Proceedings of the 8th International Conference of Recent Trends in Environmental Science and Engineering (RTESE 2024)
Chestnut Conference Centre - University of Toronto, Toronto, Canada – June 13 - 15, 2024
Paper No. 119
DOI: 10.11159/rtese24.119

An Evaluation on the Curtailment of Run-of-River Hydropower Systems and Implications for Sustainable Hydrogen Production

Selisa R. Andrus[1], Terry L. Alford[1]
[1]School for Engineering of Matter, Transport and Energy
Arizona State University, AZ 85287, United States
srollins@asu.edu; TA@asu.edu

Abstract - This study investigates the potential synergy between renewable energy curtailment and the shift towards clean fuel production and utilization. Using a long-term deterministic model of multiple reservoir systems, we examined the implications of fostering a sustainable and cost-effective hydrogen economy. The findings highlight those hydroelectric systems with limited reservoir storage capacities, such as run-of-river projects, are particularly viable for hydrogen production through electrolysis. In our analysis of eight run-of-river projects within the Federal Columbia River Power System, we found that adapting hydropower operations for hydrogen production could result in avoiding 2×10^5 metric tons of CO_2 emissions and saving 16 - 39 million U.S. dollars compared to carbon capture and storage. These substantial environmental and cost benefits underscore the importance of integrating the extensive flexibility of run-of-river hydropower operations into future strategies for decarbonizing the hydrogen ecosystem.

Keywords**:** Green Hydrogen Production, Curtailed Hydropower, Power-to-Hydrogen, Run-of-River Systems

1. Introduction

1.1. Hydrogen Production

According to a recent International Energy Agency (IEA) report, low-emission hydrogen accounts for less than 1 percent of global hydrogen production [1]. The United States primarily produces hydrogen via steam methane reforming or coal gasification [2]. Although the deployment of clean alternatives for cleaner hydrogen production such as electrolysis is rapidly increasing and emissions from this pathway are directly proportional to the carbon content of the electricity used, it is currently not economical [3]. Using renewable energy sources (RESs) such as hydropower, wind, and solar for green hydrogen production can significantly reduce carbon dioxide (CO_2) emissions and increase energy security [4].

A growing body of research explores theoretical scenarios in which curtailed energy from solar and wind is realized for various applications. These studies suggest significant potential for green hydrogen production to play a vital role in decarbonizing the hydrogen supply chain while augmenting the integration of RESs. On the contrary, the use of curtailed energy from hydropower plants offers a unique approach to producing green hydrogen and has an advantage over solar and wind due to its dispatchable capability. Limited studies in the literature have investigated the utilization of excess water accumulation from run-of-river hydropower plants for green hydrogen production [5], [6]. These case studies demonstrated feasibility of green hydrogen production in Slovenian run-of-river hydropower plants. Furthermore, key results from these studies concluded curtailed hydropower from run-of-river systems used for hydrogen cogeneration can be economically viable.

1.2. Case Study of Hydrogen from Hydropower

This paper investigates the potential for hydrogen production from curtailed hydropower generation from a controlled water system in the Pacific Northwest region of the United States. The high annual runoff in the Columbia River Basin relative to its storage capacity has several implications for water management in the Pacific Northwest region [7]. One of the primary challenges is balancing the need for hydropower generation with other competing demands for water. Climate change is expected to exacerbate these challenges by altering precipitation patterns and increasing the frequency and severity of extreme weather events and drought conditions.

The Columbia River Basin's unique hydrology presents challenges and opportunities for water management. The available reservoir storage in the basin is on the order of 7×10^{10} m^3/yr; whereas, the average annual runoff from the basin is over 3 ×10^{11} m^3/yr per year [8]. By implementing innovative and adaptive strategies, stakeholders can work together to ensure that water resources are managed sustainably and equitably in the face of ongoing hydrologic variability. The Federal Columbia River Power System (FCRPS) plays a critical role in meeting the Pacific Northwest region's energy demand and water needs [9]. The FCRPS is a coordinated system that operates under the auspices of the federal government along with state and local partners to achieve a range of congressionally authorized purposes, hydropower production being one of them.

The hydroelectric power produced by the system is a key component of the region's energy mix, providing a reliable and low-cost source of electricity that is also carbon-free. During times of water surplus, particularly in the spring and summer runoff periods, hydropower surpluses can displace gas- fired and coal-fired power generation at a relatively low cost with zero carbon emissions. However, there is a limit to how much thermal generation can be displaced, and once that limit is reached, oversupply can result in the curtailment of clean energy. This dynamic is illustrated in Figure 1, wherein forecasted hydropower and non-hydropower RESs peak in the months of April through July.

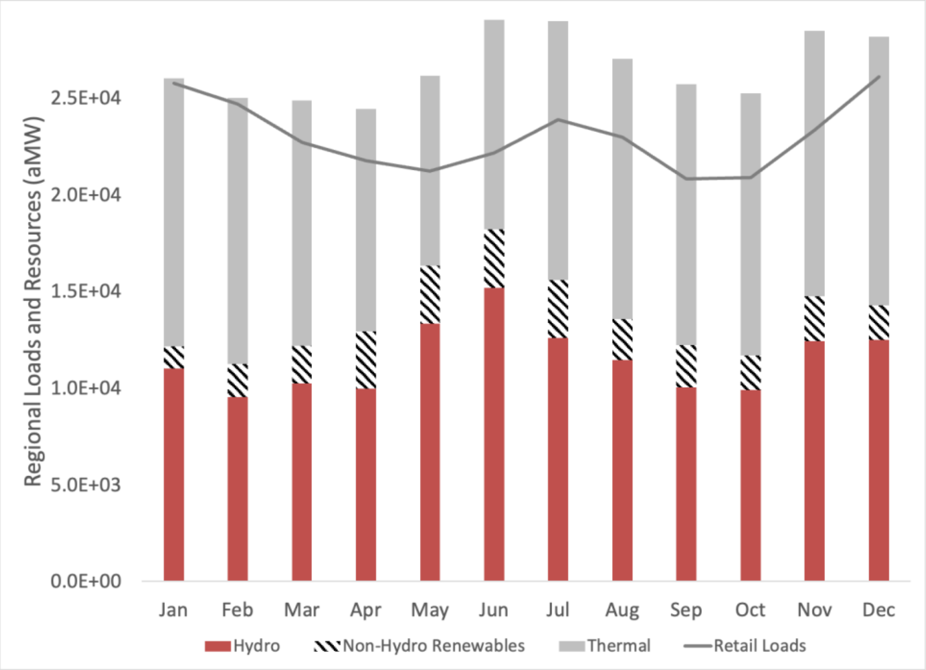

Fig. 1: Total Retail Loads and Resources.

2. Methodology

2.1. HydroSystem Simulator

A hydrologic simulation and deterministic model called HydroSystem Simulator (HYDSIM) has historically been used to model the FCRPS by incorporating flood risk management, spill regimes, and other operating criteria and constraints [10]. This model calculates results in strict accordance with its rule logic and yields studies of system-wide hydropower operations on a quasi-monthly timestep. The HYDSIM model in this study applies the 2010 Level Modified Flows for water year sequences 1929 through 2008 as an input and is run in continuous mode [10]. In continuous mode, the same load and resource parameters are applied to all water years, and the ending elevations for each historical water year become the starting elevations for the next water year. This modeling approach allows the performance of the hydropower system to be evaluated under various scenarios and conditions, including changes in water availability and climate.

Under the Pacific Northwest Electric Power Planning and Conservation Act (Northwest Power Act), rates for power and transmission services are established utilizing a biennial study. This study, also known as a rate case, focuses on modeling power operations for the purposes of ensuring that projected revenue from the electricity derived from the FCRPS will cover incurred expenses [11]. Resulting data sets from the rate case provide information on project outflows, reservoir elevations, reservoir contents, spillway flows, and power generation, which can be used to calculate overgen spill at hydroelectric projects. Overgen spill is the excess water that cannot be used for power generation and is spilled over the dam. By using historical streamflow data that accounts for current irrigation depletions and the effects of river regulation, the study can provide insights into how the FCRPS can be operated most efficiently and effectively as possible while minimizing environmental impacts.

2.2. Calculation of Theoretical Hydrogen from Curtailed Hydropower

Defined HOVK tables are used in the HYDSIM model to calculate the power generation from hydroelectric projects. HOVK measures the energy conversion efficiency of the turbines, which varies with the head of water. The head is the elevation difference between the reservoir's water surface and the turbine's outlet. The factor k is a unitless coefficient that represents the turbine efficiency, which is a function of the design of the turbine and generator.

The HOVK tables provide a lookup table of h/k values for different values of head, allowing the HYDSIM model to interpolate values for each period. Once the HOVK value is obtained, the model can calculate the expected power generation for a given flow rate. This information is then used to calculate overgen spill at each hydroelectric project. The energy (in MW) by overgen spill flow through generation/turbine produced is given by:

$$Total\ Overgen\ Spill\ (MW) = \sum (kWm^{-3}s^{-1}) Qspill \cdot t \tag{1}$$

where $\sum$ is the summation of kW produced per second, Qspill is the spill rate in cubic meters per second, and t is time in seconds.

Spilled hydropower can produce the amount of power required needed by an electrolyzer to produce hydrogen is given by [12]:

$$PH_2 = 3600 \cdot Qspill \cdot \frac{HHV}{VH_2} \tag{2}$$

where PH_2 is the potential hydrogen production in cubic meters per hour, HHV is the higher heating value of hydrogen in megajoules per cubic meter, and VH_2 is the volume of hydrogen produced by the electrolysis of one cubic meter of water, which is approximately 0.0111 cubic meters at standard temperature and pressure. The factor of 3600 is used to convert the spill rate from cubic meters per second to cubic meters per hour.

3. Results

The FCRPS projects examined in detail for this study were two storage (Grand Coulee and Dworshak) and eight run-of-river projects (Bonneville, Chief Joseph, Ice Harbor, John Day, Little Goose, Lower Monumental, McNary, and The Dalles). Operational properties of these hydropower systems are described elsewhere in the literature [11]. The passage suggests that curtailed hydroelectric energy from these projects can be converted to hydrogen, which can then be used in fuel cell systems to produce electricity and water. The study found that the production of hydrogen from spilled hydropower energy is most prevalent during the spring through summer runoff periods when there is an observed surplus of energy. The results shown in Figure 2 also suggest run-of-river hydroelectric projects are more viable than storage projects for producing hydrogen from overgen spill.

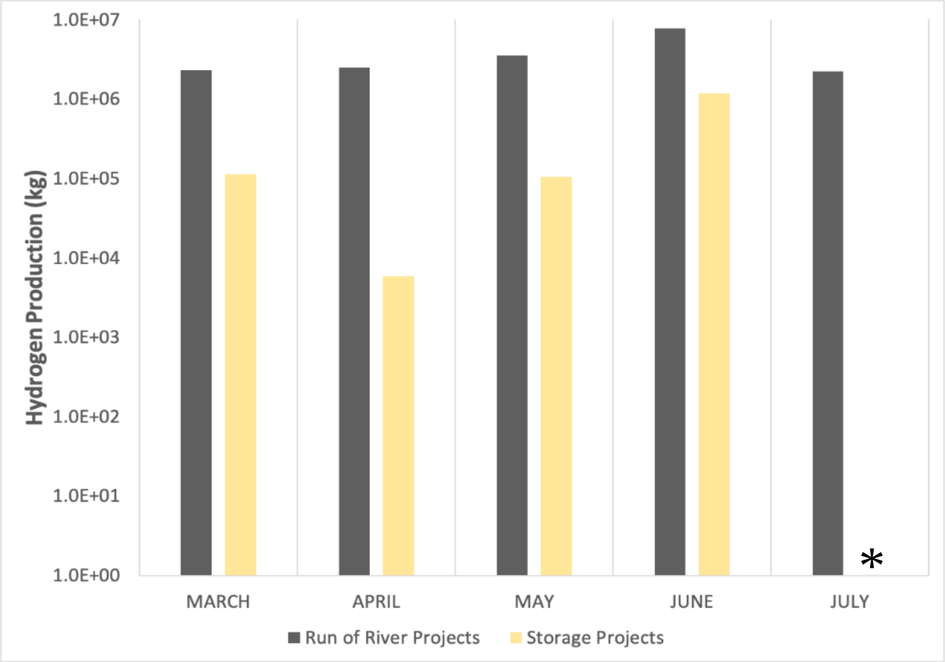

Fig. 2: Run-of-River versus Storage Projects for Hydrogen Production
(* represents zero hydrogen production)

The study relied on the HYDSIM model, which predicts potential hydrogen production from each hydroelectric project over an 80-year water record. However, the model does not capture the fluctuation in water flow as accurately as a daily model would. The lack of granularity in the data is a significant limitation of the study, but it also presents an opportunity for future work. By using a short-term model to assess hydrogen production from overgen spill on a planning basis, researchers can gain more insight into the potential for hydrogen production from wasted hydroelectric energy.

The transportation sector, in general, is the largest contributor to greenhouse gas emissions in the United States, accounting for about 28% of total emissions in 2019. Therefore, reducing emissions from heavy-duty vehicles is critical to addressing climate change and improving air quality. The equivalent CO_2 emissions avoided by select run-of-river projects analyzed in this study are shown in Figure 3. The figure suggests the month of June is the most prevalent period for reduction of emissions due to the surplus of hydropower and the inability to store river runoff.

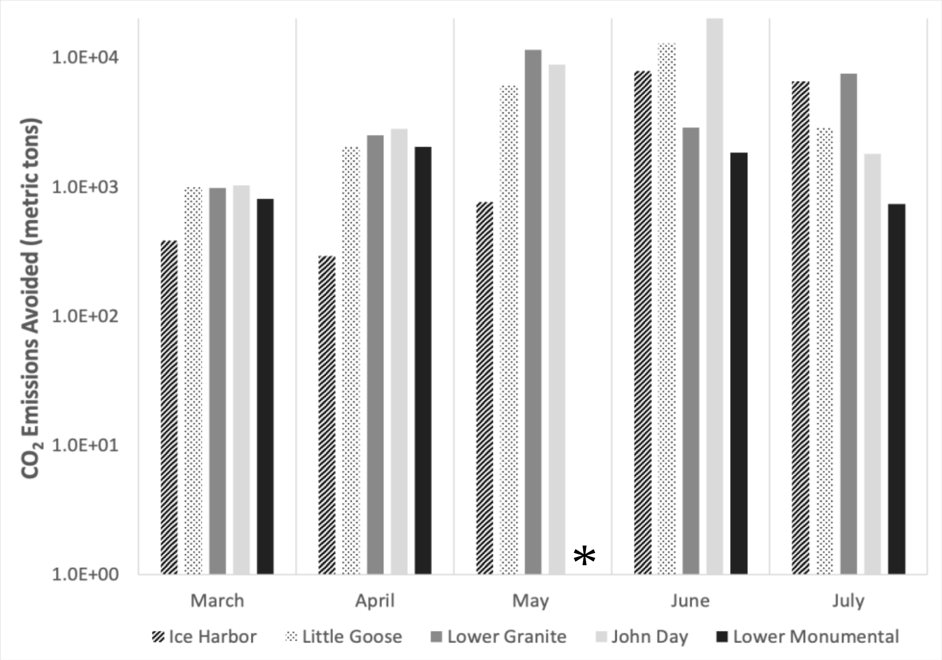

Fig. 3: CO_2 Emissions Avoided by Run-of-River Projects
(* represents zero CO_2 emissions avoided)

In comparison, storage projects such as Grand Coulee and Dworshak analyzed in this study did not display significant hydrogen production and reduced CO_2 emissions during the months of April and July due to the need for these projects to store water for flood risk management purposes (as shown in Figure 4).

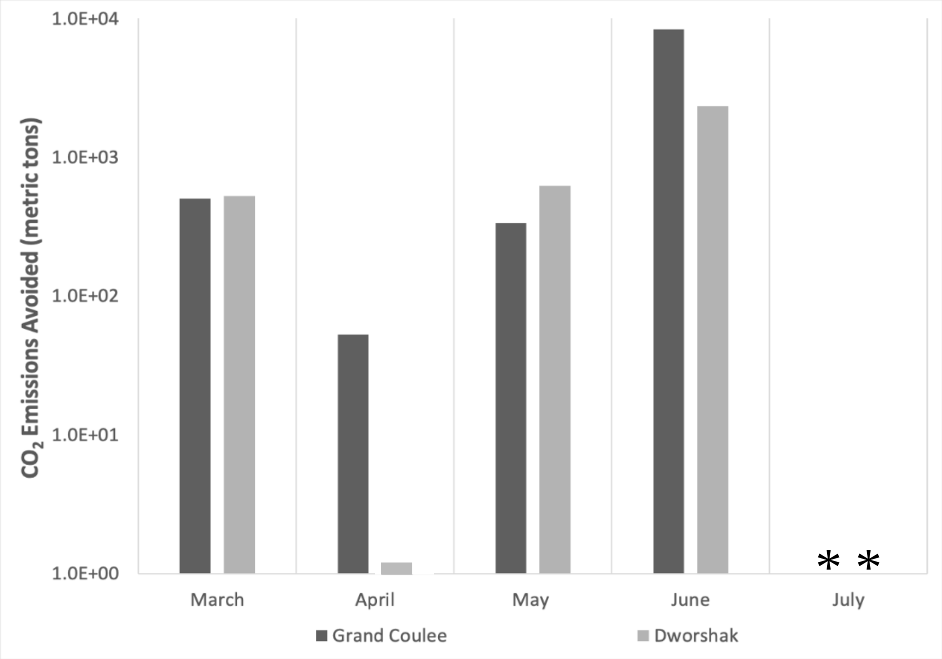

Fig. 4: CO_2 Emissions Avoided by Storage Projects
(* represents zero CO_2 emissions avoided)

The transportation sectors in Washington State and Oregon accounted for 51 and 55 percent, respectively, of total energy-related CO_2 emissions [13]. An estimation of the encouraging environmental impact of renewable hydrogen for heavy-duty transportation use in the Northwest region was addressed elsewhere and determined the total amount of CO_2 emissions associated with diesel consumption for transport in the states of Oregon and Washington was approximately 1.5×10^6 metric tons in the year 2020. Eliminating the total CO_2 emitted by diesel combustion in Oregon and Washington 2020 would cost between 1.4 - 3.5 billion U.S. dollars.

Although a direct comparison of hydrogen and diesel-fueled heavy-duty vehicles can be part of assessing the value of hydrogen fuel for transport applications in the Pacific Northwest, it may not provide a complete picture. A more comprehensive analysis can consider various factors, including the availability and cost of hydrogen infrastructure, the efficiency and emissions of hydrogen production and distribution, and the overall benefits and costs of transitioning to hydrogen fuel in the transport sector.

Several studies have assessed the production cost of grid-based electrolytic hydrogen across the United States and concluded that hydrogen could be cost-effective for current energy and transportation systems, especially when produced from curtailed renewable energy. The production cost of grid-based electrolytic hydrogen depends on several factors, including the cost of electricity, the efficiency of the electrolysis process, and the capital and operating costs of the equipment.

A report shares that the production cost of grid-based electrolytic hydrogen that hydrogen can be cost-valuable for future transportation sectors; given that, electrolysis-based hydrogen production costs range from 2.6 to 12.3 U.S. dollars per kg of H_2 [14]. The cost of the 2×10^7 kg of H_2 that can be produced via run-of-river projects along the FCRPS would cost between 4.8 to 22.6×10^7 U.S. dollars. The monetary value of these emissions savings can be estimated based on the cost of capturing and storing CO_2 through carbon capture and storage (CCS) technology. The cost of CCS varies widely depending on the specific technology used, but it can range from 54 - 109 U.S. dollars per metric ton of CO_2 captured and stored [15]. Based on this range, the emissions savings from generating hydrogen via curtailed run-of-river hydropower through electrolysis could be valued between 16 - 39 million U.S. dollars annually.

4. Conclusion

Using curtailed hydropower from run-of-river plants to generate hydrogen through electrolysis can help increase the power grid's overall efficiency. Curtailed hydropower can produce hydrogen during periods of low demand, which can help balance the power grid and reduce the need for energy storage. Furthermore, using hydrogen as a fuel can provide a range of benefits, including increased efficiency, reduced emissions, and improved energy security. Hydrogen can be used to power fuel cells that can generate high efficiency and zero emissions and can also be used as fuel for transportation, heating, and industrial processes. Overall, using curtailed hydropower from run-of-river systems to generate hydrogen through electrolysis is a promising development that can help increase the power grid's flexibility and efficiency while reducing emissions and improving energy security. In a case study of the FCRPS where variable water conditions over an 80-year period were considered, the projected hydrogen production from eight hydroelectric run-of-river plants is approximately 2×10^7 kg per year. This produced hydrogen is equivalent to 2×10^5 metric tons of CO_2 emissions avoided and a savings of 16 - 39 million U.S. dollars for CCS.

Acknowledgements

Special thanks to the Northwest Power and Conservation Council, Bonneville Power Administration's Technology Innovation Office, and the Long-Term Planning and Regional Coordination Groups under Power Services. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

References

[1] International Energy Agency (IEA), “Global Hydrogen Review 2023,” 2023. Accessed: Feb. 08, 2024. [Online]. Available: www.iea.org

[2] M. V. Navarro, J. Plou, J. M. López, G. Grasa, and R. Murillo, “Effect of oxidation-reduction cycles on steam-methane reforming kinetics over a nickel-based catalyst,” *Int J Hydrogen Energy*, vol. 44, no. 25, pp. 12617–12627, May 2019.

[3] A. Pandiyan, A. Uthayakumar, R. Subrayan, S. W. Cha, and S. B. K. Moorthy, “Review of solid oxide electrolysis cells: a clean energy strategy for hydrogen generation,” *Nanomaterials and energy*, vol. 8, no. 1, pp. 2–22, 2019.

[4] N. B. Amado, E. D. B. Pelegia, and I. L. Sauer, “Capacity value from wind and solar sources in systems with variable dispatchable capacity - An application in the Brazilian hydrothermal system,” *Energies (Basel)*, vol. 14, no. 11, p. 3196, 2021.

[5] D. J. Jovan, G. Dolanc, and B. Pregelj, “Utilization of excess water accumulation for green hydrogen production in a run-of-river hydropower plant,” *Renew Energy*, vol. 195, pp. 780–794, 2022, doi: 10.1016/j.renene.2022.06.079.

[6] D. J. Jovan, G. Dolanc, and B. Pregelj, “Cogeneration of green hydrogen in a cascade hydropower plant,” *Energy Conversion and Management: X*, vol. 10, p. 100081, Jun. 2021, doi: 10.1016/J.ECMX.2021.100081.

[7] D. E. Rupp, O. S. Chegwidden, B. Nijssen, and M. P. Clark, “Changing River Network Synchrony Modulates Projected Increases in High Flows,” *Water Resour Res*, vol. 57, no. 4, 2021.

[8] J. M. Hyde, “Columbia River Treaty Past and Future,” in *Proceedings of HydroVision International Conference*, Charlotte, VA: M. Barnes, PennWell Corporation, 2010, pp. 1–25.

[9] U.S. Bureau of Reclamation - Columbia-Pacific Northwest, “Federal Columbia River Power System Hydrosystem.” Accessed: Jun. 03, 2022. [Online]. Available: https://www.usbr.gov/pn/fcrps/hydro/index.html

[10] A. Johnson, P. Racht, and S. Wallace, “Hydro Modeling Update for the Columbia River System.” 2021. Accessed: Oct. 20, 2022. [Online]. Available: https://www.wecc.org/Administrative/BPA%20-%20Columbia%20River%20System%20Hydro%20Modeling%20for%20WECC%20PCDS%20_%202021-08-10.pdf

[11] *Columbia River System operations final environmental impact statement*. Portland, Or: U.S. Army Corps of Engineers-Northwestern Division, 2020.

[12] S. R. Andrus, R. J. Diffely, and T. L. Alford, “Theoretical analysis of green hydrogen from hydropower: A case study of the Northwest Columbia River system,” *Int J Hydrogen Energy*, vol. 48, no. 22, pp. 7993–8001, 2023.

[13] S. Lombardi, L. Tribioli, G. Guandalini, and P. Iora, “Energy performance and well-to-wheel analysis of different powertrain solutions for freight transportation,” *Int J Hydrogen Energy*, vol. 45, no. 22, pp. 12535–12554, 2020.

[14] O. J. Guerra, J. Eichman, J. Kurtz, and B. M. Hodge, “Cost Competitiveness of Electrolytic Hydrogen,” *Joule*, vol. 3, no. 10, pp. 2425–2443, Oct. 2019.

[15] W. J. Schmelz, G. Hochman, and K. G. Miller, “Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States,” *Interface Focus*, vol. 10, no. 5, pp. 20190065–20190065, 2020.