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Green hydrogen from hydropower: A non-cooperative modeling approach assessing the profitability gap and future business cases

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Abstract:	This paper investigates a possible future business case for green hydrogen production from hydropower. The main research question is to find the tradeoffs for a run-of-river hydropower plant owner between the currently prevailing business model of wholesale electricity trading and, alternatively, production of green hydrogen. Hence, a bi-level optimization framework between a hydropower plant owner (H_2 producer and price setter) and a transportation firm (H_2 consumer) is developed. The empirical scaling of the numerical example describes Central Western European wholesale electricity market settings. Results indicate that the current market environment and price setup do not allow for profitable green hydrogen production as yet. However, an increasing CO_2 price as the key determining parameter leads to improved competitiveness and expected profitability of the business case studied in this work. In the numerical example examined, a CO_2 price above 245EUR / t triggers profitability, when green hydrogen production is competing with a future electricity contract price of 45 EUR/MWh.
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Title. *Green hydrogen from hydropower: A non-cooperative modeling approach assessing the profitability gap and future business cases*

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Dear Reviewers, dear Associate Editors,

Please find attached our manuscript *"Green hydrogen from hydropower: A non-cooperative modeling approach assessing the profitability gap and future business cases"*, which we would like to submit for publication in your journal *Energy Strategy Reviews*.

The core objective of this research paper is to investigate a possible future business case for green hydrogen production from hydropower. In particular, the main research question is to find the trade-offs for a run-of-river hydropower plant owner between the currently prevailing business model of wholesale electricity trading and, alternatively, production of green hydrogen. The results indicate that the current market environment and price setup do not allow for profitable green hydrogen production as yet. However, an increasing CO2 price as the key determining parameter leads to improved competitiveness and expected profitability of the business case studied in this work.

We believe that with this work we can contribute for your journal's agenda, as our focus lies on hydropower-based green hydrogen production, future business cases, strategic-based (open-source) modeling, and optimal renewable energy resource allocation.

The manuscript is original; no part of this work has been published before nor is it under consideration for publication in another journal. An earlier version has been submitted to *Applied Energy* and rejected; a fundamentally revised and extended version is now submitted here. The authors declare that there are no conflicts of interest regarding the publication of this paper. The paper has been professionally proofread.

The corresponding author is Sebastian Zwickl-Bernhard. The contact details can be found above.

I am looking forward to your reply and thank you in advance for your consideration.

Yours sincerely,

Sebastian Zwickl-Bernhard

Response to reviewers

To the editor and reviewers,

Thank you for taking the time to consider our paper for *Energy Strategy Reviews*. The detailed feedback received has allowed the paper to be improved considerably. The suggestions and feedback have been incorporated into the revised manuscript, and a point-by-point response to feedback with changes made is detailed below. We hope the revised manuscript can be considered for publication.

Best regards, Sebastian Zwickl-Bernhard and Hans Auer

Reviewer #1: Green hydrogen from hydropower: A non-cooperative modelling approach assessing the profitability gap and future business cases - Review

This paper studies a potential business case for green hydrogen production from a run-of-river hydro plant. It does this using a bi-level optimization model with a price-setting leader (H2 producer) and follower (H2 user) in the presence of a long term electricity contract of 45€/MWh that the hydro operator alternatively can use. The results suggest that at current electricity and CO2 prices, there is not a positive business case for green hydrogen from hydro energy. We appreciate the effort that has been put towards investigating this often overlooked source of renewable energy, hydro. As the authors point out, hydro could lend itself very well to the production of hydrogen because of the higher capacity factor, which tends to lower the annuity of the electrolysers. We would suggest further sensitivity analysis of the results, extend the literature review and would welcome rewriting to improve the English.

Major comments:
Review comment: In section 2.1 the role of hydrogen in sustainable energy systems as an alternative fuel is discussed broadly. However, nothing is said about the uses that are put forward in literature as the primary uses of hydrogen, the so-called hard to abate sectors such as the steel industry, chemical industry, etc. We suggest the authors look into these uses and align the literature review with the current direction hydrogen is leading towards.
Author's response: We fully agree that there was a lack of literature addressing the primary use of hydrogen in the so-called hard to abate sectors. In the revised manuscript, we extended the literature in Section 2.1 by additional references (especially review studies). Latter may know provide the reader a broader understanding of the role of hydrogen particularly in the abovementioned industry and steel sector as well in the glass industry.

Review comment: In section 2.2 different production possibilities for hydrogen are discussed. We miss here a discussion of production from hydro. Such a discussion would

make it easier to place the paper into context, and assess what exactly it is doing different and how it is contributing to the field.
Author's response: We agree with the review comment that a discussion of literature related to the production of hydrogen from hydropower was missing in the original version of the manuscript. Therefore, we added relevant references to Section 2.1 of the revised manuscript.

Nevertheless, from our viewpoint, three aspects are to be mentioned, which also to some extent answer the question of how this work here is contributing to the scientific literature (see also the following review comment).

- From an energy economic perspective, most of the existing literature propose green hydrogen production from excess wind and photovoltaic generation. This point is discussed in the original version of the manuscript. In contrast, hydropower generation is used primarily for electricity-specific applications. This work here can be seen as a contribution to enhance the discussion of hydropower as an energy source for the production of green hydrogen. Even in case that hydropower is considered for the production of hydrogen, literature suggests using excess generation.
- In view of your review comment above, which is related to the so-called hard to abate sectors, the proposed game-theoretical approach (including agent's behavior and economic trade-offs) here could provide relevant insights to the use of hydrogen in terms of when and under which conditions the use of hydrogen can be economic viable for both the hydrogen producer and consumer.
- Existing literature often neglects the question of when switching to green hydrogen can be profitable. This work here embeds the techno-economic analysis of green hydrogen production from hydropower into European decarbonization scenarios (and associated CO_2 price trajectories), which allows to project the time of penetration of green hydrogen under European climate neutrality.

Review comment: We strongly recommend the author to point out how this work relates to other research on hydrogen production from hydro energy in Section 2.4.
Author's response: We thank the reviewer for this comment. Against the background of the extended literature (based on the suggestions for Section 2.1 & 2.2), we tried to once again improve the description of the own contribution of our work (see also the three bullet points above). We hope that the changes in the revised manuscript makes the novelties of our work more clear.

Review comment: It is not clear to us why the future contract is implemented the way it is. To our understanding, it reflects the opportunity cost of generating in the future. This is something particular about the operation of hydro. Therefore, to ensure this is clear to readers not acquainted with this technology, we suggest the author elaborates on how this contract reflects the opportunity cost of the hydro operator and why a constraint was added to ensure a constant future contract.

Author's response: In the revised manuscript, we add information on how we modeled electricity generation for future (electricity) contracts. Particularly, the mathematical formulation of generating electricity for future contract ensures a constant electricity generation band. This reflects the practical applications and business cases for hydropower plant owner. In view of that, constant green hydrogen production from hydropower competes with future contracts, which is in the foreground of this work here. As already discussed, this allows hydrogen production facilities high full load hours, which can be seen as a necessary precondition for economic viability. This advantage highlights hydropower for producing green hydrogen compared to other renewable energy sources with limited annual utilization hours (such as wind and photovoltaic).

Review comment: We also believe that the results of the paper are highly dependent on the assumption of the price of the future contract and how it relates to the day-ahead price. The results might be quite different if day-ahead prices are within the range of the future price. We would be interested to see a sensitivity analysis of this parameter and we recommend mentioning in the abstract that the resulting allowance price of 245€/MWh was found when hydrogen is competing with a 45€/MWh future contract.
Author's response: We fully agree with the review comment and would like therefore refer to the third paragraph in our work's conclusions. Particularly, the first sentence of the paragraph is states the following:

> *The different sensitivity analyses conducted in this work clearly show that hydrogen deployment may also significantly depend on the price development on the wholesale electricity markets with underlying driving factors in both directions, supporting and limiting green hydrogen deployment.*

In view of this statement, we do think that the main point of the review comment is already included in the manuscript. Besides, the following aspects and changes have been in the revised manuscript in order to improve the quality of the manuscript and reflect the review comment:

- We present the temporal resolution of the assumed spot market price on an hourly resolution in Appendix C. In principle, Figure C.1 is an extension of Figure 1. However, we thought the analogy between Figure 1 and Figure 2.a. & 3 might be helpful for the reader, as all three figures show values on an hourly resolution for two (representative) days. Nevertheless, we present the average spot market price in Figure C.1, where the reader can observe that average spot market price (41.2 EUR/MWh) is in the range of the assumed future electricity contract price (45 EUR/MWh). Moreover, we included the number of hours per year that have a spot market price in the range of the future electricity contract price, which we define from 0 to 90 EUR/MWh.
- We made it clear in the abstract that hydrogen production essentially competes with a 45€/MWh future electricity contract price.

Minor comments:

Review comment: Page 7, "process heat" is not the best example of the use of hydrogen in the industry. It is worth pointing out that hydrogen can be used as a compound in the industry.
Author's response: Thank you for the hint – we followed the suggestion and replaced the phrase 'process heat'.

Review comment: We would recommend the author to move some of the mathematical descriptions of the optimization problem to the appendix, in particular the KKT conditions, to enhance the readability and flow of the manuscript.
Author's response: Thank you for the advice – we moved parts of the mathematical formulation into the appendix.

Review comment: In the abstract, CO2 price is mentioned as the key parameter leading to better competitiveness. However, a broad sensitivity analysis beyond CO2 price is lacking to back up this statement.
Author's response: We added this to future work of this work here.

Review comment: There remain some grammatical errors in the manuscript. We encourage the authors to tackle those, e.g.: wrong conjugation in "CCGT can already been eliminated", "High annual utilization hours" should be "High number of utilization hours" or "High utilization", "an argument that has been frequently read these days." and "a core handicap becomes visible" should be rephrased. We encourage the authors to perform some extra language checks.
Author's response: We rephrased the mentioned parts of the text. In addition, the revised manuscript was again sent to a professional proofreading service.

Reviewer #2:

Review comment: Please provide more data about shadow price and opportunity cost.
Author's response: Thank you for this comment. In the revised manuscript, we added new information related to the results of different model runs in the Appendix. From our viewpoint, this improves the quality of the manuscript since a better understanding of the leader's shadow prices and opportunity costs can be derived.

Review comment: Please provide more explanation about European decarbonization policies and increasing hydrogen penetration strategies.
Author's response: We thank the reviewer for this very helpful comment. We tried to include European decarbonization policies in the revised manuscript by an extension of the literature review. In particular, we added additional references to Sections 2.1 & 2.2 (see also our response to comments from Reviewer #1). Therein, we discuss in more detail the penetration of hydrogen in the so-called hard to abate sectors such as the industry and transportation sector.

Reviewer comment: To increase the understanding please add axis names to Figure 4.
Author's response: Thanks for the hint. In this work here, we put the names of the y-axes to the top of the figure. Exemplarily, the name of the y-axis in Figure 4 (b) is 'Revenues of hydropower plant in thousand EUR'.

Highlights

- Future business case of green hydrogen production from hydropower
- Non-cooperative game between a hydropower plant owner and a transportation firm
- Trade-offs between electricity trading and hydrogen production
- Numerical example of the Central Western European wholesale electricity market
- CO_2 price above 245EUR/t triggers profitability

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Sebastian Zwickl-Bernhard: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization.

Hans Auer: Conceptualization, Validation, Writing – review & editing, Supervision.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Green hydrogen from hydropower: A non-cooperative modeling approach assessing the profitability gap and future business cases

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Abstract

This paper investigates a possible future business case for green hydrogen production from hydropower. The main research question is to find the trade-offs for a run-of-river hydropower plant owner between the currently prevailing business model of wholesale electricity trading and, alternatively, production of green hydrogen. Hence, a bi-level optimization framework between a hydropower plant owner (H_2 producer and price setter) and a transportation firm (H_2 consumer) is developed. The empirical scaling of the numerical example describes Central Western European wholesale electricity market settings. Results indicate that the current market environment and price setup do not allow for profitable green hydrogen production as yet. However, an increasing CO_2 price as the key determining parameter leads to improved competitiveness and expected profitability of the business case studied in this work. In the numerical example examined, a CO_2 price above 245 EUR/t triggers profitability, when green hydrogen production is competing with a future electricity contract price of 45 EUR/MWh.

Keywords: Green hydrogen, Hydropower, Non-cooperative game, Resource allocation, Profitability, CO_2 price

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