I-WEST

Phase One Final Report | Detailed Chapter

Hydrogen Demand

VERSION 1.0

LOS ALAMOS NATIONAL LABORATORY

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About this report

The Intermountain West Energy Sustainability & Transitions (I-WEST) initiative is funded by the U.S. Department of Energy to develop a regional technology roadmap to transition six U.S. states to a carbon-neutral energy economy. I-WEST encompasses Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming. Each state is represented in this initiative by a local college, university, or national laboratory. Additional partners from beyond the region were selected for their expertise in applicable fields. In the first phase of I-WEST, the team built the foundation for a regional roadmap that models various energy transition scenarios, including the intersections between technologies, climate, energy policy, economics, and energy, environmental, and social justice. This chapter presents work led by an I-WEST partner on one or more of these focus areas. A summary of the entire I-WEST phase one effort is published online at www.iwest.org.

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Key Findings

- Hydrogen (H_2) has potential to be a viable and affordable transition fuel as the Intermountain West shifts from carbon-based energy sources to more sustainable options within a framework of a larger place-based energy transition for the region.

- 2019 Intermountain West Highway Transportation (Base Case):
  - Approx. 18.4 million registered vehicles in the region
  - Requires approx. 1361 PJ of fuel: 8.3 billion gal gasoline and 2.1 billion gal diesel
  - Emits approx. 88.8 Mt CO_2

- Category-Specific Vehicle CO_2 Footprint
  - Categories: Motorcycles, Cars, Light Trucks (< 10,000 lbs.), Medium-Heavy Trucks (> 10,000 lbs.), and Buses
  - Med-Hvy Trucks emit more CO_2 per year per vehicle than other categories by far
    - 26.2 t CO_2 yr-1 veh-1
    - 4.8% of vehicles, consume 24.7% of fuel, emit 26.2% of CO_2
  - Med-Hvy Trucks are class to target for replacement first

- Requirements for replacement of all Internal Combustion Engine Vehicles (ICEVs) with Fuel Cell Electric Vehicles (FCEVs):
  - Requires between 2.6 and 6.1 Mt H_2 (depends on tank-to-wheels efficiencies of ICEVs replaced)
  - Water necessary:
    - If Blue H_2: Between 120.9 – 284.9 Mt H_2O
    - If Green H_2: Between 32.8 – 77.3 Mt H_2O

- Hydrogen Blending: Theoretically possible to reduce CO_2 emissions from combustion of natural gas
  - 12 blending pilot projects announced or in-process in U.S; only two in the Intermountain West
  - Gas utilities in the U.S. and Europe claim success at H_2 blend fractions of $y_{H2} \leq 0.2$

- CO_2 emissions reduction not linear with increase in H_2 blend fraction
  - H_2 has lowest energy density of any fuel (H_2-Natural Gas blend will have lower energy density than original natural gas stream)
  - Requires compensation by increasing blend consumption to avoid performance loss at appliances of end user
    - $yH_2 = 0.20$ → 16 vol% more gas required → Only 6.9% CO_2 reduction

Introduction

The transition to sustainable energy sources has already begun in much of the world. There is an overwhelming international scientific consensus that severe reductions in anthropogenic greenhouse gas emissions are required in order to limit global warming to less than 1.5 °C relative to pre-industrial quantities—the threshold necessary to mitigate the effects of irreversible climate change [1]. To this end, the Biden administration has rejoined the Paris Agreement on Climate Change [2] and established a GHG reduction goal of 50% from 2005 levels for the U.S. by 2030 [3]. Additional U.S. goals include 100% carbon-free electricity by 2035 and a completely carbon-neutral U.S. economy by 2050 [3].

Hydrogen (H_2) is anticipated to be a significant carbon-free energy vector in the transition away from fossil energy systems, and may gain permanence as the principal chemical energy carrier once the transition is complete [4]. The most significant uses for hydrogen are in refinery operations and the production of ammonia and methanol [5]. However, hydrogen has tremendous potential as a carbon-free energy carrier as it can be sustainably produced from several energy sources including solar, wind, biomass, and decarbonized fossil fuels [6,7]. It produces zero carbon emissions when combusted and only water is emitted when hydrogen is used in a fuel cell to make electricity [6,8]. Hydrogen can also be blended and transported with natural gas to partially decarbonize natural gas consumption [9]. Furthermore, hydrogen has the largest energy density by mass of any common fuel [10].

The I-WEST initiative is developing a technology roadmap for sustainable energy transition for six states in the Intermountain West—Arizona, Colorado, Montana, New Mexico, Utah, and Wyoming—using a place-based approach that focuses heavily on engagement with relevant stakeholders and investment from local communities [11]. These states have environmental and geographic similarities that offer unique sustainable energy and GHG reduction possibilities. I-WEST is supported by the U.S. Department of Energy and led by Los Alamos National Laboratory in partnership with regional colleges and universities, other national laboratories, and a non-profit entity with expertise in energy-related policy.

Hydrogen employment is especially relevant for the Intermountain West as it is a practical transition technology that can supplement the current fossil-energy production portfolio of the region while drawing on the significant solar, wind, and geothermal resources that are locally available. Currently, hydrogen production is at or near zero within the region. However, hydrogen employment has the potential to become an affordable and abundant regional energy carrier as regional hydrogen production increases and relevant technologies improve and are adopted.

In this report, hydrogen utilization is considered via a "first-pass" analysis of (i) adoption of fuel cell electric vehicles (FCEVs) and (ii) blending of hydrogen with natural gas as potential CO_2 emissions reduction vectors within the Intermountain West. A base case and current state of GHG emissions is presented, followed by a discussion of relevant technology leading to hydrogen remediation of the base case. Some necessary infrastructure is mentioned with discourse regarding the amount of hydrogen possible under various constraints. The present work offers a partial overview of hydrogen utilization options for the realization of a regional hydrogen economy.

Fuel cell electric vehicles

Figure 1 shows a generic schematic of a hydrogen fuel cell (or proton exchange membrane fuel cell) while Figure 2 shows a diagram of a typical FCEV [12]. The fuel cell functions by converting hydrogen (fuel) and O_2 (from air) into electricity while emitting only water vapor. The electricity is used to turn an electric motor similar to battery electric vehicles (BEVs). As such, tailpipe CO_2 emissions are reduced to zero when an internal combustion engine vehicle (ICEV) is replaced with a FCEV.

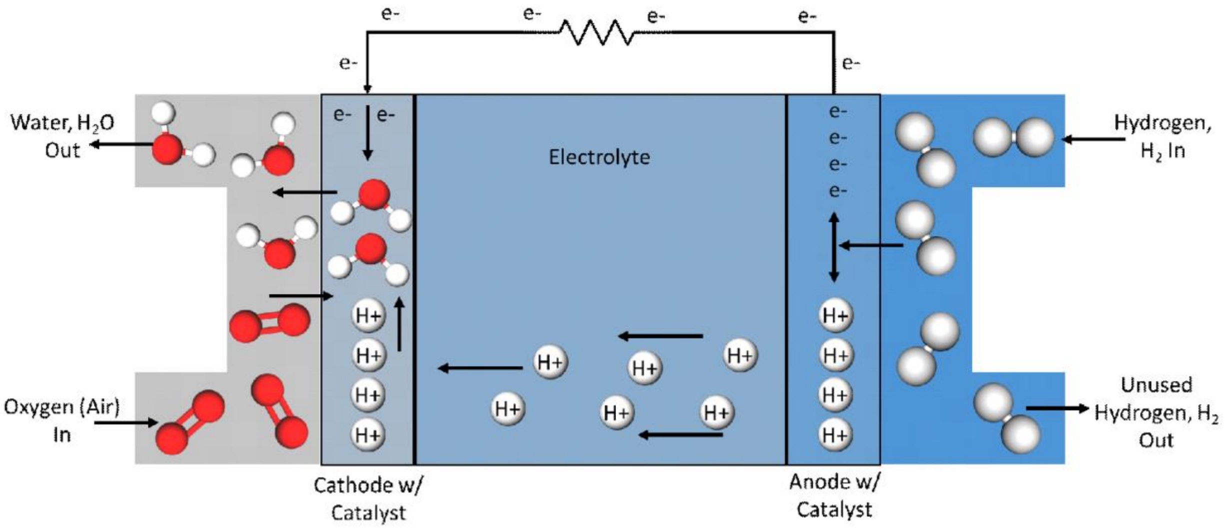

Figure 1. Schematic of a hydrogen fuel cell combining diatomic hydrogen with diatomic oxygen (O_2, from air) to produce electricity. Water is the only emission.

State	Rural (Million Miles yr^{-1})	Urban (Million Miles yr^{-1})	% Rural (--)	% Urban (--)
AZ	16,690	53,591	23.7%	76.3%
CO	16,216	38,418	29.7%	70.3%
MT	8,941	3,951	69.4%	30.6%
NM	16,423	11,349	59.1%	40.9%
UT	8,888	24,023	27.0%	73.0%
WY	7,190	3,018	70.4%	29.6%
I-WEST	74,347	134,349	35.6%	64.4%
U.S.	983,853	2,277,919	30.2%	69.8%

Table 1. 2019 Annual vehicle miles traveled by Intermountain West state compared to the broader U.S. [22].

Hydrogen blending with natural gas

Hydrogen blending may be an important transition step toward decarbonization, while minimizing energy disruptions for both producers and consumers [26]. Blends of hydrogen with natural gas (5-20 vol% H_2) are a potential opportunity to reduce combustion CO_2 emissions (i.e., residential or commercial appliances), though drawbacks may remain [27]. Hydrogen blending has been considered as a way to increase the output of renewable energy systems [9]. Employment of downstream separation operations has even been suggested as a way of supplying pure hydrogen via blending with natural gas [9].

Natural gas utilities in the U.S. have announced 26 pilot projects since 2020, 12 of which include hydrogen blending [28]. SoCalGas announced in 2021 that it has successfully blended 20% hydrogen in a closed-loop system [29]. Furthermore, German grid operator Avacon has successfully tested both 10% and 15% hydrogen blends, while 20% blends are planned in 2023 [30]. Of the 12 hydrogen blending projects announced, only two are located in the Intermountain West. A project in Colorado is performed by a collaboration between the U.S. Department of Energy and about 20 industry, academia, and public partners [28]. While a project in Tempe, Arizona is conducted by a collaboration between Southwest Gas Holdings Co. and Arizona State University [28]. Both projects seek to evaluate optimal blend ratios, investigate impact on pipelines and infrastructure, and identify economic risks and opportunities [28].

Despite recent interest by natural gas utilities in hydrogen blending, potential drawbacks exist which may limit emissions reduction via blending. Hydrogen combustion in air can yield nitrogen oxides (NO_x) which can be a potent pollutant with a global warming potential 273 times that of CO_2 over 100 years

[31,32]. Hydrogen has a global warming potential that is 5.8 times that of CO_2 over 100 years [33], and is more likely to leak in existing natural gas infrastructure due to the smaller size of hydrogen.

Methods

Highway transportation and fuel cell electric vehicles

The U.S. transportation sector generated 27% of total GHG emissions in 2020; the largest percentage of all economic sectors [34]. This principally arises from the burning of fossil fuels, and corresponding GHG emissions in transportation vehicles [34]. Conversion from conventional ICEVs to FCEVs presents an opportunity to reduce tailpipe GHG emissions to zero. Hydrogen FCEVs report a fuel efficiency (percentage of chemical energy converted into kinetic energy of the vehicle) of 42-64% [35-38], whereas conventional ICEVs can achieve a maximum efficiency of 42% [37,39,40].

The following analysis of highway CO_2 emissions is based on the number of registered vehicles reported N^{Fuel}_{Type} in 2019 for each Intermountain West state for the vehicle types of motorcycles, cars, light trucks, medium-heavy trucks, and buses [41-43]. Light trucks are those with a gross vehicle weight rating (GVWR) < 10,000 lbs. and includes minivans and SUVs [44]. Medium-heavy trucks are those for which the GVWR > 10,000 lbs. (class 3-8 vehicles) [44,45]. The average fuel efficiencies for each vehicle type [$\varepsilon^{Fuel}_{Type}$, (miles gal^{-1})], type of fuel used (gasoline or diesel), and annual vehicle miles traveled [VMT_{Type} (miles yr^{-1} veh^{-1})] for each vehicle class are assumed to reflect the average efficiencies and VMT of the national vehicle stock [44, 46, 47]. Equation 1 provides the average annual fuel consumed [AFC^{Fuel}_{Type} (gal yr^{-1} veh^{-1})] for each vehicle type.

$$AFC^{Fuel}_{Type} = \frac{VMT_{Type}}{\varepsilon^{Fuel}_{Type}} \tag{1}$$

The product of the annual fuel consumed and number of registered vehicles produces the total annual fuel consumed [$TAFC^{Fuel}_{Type}$ (gal yr^{-1})] for each vehicle category according to Equation 2.

$$TAFC^{Fuel}_{Type} = AFC^{Fuel}_{Type} \times N^{Fuel}_{Type} \tag{2}$$

Mass of CO_2 emitted m^{Type}_{CO2} (kg) is simply the product of the total annual fuel consumed and the CO_2 literature coefficient k^{Fuel}_{CO2} (kg CO_2 gal^{-1} Fuel) provided by EIA as shown in Equation 3 [48].

$$m_{CO_2}^{Type} = TAFC_{Type}^{Fuel} \times k_{CO_2}^{Fuel} \quad (3)$$

Note, the present work does not consider the tailpipe emissions of out-of-region vehicles, that is, those vehicles registered in a state other than a state under assessment by I-WEST, unless the vehicle is also registered within one of the states.

Hydrogen blending with natural gas

The efficacy of hydrogen blending in natural gas streams is evaluated by calculating the reduction in CO_2 emissions obtained via blending at several hydrogen volume fractions between zero and one. As the volume fraction of hydrogen increases, the fraction of natural gas in the binary mixture decreases. Additionally, the absolute volume of the natural gas constituent also decreases even though the total volume of the stream increases to compensate for the reduced volumetric energy density of the hydrogen on the basis of lower heating value (LHV) [49]. Equation 4 shows the calculation of CO_2 emitted as a function of volume fraction hydrogen (y_{H2}).

$$m_{CO_2} = \frac{LHV_{NatGas}\rho_{NatGas}(y_{H_2} - 1)M_{CO_2}}{M_{CH_4}\left[LHV_{NatGas}(y_{H_2} - 1) - LHV_{H_2}y_{H_2}\right]} \quad (4)$$

Where m_{CO2} (kg) is the mass of CO_2 emitted, LHV_{NatGas} (MJ m^{-3}) is the lower heating value of natural gas, ρ_{NatGas} (kg m^{-3}) is the density of natural gas, M_{CO2} (kg $kmol^{-1}$) is the molar mass of CO_2, M_{CH4} (kg $kmol^{-1}$) is the molar mass of natural gas (assuming 100% of natural gas is CH_4), and LHV_{H2} (MJ m^{-3}) is the lower heating value of hydrogen [51,51].

Results and Discussion

Fuel cell electric vehicles

A summary of the registered vehicles, estimated fuel consumption, and CO_2 emissions for the Intermountain West are presented in Table 2. Figure 4(a) shows light-duty vehicle stock (cars and light trucks) in each state where light trucks are defined as all trucks with a GVWR < 10,000 lbs. including minivans and SUVs [45]. Figure 4(b) shows the medium-heavy vehicle stock (GVWR > 10,000 lbs.) in each state separated by fuel type. While cars and light trucks are predominantly gasoline ICEVs (not shown in Figure 4a), most medium-heavy vehicles use diesel. Figure 4 (c) shows the registered vehicles by vehicle type for the region. Light trucks (including minivans and SUVs) make up the largest share followed by cars. Buses total less than 50,000. The number of registered vehicles tracks closely with state population data (see Regional Overview chapter). There are over 18.4 million registered vehicles in the Intermountain West; in principle, each vehicle is a potential candidate for replacement with a FCEV.

Vehicle Type	No. of Registered Vehicles		2019 Fuel Consumed		Annual CO_2 Emissions	
	(No.)	(%)	(PJ yr^{-1})	(%)	(10^6 t CO_2)	(%)
Motorcycles	880,486	4.8%	4.9	0.5%	0.3	0.4%
Cars	6,345,959	34.5%	275.7	25.2%	17.6	19.8%
Light Trucks	10,259,920	55.7%	730.9	64.9%	46.7	52.6%
Med-Heavy Trucks	885,938	4.8%	336.8	9.2%	23.2	26.2%
Buses	43,241	0.2%	12.9	0.2%	0.9	1.0%
Total	18,415,544	100.0%	1361.2	100.0%	88.8	100.0%

Table 2. 2019 estimated fuel consumption and CO_2 emissions in the Intermountain West region by vehicle type. Light trucks are those where GVWR < 10,000 lbs. including minivans and SUVs. Med-Heavy trucks are those with GVWR > 10,000 lbs.

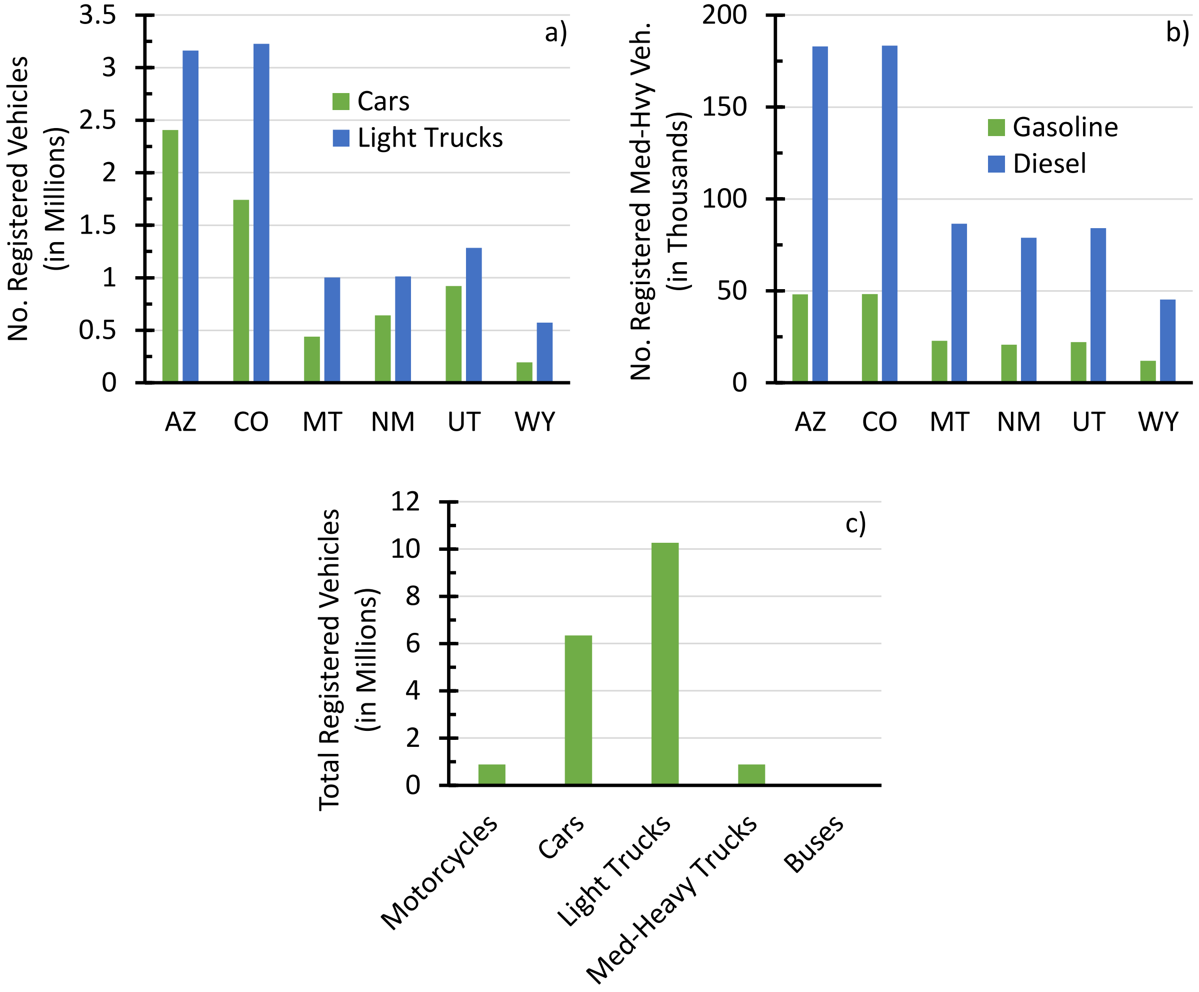

Figure 4. a) 2019 registered light-duty vehicles (cars and light trucks) in each state. b) 2019 registered medium and heavy trucks in each state. c) 2019 total registered vehicles in the entire region by vehicle type (see Table 2). Cars and light-duty trucks are Class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are Class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 5 shows the amount of highway fossil fuel consumed in 2019 by a) state and fuel type in billion gallons yr^{-1}, b) state and fuel type in petajoules (PJ, 10^{15}) yr^{-1}, and c) vehicle type in PJ yr^{-1} for the whole region. Gasoline engines are clearly the majority of registered vehicles in each state. This is expected as gasoline engines are the primary contributor to the car and light truck segments. Gasoline ICEVs include E10 engines, as almost all finished gasoline in the U.S. contains 10% ethanol, as well as ethanol flex-fuel engines.

Fuel consumption of the states tracks closely with state population data (see the Regional Overview chapter). The total highway transportation fuel consumed in the Intermountain West in 2019 is approximately equal to 1,361 PJ. This represents the sum of about 8.3 billion gallons of gasoline and 2.1 billion gallons of diesel [52].

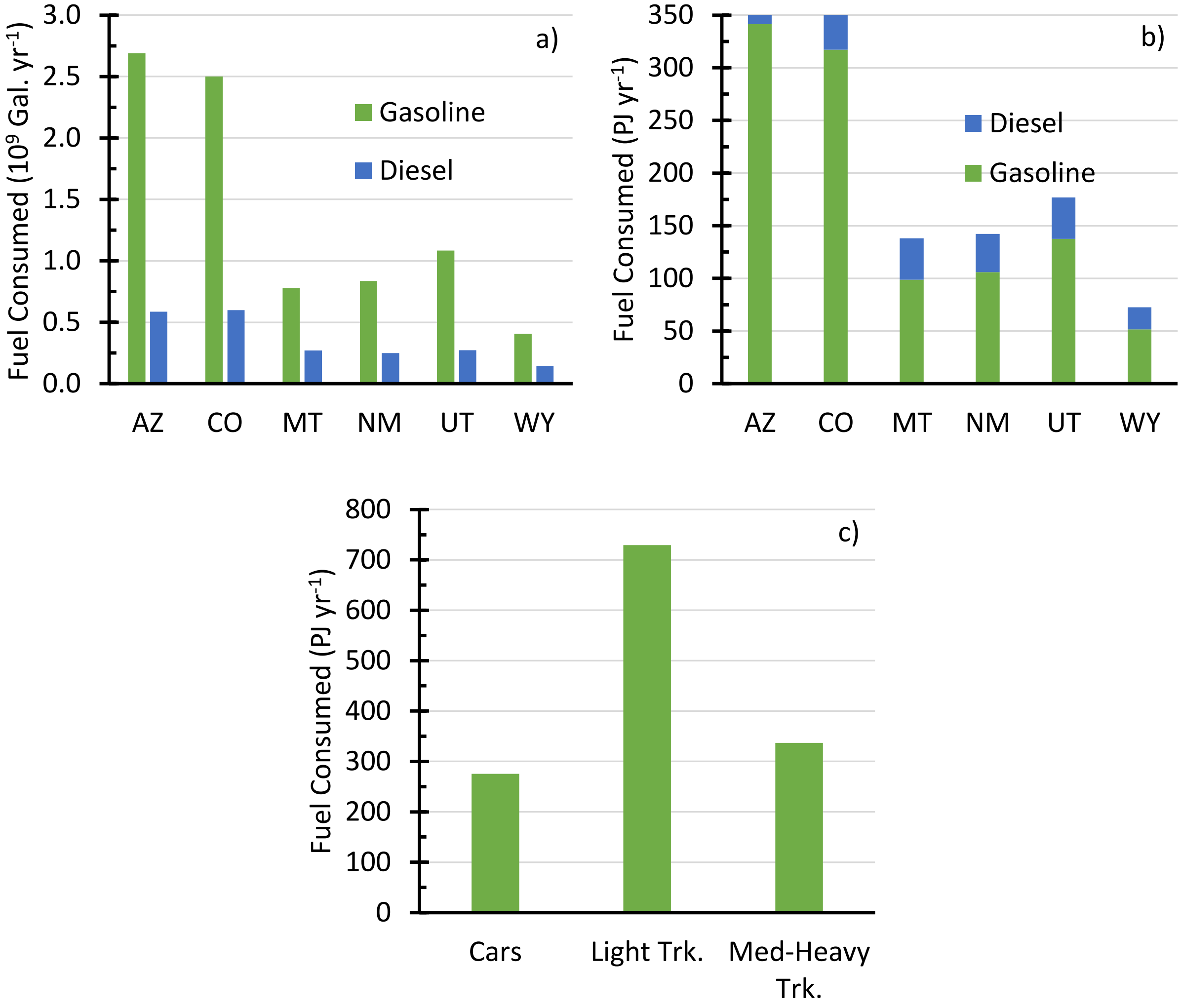

Figure 5. 2019 Intermountain West fuel consumption by a) state and fuel type in billion gallons yr-1, b) state and fuel type in PJ yr-1, and c) total highway fuel consumed in the region by vehicle type in PJ yr-1. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 6 shows the vehicle-specific fuel consumed for each vehicle category in 2019 (except motorcycles, which were negligible). Comparing Figure 6 with Figure 4 and Figure 5, it is obvious that the cars and light trucks consume the most fuel as entire vehicle categories. However, medium-heavy trucks and buses consumed the most fuel, on average, *per vehicle*. Essentially there are significantly more vehicles classified as cars and light trucks (Table 2 and Figure 4) which, on average, spend less time each year in operation and consume less fuel per vehicle [22, 44, 46]. Conversely, vehicles classified as medium-heavy trucks and buses spend more time in operation consuming fuel [22, 44, 46].

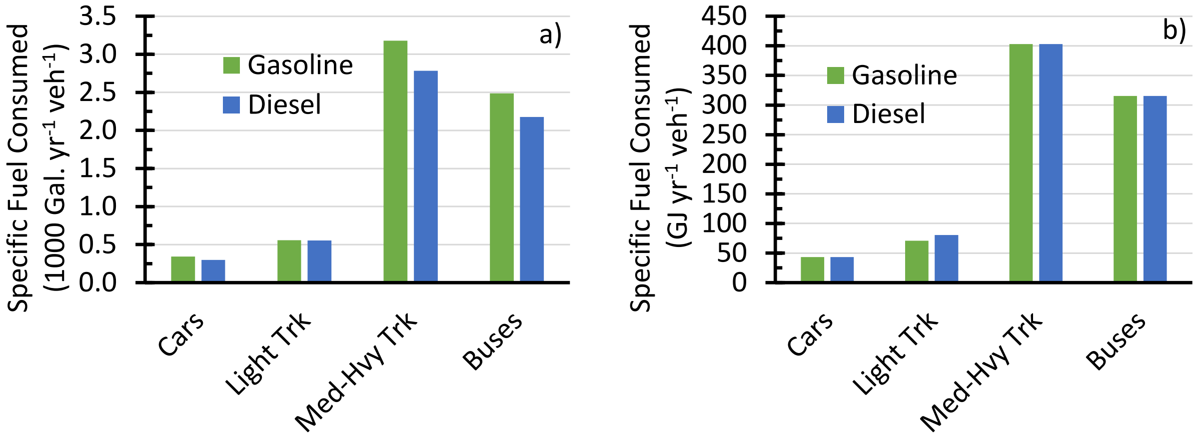

Figure 6. 2019 vehicle-specific fuel consumption for both gasoline and diesel ICEVs in a) fuel volume consumed and b) fuel energy consumed. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 7 shows the estimated 2019 CO_2 tailpipe emissions for the Intermountain West, broken down by a) state and b) vehicle type (motorcycles and buses, not shown, produce 1% or less of CO_2, see Table 2). Tailpipe CO_2 emissions by state track closely with state fuel consumption trends (Figure 5), registered vehicles (Figure 4), and ultimately state population (see the Regional Overview chapter). Not surprisingly, the tailpipe CO_2 emissions by vehicle type also possess the same trends as fuel consumption by vehicle type (Figure 5c). That is, light trucks consume the most fuel and emit the most CO_2 as a category, followed by the medium-heavy truck segment, followed by cars. Furthermore, CO_2 emissions from gasoline ICEVs represent the majority share over diesel ICEV CO_2 emissions as a greater number of gasoline-fueled ICEVs are registered in each state, and more gasoline is consumed as well. By this estimation, tailpipe CO_2 emissions of registered vehicles in the region represent 88.8 10^6 t CO_2, or approximately 73.8% of all transportation CO_2 emissions for the Intermountain West [53].

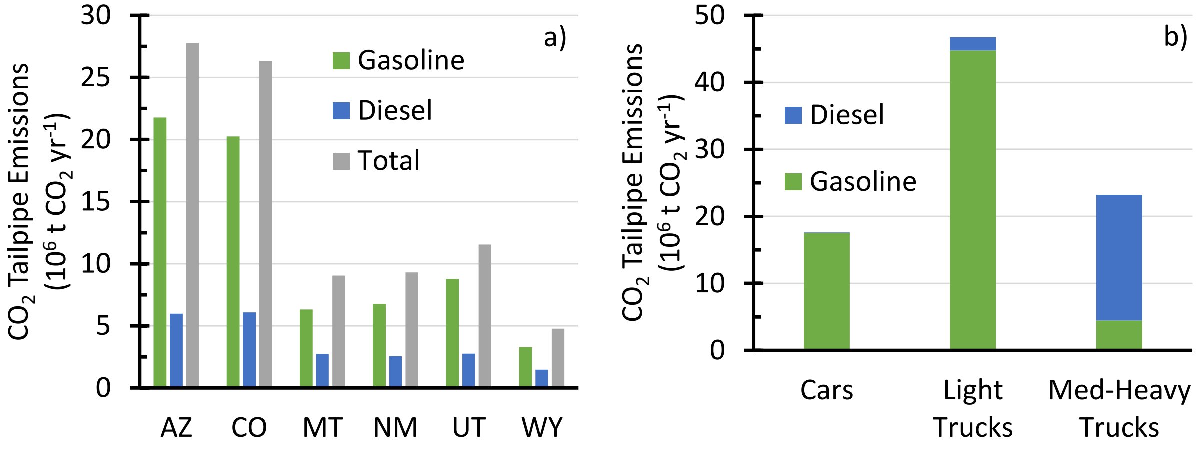

Figure 7. 2019 CO$_2$ tailpipe emissions by a) Intermountain West state and b) vehicle type. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Figure 8 represents the vehicle-specific, or average CO$_2$ emitted per vehicle, by a) fuel type and vehicle type, b) average value and vehicle type, c) fuel type and Intermountain West state, and d) average value and state. Comparing Figure 8 to Figure 6, it is clear that tailpipe CO$_2$ emissions are a function of fuel type and amount of fuel consumed in each vehicle class. Figure 8a shows that vehicle-specific CO$_2$ emissions generally increase with GVWR and that diesel ICEVs will emit more CO$_2$ than those using gasoline (diesel has a greater CO$_2$ emission coefficient than gasoline) [48]. Figure 8c-d show that (i) the average vehicle in each state emits similar amounts of CO$_2$, (ii) vehicles using diesel will emit a greater amount of CO$_2$ on average than those using gasoline, and (iii) average CO$_2$ emissions are governed primarily by gasoline ICEVs as the average values in Figure 8d are closer to parity with the gasoline values in Figure 8c (arising from the significantly greater number of gasoline-fueled ICEVs, see Figure 4).

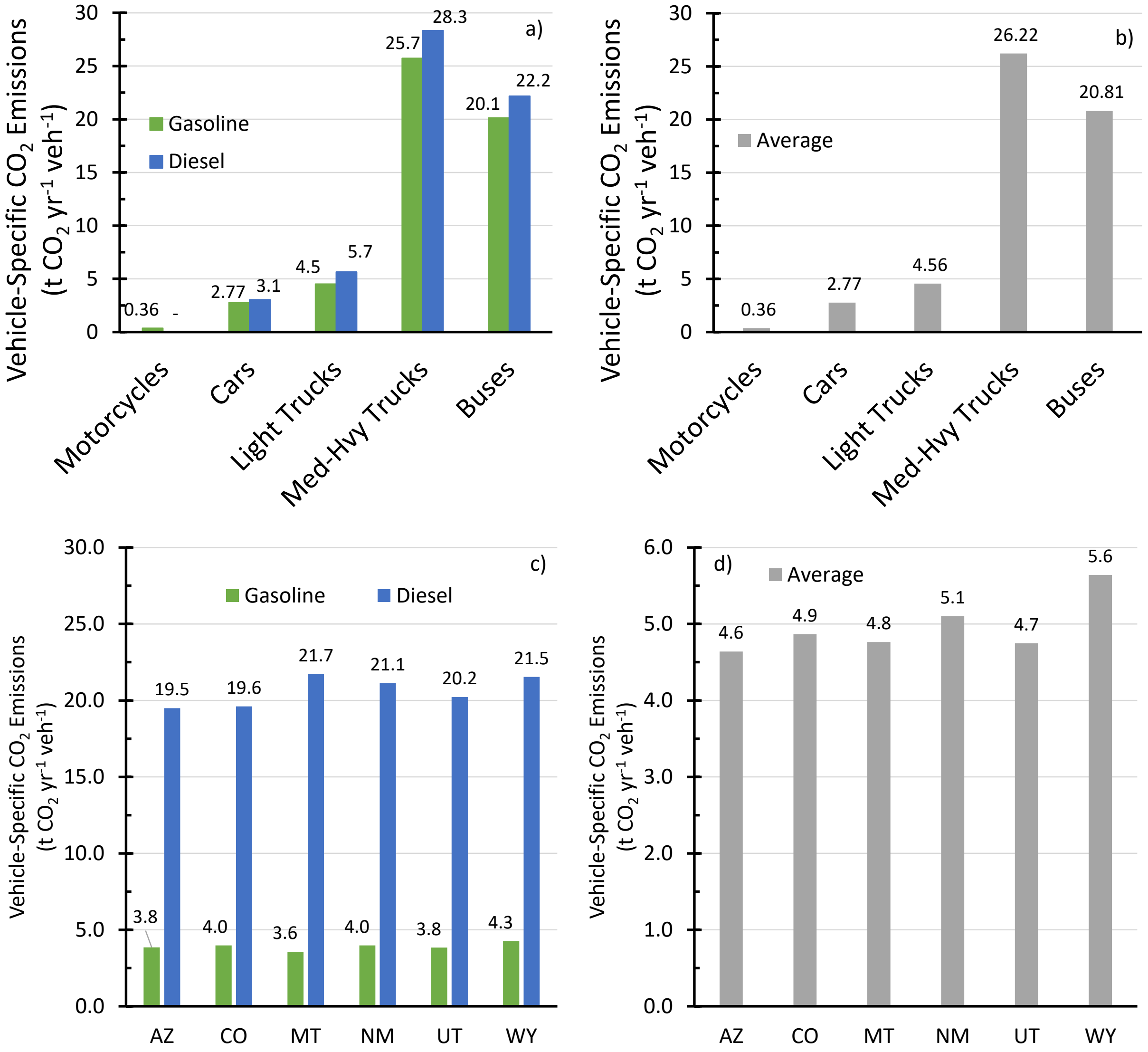

Figure 8. 2019 vehicle specific tailpipe CO_2 emissions by a) fuel type and vehicle type, b) average value and vehicle type, c) fuel type and state, and d) average value and state. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Perhaps most importantly, Figure 8a-b shows the average benefit that can be expected by replacing 1 ICEV with a FCEV in the region. That is, replacing an ICEV from one of the vehicle types shown in Figure 8b will yield an annual reduction in CO_2 emissions, on average, of the value shown for that vehicle type (i.e., 2.77 t CO_2 yr^{-1} veh^{-1} for cars). Knowing if the FCEV is replacing a diesel or gasoline ICEV will yield the corresponding value in Figure 8a.

As a group, light trucks represent the largest CO_2 emitter at 46.7 Mt CO_2 yr^{-1} or 52.6% of regional tailpipe CO_2 emissions in 2019. Yet, only 4.6 t CO_2 yr^{-1} veh^{-1}, on average, are saved when a light truck ICEV is replaced by a FCEV as "light trucks" are the largest vehicle category at 55.7% of vehicles in the Intermountain West region (compare Figure 8 with Figure 4 and Table 2). Conversely medium-heavy trucks emit 23.2 Mt CO_2 yr^{-1}, or 26.2% of regional tailpipe CO_2 emissions, but are only 4.8% of regional vehicles. Thus, replacing a medium-heavy truck ICEV with a FCEV will prevent 26.2 t CO_2 yr^{-1} veh^{-1}. This arises from very low diesel efficiency (approx. 8.8 avg. miles gal^{-1} diesel) [46], the greater annual vehicle miles traveled (approx. 24,465 avg. miles yr^{-1} veh^{-1}) [46], and the greater CO_2 emissions factor for diesel fuel (10.19 kg CO_2 gal^{-1} diesel vs. 8.10 kg CO_2 gal^{-1} gasoline) [46, 48]. This suggests that replacing diesel ICEVs with H_2 FCEVs is the highway transportation vector most likely to provide the best decarbonization efficiency; that is, the largest CO_2 reduction for the lowest cost or effort.

Figure 9 shows the sum of all transportation CO_2 emissions in the region, including the major contributors from the above tailpipe emissions analysis. The U.S. EIA states all transportation emissions for the region in 2019 summed to 120.3 Mt CO_2. After subtracting contributions from cars, light trucks, and medium-heavy trucks (87.5 Mt CO_2 in sum), 32.8 Mt CO_2 are absent from the current estimation. These remaining CO_2 emissions are from aviation (15.5 Mt CO_2) [54], out-of-region vehicles (vehicles not registered in an Intermountain West state) as the Intermountain West possesses two major freight corridors [52, 54-56], and other sources which include motorcycles, buses, recreational vehicles, as well as rail and marine sources [57].

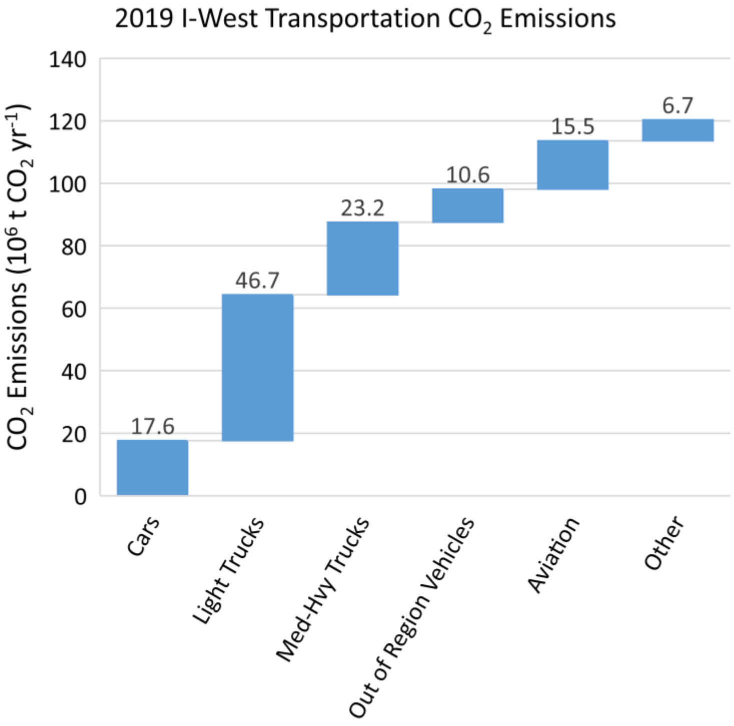

Figure 9. 2019 Transportation CO_2 Emissions in the Intermountain West region totaling 120.3 Mt CO_2. "Other" includes CO_2 emissions from motorcycles, buses, RVs, rail, and marine sources. Cars and light-duty trucks are class 1 and 2 vehicles where the GVWR ≤ 10,000 lbs.; medium-heavy trucks are class 3-8 vehicles where GVWR > 10,000 lbs. Categories with "truck" labels include vans and SUVs.

Table 3 and Figure 10 show the maximum and minimum required hydrogen and H_2O for ICEV replacement with a FCEV as a function of vehicle class. The minimum and maximum requirements are based on the maximum and minimum engine efficiencies, η_{Fuel}, for ICEVs ($0.14 \leq \eta_{Gas} \leq 0.40$, $0.28 \leq \eta_{Diesel} \leq 0.42$, and $\eta_{FCEV} = 0.64$) [38, 58, 59]. The maximum and minimum H_2O requirements are a function of the corresponding hydrogen requirement and a conversion for both blue and green hydrogen processes (see the Hydrogen Supply chapter).

Vehicle Type	H_2 Required		H_2O Required (Blue H_2)		H_2O Required (Green H_2)	
	Min Mt H_2 yr^{-1}	Max Mt H_2 yr^{-1}	Min Mt H_2O yr^{-1}	Max Mt H_2O yr^{-1}	Min Mt H_2O yr^{-1}	Max Mt H_2O yr^{-1}
Motorcycles	0.008	0.022	0.358	1.022	0.097	0.277
Cars	0.43	1.22	20.07	57.11	5.44	15.49
Light Trucks	1.18	3.24	54.89	151.39	14.89	41.06
Med-Hvy Trucks	0.94	1.55	43.75	72.53	11.87	19.67
Buses	0.04	0.06	1.79	2.79	0.49	0.76
Total	2.59	6.10	120.86	284.85	32.78	77.26

Table 3. 2019 Hydrogen and H_2O required for ICEV replacement with FCEV. Minimum and maximum values are based on minimum and maximum ICE efficiencies.

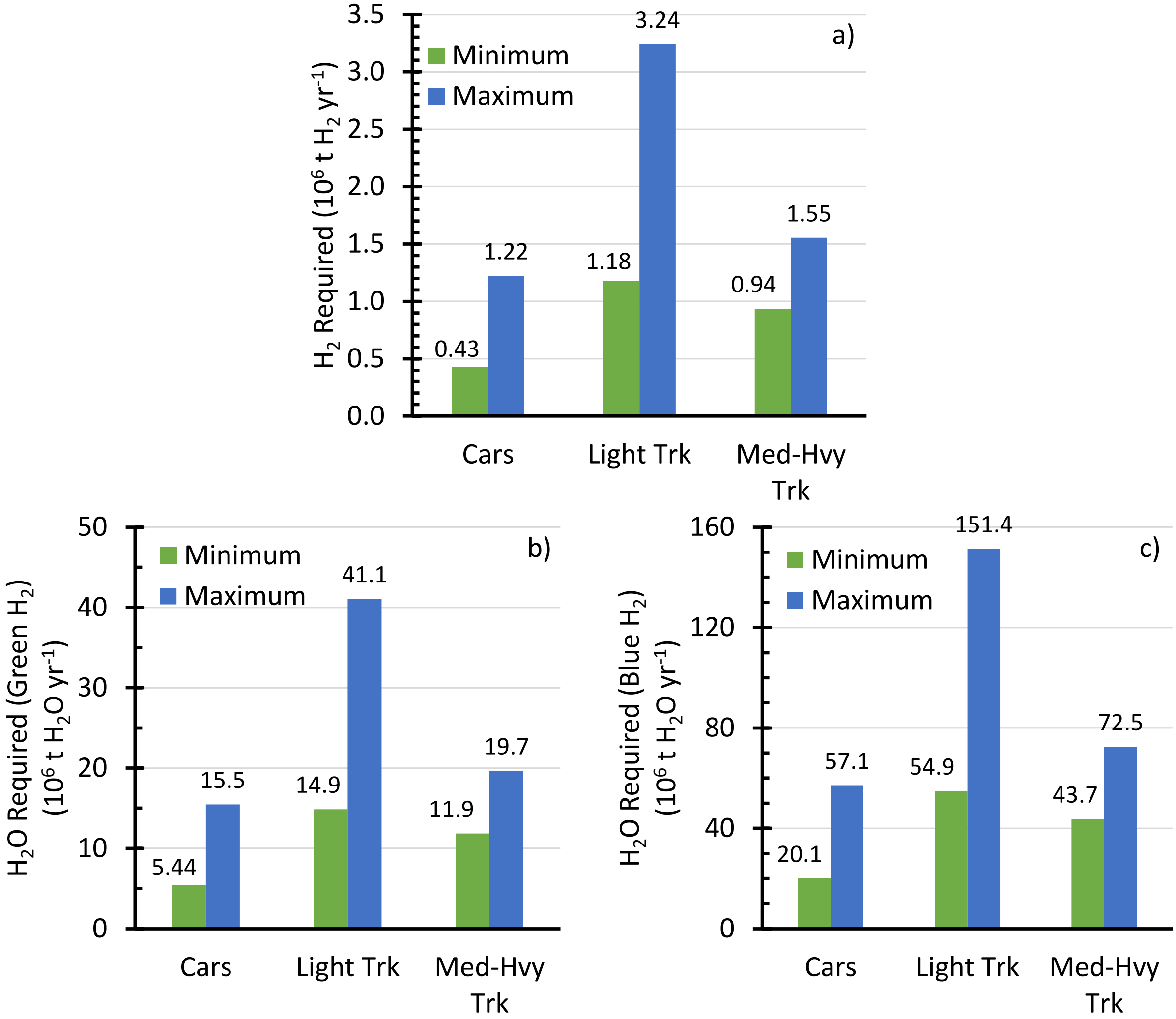

Figure 10. 2019 maximum and minimum requirements by vehicle class (depending on ICE efficiencies) for a) hydrogen, b) H_2O for green hydrogen, and c) H_2O for blue hydrogen.

Replacing all 18.4 million ICEVs registered in the Intermountain West with H_2 FCEVs will require between 2.6 and 6.1 Mt H_2 yr^{-1}. Current hydrogen production capacity in the U.S. is only approximately 10 Mt H_2 yr^{-1}, while global hydrogen production in 2021 was 94.2 Mt H_2 [60-62]. As such, replacing all regional ICEVs with FCEVs would require approximately 26-61% of all hydrogen currently produced in the U.S. or 2.7-6.5% of hydrogen globally. While this is highly improbable in the near- to medium-term, there is unprecedented momentum for hydrogen as a pivotal carbon-neutral energy carrier as the world transitions away from fossil energy and toward a more sustainable future [60, 63].

As previously discussed (see Figure 8), targeting the medium-heavy trucks category makes sense as an initial attempt to stimulate adoption of FCEVs as this reduces tailpipe CO_2 emissions by approximately

26.2 t CO_2 yr^{-1} veh^{-1}. Furthermore, this can be accomplished with a hydrogen requirement of about 25-36% of the hydrogen necessary to switch out all ICEVs in the Intermountain West.

Figure 11 shows the maximum and minimum hydrogen and H_2O required as a function of Intermountain West state rather than vehicle class. FCEVs and BEVs are complementary technologies. FCEVs excel in cases of heavier vehicles (as discussed above) and in cases where rural miles are driven significantly more than urban miles. As mentioned previously (see Table 1), the region has three states (MT, NM, and WY) where the annual vehicle miles traveled (VMT) were more rural than urban. While BEVs have a higher energy density than a FCEV, the hydrogen fuel has a greater energy density by mass than batteries. This makes a FCEV more suitable for heavier vehicles and longer trips [6]. Where the BEV has less of a range and may require significant down time to recharge, the FCEV can refuel in less than 20 min (similar to an ICEV) [6]. Furthermore, Figure 11a shows that the rural states MT, NM, and WY are also the states which would require the least amount of hydrogen to enable ICEV replacement by FCEVs.

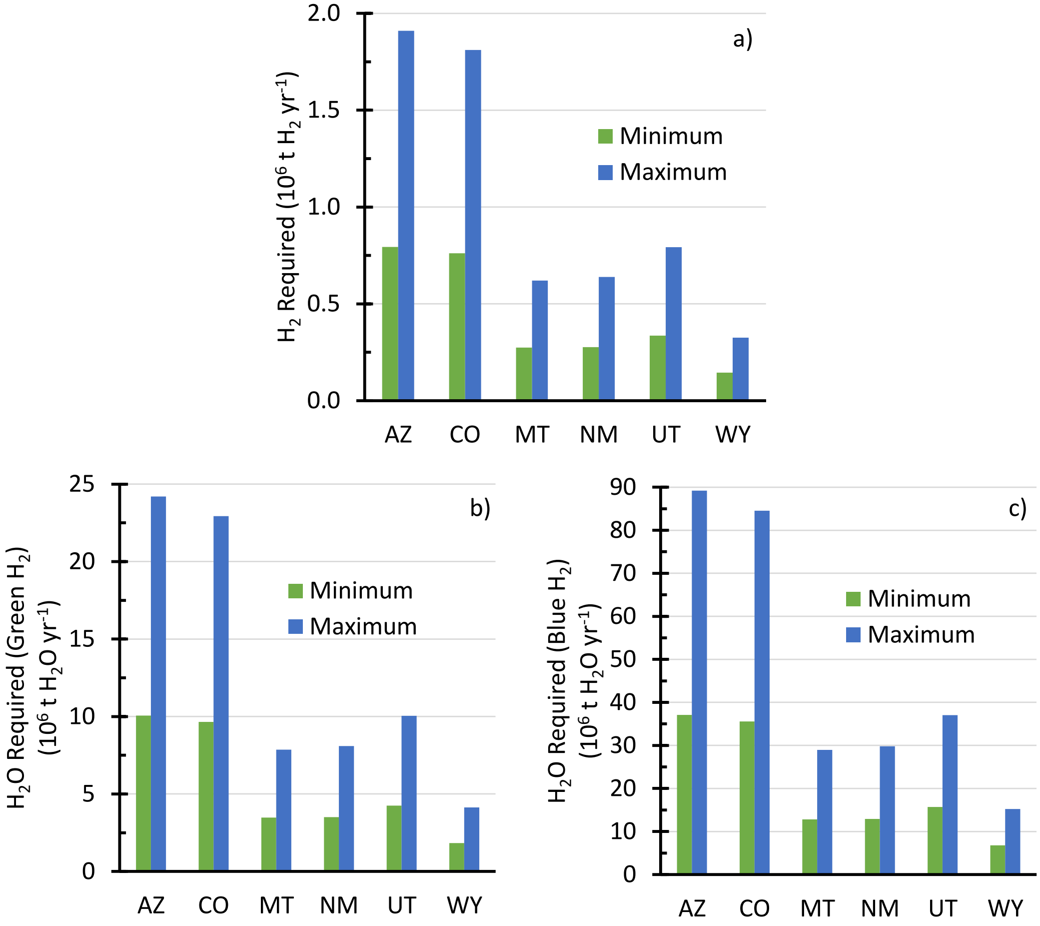

Figure 11. 2019 maximum and minimum requirements by Intermountain West state (depending on ICE efficiencies) for a) hydrogen, b) H_2O for green hydrogen, and c) H_2O for blue hydrogen.

Cars and light-duty trucks may provide additional opportunities for highway transportation decarbonization in the Intermountain West as each comprise over 34.5% and 55.7% of the region's vehicles respectively. In Table 2 cars are estimated to consume 20.3% of fuel and emit 19.8% of CO_2 emissions while light-duty trucks are estimated to consume 53.7% of fuel and emit 52.6% of CO_2 emissions. Currently, battery electric vehicles (BEVs) have achieved more adoption in the light-duty market, both regionally as well as nationally [17, 20, 64], and their implementation reduces GHG emissions by 45, 56, and 74 t CO_2e for sedans, sport utility vehicles, and pickup trucks, respectively, relative to ICEVs on a life cycle basis [65]. This analysis becomes more complicated once local electricity sources are considered for BEVs; however, BEVs successfully reduce CO_2 emissions relative to ICEVs in over 98% of U.S. counties [65]. It may be possible that FCEVs can compete with BEVs in the light-duty market and can improve upon BEV implementation if the hydrogen is produced using carbon capture or completely renewably such as blue or green hydrogen as discussed in previous sections.

Hydrogen blending with natural gas

Hydrogen has the potential to perform as a transition fuel that can supplement the current fossil-energy portfolio of the Intermountain West while drawing on the region's considerable solar, wind and geothermal resources. Research from some natural gas utilities suggests that low hydrogen blend fractions ($y_{H2} \leq 0.2$) are possible without requiring significant upgrading to the infrastructure [27-30]. However, larger hydrogen blend fractions ($y_{H2} > 0.2$) will likely require upgrading and modification of infrastructure [9]. Furthermore, correct hydrogen blend fractions are expected to be highly infrastructure-dependent and should be comprehensively evaluated on the basis of each system [9].

Based on Equation 4, Figure 12 shows the theoretical reduction of CO_2 results from natural gas combustion as $0 \leq y_{H2} \leq 1$. Although hydrogen has the largest energy density by mass of any fuel, it unfortunately has the lowest energy density by volume [7, 21]. Thus, when hydrogen is blended into natural gas at constant volume (meaning, to add hydrogen an equal volume of natural gas is removed), the resulting stream has a lower energy density than the natural gas alone. To compensate, the end user will need to consume a greater volume of the gas stream in order to receive the same amount of energy from the utility. The result is the half-parabolic shape shown in Figure 12 where an increase in the H_2 blend fraction, y_{H2}, does reduce CO_2 emissions upon combustion but not linearly.

The first five data points from Figure 12 are shown in Table 4 to further illustrate this phenomenon. Presently, gas utilities in the U.S. and Europe claim to have successfully tested hydrogen blend fractions as high as 15-20% [29, 30]. The results from Table 4 and Figure 12 show that as the hydrogen blend fraction increases, the total volume of the gas stream must also increase in order to compensate for the reduction in energy density. Thus, theoretical hydrogen blends of 15% and 20% require corresponding increases in volume of 12% and 16%, respectively, and the CO_2 reduction potential is limited to 5% and 6.9% respectively.

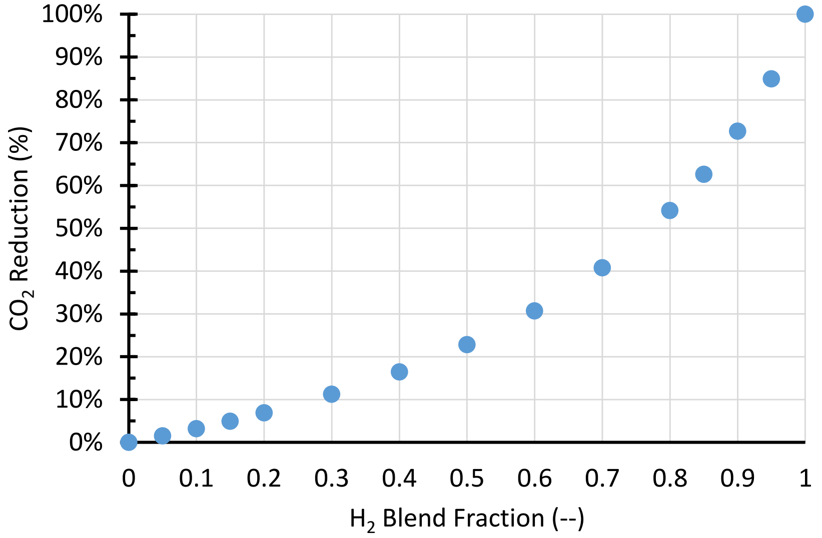

Figure 12. Results from Equation 4 verifying theoretical CO_2 reduction possible when blending hydrogen between $0 \leq y_{H2} \leq 1$ in natural gas distribution systems.

y_{H2} (--)	y_{NatGas} (--)	LHV (MJ m^{-3})	V_{Total} (m^3 hr^{-1})	V_{H2} (m^3 hr^{-1})	V_{NatGas} (m^3 hr^{-1})	y_{CO2} (--)	CO_2 Reduction (%)
0.00	1.00	36.63	1.00	0.00	1.00	1.000	0.0%
0.05	0.95	35.34	1.04	0.05	0.98	0.985	1.5%
0.10	0.90	34.05	1.08	0.11	0.97	0.968	3.2%
0.15	0.85	32.76	1.12	0.17	0.95	0.950	5.0%
0.20	0.80	31.47	1.16	0.23	0.93	0.931	6.9%

Table 4. The first five results from Equation 4 corresponding to hydrogen blends at $0 \leq y_{H2} \leq 0.2$. See Figure 12. LHV represents the Lower Heating Value of the gas stream [49-51].

Issues relating to the costs of hydrogen blending remain unsettled. At present, renewable (green) hydrogen costs 4-5 times more than natural gas [27]. The present natural gas distribution system in the Intermountain West was not designed for hydrogen. Thus, there may be issues with hydrogen embrittlement of the pipeline infrastructure if the hydrogen blend fraction increases above a critical concentration and the storage and transport systems are lacking integrity [66]. Additionally, hydrogen is expected to have a greater leak rate than natural gas within the existing natural gas infrastructure due to the small size of hydrogen. The extra gas flow required to maintain the energy density of the original stream is likely a cost that will be forwarded to the customer. The customer may increase the gas flow (if possible) to maintain the same performance from their appliances, learn to live with decreased performance, or the utility may compensate for this further upstream. Costs that are forwarded to the end user may yield consumer pushback, or struggle to gain regulatory approval.

Hydrogen blending, using green hydrogen, has the potential to reduce CO_2 emissions in the Intermountain West and provide a transition fuel as the region shifts from fossil-energy sources. As the costs and technical barriers associated with blending remain unsettled, cooperation and transparency between producers and consumers will be required.

Conclusion

Presently, there is no hydrogen production in the Intermountain West, though some projects are under development. Hydrogen has tremendous potential to be a viable and affordable transition fuel as the region shifts from fossil-based energy sources to more sustainable options. A "first-pass" analysis was used to consider the possibilities of FCEV technology and hydrogen blending of natural gas as part of a place-based transition to sustainability within the region.

Replacing ICEVs with FCEVs presents a tremendous opportunity to decarbonize the transportation sector of the region. The literature was used to estimate that there are approximately 18.4 million registered ICEVs in the Intermountain West. These vehicles consume approximately 1361 PJ of fossil fuel annually while producing about 89 Mt CO_2 in tailpipe emissions alone. This accounts for roughly 73.8% of transportation CO_2 emissions in the region.

Cars and light trucks combine for over 90% of registered vehicles. Light trucks as a class consume the most fuel and emit the most CO_2 annually. After light trucks, medium-heavy duty trucks consume the most fuel and emit the most CO_2. This is interesting as cars make up 34.5% of the regional vehicle stock, while medium-heavy trucks comprise only 4.8%. The disparity between percentage of vehicle stock and CO_2 emitted suggests that targeting the medium-heavy vehicle class for transition to FCEVs is likely the transportation vector with the best decarbonization efficiency.

An average vehicle-specific CO_2 footprint was used to further settle on medium-heavy trucks (average of 26.2 t CO_2 yr^{-1} veh^{-1}) as the vehicle class to target for ICEV replacement with FCEVs to provide the most CO_2 mitigation efficacy.

Future work regarding FCEVs in the Intermountain West will require a much more granular look at vehicle data within the region to more clearly identify CO_2 emissions coming from other transportation sources while also evaluating risks from NO_x, particulate matter, SO_x and other pollutants with GWP. Additionally, the economic and policy conditions necessary to begin and accelerate adoption of FCEVs within the region will be evaluated to identify a realistic strategy and timeline for the technology to have a measurable climate impact.

Hydrogen blending into natural gas streams, at hydrogen blend fractions of $y_{H2} \leq 0.2$, appears to be viable based on research primarily performed by natural gas utilities outside of the region. However, the addition of hydrogen into a natural gas stream reduces the energy density of the mixture by a nontrivial percentage. To compensate, the end user will need to consume more of the gas mixture to maintain appliance performance than otherwise would have been necessary. While much remains uncertain, or even controversial, even fairly low hydrogen blend fractions can have a measurable reduction in natural gas combustion CO_2 emissions. Though transparency and cooperation will be required between all stakeholders if such a hydrogen transition is to be implemented.

Further work regarding hydrogen blending in natural gas streams will more clearly evaluate the integrity of the natural gas infrastructure within the Intermountain West as it was not designed for hydrogen blending. An in-depth exploration of all issues relating to cost is already in process, including considerations of non-CO_2 emissions (i.e., NO_x) as well as equity-related issues that may accompany shifting industrial technology or strategies.

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