

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
<i>Production</i>	Electrolysis	48-81% ^{23,64,56,47,32,25,39}
<i>Conversion</i>	Compression	80-97% ^{23,12,55,26,10,24,57}
	Liquefaction	55-80% ^{23,12,55,24,39,51}
<i>Distribution</i>	Pipelines	90-99% ^{21,24,10,55,23,4}
	Liquid H2 Trucks	94-99% ^{24,55,4,21,10}
<i>Preparation for Use</i>	Refueling	86-97% ^{9,10,11}
<i>End-Uses</i>	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
<i>Distribution</i>	Transmission & Distribution	90-95% ^{59,24,45,63,21}
<i>Preparation for Use</i>	Charging electric bus	75-97% ^{3,13,44,18,14}
	Charging electric truck	95-97% ^{7,17}
	Charging light duty vehicle	90% ^{24,62}
<i>End-Uses</i>	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}
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*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%

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