# A short note on integrated assessment modeling approaches: Rejoinder to the review of "Making or breaking climate targets – the AMPERE study on staged accession scenarios for climate policy"


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[1] The views expressed in this article are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission.

We provide a rejoinder to a review (Rosen, 2015) of our original article "Making or breaking climate targets – the AMPERE study on staged accession scenarios for climate policy" (Kriegler et al., 2015a). We have a substantial disagreement with the content of the review, and feel that it is plagued by a number of misconceptions about the nature of the AMPERE study and the integrated assessment modeling approach employed by it. We therefore see this rejoinder as an opportunity to clarify these misconceptions and advance the debate by providing a clearer understanding of the strengths, weaknesses, and ultimately the value of integrated assessment.

Critical reviews of published work can foster scientific debates and advance research. In this spirit, we provide a rejoinder to a review (Rosen, 2015) of our original article "Making or breaking climate targets — the AMPERE study on staged accession scenarios for climate policy" (Kriegler et al., 2015a) and the wider results of the AMPERE project.[2] We have a substantial disagreement with the content of the review, and feel that it is plagued by a number of misconceptions about the nature of the AMPERE study and the integrated assessment modeling approach employed by it.

Our rejoinder is organized into five sections, a conclusion and supplementary information. The sections contain a point by point rebuttal of the central points of criticism in the review article, to which we will refer as simply, "the critique". Those central claims are: 1. our study was motivated by the desire to advocate globally fragmented climate policy approaches, 2. the model comparison approach that we are using was not credible, 3. our estimation of mitigation costs was inadequate and misleading, 4. the integrated assessment models (IAMs) used in our study were not well documented and 5. the peer review of our study did not serve its purpose. In our rebuttal, we will clarify 1. the objective of our study, 2. the validity of the model comparison approach, 3. the nature of mitigation cost estimates, 4. the extensive documentation of modeling tools and study design in the publication, and 5. the adequacy of the review process of our study. The supplementary information provides more detailed

[2]Published in a special issue on the economics of climate stabilization in *Technological Forecasting and Social Change* (see supplementary information for a full list of articles in the special issue). In addition to our study on staged accession scenarios, the special issue included studies on the role of delayed mitigation and technology availability (Riahi et al., 2015) and model diagnostics (Kriegler et al., 2015b).

discussions of relevant points, including further discussion of misconceptions of our approach and specific claims that appear to contradict the content of our publication. We will also point out instances where the critique does not appear to account for the broad coverage of topics by the articles in the special issue and the recent literature on IAM model comparison studies.

1. **Objective of the AMPERE study**: The AMPERE study aims to assess the implications of the fragmented state of near-term international climate policy action for the attainability of long-term climate targets (Kriegler et al., 2015c). We developed the analysis by comparing scenarios of staged accession to a global climate regime vis-à-vis a benchmark case of global cooperative climate action. The staged accession scenarios allowed better representation of short term climate policy choices and provided new insights on their alignment with long term goals. Their use was motivated by the research question, not by a desire to advocate specific climate policy scenarios.

2. **Validity of the model comparison approach:** We agree with Rosen (2015) that changing parameters of a model to evaluate their influence on model output is a very valuable exercise to understand model sensitivities to input assumptions. Such studies have been frequently performed with individual integrated assessment models (e.g. Gritsevskyi & Nakicenovic, 2000; Clarke et al., 2008; McJeon et al., 2011; Luderer et al., 2013; Rogelj et al., 2013). However, single model sensitivity analyses are not directly transferable to multi-model comparison studies such as the AMPERE study. Models differ in many input and structural assumptions, and what may be an input parameter to one model could be a constraint or a structural assumption in another model. Model comparisons undertake controlled variations of, e.g., a set of policy assumptions (such as the such as the AMPERE (Kriegler et al., 2015c) and EMF22 studies (Clarke et al., 2009)), technology assumptions (such as the AMPERE (Riahi et al., 2015) and EMF27 studies (Weyant & Kriegler, 2014)) or socio-economic development assumptions (such as the RoSE study (Kriegler et al., 2013)) to understand robust and sensitive features of energy emissions pathways along the selected dimensions given the full set of differences between models along the other dimensions. This is an effective way to capture "between model" uncertainty. It also allows us to better understand differences in model behavior due to the iterative process of

comparing model output and discussing underlying reasons for output differences among modeling teams. Here the goal is to identify key underlying factors for output differences independently of whether those are input or structural assumptions. Model comparison studies differ in their emphasis placed on capturing the degree of “between model” uncertainty in policy applications vs. diagnosing differences in model results in more stylized experiments. AMPERE has undertaken both types of study. Kriegler et al. (2015a) and Riahi et al. (2015) emphasize application, while Kriegler et al. (2015b) emphasizes model diagnostics.

The value of model comparisons is underlined by the fact that they are conducted in many modeling communities, including the climate modeling community (CMIP1-5), the climate impact modeling community (ISI-MIP), the agricultural modeling community (AgMIP) and the water modeling community (WaterMIP). The model comparison approaches in these communities do not differ structurally from the approach taken in integrated assessment modeling studies.

**3. Nature of mitigation cost estimates:** The critique suggests that the mitigation cost estimates in the AMPERE study are flawed. However, we used standard cost-effectiveness analysis to estimate mitigation costs as many other integrated assessment modeling studies have done before. It is long standing practice in climate change economics to differentiate between cost-benefit and cost-effectiveness analysis of climate policy. By definition, cost-effectiveness analysis does not consider the magnitude of climate damages nor the intertemporal trade-off between mitigation costs and climate damages. Cost-effectiveness studies focus on the economics of reaching pre-defined climate goals. The benefit of this approach is to gain a deeper understanding of mitigation dynamics and the direct costs of mitigation policy, inter alia because it allows the use of models with higher sector detail. There is value in research that looks at both the cost and benefit components separately. The IPCC, for example, devotes separate working groups to the assessment of climate impacts and damages (Working Group II) and mitigation costs (Working Group III).

Contrary to what is suggested in the critique, we clearly indicated the nature of mitigation cost estimates in our article, in particular the fact that they do not include the benefits of reduced global warming[3]. Furthermore, we included an entire section (4.4) and a dedicated Figure (Fig. 4) to compare global warming reductions due to mitigation action with mitigation costs. It appears that the critique neither recognized the cost-effectiveness approach that we took in the AMPERE study nor the discussion of mitigation benefits in our article.

The critique places an emphasis on technology cost assumptions which it hypothesizes to be the main driver of mitigation costs. As further discussed in the supplementary information, this is by no means obvious. Mitigation costs are calculated relative to a dynamic baseline as is common practice in integrated assessment modeling. This implies that if a low carbon technology outperformed a fossil fuel technology without any climate policy intervention, it would already be reflected in the baseline. The cost estimates thus capture the additional effort due to climate policy. We discuss the important topic of the choice of baseline and the assessment of the changes between baseline and policy scenario in greater depth in the supplementary information. Contrary to what is claimed in the critique, the AMPERE study accounted for and investigated the climate policy impact on energy efficiency improvements, learning-by-doing of low-carbon technologies and fossil fuel prices.

The critique comes to the general conclusion that mitigation costs over the 21st century are unknowable because technology costs in the far future are unknowable. We agree with Rosen (2015) that no robust prediction of economic outcomes can be made even over much shorter time spans. But no unconditional predictions are attempted. Rather, it is the careful framing of mitigation cost estimates relative to a dynamic baseline that allows a structured exploration of economic impacts conditional on a range of different, and uncertain, scenarios. The integrated assessment modeling community is well aware about the deep uncertainty about long-term technology developments as documented by, e.g., its involvement in research on technological innovation in the energy system (e.g. Wilson et al., 2013; Grübler & Wilson, 2014). It is indeed an important debate how the tension

[3] We state in our article: "*Reported values are direct (or gross) mitigation costs that do not include the direct benefits from avoided climate damages, or any co-benefits and adverse side-effects from mitigation action.*" ((Kriegler et al., 2015a), pg. 33).

between deep uncertainty in the long run and the need to perform century-scale analysis due to the long-term nature of climate change and mitigation goals can be adequately addressed (e.g. Morgan & Keith, 2008). This debate needs to be informed by the existing research on the topic and should not suffer from misinterpretations of methodological approaches.

**4. Extensive documentation of modeling tools:** The critique states that the modeling tools and assumptions used in the AMPERE study were not adequately documented. Here we disagree. Our article (Kriegler et al., 2015a) provides a comparative overview of key characteristics of the underlying models both in the main paper and the supplementary information. To this end, the supplement includes a detailed spreadsheet on model characteristics providing harmonized descriptions across models to allow for direct comparisons. In addition, we have provided a 50 page supplementary documentation of the study approach, the scenario setup (including the original study protocol) and the participating models. This documentation includes a summary paragraph on each model with further references to articles and model documentations for the interested reader. Quantitative information on model input assumptions, including cost assumptions, can be found in several of these references[4].

Moreover, we have published the data of the full set of AMPERE scenarios used in our study, and the two companion studies (Riahi et al., 2015; Kriegler et al., 2015b), in a database hosted by IIASA and referenced in our article (http://tntcat.iiasa.ac.at/AMPEREDB). This database includes, e.g., information about capital costs of electricity generation technologies, fossil fuel prices, socio-economic drivers (GDP and population) and energy demand (which the critique mistakenly claims to have not been disclosed) along with a large set of other key variables characterizing the scenarios. Finally, the special issue contains a companion study (Kriegler et al., 2015b), which is one of the largest integrated assessment model diagnostic studies to date featuring the explicit aim of increasing transparency about the differences in model response patterns. Given this wealth of information, and contrary to

[4] E.g. Luderer et al. (2011) for the REMIND model and providing the entry point to the GCAM wiki at http://wiki.umd.edu/gcam

what is claimed in the critique, we conclude that modeling tools, study design and scenario results are documented extensively in our publication of the AMPERE study.

**5. Adequacy of peer review process:** The critique raises concerns about the peer review of our study and the modeling tools. Those concerns are unfounded with regard to the publication of the AMPERE special issue in Technological Forecasting and Social Change. We followed the journal´s peer review process rigorously and relied on expert reviewers with deep knowledge about integrated assessment modeling tools and approaches. The AMPERE project itself was supervised by a scientific advisory board throughout its lifetime. Numerous studies based on the models in the AMPERE study have been published in the peer-reviewed literature before. The critique´s recommendation to zero-base the review of modeling tools in each study that uses them contradicts the basic notion of the scientific enterprise to build on published work.

The critique makes the broader point of an external review of modeling tools independently from individual applications. We agree with Rosen (2015) that improving comprehensibility and comprehensiveness of model documentations and subjecting them to external review have large benefits for transparency and model evaluation (see also Schwanitz, 2013). To this end, the integrated assessment modeling community is actively working on expanding and harmonizing model documentation standards, e.g. in the ADVANCE project (see http://www.fp7-advance.eu/content/model-documentation). But before claiming a lack of model documentation, the available resources[5] and peer-reviewed literature should be recognized and put into the context of documentation standards for large-scale numerical models in other research areas.

[5] For a few examples of web-based documentations of integrated assessment models see the documentation of the GCAM Model developed by the Joint Global Change Research Institute at http://wiki.umd.edu/gcam, of the REMIND model developed by the Potsdam Institute for Climate Impact Research (PIK) at http://pik-potsdam.de/research/sustainable-solutions/models/remind, of the IMAGE model developed by the Netherlands Environmental Assessment Agency (PBL) at http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation, and of the WITCH model developed by the Fondazione Eni Enrico Mattei (FEEM) at www.witchmodel.org.

**Conclusion:** Based on the above discussion, we find the central points of the critique of our AMPERE study to be unfounded, and largely based on misinterpretations of its methodological approach. Since this approach is fairly standard in integrated assessment modeling, there is an apparent need for better explanation of integrated assessment modeling practices. To this end, we hope that our rejoinder has been able to clarify a number of items concerning the purpose, scope and role of IAM studies, model comparisons, mitigation cost estimates, and model documentation, and thus will contribute to an improved understanding of the AMPERE approach, and of that involved in many integrated assessment modeling studies more generally.

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## References

Clarke, L. E., Kyle, P., Wise, M. A., Calvin, K., Edmonds, J. A., Kim, S. H., Placet, M., Smith, S. (2008) CO2 emissions mitigation and technological advance: an updated analysis of advanced technology scenarios. Technical Report PNNL-18075. Pacific Northwest National Laboratory, Richland, WA.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M. (2009) International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Economics 31(S2): S64-S81.

Gritsevskyi, A., Nakicenovic, N. (2000) Modeling uncertainty of induced technological change. Energy Policy 28: 907-921.

Grübler, A., Wilson, C. (eds.) (2014) Energy Technology Innovation. Learning from Historical Successes and Failures. Cambridge University Press, Cambridge, UK, 400 pp.

Kriegler, E., Mouratiadou, I., Luderer, G. et al. (2013) Roadmaps towards Sustainable Energy futures and climate protection: A synthesis of results from the RoSE project. Report, Potsdam Institute for Climate Impact Research, Potsdam.

Kriegler, E., Riahi, K., Bauer, N., et al. (2015a) Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technol Forecast Soc Change 90, Part A:24–44. doi: 10.1016/j.techfore.2013.09.021

Kriegler, E., Riahi, K., Bosetti, V., et al. (2015b) Introduction to the AMPERE model intercomparison studies on the economics of climate stabilization. Technol Forecast Soc Change 90, Part A: 1–7. doi: 10.1016/j.techfore.2014.10.012

Kriegler, E., Petermann, N., Krey, V., et al (2015c) Diagnostic indicators for integrated assessment models of climate policy. Technol Forecast Soc Change 90, Part A: 45–61. doi: 10.1016/j.techfore.2013.09.020

Luderer, G. et al. (2011) Description of the ReMIND-R model, http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/REMIND_Description.pdf (last accessed June 2015)

Luderer, G., Pietzcker, R. C., Bertram, C., Kriegler, E., Meinshausen, M., Edenhofer, O. (2013) Economic mitigation challenges: how further delay closes the door for achieving climate targets. Environmental Research Letters 8(3): 034033. doi: 10.1088/1748-9326/8/3/034033.

McJeon, H. C., Clarke, L. E., Kyle, G. P., Wise, M. A., Hackbarth, A., Bryant, B., Lempert, R. (2011) Technology Interactions among Low Carbon Energy Technologies: What Can We Learn from a Large Number of Scenarios? Energy Economics 33(4): 619-631.

Morgan, M. G., Keith, D. (2008) Improving the way we think about projecting future energy use and emissions of carbon dioxide. Climatic Change 90: 189-215.

Riahi, K., Kriegler, E., Johnson, N., et al. (2015c) Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol Forecast Soc Change 90, Part A:8–23. doi: 10.1016/j.techfore.2013.09.016

Rogelj, J., McCollum, D. L., Reisinger, A., Meinshausen, M., Riahi, K. (2013) Probabilistic cost estimates for climate change mitigation. Nature 493: 79–83. doi: 10.1038/nature11787

Rosen, R. A. (2015) Critical review of: “Making or breaking climate targets — the AMPERE study on staged accession scenarios for climate policy” (TFSC 17862). Technol Forecast Soc Change. doi: 10.1016/j.techfore.2015.01.019

Schwanitz, V. J. (2013) Evaluating integrated assessment models of global climate change. Environmental Modelling & Software 50: 120–131, doi: 10.1016/j.envsoft.2013.09.005

Weyant, J., Kriegler, E. (2014) Preface and introduction to EMF 27. Climatic Change 123: 345–352. doi: 10.1007/s10584-014-1102-7

Wilson, C., Grübler, A., Bauer, N., Krey, V., Riahi, K. (2013) Future capacity growth of energy technologies: Are scenarios consistent with historical evidence? Climatic Change 118:381-395. doi: 10.1007/s10584-012-0618-y

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## Supplementary Information

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The supplementary information serves a threefold purpose: to highlight claims of the critique that appear to contradict the content of our original paper, to provide a more detailed discussion of methodological questions and possible misconceptions about the approach taken in the AMPERE study, and to address several additional claims of the critique.

**Documentation of modeling tools and study approach:** The review criticizes the AMPERE study for a lack of documentation: "*Unfortunately, however, from the perspective of a reader of this paper, each model is essentially a proverbial "black box". The reader can have little idea as to what is going on inside the "black box" based on the information presented in the TFSC article (Kriegler et al., 2014)."* (Rosen 2015, pg 2[2]). As pointed out above, this criticism does not withstand closer scrutiny. The AMPERE study was documented exceedingly well with (i) a 50 page supplementary document containing summary descriptions of participating models, a detailed description of the scenario approach and its adoption by individual models, and the full study protocol (in addition to the description of methods and participating models in the main article), (ii) a spreadsheet with an extensive description of model characteristics and (iii) a database containing the full scenario data used in our AMPERE study and its two companion studies. The detailed spreadsheet on model characteristics includes, e.g., solution approach, economic coverage, cost metrics, emissions coverage, representation of energy technologies (wind, solar, geothermal, nuclear, hydropower, coal, gas, biomass-fired power with and w/o CCS, biomass and coal to liquids) and resource availability (coal, oil, gas, bioenergy, uranium, CO2 storage). An important and innovative feature of the documentation is to provide harmonized descriptions across models and arranged by topic in order to allow for direct and easy comparison between models.

The critique asserts: "*To get a somewhat better, but still not complete idea, of how the different models function, one would have to undertake a major research project consisting of trying to find documentation of all the eleven models on the websites of the research teams. However, a reasonably complete set of the important input assumptions, especially cost assumptions, used in this paper cannot be found anywhere, including in the supplementary online material that was published with the paper."* (Rosen 2015, pg. 2). This claim does not accurately reflect the published information. Both the main paper and the supplementary information provide references to individual model descriptions and/or articles for each model. Thus, the reader is not required to research these references by him or herself. As pointed out in the main text, quantitative information on model input assumptions, including cost assumptions, can be found in several of these references (see Footnote 4 in the main text). In addition, the AMPERE database provides a host of quantitative information by model, scenario, region and point in time. This includes, inter alia, capital costs of electricity generation technologies, deployment of energy technologies, fossil fuel use and prices, socio-economic drivers (GDP and population) and energy demand. Thus, the critique's claim that "*major baseline assumptions are not provided."* (Rosen 2015, pg. 3) is inaccurate.

**Sensitivity analysis:** The critique asserts a lack of sensitivity analysis in our article, and by implication the larger set of AMPERE studies presented in the special issue in Technological Forecasting and Social Change (as stated: "*I will focus attention on this single overview paper as representative of the others."* Rosen, 2015, pg. 2). Concretely, it is claimed: *"In fact, no sensitivity analyses based on varying key cost input assumptions are presented at all."* (Rosen 2015, pg. 2), and *" … higher levels of*

[2] Page numbers do not refer to the journal page numbers of the published review, but are given relative to the first page of the review.

*possible cost effective investments in energy efficiency than the models allow for in the mitigation scenarios have been totally ignored. [Footnote: In fact, no discussion at all of enhanced energy efficiency as a technological mitigation strategy is even mentioned in the article.]"* (Rosen 2015, pg.4). However, the AMPERE companion study conducted by Riahi et al. (2015) looks, inter alia, into the effect of limited mitigation technology availability and increased energy efficiency on mitigation pathways. As a result, energy efficiency is an important topic in Riahi et al. (2015) as well as in other papers of the AMPERE special issue (e.g. Bertram et al. 2015; Bibas et al. 2015). Also, Riahi et al. (2015) conduct a sensitivity analysis that takes individual technologies off the table and thus provides an upper bound on the impact of increased technology costs on mitigation pathways. In addition, two other recent integrated assessment model intercomparison studies have focused on sensitivity analyses of socio-economic assumptions (RoSE study: Kriegler et al. 2013; Mouratiadou et al. 2015), and technology and energy efficiency assumptions (EMF27 study: Weyant and Kriegler 2014; Kriegler et al. 2014).

**Mitigation cost estimates:** For a proper interpretation of the mitigation cost estimates, it is crucially important to recognize the nature of cost-effectiveness analysis as opposed to cost-benefit analysis, and the role of the baseline in describing the counterfactual case of no climate policy intervention. Integrated assessments of the cost-benefit type include a representation of climate damages on the economy, and attempt to calculate a cost-optimal climate policy trajectory. The outcome of such fully integrated cost-benefit analyses is sensitive to assumptions about climate damages and the discount rate of consumption. In contrast, cost-effectiveness analyses deliberately do not account for the trade-off between mitigation and climate damages, but instead focus on the economics of reaching pre-defined climate goals. The benefit of this approach is to gain a deeper understanding about the mitigation dynamics and the direct costs of mitigation policy, because it allows the use of more detailed energy-economy-land-climate models, and the sensitivity of results to uncertainty about climate damages and consumption discounting is significantly reduced.

Despite the fact that cost-effectiveness analysis is a standard approach taken by many integrated assessment modeling studies, the critique apparently fails to recognize that the AMPERE study uses this approach. Although it is impossible - by definition - to generate negative cost estimates due to the benefit of avoided climate damages with a cost-effectiveness approach, the critique appears to claim that such results should exist[3].

Furthermore, the critique asserts "*that the term mitigation benefits as opposed to mitigation costs is not even mentioned or discussed as a possible outcome of mitigating climate change*" (Rosen 2015,

[3] For example, the critique states on pg. 3, 2nd paragraph: "*Every model run reported in Fig. 3 shows net "consumption losses" and none show net benefits. Furthermore, the authors state that they "expect global direct mitigation costs to rise with mitigation stringency". Why, they never say. Their reason is probably that if there are net costs for less stringent mitigation, then since the marginal costs of more stringent mitigation would be higher than the average costs for less stringent mitigation, the average costs of more stringent mitigation scenarios will increase. But what if there were many scenarios that the modeling teams could have run that would have produced net economic benefits from mitigating climate change? Then more stringent mitigation scenarios might yield even greater net benefits to society. Why weren't those scenarios run and described in this article? Based on my review of many other papers written by the authors of this paper, I suspect that, in fact, each modeling team only made scenario runs with one set of most input assumptions, including only one set of input cost assumptions, even though no research team could possibly know which values of such input assumptions were most likely to occur in 20, 50, or 90 years from now.*" The overall finding of positive mitigation costs is unrelated to the choice of (cost) input assumptions as suspected in the critique. It is due to the fact that the AMPERE study is a cost-effectiveness analysis.

pg. 3) and *"..., the study neglects to mention that many possible types of economic benefits of mitigating climate change over the long run have been completely left out of the models used, especially the avoidance of damages from climate change to the world's economy, people, and ecosystems.*" (Rosen 2015, pg. 4). This is inaccurate. For example, we state in our paper: "*Reported values are direct (or gross) mitigation costs that do not include the direct benefits from avoided climate damages, or any co-benefits and adverse side-effects from mitigation action.*" (Kriegler et al. 2015a, pg. 33). Furthermore, we included an entire section (4.4) to compare warming reductions due to mitigation with mitigation costs. This section starts as follows: "*A global assessment of staged accession has to contrast the benefits in terms of avoided climate change and the mitigation costs relative to the reference case of fragmented and moderate climate action over the 21st century. Fig. 4 provides such an overview.*" (Kriegler et al. 2015a, pg. 33-34). We also state in the conclusions: "*Several caveats of this study need to be mentioned. … Second, we have used a range of metrics to explore the benefits (maximum and 2100 global mean warming, probability of exceeding two degrees) and costs (aggregate mitigation costs, transitional costs, carbon price expenditures) of climate action. While these cover key elements of cost-benefit considerations, a full assessment of the costs and benefits of climate policy will rely on a broader set of indicators, including regional climate impacts, institutional challenges, and co-benefits and adverse side effects.*" (Kriegler et al. 2015a, pg. 41).

**The role of the baseline:** Several elements of the critique may have been affected by a lack of appreciation of the nature and role of the baseline in integrated assessment modeling studies. First, these baselines are fully dynamic, i.e. they will include any energy transition processes that are triggered by other factors than climate policy intervention (e.g. by fossil resource scarcity or optimistic assumptions about future performance of renewable energies). Such transitions happen indeed in some of the baselines, e.g. the REMIND model begins to substitute substantial amounts of fossil fuels with renewable energy in the second half of the century due to falling investment costs for renewable energy and increasing extraction costs for fossil fuels. Nevertheless, a robust message from the multitude of integrated assessment modeling studies of mitigation pathways is that mitigation does not happen at the scale required for climate stabilization (implying net zero greenhouse gas emissions in the long run) without climate policy intervention. In other words, the message is that mitigating climate change needs climate policy, not the least due to the worldwide availability of significant resources of cheap coal.

Second, the changes between the baseline and climate policy scenario are the central result of integrated assessment models and therefore should emerge from the model dynamics, not from changing model input assumptions between baseline and policy cases. The latter would open the door to arbitrary results directly related to ad hoc changes of exogenous input assumptions. Although the critique appears to be concerned about the arbitrariness of results, it seems to call for such an exogenous adjustment of input assumptions (Rosen 2015, Footnote 3): "*This is not a minor point, namely the need to consider baseline vs. mitigation scenario assumptions separately, since most studies like the AMPERE study fail to discuss the need to create systematically different sets of input assumptions for these qualitatively different kinds of scenarios. This is especially true for energy efficiency assumptions, which should be one of the highest priority mitigation options, but which the article ignores entirely. Clearly, most analysts would assume more energy efficiency in the mitigation case than in the reference or baseline case as an input. Also, the input costs of renewable energy supplies should generally be lower in the mitigation cases than in the reference cases, since more investment in them would occur in the mitigation scenarios, and there would be more cost reductions* *via "learning by doing". Similarly, the cost of fossil fuels should be higher in the reference case, since demand for them would be much higher.*" We should clarify that even though the model input assumptions are identical between baseline and policy scenarios (as they should be), this does not mean that energy efficiency, costs of renewable energy and fossil fuel prices are identical as well. These are endogenous variables in integrated assessment models, and they respond to climate policy. As an example, and contrary to what the critique asserts, energy efficiency indeed increases in the climate policy scenarios in response to higher energy prices. And fossil fuel prices decrease because of a cut in demand for fossil fuels induced by climate policy. And higher deployment of renewable energy technologies leads to lower investment costs for these technologies in those models that include learning by doing effects. So the type of dynamics that the critique is calling for lies at the heart of integrated assessment models as those used in the AMPERE study. These crucial determinants of climate change mitigation costs are explicitly mentioned and discussed in the synthesis articles by Riahi et al. (2015) and Kriegler et al. (2015a), and further detailed in specific studies of the AMPERE special issue (see e.g. Bertram et al. (2015) and Bibas et al. (2015) on the role of energy efficiency improvements, Bauer et al. (2015) on fossil fuel price responses, and Marcucci and Turton (2015) on technology learning effects).

Third, the dynamic baseline is used as a counterfactual to calculate the costs of mitigation policy by comparing household consumption, economic output etc. in the mitigation policy scenario with the baseline scenario. The critique may not have fully appreciated this fact, e.g. when writing: "*The authors seem blind to the fact that, certainly, there must be some sets of reasonable technology cost and availability input assumptions for energy supply and demand technologies, and for fossil fuels, that would lead to high net economic benefits of mitigating climate change over the long run.*" (Rosen 2015, pg. 3). If conditions would be so favorable that climate policy would not be needed to induce a decarbonization of the energy system, then the transition to a low carbon economy would occur already in the baseline, and the costs of the (superfluous) policy intervention would be zero – unless the baseline contained additional externalities that would prevent adoption of low-carbon technologies once they become economic. This case is discussed in the next paragraph.

**1st and 2nd best settings:** There is one set of circumstances, in which a policy cost measure in a cost-effectiveness analysis using a dynamic baseline can become negative (i.e. showing economic benefits; see Clarke et al. (2014), Section 6.3.6.5, for an overview). Here we need to briefly introduce the concept of first and second best settings and how it relates to the choice of baseline and climate policy intervention. In a first best policy environment characterized by functioning markets in the baseline, with climate change being the only market externality, any addition of climate policy would lead to aggregate gross economic costs (before accounting for the benefits of avoided climate damages). This is due to the fact that any economic low-carbon technologies would already be picked up by the markets in the baseline. In such a setting, a first best policy introducing a global carbon price will be the least cost strategy to reduce climate change below the baseline. In a second best policy environment with imperfectly functioning markets in the baseline, e.g. due to distortionary taxes and subsidies, a second best policy would still lead to aggregate gross economic costs, but those are potentially lower than for a first best "carbon pricing only" policy imposed on the second best environment (Lipsey and Lancaster 1957)]. Only if policy instruments are added to reduce some of the ancillary externalities (e.g. revenue recycling to reduce labor market imperfections or spillover externalities), economic co-benefits of mitigation policy can occur. The extent to which they can lower costs or even lead to net economic benefits (before accounting for the direct economic benefits of avoided climate damages) is an empirical question, and depends on the formulation of the baseline and the second best policy (Fullerton and Metcalf 1997). These important points have been highlighted repeatedly in the literature, including the 5th Assessment Report of the IPCC (Clarke et al. 2014; Kolstad et al. 2014).

So what assumptions about baseline and climate policy did the AMPERE study make? First, many models included some element of second best policy environment in their no policy baseline (e.g. fossil fuel subsidies), although the assumed market distortions were relatively small in most models - with the exception of the IMACLIM model which accounts for labor market distortions and inertias in technical systems (Waisman et al. 2012), and the WITCH model which accounts for international externalities of innovation (Bosetti et al. 2008). Second, all models calculated a reference policy case that included technology policies (renewable energy portfolio standards, minimum capacity requirements). The costs of more stringent climate policy cases were calculated relative to both the no policy baseline and the reference policy case. Third, the mitigation policy imposed was a transitional carbon pricing policy that followed the regionally fragmented climate action in the reference case until 2030 (also including the technology policies of the reference case) and then transitioned to globally comprehensive carbon pricing at the optimal level. The IMACLIM model further added an infrastructure policy and recycled carbon pricing revenues to reduce labor market distortions. Thus, the AMPERE study went a good deal beyond the standard approach of considering first best baselines and first best carbon pricing policies. And it included one model, IMACLIM, that showed large enough co-benefits of the added infrastructure policy to yield aggregate economic benefits of mitigation policy in some cases (Bibas et al. 2015; see also the caption of Figure S2 in the supplementary information of Kriegler et al. 2015a). Future research on economic co-benefits and adverse side effects of mitigation policies will require a solid understanding of cost-effectiveness analysis of 2nd best policies, a sound description of the nature and role of the baseline, and a clear separation of baseline and climate policy intervention as pursued in the AMPERE study.

**Net present value cost estimates:** The review criticizes our presentation of aggregate mitigation costs in net present value terms: "*With respect to the discount rates used in the various IAMs, which strongly affect the magnitude of the reported results, footnote #5 on page 10 states that different models used different discount rates for optimization purposes when computing results, ranging from 3% to 8%. However, Fig. 3 seems to indicate that cost results from every model were discounted at a 5% discount rate for presentation purposes. However, unless the models were actually run using a 5% discount rate for the preparation of Fig. 3, it is totally meaningless, inconsistent, and visually deceptive to take results that were created utilizing one discount rate and then present them (in Fig. 3) based on a different discount rate*" (Rosen 2015, pg. 3). This is a strong exaggeration. The discount rate of most models that performed an intertemporal optimization (as opposed to other models that did not optimize over time) clustered around 5%. We also provided a sensitivity analysis of net present value cost estimates to the choice of discount rate in the range from 3% to 8% in Figure S2 in the Supplementary Information of Kriegler et al. (2015a). The qualitative results drawn from Figure 3 are unchanged.

**Cost input assumptions**: The critique directs large attention to model input assumptions on technology costs. For example, it asserts: "*Importantly, different assumptions by different modeling teams regarding the cost of mitigation options are very likely to be a key determinant, if not the key determinant, of the very different CO2 prices, because input costs generally determine output prices in such models.*" (Rosen 2015, pg. 3). This is an overstatement for several reasons. First, levelized costs of energy emerge endogenously in the models, and usually reflect more than just cost input parameters, e.g. integration requirements and carbon pricing (i.e. they are scenario dependent). Moreover, not the absolute cost of energy produced by a technology, but the relative costs between technologies influence the technology deployment in the energy sector[4]. Finally, technology deployment may be equally or more strongly affected by additional constraints, e.g. concerning energy resource availability and diffusion rates. Thus, it is by no means a "*logically obvious point that different assumptions about cost inputs might account for much of the different price results for CO2.*", as claimed in the critique (Rosen 2015, pg. 3). On the contrary, as stated in our paper, we think that differences in emissions reduction requirements (due to different emissions baselines) and substitutability of energy technologies (as determined by model structure and availability of mitigation options) have a much larger impact on differences in $CO_2$ prices and mitigation costs.

## References


Bauer N, Bosetti V, Hamdi-Cherif M, et al (2015) CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. Technol Forecast Soc Change 90, Part A: 243–256. doi: 10.1016/j.techfore.2013.09.009

Bertram C, Johnson N, Luderer G, et al (2015) Carbon lock-in through capital stock inertia associated with weak near-term climate policies. Technol Forecast Soc Change 90, Part A: 62–72. doi: 10.1016/j.techfore.2013.10.001

Bibas R, Méjean A, Hamdi-Cherif M (2015) Energy efficiency policies and the timing of action: An assessment of climate mitigation costs. Technol Forecast Soc Change 90, Part A: 137–152. doi: 10.1016/j.techfore.2014.05.003

Bosetti V, Carraro C, Massetti E, Tavoni M (2008) International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. Energy Econ 30(6): 2912–2929. doi: 10.1016/j.eneco.2008.04.008

Clarke L, Jiang K, Akimoto K, et al (2014) Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fullerton D, Metcalf GE (1997) Environmental Taxes and the Double-Dividend Hypothesis: Did You Really Expect Something for Nothing? NBER Working Papers 6199, National Bureau of Economic Research

Kolstad C, Urama K, Broome J, et al (2014) Social, Economic and Ethical Concepts and Methods. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.


[4] This also implies that changing cost parameters for only a single technology may lead to inconsistencies if the underlying argument for this change would also affect other technology cost parameters.

Kriegler E, Mouratiadou I, Luderer G, et al (2013) Roadmaps towards Sustainable Energy futures and climate protection: A synthesis of results from the RoSE project (1st edition). Potsdam Institute for Climate Impact Research, Potsdam

Kriegler E, Riahi K, Bauer N, et al (2015a) Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technol Forecast Soc Change 90, Part A: 24–44. doi: 10.1016/j.techfore.2013.09.021

Kriegler E, Weyant JP, Blanford GJ, et al (2014) The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Clim Change 123:353–367. doi: 10.1007/s10584-013-0953-7

Lipsey RG, Lancaster K (1957) The General Theory of Second Best. Rev Econ Stud 24: 11–32.

Marcucci A, Turton H (2015) Induced technological change in moderate and fragmented climate change mitigation regimes. Technol Forecast Soc Change 90, Part A: 230–242. doi: 10.1016/j.techfore.2013.10.027

Mouratiadou I, Luderer G, Bauer N, Kriegler E (2015) Emissions and their drivers: sensitivity to economic growth and fossil fuel availability across world regions. Clim Change, in press. doi: 10.1007/s10584-015-1368-4

Riahi K, Kriegler E, Johnson N, et al (2015) Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol Forecast Soc Change 90, Part A: 8–23. doi: 10.1016/j.techfore.2013.09.016

Rosen RA (2015) Critical review of: “Making or breaking climate targets — the AMPERE study on staged accession scenarios for climate policy” (TFSC 17862). Technol Forecast Soc Change 96: 322-326. doi: 10.1016/j.techfore.2015.01.019

Waisman H, Guivarch C, Grazi F, Hourcade J (2012) The Imaclim-R Model: Infrastructures, Technical Inertia and the Costs of Low Carbon Futures under Imperfect Foresight. Clim Change 114(1): 101–120.

Weyant J, Kriegler E (2014) Preface and introduction to EMF 27. Clim Change 123: 345–352. doi: 10.1007/s10584-014-1102-7

## Full list of articles of the special issue “The AMPERE intermodel comparison on the economics of climate stabilization”

Kriegler E, Riahi K, Bosetti V, et al. (2015c) Introduction to the AMPERE model intercomparison studies on the economics of climate stabilization. Technological Forecasting and Social Change 90, Part A: 1–7. doi: 10.1016/j.techfore.2014.10.012

Riahi K, Kriegler E, Johnson N, et al. (2015) Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90, Part A: 8–23. doi: 10.1016/j.techfore.2013.09.016

Kriegler E, Riahi K, Bauer N, et al. (2015b) Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technological Forecasting and Social Change 90, Part A: 24–44. doi: 10.1016/j.techfore.2013.09.021

Kriegler E, Petermann N, Krey V, et al. (2015a) Diagnostic indicators for integrated assessment models of climate policy. Technological Forecasting and Social Change 90, Part A: 45–61. doi: 10.1016/j.techfore.2013.09.020

Bertram C, Johnson N, Luderer G, et al. (2015) Carbon lock-in through capital stock inertia associated with weak near-term climate policies. Technological Forecasting and Social Change 90, Part A: 62–72. doi: 10.1016/j.techfore.2013.10.001

Eom J, Edmonds J, Krey V, et al. (2015) The impact of near-term climate policy choices on technology and emission transition pathways. Technological Forecasting and Social Change 90, Part A: 73–88. doi: 10.1016/j.techfore.2013.09.017

Johnson N, Krey V, McCollum DL, et al. (2015) Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. Technological Forecasting and Social Change 90, Part A: 89–102. doi: 10.1016/j.techfore.2014.02.028

Iyer G, Hultman N, Eom J, et al. (2015) Diffusion of low-carbon technologies and the feasibility of long-term climate targets. Technological Forecasting and Social Change 90, Part A: 103–118. doi: 10.1016/j.techfore.2013.08.025

Criqui P, Mima S, Menanteau P, Kitous A (2015) Mitigation strategies and energy technology learning: An assessment with the POLES model. Technological Forecasting and Social Change 90, Part A: 119–136. doi: 10.1016/j.techfore.2014.05.005

Bibas R, Méjean A, Hamdi-Cherif M (2015) Energy efficiency policies and the timing of action: An assessment of climate mitigation costs. Technological Forecasting and Social Change 90, Part A: 137–152. doi: 10.1016/j.techfore.2014.05.003

Sano F, Wada K, Akimoto K, Oda J (2015) Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro- and sectoral decomposition analyses. Technological Forecasting and Social Change 90, Part A: 153–165. doi: 10.1016/j.techfore.2013.11.002

Schwanitz VJ, Longden T, Knopf B, Capros P (2015) The implications of initiating immediate climate change mitigation — A potential for co-benefits? Technological Forecasting and Social Change 90, Part A: 166–177. doi: 10.1016/j.techfore.2014.01.003

Bollen J (2015) The value of air pollution co-benefits of climate policies: Analysis with a global sector-trade CGE model called WorldScan. Technological Forecasting and Social Change 90, Part A: 178–191. doi: 10.1016/j.techfore.2014.10.008

Arroyo-Currás T, Bauer N, Kriegler E, et al. (2015) Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets. Technological Forecasting and Social Change 90, Part A: 192–203. doi: 10.1016/j.techfore.2013.10.002

Paroussos L, Fragkos P, Capros P, Fragkiadakis K (2015) Assessment of carbon leakage through the industry channel: The EU perspective. Technological Forecasting and Social Change 90, Part A: 204–219. doi: 10.1016/j.techfore.2014.02.011

Otto SAC, Gernaat DEHJ, Isaac M, et al. (2015) Impact of fragmented emission reduction regimes on the energy market and on CO2 emissions related to land use: A case study with China and the European Union as first movers. Technological Forecasting and Social Change 90, Part A: 220–229. doi: 10.1016/j.techfore.2014.01.015

Marcucci A, Turton H (2015) Induced technological change in moderate and fragmented climate change mitigation regimes. Technological Forecasting and Social Change 90, Part A: 230–242. doi: 10.1016/j.techfore.2013.10.027

Bauer N, Bosetti V, Hamdi-Cherif M, et al. (2015) CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. Technological Forecasting and Social Change 90, Part A: 243–256. doi: 10.1016/j.techfore.2013.09.009

Schaeffer M, Gohar L, Kriegler E, et al. (2015) Mid- and long-term climate projections for fragmented and delayed-action scenarios. Technological Forecasting and Social Change 90, Part A: 257–268. doi: 10.1016/j.techfore.2013.09.013