# GREEN HYDROGEN SUPPLY POTENTIAL FROM PHOTOVOLTAICS IN THE MIDDLE EAST

[1*] Philipp-Matthias Heuser,[1] Thomas Grube,[1] Heidi Heinrichs,[1] Martin Robinius[1,2] and Detlef Stolten
[1] Institute of Techno-Economic Systems Analysis (IEK-3),
Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., D-52428, Germany
[2] Chair for Fuel Cells, RWTH Aachen University, c/o Techno-Economic Systems Analysis (IEK-3),
Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Str., D-52428, Germany

*Corresponding author e-mail: p.heuser@fz-juelich.de

## ABSTRACT

The threats of climate change and the difficulty of supplying sustainable energy to all require an international approach. Producing green hydrogen with power from variable renewable energy sources like wind and solar represents an attractive option to mitigate the aforementioned challenges. In this context, this work examines the potential of hydrogen produced by means of photovoltaics in selected regions of the Middle East to meet global hydrogen demand. This includes not only determining the potential electricity production from photovoltaics, but also conceptualizing a detailed hydrogen infrastructure with corresponding supply and cost curves for potential solar energy. This infrastructure will comprise all elements of the value chain, from hydrogen production via water electrolysis to the supply of liquefied and stored hydrogen at suitable port locations. The most eligible of the locations considered in Saudi Arabia and Oman show immense potential with 517 and 117 million tons of hydrogen, respectively, being hypothetically produced. The supply cost at the harbor shows very little sensitivity to the degree of potential solar utilization and remains relatively constant at between 3.55 and 3.65 EUR/$kg_{H2}$. Due to comparatively low full-load hours as a result of the nightly downtimes of the electrolysis process, hydrogen production will contribute in particular to the supply cost.

***Keywords:*** Solar-to-hydrogen, photovoltaics, hydrogen infrastructure, electrolysis, Middle East

## INTRODUCTION

In light of declining fossil fuel reserves, particularly oil, climate change and growing global energy demand, hydrogen derived from solar energy is a promising option in the Middle East for covering local energy demand and the possibility of of exporting renewable energy in the post-oil era. The use of hydrogen represents a technically- and economically-attractive option for the substitution of fossil energy carriers in that, unlike electricity, it can be stored on a large scale and transported without being tied to a grid. Moreover, its conversion into energy does not release any emissions that are harmful to the climate or environment. In this work, the concept of an infrastructure for solar energy-based hydrogen includes the assessment and utilization of the photovoltaic (PV) potential of certain international regions and the provision of hydrogen for export at selected port locations. With regard to different research objectives, hydrogen supply pathways and infrastructures have already been analyzed separately with reference to some regions. However, due to different geographical and climactic conditions, previous study results cannot be automatically transferred to various regions. Moreover, coupling internationally transferable modeling approaches to determine PV potential and infrastructure pathways together is beneficial for projecting accurate potential hydrogen supply figures and associated costs. Thus far, however, no such coupling approach for a green hydrogen infrastructure has been applied on a worldwide level. The utilization of the solar energy potential of high solar insolation regions in the Middle East for the supply of an emission-free energy carrier such as hydrogen is of great interest. This work comprises the analysis of the PV potential and hydrogen supply infrastructure in both Saudi Arabia and Oman.

## MATERIALS AND METHODS

Building on the work of Ryberg [1; 2; 3; 4], solar energy potential is determined over four steps. First, the GLAES model of Ryberg [1; 2; 3; 4] is used to determine the land eligibility for open-field PV parks based on geo-referenced datasets. Then, prospective locations for open-field PV modules are determined with the help of minimum distance. Utilizing weather data from MERRA-2 [5; 6; 7; 8] and the Global Solar Atlas [9], in combination with Ryberg's [1] PV simulation model, the full-load hours of all eligible PV locations are calculated. The third step comprises defining scenarios representing various degrees of expansion. Using the cluster algorithms DBSCAN [10; 11; 12] and K-means [11; 13], PV modules are combined in solar parks whose internal grids are determined by means of a minimal spanning tree. With the aim of reducing hydrogen production costs, the electricity generation capacity is curtailed at optimal costs on the basis of hourly generated profiles, resulting in modified electricity generation time series. These are then used to calculate electricity generation and costs for varying degrees of PV expansion in the fourth step.

The production, pipeline transport, conditioning and storage of hydrogen forms the applied supply chain. A module to depict overseas transport is then added to allow for the export of green hydrogen to demand regions around the world. The supply chain setting is selected due to the fact that, for high quantities, hydrogen transport is more cost-efficient

than electricity transport [14; 15]. The hydrogen is produced at electrolysis sites in the PV park centers. From there, it is transported by pipeline to suitable harbors. Subsequently, it is liquefied and stored in liquid form, as the economically viable ship transport of hydrogen requires increased energy density to reduce the transport volume.

The applied modeling of the individual infrastructure elements is explained in detail in the work of Reuß [14; 15; 16], which takes into account investment costs, energy demand and the specific hydrogen costs. In order to account for the required temporal resolution, these modules were adjusted so that the generation time series for the electricity, as well as the hydrogen generation, are processed. After harbor storage, a temporally-resolved hydrogen supply is obsolete, as the storage itself enables a constant hydrogen supply. Supply and cost curves for the hydrogen supply at the respective harbors are obtained by adding the supply chain element cost contributions to the corresponding supply and cost curves for electricity generation.

## RESULTS AND DISCUSSION

Saudi Arabia has greater hydrogen supply potential than Oman in the context of this analysis. The results of the land eligibility analysis and PV simulation are shown for Saudi Arabia in Figure 1. About 1.4 million km² (72.5%) of land is theoretically eligible for PV parks in Saudi Arabia, of which 25% are considered in this study. This leads to a maximum PV capacity of 17,736 GW with an average of 2,335 full load hours (FLH). The bandwidth of the FLH ranges from 2,252 to 2,481 h/a, while the simplified levelized cost of electricity (LCOE), not taking networking and curtailment into account, ranges from 2.43 to 2.71 EUR-ct/kWh. The annual generation potential of these PV locations amounts to over 41,400 TWh.

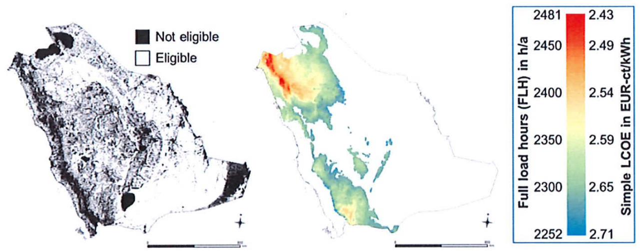


Figure 1. Results of the land availability analysis (left) and simulation of the full load hours and simplified electricity costs for PV modules (right) in Saudi Arabia (25% of all possible locations considered).

With respect to FLH, the best 25% of all eligible PV locations in Saudi Arabia translate to a minimum of 2,252 FLH. In this expansion scenario, 517 $Mt_{H2}$/a can be supplied. By increasing the number of FLH by 25 h/a, hydrogen supply and cost curves are derived. At a minimum of 2,453 FLH, a supply potential of 3.6 $Mt_{H2}$/a remains. With the decreasing degree of PV expansion, the hydrogen supply is significantly reduced. However, supply costs remain relatively constant (compare Figure 2).

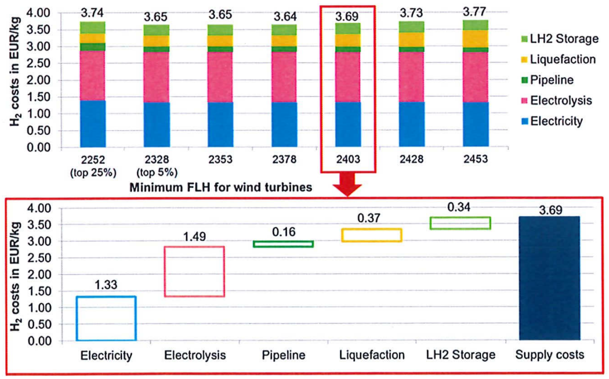


Figure 2. Cost distribution over all elements of the hydrogen supply chain for the considered degrees of expansion of wind energy in Saudi Arabia.

## CONCLUSIONS

The results of the PV potential analysis of selected regions in the Middle East show that the costs of electricity supply are comparatively independent of the degree of PV expansion. Therefore, the choice of a degree of expansion for the provision of green hydrogen depends in particular on the energy demand and not significantly on the underlying electricity costs. For the supply of hydrogen based on photovoltaics in Saudi Arabia and Oman, there is high production potential, even when considering only 25% of all eligible locations. This is due in particular to the comparatively high availability of land in desert regions.

On the cost side, the production costs of hydrogen show a big share in the overall hydrogen supply costs at the respective harbors. The relatively low FLH caused by the nightly downtimes of electrolysis operations contribute the most to the hydrogen costs. In contrast, the comparatively high energy losses due to the slip in compression during pipeline transport only contribute insignificantly to the costs. Thus, the largest cost reduction potential in hydrogen supply cost lies in a reduction in the investment costs for PV and electrolysis or in an increase in the FLH of electrolysis, for instance via battery storage or a combination of different renewable energies.

Overall, green hydrogen generated using PV in Saudi Arabia and Oman can constitute an economically-viable alternative to the export of fossil fuels due to the sufficient supply potential and relatively low and constant supply costs. Hence, green hydrogen can significantly contribute to the renunciation of an oil-dominated economy in these regions.

## REFERENCES

[1] Ryberg D. S., *Generation Lulls from the Future Potential of Wind and Solar Energy in Europe - Kalte Dunkelflauten der zukünftigen Potentiale der Wind- und Solarenergie in Europa*, in *Fakultät für Maschinenwesen*. 2019, RWTH Aachen University: Aachen.

[2] Ryberg D. S., Robinius M., and Stolten D. Methodological Framework for Determining the Land Eligibility of Renewable Energy Sources. ArXiv 2017.

[3] Ryberg D. S., Tulemat Z., Robinius M., and Stolten D. Geospatial Land Availability for Energy Systems (GLAES). https://github.com/FZJ-IEK3-VSA/glaes/releases/tag/v1.0.0 2017 [accessed 14.05.2018]

[4] Ryberg S. D., Robinius M., and Stolten D. Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe. Energies 2018;11.

[5] Bosilovich M., and Lucchesi R. MERRA-2: File Specification. 2016.

[6] Bosilovich M. G., Akella S., Coy L., Cullather R., Draper C., Gelaro R., Kovach R., Liu Q., Molod A., Norris P., Wargan K., Chao W., Reichle R., Takacs L., Vikhliaev Y., Bloom S., Collow A., Firth S., Labow G., Partyka G., Pawson S., Reale O., Schubert S. D., and Suarez M. MERRA-2: Initial Evaluation of the Climate. National Aeronautics and Space Administration - Goddard Space Flight Center. 2015.

[7] Gass J. Global Modeling and Assimilation Office. National Aeronautics and Space Administration, https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/; 2019 [accessed 07/05/2019]

[8] Gelaro R., McCarty W., Suárez M. J., Todling R., Molod A., Takacs L., Randles C. A., Darmenov A., Bosilovich M. G., Reichle R., Wargan K., Coy L., Cullather R., Draper C., Akella S., Buchard V., Conaty A., da Silva A. M., Gu W., Kim G.-K., Koster R., Lucchesi R., Merkova D., Nielsen J. E., Partyka G., Pawson S., Putman W., Rienecker M., Schubert S. D., Sienkiewicz M., and Zhao B. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Journal of Climate 2017;30. p. 5419-5454.

[9] World Bank Group. Global Solar Atlas. World Bank Group, https://globalsolaratlas.info/; 2016 [accessed 08/05/2019]

[10] Ester M., Kriegel H.-P., Sander J., and Xu X. A density-based algorithm for discovering clusters in large spatial databases with noise. Proceedings of the Second International Conference on Knowledge Discovery and Data Mining (KDD-96), Portland, Oregon, USA 1996; p. 226-231.

[11] Ester M., and Sander J. Knowledge Discovery in Databases - Techniken und Anwendungen. Berlin, Heidelberg, New York: Springer; 2000.

[12] Liu Q., Deng M., Shi Y., and Wang J. A density-based spatial clustering algorithm considering both spatial proximity and attribute similarity. Computers & Geosciences 2012;46. p. 296-309.

[13] MacKay D. J. C. Informations Theory, Inference, and Learning Algorithms. Cambridge: Cambridge University Press; 1995.

[14] Reuß M., Grube T., Robinius M., Preuster P., Wasserscheid P., and Stolten D. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Applied Energy 2017;200. p. 290-302.

[15] Reuß M., Grube T., Robinius M., and Stolten D. A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany. Applied Energy 2019;247. p. 438-453.

[16] Reuß M., *Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur*, in *Fakultät für Maschinenwesen*. 2019, RWTH Aachen University: Aachen.