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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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Cover Letter

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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 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: We thank the authors for this revised version and the changes made. We have no further comments.
Author's response: We thank Reviewer #1 for the review comments provided, which allowed us to significantly improve the quality of the manuscript. In particular, the additional sensitivity analysis requested in the previous round of review was helpful and completed the results from our viewpoint. We acknowledge the contribution to improve this manuscript in the acknowledgments. Thank you very much!

Reviewer #2: Dear authors,
Review comment: Please explain why there is no fluctuation in Future contract curve within a 2-day interval in different hours.
Author's response: In the manuscript, Equation (11) describes the constant future contract generation of the hydro power plant. It is assumed that the future contract is a constant generation band throughout the year, which results in a constant generation in each hour. Therefore, there is no fluctuation in future contract curves, such as shown in Figure 2a and 2b. This fact is already described in the methodology section of the manuscript. In particular, it is explained in Section 3.2 Leader's mathematical framework. We refer to the following text which is stated in the Constraints paragraph at page 15:

> *Equations (11)-(13) ensure a constant future electricity contract and hydrogen production at each time step t. For simplicity, annual future electricity contracts are considered only. Therefore, a constant electricity generation during the year is modeled.*

In order to make this point even more clear, we added the following text to the last sentence of the aforementioned text: *Therefore, a constant electricity generation during the year is modeled* ***and thus there is no fluctuation in the future contract curve.*** We do think that this point is now clear in the manuscript. Thank you for the comment.

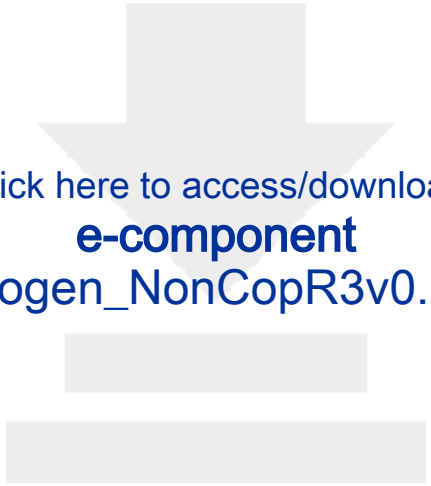
Review comment: The feasibility of the proposed scheme is still a matter debate.
Author's response: Regarding the feasibility of the proposed scheme, we would like to refer to our response for the previous rounds of revisions where we carefully addressed the issues related to the general approach of the paper. From our viewpoint, at least the following points are important when considering our proposed non-cooperative game between the hydrogen producer (hydro power plant) and hydrogen consumer (transportation firm):

- Our study primarily focuses on the cost-optimal trade-off decision for a hydropower plant owner on where to place its available electricity generation. In our work here, we propose a (non-cooperative) game-theoretical approach, which allows us to investigate the optimal strategy for each agent individually (i.e., both hydrogen producer and consumer).
- From our viewpoint, a high number of utilization hours for the hydrogen production facilities are crucial in order to enable a profitable penetration of hydrogen to the market. Again we refer to Section 5.5 in the revised manuscript which covers from our perspective the more flexible generation of hydrogen. In that case, the constant hydrogen production constraint is excluded.
- The used benchmark indicator of the number of utilization hours (or utilization ratio) provides highly relevant information of the profitability of (green) hydrogen production. Therefore, ensuring a constant hydrogen production in case that the hydropower plant owner decides so from an economic-driven perspective could lead to a business case in practice. We do want to show that hydrogen production based on hydropower competes with producing and selling electricity at different markets. Particularly, repurposing hydropower capacities might take place only when the power plant owner gets monetary incentives for this action. Otherwise, it is more likely that generation capacities are used for electricity only.

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

CLEAN VERSION



Credit Author Statement

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:

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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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