions". However, in the original TIAM the evolution of energy service demands is strongly dependent from the assumptions on the elasticity of energy service demands to their drivers. I understand that a full description of the evolution of energy service demands is not easy to do, and difficult to understand for the reader. As said, an alternative could be to give to the reader at least the "feeling" about the key results of the reference scenarios, i.e. in terms of total energy demand, energy mix, etc… At least up to the middle of the century these reference scenarios can be compared with some other literature.

Total energy demand and mix have been added in a new annex (see response to comment 17)

23.2. The paper includes a wide and interesting discussion about shale gas costs. Table 3 describes the assumptions used. But if I'm not wrong the actual numbers used in the model are not explicitly presented. I think this would help understanding some interesting results, among which the fact that the "system cost is more sensitive to conventional gas cost sensitivities rather than shale gas cost sensitivities". This outcome is something that can be explained, however at first sight one can assume that the uncertainty around the cost of conventional resources should be much lower than the uncertainty around the cost of unconventional, therefore the latter range of values should lead to a higher variation in the results.

The costs used are presented in Fig 4, but labelled according to source, rather than scenario names. Added references in Table 3 to increase clarity. We found similar levels of uncertainty in literature on cost and supply of conventional and unconventional gas costs. However, because the conventional resource is so much larger than the shale resource, the uncertainties surrounding conventional have a much larger impact on the system.

23.3. It is said that "All technology and resource costs are taken from ETSAP's 2012 TIAM model version with the exception of gas resources". As said above, to my knowledge the version of TIAM delivered to ETSAP users produced some debatable results under several aspects (e.g. total demand and trade). As it is impossible to describe the inputs of a model including more than a thousand of processes, it would be useful to see at least how the model project the evolution of the global energy system, particularly in the medium-term (when it can be compared with other literature).

See response to 17, 23. We certainly acknowledge TIAM has some limitations, but nonetheless consider it a useful tool in this context, as the reviewer acknowledges.

24. *Do the results appear to follow logically from assumptions, scenarios and approach? If not explain why.*

24.1. Yes. But see what said under the previous question with respect to the opportunity to include more details about the assumptions.

25. *Are the conclusions supported by the results?*

25.1. I think all the conclusions related to the main set of scenarios are quite well supported by the results.

25.2. As said above, I'm not convinced about the possibility to draw robust conclusions from the other scenarios, in particular the scenarios on the potential diversion of public and private funding away from cleaner technologies and the ones on methane emissions. As the latter issue has quite a strong weight in the discussion, I would suggest at least to redraw a bit some conclusions related to the results of these set of scenarios.

These are discussed individually earlier and have been signposted as illustrative and appropriately caveated.

26. *How do the conclusions compare with other literature?*

26.1. The literature is not so wide. I agree with the paper when it says that there is an analytical gap and that it is a contribution to fill this gap.

26.2. However, there is indeed some literature exploring the cost relativities of shale gas, but at present it is not easy to compare the results of the paper with this literature (even taking into account the original aspects of this report); it would help to have a wider description of the results of the model, even as table in an annex, including e.g. primary energy demand and its composition by fuel, the mix of electricity generation, the actual development of renewables under the different scenarios, the change of gas demand in the low cost shale scenarios with respect to the high cost shale.

See response to Q21.

27. *Can you comment on the overall quality and balance of the study?*

27.1. In general the study is interesting and presents indeed important original features, i.e. basically the ones highlighted in it: a scenario analysis on the cost relativities of both shale and conventional gas resources, a very long-term pathways consistent with the 2°C long-term temperature goal, an assessment of the consequences of plausible rates of methane leakage from shale gas. I see a few main problems:

27.1.1. In order to make it possible for the reader to put the results in the right context, it would help to have a wider description of some key inputs as well as of the trajectories of the global energy system depicted by the model (as said, in terms of primary energy demand, energy mix, …)

See response to Q21. Box 1 does provide details of the TIAM model. We feel there is sufficient literature on the structure of this model that too much detail here would be inappropriate.

27.1.2. The conclusions about the consequences of methane leakage do not seem derived from a sufficiently robust analysis.

See response to 20.2

27.1.3. The same is true for the issue of the potential diversion of public and private funding away from cleaner technologies.

See response to 20.1

27.1.4. I guess it can easily happen that the reader wonders if the results are not affected by the fact that the model does not seem to capture in a proper way what has been so far the main impact of unconventional gas, that is its impact on US gas prices and indirectly also on gas prices in the other two main regional gas markets. This issue should be either addressed or at least mentioned in the discussion.

See response to 15.3, 20.4

27.1.5. In conclusion, overall I think the paper look a bit biased towards the weaknesses of shale gas as well as the potential problems related to its development. However, so far it has had a strong impact on the global gas market, and it showed a quite impressive resilience in a low price environment. I believe the general impression of the paper would benefit if it could give a bit more space to the strengths of shale gas.

The study has not been designed to give a view on the potential strengths and weaknesses of shale gas, but rather to set out what data there is on the supply, costs and methane leakage rates of shale gas, and to utilise these data in an energy systems model which helps to assess the potential impact on the feasibility and cost of meeting stringent long term temperature goals. As such, we feel the scenarios are sufficiently clearly set out and –where necessary – caveated that the study provides an informative but unbiased description of the potential impacts of shale gas exploitation in a low-carbon world. This review highlights a number of interesting and important elements around shale gas development, but so long as there is not any additional robust data that is missing from our study, and that would significantly change the results, we are confident that this provides a scientific, unbiased analysis of the potential implications of shale gas in light of the considerable uncertainties that continue to pervade this issue.