Methodology for Green Hydrogen Energy Intensity Blog Post

Data for the analysis in Tables 1 & 2 below were sourced from reports, peer-reviewed publications, and government databases and models. All sources are listed at the end of this document.

The configuration for the pathway of each application was chosen based on reviewed literature. For each pathway, we calculated the energy intensity, or the full pathway efficiency, by multiplying together the efficiencies of each process within the pathway. The energy intensity for each pathway is calculated using the median value of the efficiency range for each step in the process; ranges may represent different estimates, technologies, and conditions for each process. We use the mean values to estimate an average energy intensity, and the maximum and minimum values to calculate the total upper and lower bounds.

Table 1. Green Hydrogen Pathway Efficiencies

Green hydrogen pathway efficiencies	**Process component**	**Energy efficiency range**
Production		
	PEM Electrolysis	50-72%[1,2, 21]
Conversion		
	Compression	83-88%[3,4]
	Liquefaction	55-79%[5,6]
Distribution		
	Pipeline	95-99%[7]
	LH_2 Truck (loading + storage)	82-97%[6, 8, 9]
Preparation for use		
	Refueling	86-98%[10, 11, 12]
End-uses		
	Light duty fuel cell vehicle	32-54%[10, 13, 14, 15, 18]
	Heavy duty fuel cell vehicle	52-58%[10, 16, 17, 18]
	Transit bus	30-35% [10, 18]
	Hydrogen home boiler	90-107%[18,19, 20]

Table 2. Direct Electrification Pathway Efficiencies

Direct electrification pathway efficiencies	**Process component**	**Energy efficiency range**
Distribution		
	Transmission & Distribution	95-98%[21, 22]
Preparation for use		
	Charging light duty vehicle	83-90%[10, 18, 23]
	Charging heavy duty vehicle	83-90%[10, 18, 24, 25]
	Charging transit bus	83-90%[10, 18]
End-uses		
	Light duty fuel cell vehicle	69-73%[10, 18, 26]
	Heavy duty fuel cell vehicle	44-48%[10, 18, 27, 28, 29]
	Transit bus	61-73%[10, 18, 27]
	Electric heat pump	*200-500%[22, 30, 31]

*Energy efficiency of a heat pump can exceed 100% because it absorbs ambient heat from the environment as additional energy input.

Assumptions in this data include:

- The pathways primarily do not account for hydrogen leakage. All losses refer to energy loss down the value chain.
- The start of our life cycle efficiency analysis assumes that we already have renewable electricity for both alternatives. We also assume that renewable energy is an unlimited electricity source, so we do not account for efficiency consideration of renewable electricity generation technology.
- We assume that renewable energy is generated near the hydrogen production plant such that transmission losses are minimized; also assume no AC/DC conversion is needed. For this reason, we start including efficiency estimates from the hydrogen production segment of the hydrogen value chain.
- When both lower heating value (LHV) and higher heating value (HHV) efficiencies were available, we used LHV estimates for green hydrogen production through electrolysis.
- We assume pipelines exclusively transport gaseous hydrogen and trucks exclusively transport liquid hydrogen.
- We do not consider hydrogen boil off rates and leakage in this calculation. Boil-off rates for liquid hydrogen storage according to the literature is between 0.5 – 1% per day, so liquid hydrogen is not stored for longer than a few days and we assume that the configuration we have chosen has insignificant energy losses from storage. Any consideration of further hydrogen leakage will lower the efficiency and increase the energy intensity of the hydrogen pathway.
- Liquid fuels are critical in transport because they have a higher volumetric energy density than gaseous hydrogen. We assume that green hydrogen is transported in a liquid state from production to the refueling station in all hydrogen transport pathways due to the large throughput needed for transport and the higher relative energy density.
- Light Duty Fuel Cell Vehicles are generally refueled at separate refueling dispensers from Fuel Cell Transit Buses and Heavy-Duty Fuel Cell Trucks because the refueling protocols and volume of hydrogen required are different. Refueling data for LDFCVs is taken from Argonne National Laboratory's HRSAM and HDSAM models. Refueling data for transit buses and heavy-duty trucks use Argonne's HDRSAM model as an additional data point.
- Lithium-ion batteries and fuel cell efficiencies demonstrate modest degradation over time because of use and climatic changes. We used the starting efficiency.
- Vehicle efficiencies include both the fuel cell/battery efficiency as well as the electric drive efficiency (assumed 85%) and mechanical efficiency (assumed 95%).

Pathways included in the blog post with low, median, and high efficiency estimates at each process and their total process energy efficiency in the last column. The range in the total column provides the range of full pathway efficiency considering low and high efficiency ranges at each process.

Light Duty Vehicles

Electric						
	Transmission and distribution			Charging	Electric vehicle	TOTAL
Low	95%			83%	69%	**54%**
Mean	97%			87%	71%	**59%**
High	98%			90%	73%	**64%**
Green Hydrogen						
	Electrolysis	Liquefaction	LH2 transport	Refueling	Fuel cell vehicle	TOTAL
Low	50%	55%	82%	86%	32%	**6%**
Mean	61%	67%	90%	92%	43%	**14%**
High	72%	79%	97%	98%	54%	**29%**

Heavy Duty Vehicles

Electric						
	Transmission and distribution			Charging	Electric vehicle	TOTAL
Low	95%			83%	44%	**35%**
Median	97%			87%	46%	**38%**
High	98%			90%	48%	**42%**
Green Hydrogen						
	Electrolysis	Liquefaction	LH2 transport	Refueling	Fuel cell vehicle	TOTAL
Low	50%	55%	82%	86%	52%	**10%**
Median	61%	67%	90%	92%	55%	**19%**
High	72%	79%	97%	98%	58%	**31%**

Transit Bus

Electric						
	Transmission and distribution			Charging	Electric vehicle	TOTAL
Low	95%			83%	61%	**48%**
Mean	97%			87%	67%	**56%**
High	98%			90%	73%	**64%**
Green Hydrogen						
	Electrolysis	Liquefaction	LH2 transport	Refueling	Fuel cell vehicle	TOTAL
Low	50%	55%	82%	86%	30%	**6%**
Mean	61%	67%	90%	92%	33%	**11%**
High	72%	79%	97%	98%	35%	**19%**

Home Heat

Electric					
	Transmission and distribution			Heat pump	TOTAL
Low	95%			200%	**190%**
Mean	97%			350%	**338%**
High	98%			500%	**490%**
Green Hydrogen					
	Electrolysis	Compression	Pipeline	Hydrogen boiler	TOTAL
Low	50%	83%	95%	90%	**35%**
Mean	61%	86%	97%	99%	**50%**
High	72%	88%	99%	107%	**67%**

References:

1. Tashie-Lewis, B.C., Nnabuife, S. G., "Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review", *Chemical Engineering Journal Advances*, **2021**, *8* (100172), https://doi.org/10.1016/j.ceja.2021.100172
2. Wang, T., Cao, X., Jiao, L. "PEM water electrolysis for hydrogen production: fundamentals, advances, and prospects". *Carb Neutrality*, **2021**, *1*, 21. https://doi.org/10.1007/s43979-022-00022-8
3. Pellow, M. A., Emmott, C. J., Barnhart, C. J., Benson, S. M. "Hydrogen or batteries for grid storage? A net energy analysis". *Energy & Environmental Science*, **2015**, *8*(7), 1938-1952. https://doi.org/10.1039/C4EE04041D
4. S. Giddey, S. P. S. Badwal, C. Munnings, M. Dolan "Ammonia as a Renewable Energy Transportation Media". *ACS Sustainable Chemistry & Engineering*, **2017**, *5* (11), 10231-10239. https://pubs.acs.org/doi/10.1021/acssuschemeng.7b02219
5. Ghafri, S. et.al. "Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities". *Energy Env Science*. **2022**,*15*, 2690-2731. https://pubs.rsc.org/en/content/articlehtml/2022/ee/d2ee00099g
6. Wolfram, P., O'Rourke, P., McJeon, H., Kyle, P. "Helping the climate by replacing liquefied natural gas with liquefied hydrogen or ammonia?". *Environmental Research Letters*, **2024**, *19*(5), 054005. https://doi.org/10.1088/1748-9326/ad376f
7. The Oxford Institute for Energy Studies. "Hydrogen pipelines vs. HVDC lines: Should we transfer green molecules or electrons?". **2023**. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/11/ET27-Hydrogen-pipelines-vs.-HVDC-lines_HG_AP_2.pdf
8. Lavanya, M., Shrivastava, S., Lakshmi, T., Sandadi, E. R., Gour, S., Thomas, N. A., Sudhakar, K. "An overview of hydrogen storage technologies–Key challenges and opportunities". *Materials Chemistry and Physics*, **2024**, *325*, 129710. https://doi.org/10.1016/j.matchemphys.2024.129710.
9. Wu, C., Zheng, S., Wang, Z., Chen, R., Hu, X., Chen, J. "Discussion on ammonia as one of the energy storage media of solar energy in China". *Energy Strategy Reviews*, **2021**, *38*, 100697. https://doi.org/10.1016/j.esr.2021.100697
10. Wallington, T. J., Woody, M., Lewis, G. M., Keoleian, G. A., Adler, E. J., Martins, J. R., Collette, M. D. "Green hydrogen pathways, energy efficiencies, and intensities for ground, air, and marine transportation". *Joule*, **2024**, *8*(8), 2190-2207. https://doi.org/10.1016/j.joule.2024.07.012
11. Hydrogen Delivery Scenario Analysis Model (HDSAM) V4, Argonne National Laboratory, V4, **2023.** https://hdsam.es.anl.gov/index.php?content=hdsam
12. Hydrogen Refueling Station Analysis Model (HRSAM) V4, Argonne National Laboratory, V4, **2023**. https://hdsam.es.anl.gov/index.php?content=hdsam
13. Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., Hissel, D. "Hydrogen energy systems: A critical review of technologies, applications, trends and challenges". *Renewable and Sustainable Energy Reviews*, **2021**, 146, 111180. https://doi.org/10.1016/j.rser.2021.111180
14. Sery, J., Leduc, P. "Fuel cell behavior and energy balance on board a Hyundai Nexo". *International Journal of Engine Research*, **2022**, *23*(5), 709-720. https://doi.org/10.1177/14680874211059046
15. Carignano, M., Costa-Castelló, R. "Toyota Mirai: powertrain model and assessment of the energy management". *IEEE Transactions on Vehicular Technology*, **2023**, 72(6), 7000-7010. https://doi.org/10.1109/TVT.2023.3237173
16. Cullen, D. A., Neyerlin, K. C., Ahluwalia, R. K., Mukundan, R., More, K. L., Borup, R. L., Kusoglu, A. "New roads and challenges for fuel cells in heavy-duty transportation". *Nature energy*, **2021**, *6*(5), 462-474. https://doi.org/10.1038/s41560-021-00775-z

17. Marcinkoski, J., Vijayagopal, R., Adams, J., James, B., Kopasz, J., Ahluwalia, R. DOE Hydrogen and Fuel Cells Program, Record 19006: Hydrogen Class 8 long haul truck targets. **2019**. www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf
18. Salahuddin, U., Ejaz, H., & Iqbal, N. “Grid to wheel energy efficiency analysis of battery-and fuel cell–powered vehicles”. *International Journal of Energy Research*, **2018**, *42*(5), 2021-2028. https://doi.org/10.1002/er.3994
19. Rosenow, J. “A meta-review of 54 studies on hydrogen heating”. *Cell Reports Sustainability*, **2024**, *1*, 100010. https://doi.org/10.1016/j.crsus.2023.100010
20. Baldino, C., O’Malley, J., Searle, S., Zhou, Y., Christensen, A. “Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050”. Int. Counc. Clean Transp. **2020**. https://theicct.org/sites/default/files/publications/Hydrogen-heating-UK-dec2020.pdf
21. IEA. “Global Hydrogen Review 2024”. **2024**. https://iea.blob.core.windows.net/assets/89c1e382-dc59-46ca-aa47-9f7d41531ab5/GlobalHydrogenReview2024.pdf
22. Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., & Luderer, G. "Potential and risks of hydrogen-based e-fuels in climate change mitigation”. *Nature Climate Change*, **2021**, *11*(5), 384-393. https://doi.org/10.1038/s41558-021-01032-7
23. Tasnim, M. N., Akter, S., Shahjalal, M., Shams, T., Davari, P., Iqbal, A. “A critical review of the effect of light duty electric vehicle charging on the power grid”. *Energy Reports*, **2023**, *10*, 4126-4147. https://doi.org/10.1016/j.egyr.2023.10.075
24. Wang, M., Elgowainy, A., Lee, U., Benavides, P., Burnham, A., Cai, H., Dai, Q., Hawkins, T., Kelly, J., Kwon, H., Liu, X., Lu, Z., Ou, L., Sun, P., Winjobi, O., Xu, H. “Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model”. USDOE Office of Energy Efficiency and Renewable Energy (EERE). **2019**. https://doi.org/10.11578/GREET-Excel-2019/dc.20200706.1
25. Tong, F., Wolfson, D., Jenn, A., Scown, C. D., Auffhammer, M. "Energy consumption and charging load profiles from long-haul truck electrification in the United States”. *Environ. Res: Infrastruct. Sustain*. **2021**, *1*, 025007. https://doi.org/10.1088/2634-4505/ac186a
26. Alcázar-García, D., Romeral Martínez, L. "Energy Consumption and Total Vehicle Efficiency Calculation Procedure for Electric Vehicles (EV, HEV and PHEV)." Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 3: 20th International Conference on Advanced Vehicle Technologies; 15th International Conference on Design Education. Quebec City, Quebec, Canada. August 26–29, **2018**. V003T01A036. ASME. https://doi.org/10.1115/DETC2018-85182
27. California Air Resources Board. “Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles”. **2018**. https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbevefficiency.pdf
28. Jones, R., Köllner, M., Moreno-Sader, K., Kovács, D., Delebinski, T., Rezaei, R., Green, W. H. “Realistic US long-haul drive cycle for vehicle simulations, costing, and emissions analysis”. *Transportation Research Record*, **2024**, *2678*(7), 340-360. https://doi.org/10.1177/036119812312156
29. 21st Century Truck Partnership, Electrification Techhnologies Sector Team Roadmap. **2023**. https://www.energy.gov/sites/default/files/2023-12/21CTP-ETT-Roadmap_Final_Sep2023_compliant_corrected_08Dec23.pdf
30. Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., Bertsch, S. S. “High temperature heat pumps: market overview, state of the art, research status, refrigerants, and application potentials”. *Energy*. **2018**, *152*, 985–1010. https://doi.org/10.1016/j.energy.2018.03.166
31. Gaur, A. S., Fitiwi, D. Z., Curtis, J. “Heat pumps and our low-carbon future: A comprehensive review”. *Energy Research & Social Science*. **2021**, *71*, 101764. https://doi.org/10.1016/j.erss.2020.101764