Energy Strategy Reviews

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

--Manuscript Draft--

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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 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: We thank the authors for considering our remarks, especially the extension of the literature review. The authors have addressed most concerns raised in the first revision. Nevertheless, before recommending this study for publication, we would like the authors to consider the following remarks:

Review comment: We found it unfortunate that no additional sensitivity analysis was performed on the price of the future contract, as requested. We still believe it would be beneficial and would alleviate the usability of the results from case-specific to wider applicable.
Author's response: Thank you for this review comment. We thoroughly discussed the raised issue and do agree with the reviewer that an additional sensitivity analysis will further increase the quality of the manuscript. Accordingly, we did further model runs to obtain results under varying the future contract price focusing on the quantities of the spot market, future contract, and hydrogen generation and their related revenues. In particular, we present the share of revenues from the three competing generation options for a CO2 price of 100 and 150 EUR/t. The results show that lower future electricity contract prices lead to profitable hydrogen production for the hydropower plant owner. Consequently, and this already has been stated in the manuscript's conclusions, the results of hydrogen generation significantly depend on the future contract price (as the reviewer expected). We added extra text to the conclusions to state that not only higher CO2 prices but also lower future prices can trigger hydropower-based hydrogen generation. From our viewpoint, the results are improved in both robustness and applicability. Once again, we thank the reviewer for raising his request for the conducted sensitivity analysis.

Review comment: The author could also consider adding a case without a future contract. While the author correctly points out that the presence of a future contract may be needed for capital intensive investments, this might not be the case if hydro assets would be repurposed for hydrogen production. The latter seems more likely in Europe, where the most hydro potential is already exploited.
Author's response: We thank the reviewer for the comment. We like to refer to Section 5.5 in the revised manuscript ('Constant hydrogen production relaxation': In the following

sensitivity analysis, a constraint of the modeling framework is relaxed to enable more flexible hydrogen production.) as it already covers (at least parts) of the raised concern. Additionally, we would like to mention that 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). We fully agree that hydrogen production based on hydropower from a systemic perspective could be triggered even earlier and under different market and price conditions (lower CO2 price, etc.). However, from our point of view, repurposing of hydropower production for hydrogen will take place only when the hydropower plant owner achieves economic viability compared to other purposes for electricity generation such as spot market and future contracts. This underlying concept is the motivation of the non-cooperative game presented in this work.

Review comment: We do not see what value is added by reporting on the results with a constant hydrogen production constraint, such a constraint severely limits the operation of the electrolyser. We find the argumentation that this is a prerequisite for economic feasibility questionable since the constraint withholds the electrolyser from operating in hours when it can recuperate part of its investment cost. Therefore, we welcome the case in which this constraint is relaxed but would encourage the authors to further clarify in the text why this constraint was added. We would also want the author to consider adding a table similar to table 1 for the case this constraint is relaxed.
Author's response: We fully agree with the reviewer that the constant hydrogen production constraint limits the operation of the hydrogen producer. 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. However, we thank the reviewer for the comment and tried to further add information about the constant hydrogen production constraint. We added the following text in the methodology section:

> *In fact, to some extent, the operation of hydropower plant owners is limited by the constraints. However, since the mathematical formulation does not include investment costs so far, constant hydrogen production and thus a high number of utilization hours of the hydrogen production assets are used as an efficiency benchmark indicator for its investment.*

In addition, we would like also to refer to our response of the second review comment above. From our viewpoint, 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

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:

# 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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