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		
	Electrolysis	48-81%[23,64,56,47,32,25,39]
Conversion		
	Compression	80-97%[23,12,55,26,10,24,57]
	Liquefaction	55-80%[23,12,55,24,39,51]
Distribution		
	Pipelines	90-99%[21,24,10,55,23,4]
	Liquid H2 Trucks	94-99%[24,55,4,21,10]
Preparation for Use		
	Refueling	86-97%[9,10,11]
End-Uses		
	Light duty fuel cell vehicle	38-61%[24,45,48,50,61]
	Heavy duty fuel cell truck	44-60%[59,52,35]
	Transit bus	41-43%[52,59]
	Hydrogen home boiler	87-90%[23,45,61]

Table 2 Direct Electrification Pathway Efficiencies

Direct Electrification Pathway Efficiencies	**Process Component**	**Energy Efficiency Range**
Distribution		
	Transmission & Distribution	90-95%[59,24,45,63,21]
Preparation for Use		
	Charging electric bus	75-97%[3,13,44,18,14]
	Charging electric truck	95-97%[7,17]
	Charging light duty vehicle	90%[24,62]
End-Uses		
	Light duty electric vehicle	60-85%[24,33,48,61]
	Heavy duty electric truck	87-89%[7,17]
	Electric transit bus	80-84%[18,1]

Electric heat pump	200-500%*[33,45,48,61]

*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 the 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; and also assume that 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 it has 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 are 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.

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	90%			90%	60%	49%
Median	93%			90%	73%	60%
High	95%			90%	85%	73%
Green hydrogen						
	Electrolysis	Liquefaction	LH2 transport	Refueling	Fuel cell vehicle	TOTAL
Low	48%	55%	94%	86%	38%	8%
Median	65%	68%	97%	92%	50%	19%
High	81%	80%	99%	97%	61%	38%

Transit Bus

Electric						
	Transmission & distribution			Charging	Electric bus	TOTAL
Low	90%			75%	80%	54%
Median	93%			86%	82%	65%
High	95%			97%	84%	77%
Green Hydrogen						
	Electrolysis	Liquefaction	LH2 transport	Refueling	FCEB	TOTAL
Low	48%	55%	94%	86%	41%	9%
Median	64%	68%	97%	92%	42%	16%
High	81%	80%	100%	97%	43%	27%

Semi-truck

Electric						
	Transmission & distribution			Charging	Electric truck	TOTAL
Low	90%			95%	87%	74%
Median	93%			96%	88%	78%
High	95%			97%	89%	82%
Green Hydrogen						
	Electrolysis	Liquefaction	LH2 transport	Refueling	FC Semi Truck	TOTAL
Low	48%	55%	94%	86%	44%	9%
Median	64%	68%	97%	92%	52%	20%
High	81%	80%	100%	97%	60%	38%

Heat Pump

Electric					
	Transmission and distribution			Heat pump	TOTAL
Low	90%			200%	180%
Median	93%			350%	324%
High	95%			500%	475%
Green hydrogen					
	Electrolysis	Compression	Pipelines	Hydrogen boiler	TOTAL
Low	48%	80%	90%	87%	30%
Median	65%	89%	95%	89%	48%
High	81%	98%	99%	90%	71%

Sources

1 Basma et al "Comprehensive Energy Assessment of Battery Electric Buses and Diesel Buses," June 2019

2 "Building the Infrastructure for Acela Express" Amtrak, Feb 2016

3 "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles" California Air Resources Board, May 2018, CARB 2018

4 Bossel and Eliasson, "Energy and the Hydrogen Economy", Alternative Fuels Data Center AFDC Report

5 "Coradia iLint: Alstom Presents the World's First Hydrogen Passenger Train in Poland" Alstom, June 2021

6 "Cummins Hydrogen Power Takes Flight" Cummins, Apr 2021

7 Earl et al "Analysis of Long Haul Battery Electric Trucks in EU," Aug 2018

8 "eCascadia" Freightliner

9 Elgowainy and Reddi "Heavy Duty Refueling Station Analysis Model (HDRSAM)" Argonne National Laboratory, Sept 2017, HDRSAM

10 Elgowainy and Reddi "Hydrogen Delivery Scenario Analysis Model (HDSAM) V3.1" Argonne National Laboratory, HDSAM

11 Elgowainy and Reddi "Hydrogen Refueling Station Analysis Model (HRSAM)" Argonne National Laboratory, Oct 2017, HRSAM

12 "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs", DOE Hydrogen and Fuel Cells Program Record #9013, Oct 2009 DOE 2009

13 Eudy and Jeffers "Foothill Transit Battery Electric Bus Demonstration Results: Second Report," June 2017, NREL 2017

14 Eudy and Jeffers "Zero-Emission Bus Evaluation Results: County Connection Battery Electric Buses" NREL 2018

15 Eudy and Post "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2020," Mar 2021, NREL 2021

16 Frangoul "Volvo Says It Has Started Testing Trucks with Fuel Cells Powered by Hydrogen" CNBC, June 2022

17 Gao et al "Energy Consumption and Cost Savings of Truck Electrification for Heavy-Duty Vehicle Applications," Jan 2017, OSTI 2017

18 Gao et al 2017 "Battery Capacity and Recharging Needs for Electric Buses in City Transit Service" 2017

19 Harris "ZeroAvia's Hydrogen Fuel Cell Plane Ambitions Clouded by Technical Challenges." TechCrunch, Apr 2021

20 Hepperle "Electric Flight – Potential and Limitations" NATO 2012

21 Hoffrichter "Hydrogen as an Energy Carrier for Railway Traction" University of Birmingham, Apr 2013

22 Hoffrichter "Hydrogen-Rail (Hydrail) Development" H2@Rail Workshop 2019

23 “Hydrogen applications and business models” Kearney Energy Transition Institute, June 2020 ETI 2020

24 “Hydrogen-Based Energy Conversion” A.T. Kearney Energy Transition Institute, Feb 2014, ETI 2014

25 “Hydrogen in Electricity’s Future” Congressional Research Service, June 2020 CRS 2020

26 “Hydrogen or batteries for grid storage? A net energy analysis” Energy & Environmental Science, Pellow et al. 2015

27 “Hydrogen-Powered Aviation A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050,” May 2020, FCH 2020

28 Jefferson and Smith "HFCTA Hydrogen Fuel Cell Overview" Railway Age, Apr 2022

29 Kaminski-Morrow "EasyJet 'Electric Aircraft' Partner Aims to Fly Engine in 2023" FlightGlobal, Jan 2020

30 Katalenich and Jacobson “Toward Battery Electric and Hydrogen Fuel Cell Military Vehicles for Land, Air, and Sea” Stanford University, May 2022

31 Lambert "Tesla Semi Electric Truck to Have up to 621 Miles of Range, Says Elon Musk" Electrek, Nov 2020

32 “Life-cycle greenhouse gas emissions of biomethane and hydrogen pathways in the European Union”, ICCT White paper, Oct 2021, ICCT 2021

33 “Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy”, Energy Transitions Commission, April 2021 ETC 2021

34 "MAN Sets the Standard for Range: Fully Electric Bus Breaks the 550 Kilometre Barrier" Automotive World, May 2021, MAN 2021

35 Marcinkoski et al “Hydrogen Class 8 Long Haul Truck Targets” DOE, Oct 2019

36 Marsh "LG Chem RESU: The Complete Review." EnergySage, Dec 2021.

37 McBain and Bibra “Electric Vehicles” Paris, 2021, IEA 2021

38 Molloy "Hydrogen Fuel Cell Trucks Can Decarbonise Heavy Transport" Energy Post, Oct 2019

39 Müller and Arlt “Status and Development in Hydrogen Transport and Storage for Energy Applications,” Aug 2013

40 Nunno "Electrification of U.S. Railways: Pie in the Sky, or Realistic Goal?" Environmental Energy Study Institute, May 2018, EESI 2018

41 "OCTA Debuts Nation's Largest Hydrogen Fueling Station and 10 Zero-Emission Fuel Cell Electric Buses" OCTA, Jan 2020

42 "Old Planes to Be Transformed into 100-Passenger Electric Planes by 2026, Startup Announces" EcoWatch, Nov 2021

43 "Panasonic Launches 5 kW Type Pure Hydrogen Fuel Cell Generator" Panasonic Corporation, Sept 2021

44 Penn State University "Federal Transit Bus Test," June 2018, PSU 2018

45 "Potential and risks of hydrogen-based e-fuels in climate change mitigation" Nature Climate Change, Ueckerdt et al 2021

46 "Powerwall" Tesla

47 Ramsden and Steward, "Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using the H2A Production Model, Version 2" NREL 2009

48 "Reclaiming Hydrogen for a Renewable Future: Distinguishing Fossil Fuel Industry Spin from Zero-Emission Solutions", Earth Justice, Aug 2021 Earth Justice 2021

49 "Revolutionizing Transit: The Proterra ZX5 Electric Transit Bus" Proterra

50 Ruth et al. "The Technical and Economic Potential of the H2@Scale Concept within the United States", Technical Report, National Renewable Energy Laboratory (NREL) NREL 2020

51 Salehi "Application of a Holistic Approach of Hydrogen Internal Combustion Engine (HICE) Busses," Aug 2021

52 Schaller and Gruber "Hydrogen Powered Fuel-Cell Buses Meet Future Transport Challenges" 2001

53 "Semi" Tesla

54 "Specifications" Freightliner

55 Tashie-Lewis and Nnabuife "Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review," Aug 2021

56 "Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term" International Journal of Hydrogen Energy, Mueller-Langer et al 2007

57 Thomas "Fuel Cell and Battery Electric Vehicles Compared," March 2009

58 "Transit Bus" Ballard

59 Transport & Environment "Roadmap to Climate-Friendly Land Freight and Buses in Europe" European Federation for Transport and Environment AISBL, June 2017

60 "Two FCEV" Nikola

61 UK Committee on Climate Change, "Hydrogen in a low-carbon economy", Nov 2018 CCC 2018

62 U.S. Department of Energy, "Where the Energy Goes: Electric Cars", https://fueleconomy.gov/feg/atv-ev.shtml

63 U.S. Energy Information Administration (EIA), “How much electricity is lost in electricity transmission and distribution in the United States? https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

64 Ustolin et al 2020, “Loss of integrity of hydrogen technologies: A critical review” International Journal of Hydrogen Energy

65 "Vehicle Weight Classes & Categories" DOE, June 2012

66 "The Wright Spirit" Wright