I-WEST

Phase One Final Report | Detailed Chapter

Hydrogen Supply

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.

Authors

Prashant Sharan, Los Alamos National Laboratory
Manvendra Dubey, Los Alamos National Laboratory
Troy Semelsberger, Los Alamos National Laboratory
Michael Heidlage, Los Alamos National Laboratory
Rajinder Singh, Los Alamos National Laboratory

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Introduction

Currently, about 10 million tons of hydrogen (H_2) is produced in the U.S. annually, predominantly for use in industrial processes and fertilizer production. With water being the only product of its combustion, H_2 is a clean energy carrier and is expected to play a significant role in achieving carbon neutrality. Given the presence of large natural gas (NG) reserves in the Intermountain West, the region has potential to emerge as a leader in H_2 production for local use, as well as for export to other regions. While H_2 itself is a “clean” fuel, there are greenhouse gas emissions associated with certain types of hydrogen production; specifically, carbon dioxide (CO_2) released during steam methane reforming (SMR), and fugitive methane during the production of natural gas. Integrating carbon capture and sequestration (CCS) is a potential pathway to mitigate CO_2 emissions from the SMR process, and siting SMR process units near regional natural gas wells would mitigate methane emissions. Water electrolysis is rapidly emerging as a hydrogen production technology for CO_2-free hydrogen production via integration with renewable solar and wind power sources. It is anticipated that H_2 production from fossil fuels, as well as from water electrolysis, will be the two key pathways to meeting existing industrial needs and future transportation sector needs for H_2 over the next five years.

Methodology

In this report, we briefly discuss various H_2 production routes, namely SMR process with and without carbon capture, renewable-energy-driven H_2 production from natural gas, and water electrolysis. A detailed analysis of blue hydrogen was conducted to quantitatively determine its potential to reduce regional carbon emissions. Finally, a preliminary assessment of H_2 production in the Intermountain West region is presented.

Steam methane reforming

Steam methane reformation (SMR) is the industry standard for H_2 production. In current standard process schemes, CO_2 generated during the SMR process is emitted into the atmosphere—this is commonly referred to as “gray hydrogen.” Gray H_2 production is environmentally polluting and has a higher carbon footprint than direct methane burning. However, if the CO_2 generated during this type of H_2 production is captured and sequestered, then it’s referred to as “blue hydrogen.”

Figure 1(a) shows the schematic for gray H_2. The natural gas feed along with steam is heated to 700-900 °C, and flows into the steam methane reactor where the methane is reduced to synthesis (syn) gas:

$$CH_4 + H_2O = CO + 3H_2 \quad \text{Eq. (1)}$$

The syngas then flows into the water gas shift reactor where CO is reacted with steam to produce additional H_2:

$$CO + H_2O = CO_2 + H_2 \quad \text{Eq. (2)}$$

The shifted syngas mixture then flows into pressure swing adsorption (PSA) for H_2 purification generating >99% H_2. The natural gas is used as a fuel source for the SMR process. The overall reaction taking place can be written as:

$$CH_4 + 2H_2O = 2CO_2 + 4H_2 \quad \text{Eq. (3)}$$

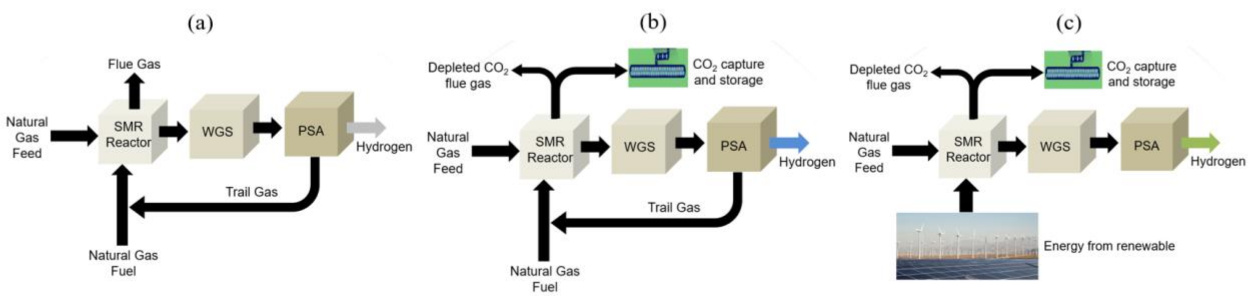

Figure 1: Schematic for different hydrogen production process schemes as a function of carbon capture and energy source: (a) gray hydrogen (b) blue hydrogen, and (c) turquoise hydrogen.

For gray H_2, the CO_2 is produced by the SMR process as well by the heating fuel. The CO_2 coming out from the SMR process is at high concentration and can be readily separated and captured. The H_2 produced by this process is blue hydrogen with SMR CO_2 capture.

Using natural gas as a fuel source is polluting; additionally, the chances of methane leakage always exist. Use of renewable energy as a fuel source can help in reducing the carbon footprint. In this study, we used solar photovoltaics (PV), wind energy, and concentrating solar thermal (CST) as a heat source for "turquoise hydrogen" production.

We have used a cradle-to-grave approach for life cycle assessment. The process involved in natural gas (NG) derived H_2 production includes NG extraction, NG processing and treatment to produce pipeline grade NG, NG transportation, H_2 production, CO_2 capture and sequestration and H_2 utilization. There are leakages associated with NG extraction, compression, transportation, and storage. Detailed analyses of

H_2 production from NG, including influence of several process parameters such as NG leak rate, process efficiency, and carbon capture rate, are provided in the Appendix.

Case study

We have considered the Intermountain West as a case study for decarbonizing regional energy sectors, including transportation and electricity generation.

Transportation

The two major contributors to the Intermountain West transportation sector are gasoline and diesel. Gasoline contributes 60.8%, diesel 30.9%, natural gas 5.3% and propane 0.023% of the net fuel energy in the region, with net energy content of ca. 408 TWh/yr (Figure 2(a)) [1]. The net CO_2 emissions is 101.2 million ton/yr, with gasoline contributing 58%, diesel 32% and natural gas 10%. For natural gas we have assumed 3.5% methane leakage for 100 years of lifetime.

Fuel production is a water-intensive process, with gasoline consuming 0.84 kg/kWh, diesel 0.98 kg/kWh, and natural gas 0.21 kg/kWh. Note, the natural-gas-specific water consumption is 70-80% lower as compared to gasoline and diesel. The net water consumption for fuel production is 283k acre-feet/yr (349.39 million ton/yr).

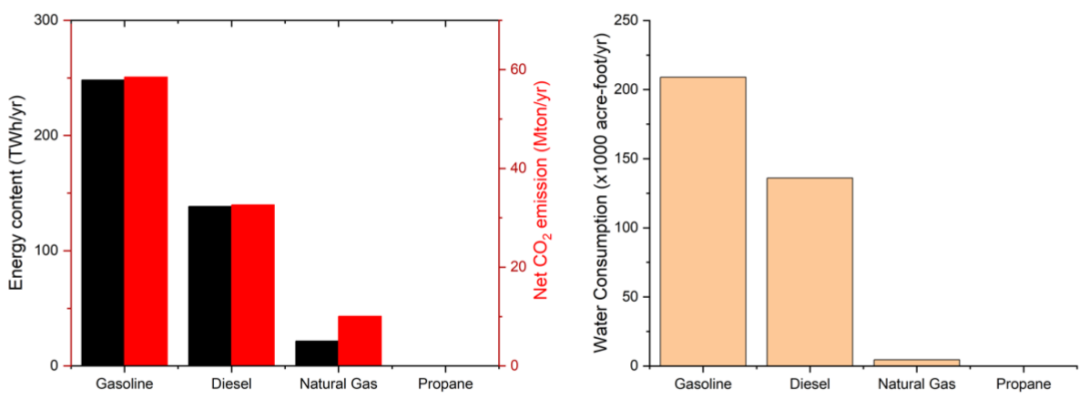

Figure 2: (a) Net energy content and CO_2 emission (b) net water usage for different hydrocarbon sources used for the transportation sector in the Intermountain West [1–3].

One pathway to reducing net CO_2 emissions in the transportation sector is with hydrogen fuel cells. The energy efficiency for an internal combustion engine using gasoline is 19%, diesel is 31%, and natural gas is 17% [4]; meanwhile, the H_2 fuel cell efficiency varies in the range of 40-60% [5]. Assuming an average efficiency of 50% for H_2 fuel cell vehicles, the net H_2 requirement to meet current transportation sector energy demand is 4.72 million ton/yr. The effects of transitioning from hydrocarbon fuel to hydrogen fuel cell are shown in Figure 3. In this calculation of replacing current transportation fuels with H_2, the following assumptions are applied: methane leakage of 3.5%, SMR energy consumption of 2.25 $kWh/m^3_{H2,STP}$, carbon capture efficiency of 85%, carbon capture energy requirement of 3000 J/g CO_2, and methane lifetime of 100 years and fuel cell efficiency of 50% [5] (Figure 3(a) and (b)). For the current regional scenario, replacing existing fuel sources with H_2 would reduce CO_2 emissions as follows: gray H_2, 19%; blue H_2, 55%, turquoise H_2, 67%, regional H_2, 82% and green H_2, 91%. In the cases of turquoise and renewable hydrogen, the electrolysis energy consumption of 50 kWh_e/kg_{H2} [6] was used in the calculations.

While applying turquoise and renewable hydrogen helps reduce the H_2 requirement significantly, it might be expensive due to the use of renewable energy. The other alternative is the use of regional blue H_2. Gray H_2 has the lowest water requirement (78k acre-foot/yr), as it requires water only for the SMR process and natural gas extraction. With blue H_2, the net water requirement increases threefold (210 acre-foot/yr) compared to gray H_2. This is due to high water requirements for carbon capture technologies. With turquoise H_2 the water requirement is 30% lower than blue H_2 and is maximum for regional blue H_2 (243k acre-foot/yr). Green H_2 has a net water requirement of 112k acre-foot/yr. In addition to the total water requirement, the water quality is also an important parameter. Electrolysis would require deionized water, while the SMR process would require potable-quality water. For mining and natural gas extraction we can use brackish water. (The water required for mining, natural gas extraction, and panel cooling are taken from [7–9]. Similarly, for cooling the system we can use produced water. This can help in significantly reducing the dependence on potable water sources; the net potable water required for blue H_2 is one-third of that for green H_2. Therefore, moving toward blue, turquoise, and regional blue H_2 with current state-of-art will help in reducing CO_2 emissions by 55-82%, with a marginal increase in potable water requirements.

The second scenario we have considered is an optimized SMR-H_2 production process with methane leakage decreased to 1% and improved energy efficiency of the SMR process unit operations. As discussed in the Appendix, the major contributor to NG fugitive methane emissions is compressor leakage. One way of reducing this is to place the compressor inside a box; the leaked NG can then be collected in the box and used as an energy source for compressor pumping. Similarly, significant efforts are being made to reduce the fugitive emissions with advanced NG storage design and pipeline materials selection. For the base case discussed above, we have assumed SMR energy consumption of 2.25 $kWh/m^3H_{2,\,STP}$. With advanced process design and process intensification, the SMR energy requirement can be brought down to 0.5 $kWh/m^3H_{2,STP}$ [10]. Similarly, with advancements in carbon capture technologies, the capture efficiency can be increased to 97%. Additional process energy efficiency improvements are anticipated as technology matures, including H_2 fuel cell efficiency increasing to 60% [5] and the SMR reactor energy consumption decreasing to 25 kWh_e/kgH_2 [6]. Using the assumptions made in the advanced SMR-H_2 process, transition to gray, blue, turquoise, and green

H_2 is calculated to further reduce the net CO_2 emission by 65%, 90%, 92%, 92% and 95%, respectively. Additionally, the net water requirement also improves (Figure 3(c) and (d)). Therefore, blue H_2 and regional blue H_2 could be critical in reducing net CO_2 emissions, provided technology advancements lead to reductions in methane leakage and SMR energy consumption.

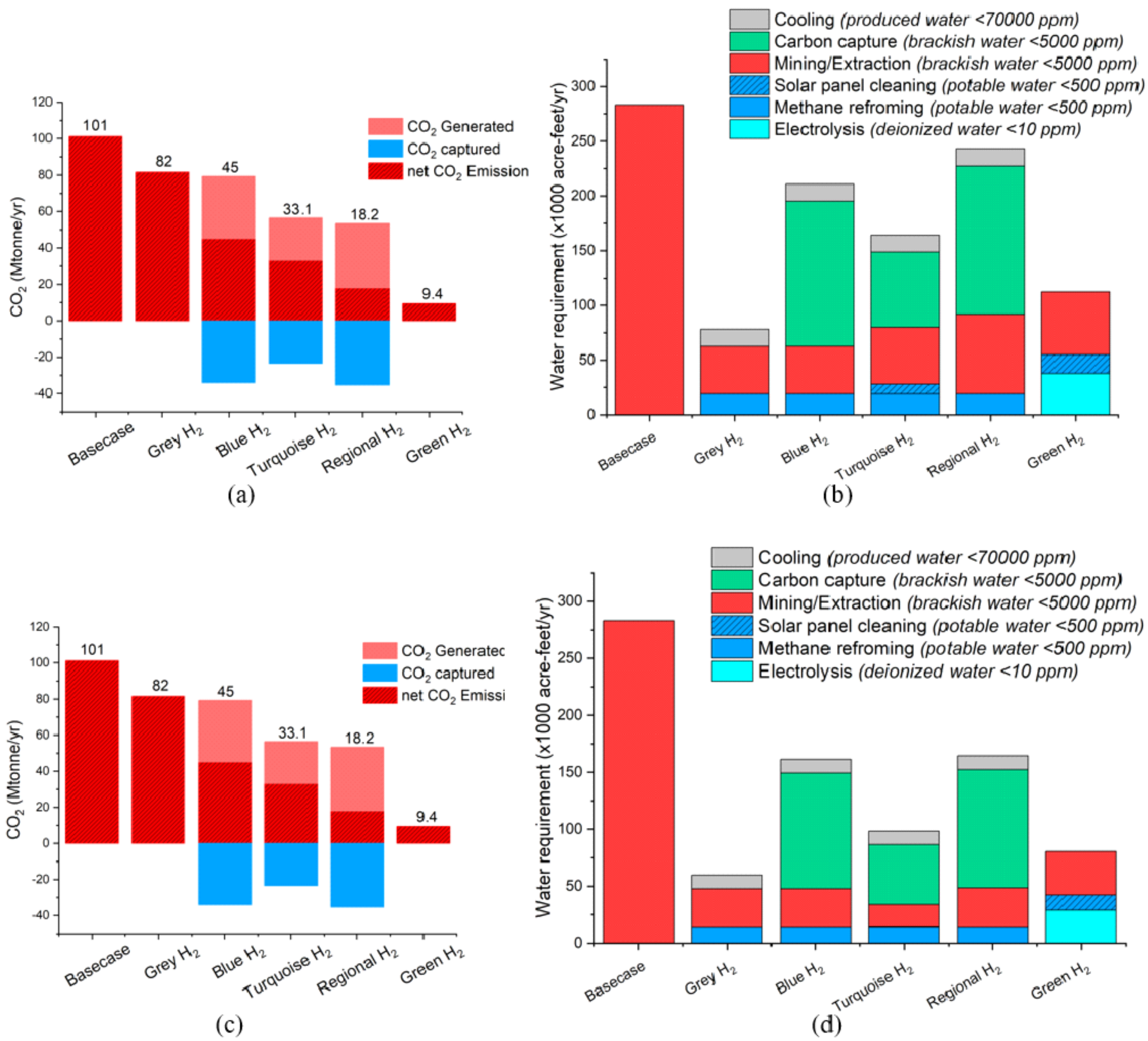

Figure 3: Role of blue, turquoise and regional H_2 in decarbonizing the transportation sector for the Intermountain West, and the impacts on the water footprint for (a, b) current scenario (methane leak 3.5%, energy 2.25 kWh/m^3, carbon capture efficiency and energy requirement of 85%, fuel cell efficiency of 50% and electrolysis energy requirement of 50 kWh$_e$/kg$_{H2}$), and (c, d) optimized SMR process (methane leak 1%, energy 0.5 kWh/m^3, carbon capture efficiency and energy requirement of 97%, fuel cell efficiency of 60% and electrolysis energy requirement of 25 kWh$_e$/kg$_{H2}$).

Electricity generation

Figure 4 (a) shows the net electricity profile for the Intermountain West, with an annual production of 307 TWh_e. Coal is the major contributor at 30.5%, natural gas power plants at 14.5%, natural gas combined cycle (NGCC) at 12.8%, wind energy at 11.1%, nuclear energy at 10.4%, hydro energy at 6.3%, solar energy at 4.4%, and a small contribution from petroleum, geothermal and biomass at 0.7% combined. The net annual CO_2 emissions from electricity production is 172 million tons/year. Due to the lower efficiency of coal power plants (33%), the net CO_2 emission is the highest at 67%. Natural gas power cycle contributes to 19.2%, while natural gas combined cycle contributes to 11.8% of the total CO_2 emissions.

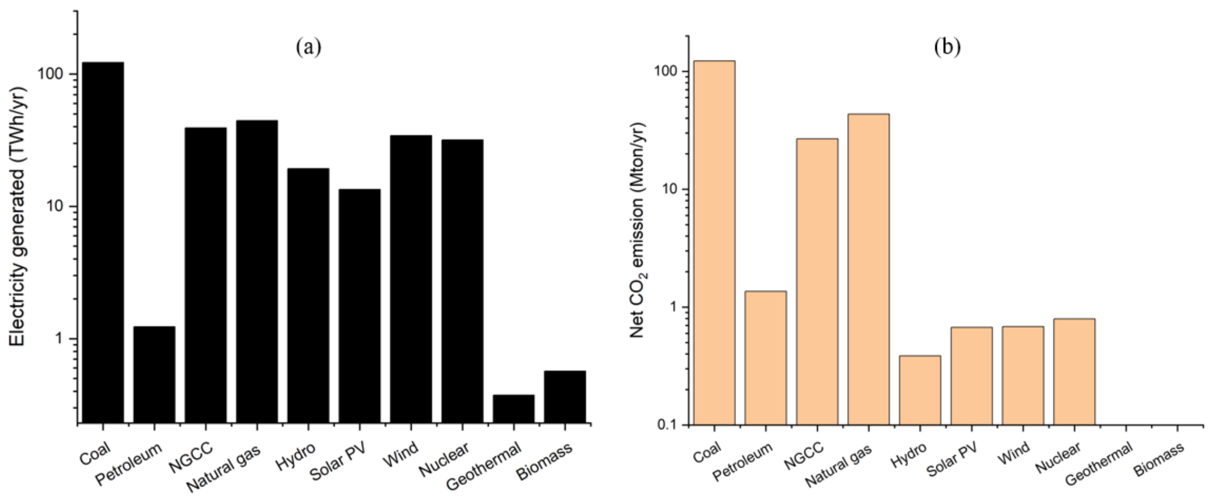

Figure 4: (a) Net electricity production (b) and net CO_2 emission for different energy sources in the Intermountain West.

Figure 5 (a) shows the possible approaches for reducing CO_2 emissions from electricity generation in the Intermountain West. The first possible approach considering the current scenario is replacing all coal power plants, natural gas power, and other hydrocarbon power with natural gas combined cycle (NGCC). Due to the higher energy efficiency of NGCC (60%), the net CO_2 emission can be reduced by 44% (with current average NG leakage of 3.5%), and by 52% (under only 1% methane leak). The other approach is blending the natural gas with 30% H_2 (by volume). Currently, NGCC operation is limited to 30% H_2, but with advanced turbine technology under development, it may be possible to operate with 100% H_2. By blending with 30% blue H_2, net CO_2 emissions reduce by 47%, while turquoise and regional blue H_2 blending results in a 50% reduction (for current scenario).

In the future, NGCC can be operated with 100% H_2, which will further help in reducing CO_2 emissions. Moreover, under a futuristic scenario, with reduced methane leakage and efficient SMR and carbon capture efficiency, the net CO_2 emissions could be reduced by 85%, 88.9% and 89.3% with blue, turquoise, and regional blue hydrogen, respectively.

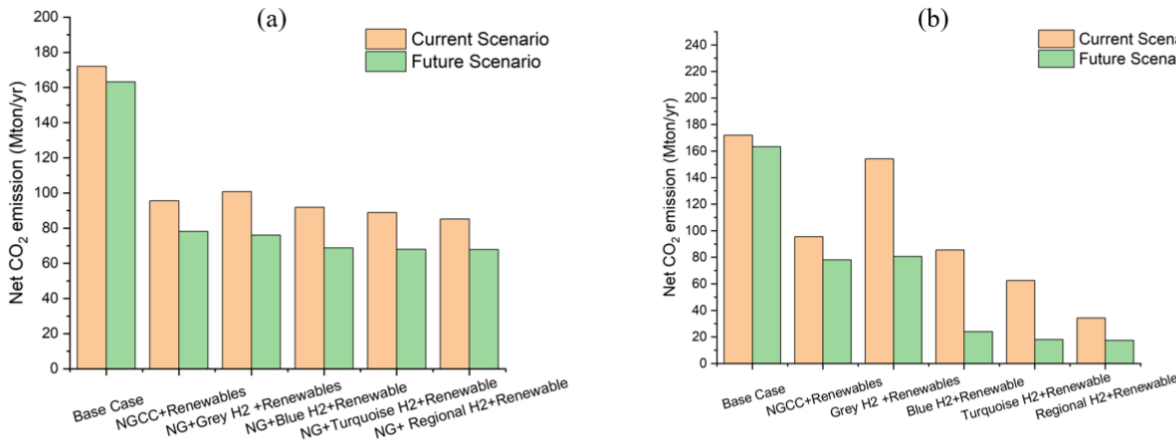

Figure 5: Role of blue, turquoise and regional H_2 in decarbonizing the electricity sector by blending, (a) 30% H_2 by volume and (b) 100% H_2 for NGCC operation. For current scenario (methane leak 3.5%, energy 2.25 kWh/m^3, and carbon capture efficiency of 85%), and future scenario (methane leak 1%, energy 0.5 kWh/m^3, and carbon capture efficiency of 97%).

Hydrogen as a replacement fuel for natural gas

Figure 6(a) shows the net NG production in the Intermountain West, which is about 5051 billion cu. feet/yr, [11]. New Mexico is the major contributor for NG production with 40% share, Colorado contributes 33%, followed by Wyoming 21%, Utah 5%, and Montana 1%. If all the NG produced annually is converted to H_2, the net gray H_2 will be 52 million ton/yr, net blue H_2 will be 22.5 million ton /yr, net turquoise H_2 will be 5.3 million ton /yr, and net regional H_2 will be 22.6 million ton/yr (Figure 6(b)). These calculations were carried out using a current SMR scenario of 3.5% methane leakage, 2.25 kWh/m^3 energy consumption, and carbon capture efficiency of 85%. However, for future scenarios (1% methane leak, 0.5 kWh/m^3 energy consumption and carbon capture efficiency of 97%) the net H_2 production from gray, blue, turquoise and regional H_2 will be 43, 41.3, 53.4 and 40.6 million ton /yr, respectively.

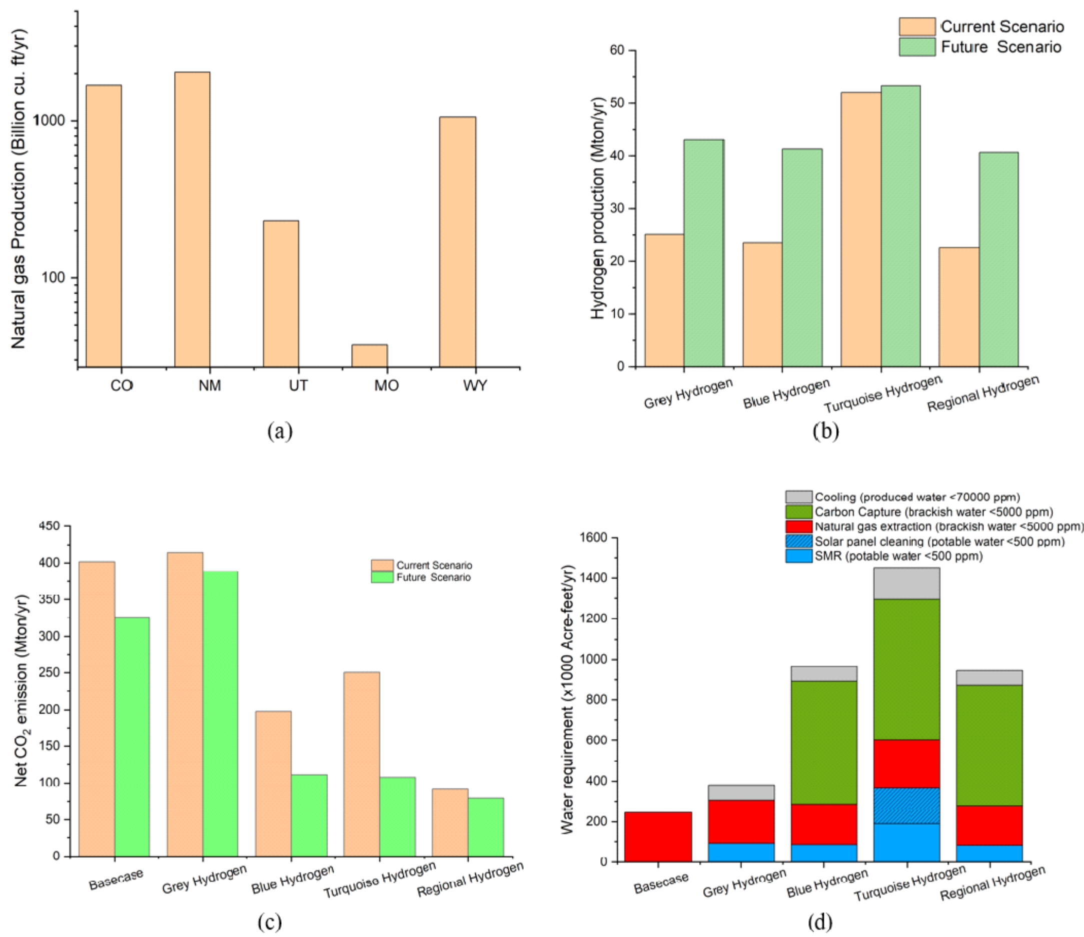

Figure 6: (a) Natural gas reserve and annual natural gas production, (b) potential hydrogen production by using annual natural gas production for current and future scenario, (c) effect on CO_2 emission while transitioning from natural gas to H_2 production for current and future scenario, and (d) net water demand to transition toward different H_2 production based on the current scenario.

Figure 6 (c, d) shows the net CO_2 generated and net water usage per year. For the base case of natural gas production with 3.5% methane leakage, the net CO_2 emissions are 401 million ton/yr. Transitioning toward gray H_2, the net CO_2 emissions increase by 3%, while blue, turquoise and regional H_2 can help reduce CO_2 emissions by 50%, 34% and 77%, respectively. Note, the net reduction in CO_2 emissions with turquoise H_2 is lower due to almost two times higher H_2 production compared to blue H_2. Figure 6 (d) shows the water demand for various scenarios, with a base case of 245k acre-feet. The net increase in total water demand compared to the base case is 55.7%, 293%, 493% and 285% for gray, blue, turquoise and regional H_2, respectively. The net increase in potable water demand is around 90k acre-feet for gray, blue and regional H_2, and 360k acre-feed for turquoise H_2.

Based on the transportation and electricity production analysis (with 30% blending with natural gas), an additional 6.4 million ton/yr of H_2 would need to be produced. This roughly translates to 1383 billion cu. ft/yr of natural gas, i.e., the current natural gas production from the Intermountain West needs to be increased by 27% to meet the increased blue H_2 demand for the electricity and transportation sectors. This would reduce net CO_2 emissions by 50%.

Conclusion

Hydrogen can play an important role in decarbonizing Intermountain West energy sectors. Numerous studies have been presented in literature comparing different types of H_2 production. Our study aimed to identify the key components contributing to the carbon footprint of H_2 production processes. While methane leakage is one of the most dominating factors, and could limit regional transition to H_2-based energy economies, the other key component is the specific energy usages for H_2 production. With optimal energy integration and system design, the net energy consumption can be brought down to 0.5 kWh/m^3 (compared to 2.25 kWh/m^3 prevalent today). This would reduce net CO_2 emissions by 50%.

To show the applicability of H_2 in decarbonizing the energy sector, we considered replacing the transportation and electricity generation sectors with H_2 in the Intermountain West. We considered two scenarios: in the first, we assumed the existing trend, whereas in the second, we considered a more optimistic outlook. The Intermountain West contributes 101.2 million ton/yr of CO_2 and requires 283k acre-foot/yr of water. For the current scenario (3.5% leak and 2.25 kWh/m^3 energy requirement) the use of regional blue H_2 can reduce the CO_2 emissions by 55%, while in the future scenario (1% leak and 0.5 kWh/m^3), CO_2 emissions can be reduced by 90%. The net electricity generated in the region is 307 TWh_e/yr, which contributes to 182.9 million ton/yr of CO_2 per year and requires 1157k acre-foot/yr of water. Replacing all hydrocarbon power thermal power plants with NGCC can help reduce CO_2 emissions by 56%. For the current scenario (30% hydrogen blending with NG for NGCC power production process), use of regional H_2 can reduce the net CO_2 emissions by 65%, and in the future scenario (100% hydrogen), could result in 96% reduction in CO_2 emissions. Replacing the regional transportation sector and blending NGCC with 30% blue H_2 can reduce the CO_2 emissions by 50%. However, this needs an additional 27% increase in NG production.

Hydrogen production is a water-intensive process, especially considering potable water use. However, impaired water sources, including produced water (water produced during oil and gas extraction) and brackish water, can be treated and used in H_2 production. Future I-WEST assessments should include a detailed life cycle analysis and development adoption curve for the H_2 production technologies discussed in this report. Additionally, otherH_2 production processes, including autothermal reforming, partial oxidation, biomass reforming, and electrolysis should be assessed in detail, along with industry-standard SMR processes.

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Appendix

In this study, we used a cradle-to-gate approach for life cycle assessment, with the following assumptions:

- Methane leakage base case: 3.5%[12]
- SMR energy requirement base case: 2.25 kWh_{th}/m^3 [12]
- CO_2 capture efficiency base case: 85% [12]
- Concentrating solar power CO_2 emission: 10 g/kWh_{th}[13]
- CH_4 global warming potential is 28 for 100 years and 84 for 20 years lifetime.
- NG consist of 100% CH_4.
- Calculation done for producing 1 MJ_{th} energy from hydrogen.

Figure A1 shows the net CO_2 emission breakdown for different H_2 production technologies. For a 20-year lifetime, methane leakage is the major contributor for net CO_2 emissions (45% for gray H_2, 65% for blue H_2, 58% for turquoise H_2 and 42% for direct methane burning). Due to the high contribution of methane leakage, the improvement in going from gray to blue H_2 is only 25%, and the net emission for blue H_2 and direct methane burning is the same. For blue H_2, SMR contributes to 40% of total emissions, fuel is 33%, carbon capture 11% and natural gas extraction process is 14%.

For a 100-year lifetime, the methane leak contribution to net CO_2 emissions significantly reduces (21% for gray H_2, 40% for blue H_2, 50% for turquoise H_2 and 25% for direct methane burning). In addition, blue H_2 reduces the net CO_2 emissions by 50% and 30% compared to gray H_2 and direct methane burning. Using renewable as an energy source (Turquoise hydrogen) helps reduce CO_2 emissions by 60% to direct methane burning, and by 30% compared to blue H_2 (>60% reduction in net CO_2 emissions). The other benefit of turquoise H_2 is up to 50% reduction in carbon capture compared to blue H_2.

Major contributors to net CO_2 emissions are methane leakage and fuel energy requirements. Here, we have studied the sensitivity of important parameters affecting the H_2 carbon footprint.

Methane leakage

Methane leakage is a function of extraction, compression, transportation, and storage [14–16]. Different values for methane leakage have been reported in literature. Here we have varied the methane leakage from 0-5%. For a 20-year lifetime, the methane leakage needs to lower than 3.5% for blue H_2 to be environmentally friendly compared to direct methane burning. For a 100-year lifetime, the blue H_2 gives superior performance to direct methane burning and is 28% lower than direct during of methane even at 5% methane leakage. Reducing the methane leakage from 3.5% to 1%, reduces the net CO_2 emissions for blue H_2 by 55% and 36% for 20-year and 100-year lifetimes, respectively (Figure A2 (a) and (b)). Therefore, the focus should be to minimize the methane leakage, especially for shorter methane lifetimes, as the penalty due to methane leak can be severe.

However, turquoise H_2 needs methane only for SMR, while direct methane burning needs methane as fuel; therefore, the improvement in net CO_2 emissions with turquoise H_2 remains constant at 50% and 63% as a function of methane leakage for a lifetime of 20 years and 100 years (Figure A2 (a) and (b)).

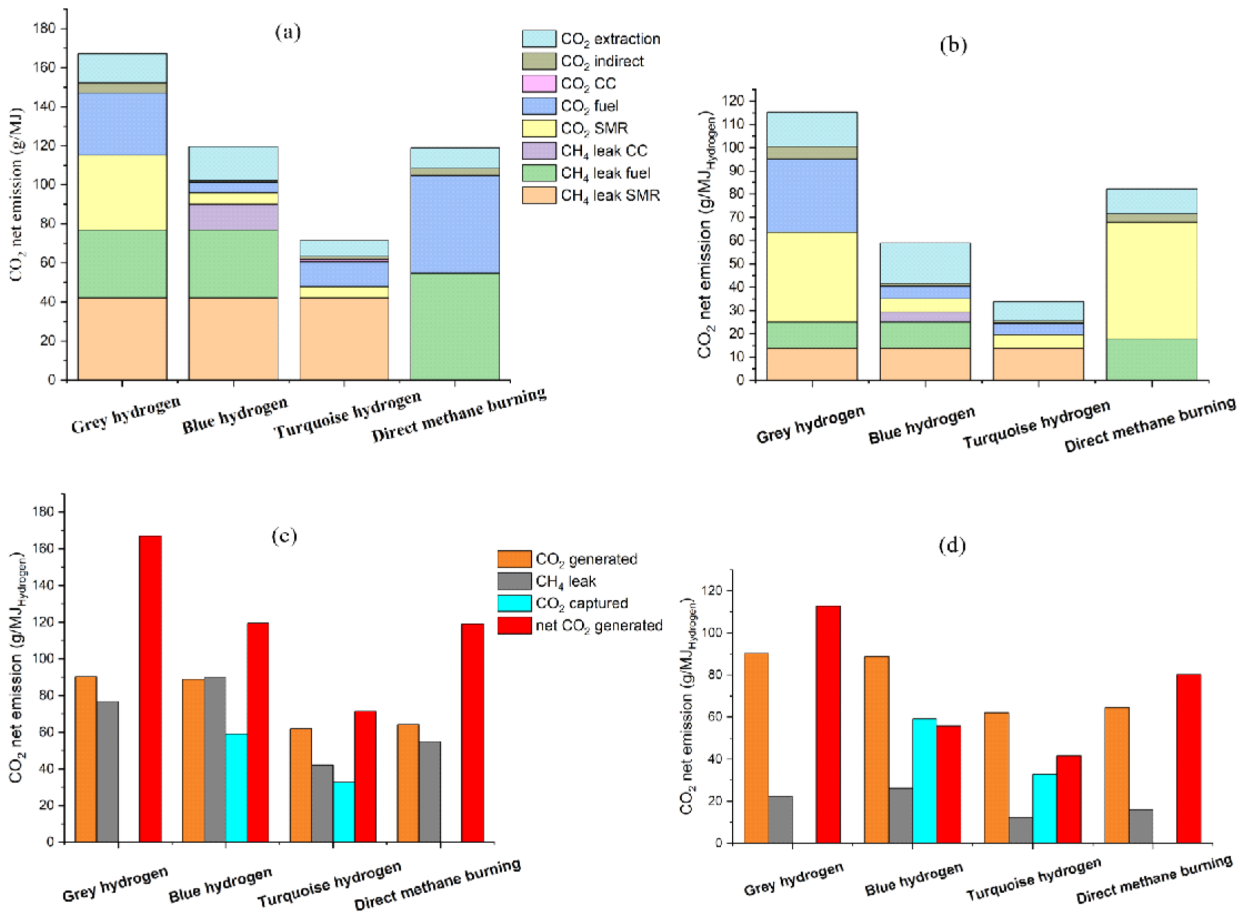

Figure A1: CO_2 net emission source breakdown as a function of methane lifetime (a) 20 years (b) 100 years. Plot of carbon emission and captured as a function of methane lifetime (c) 20 years and (d) 100 years. Methane leakage is fixed at 3.5%, SMR energy consumption of 2.25 kWh/m^3, carbon capture efficiency and energy consumption 85%.

SMR energy consumption

Steam methane reforming is an energy-intensive process with energy consumption of 2.25 kWh/m$^3_{H2,STP}$[12]. Stoichiometric ratio of steam and methane is 2; however, to improve the reaction kinetics and conversion ratio, often the steam to methane ratio is varied between 3-4. This increases the heat requirement for the SMR process. Therefore, improving the energy efficiency of the system heat integration becomes essential, especially for feed pre-heating. The heat released from water gas shift reaction (exothermic reaction) and cooling of gas streams before it enters the PSA can also be used as a heat source for feed preheating. With optimal system design and process integration the SMR energy requirement can be brought down to 0.5 kWh/m$^3_{H2,STP}$ [10].

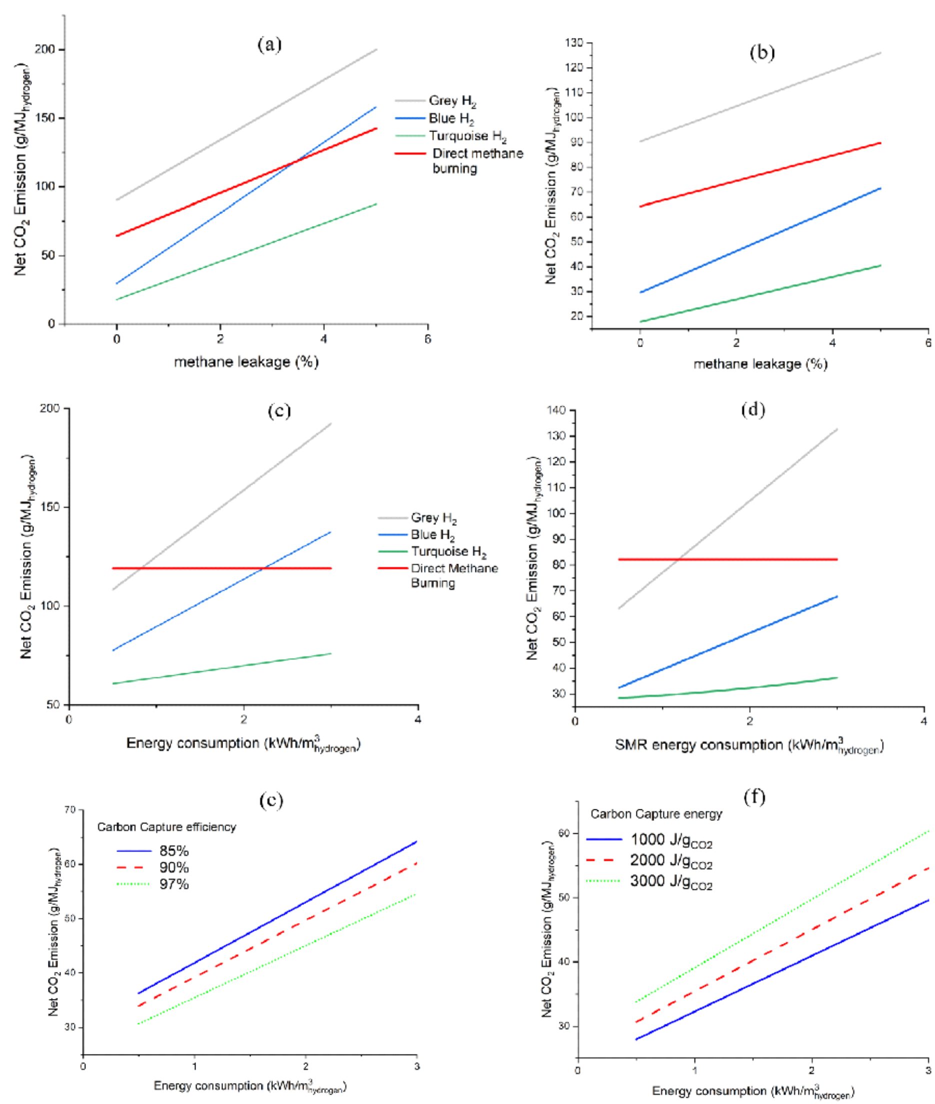

Figure A2: Net CO_2 emissions as a function of methane leakage for a lifetime of (a) 20 years (b) 100 years, while the SMR energy requirement, carbon capture efficiency and energy requirement are

kept constant at 2.25 kWh/m^3, 85% and 2000 J/g$_{CO2}$. Net CO_2 emission as a function of SMR energy requirement for a lifetime of (c) 20 years (d) 100 years, while the methane leakage, carbon capture efficiency and energy requirement are kept constant at 3.5%, 85% and 2000 J/g$_{CO2}$. Net CO_2 emission as a function of SMR energy requirement and (e) carbon capture efficiency (f) carbon capture energy requirement, while the methane leakage, carbon capture energy requirement (e) and efficiency (f) are kept constant at 3.5%, 2000 J/g$_{CO2}$ and 85%.

Reducing the SMR energy consumption from 2.25 to 0.5 kWh/m$^3_{H2,STP}$ can reduce the net CO_2 emission by 50% for blue H_2. Additionally, lower energy consumption of 0.5 kWh/m$^3_{H2,STP}$ lowers the net CO_2 emission by up to 50% compared to direct methane burning. While with turquoise H_2, reducing the SMR energy consumption from 2.25 to 0.5 kWh/m$^3_{H2,STP}$ gives a marginal improvement of 15% (Figure A2 (c) and (d)).

Carbon capture efficiency and energy consumption

Carbon capture efficiency and energy requirement can be critical in the advancement of the blue H_2 technology and is shown in Figure A2 (e) and (f). Recently, the Department of Energy issued a funding opportunity announcement that focused on increasing the carbon capture efficiency from 85% to 97%. This would result in a marginal improvement of 16%, similarly reducing the carbon capture energy consumption from 3000 J/g$_{CO2}$ to 1000 J/g$_{CO2}$ reduces the net CO_2 emission by 15%.

Based on a sensitivity analysis, it can be concluded that methane leakage and SMR energy consumption are major contributors to net CO_2 emission.

Use of various renewable energy sources as fuel for hydrogen

For turquoise H_2, different renewable energy sources can be used as a heat source, including solar photovoltaics (PV), wind energy, and concentrating solar thermal (CST). The renewable energy source is an intermittent source of energy and has a low annual capacity factor. Where capacity factor is defined as the ratio of actual annual generation to the amount generated had the plant operated at its nameplate capacity for the entire year [16]. Lower capacity factor will reduce the operation hour of the plant. To meet the SMR annual demand, energy storage for renewable energy is required. Since solar PV and wind produce electricity, we have used battery energy storage. Concentrating solar power typically uses molten storage tanks to increase its capacity factor to 60%. The remaining heat can be supplied by blue H_2.

Figure A3 shows the comparison between different energy sources for turquoise H_2 compared to blue H_2. It is interesting to note for turquoise H_2 powered by solar PV, the net CO_2 emissions are greater than blue H_2. This is due to lower capacity factor for solar PV systems, and use of battery storage for the remainder. Batteries for energy storage have a high carbon footprint and have an efficiency of 80%, which further increases the net input electricity required. The overall effect is a higher carbon footprint of turquoise H_2 compared to blue H_2. Since wind energy has lower carbon footprint than solar PV and higher capacity factor, using wind energy helps in reducing the CO_2 emission by 10-20% compared to blue H_2. CST has the lowest carbon footprint and use of thermal energy storage increases the net capacity factor. This results in significant improvement in the system performance compared to blue H_2 and can help in reducing the net CO_2 emission by 50%.

Table A1: Operating parameters for various renewable energy sources [13,17,18]

	Capacity factor	Emission (g/kWh)
Wind	50%	20
Solar photovoltaics	27%	50
Concentrating solar thermal	65%	10
Battery efficiency/emission	85%	100

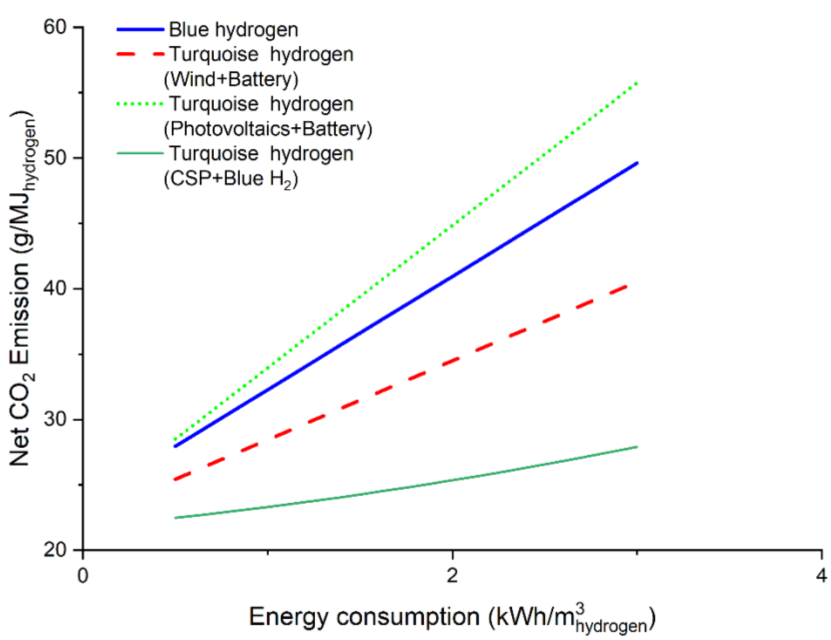

Figure A3: Comparison between the performance of blue H_2 and turquoise H_2 powered with different renewable energy sources, including solar photovoltaics, wind energy, and concentrating solar thermal. Methane leak and carbon capture efficiency and energy requirements are kept constant at 3.5% and 85% for a 100-year methane lifetime.

Regional Hydrogen

Figure A4 shows the breakdown for methane leakage. The major contributor is the gas compressor, where the gas leaks through the rod packing case for the reciprocating compressor and from wet seals for the centrifugal compressor. The methane needs to pressurize to 1000 psi for interstate transfer. Storage and pipeline methane leakage accounts for 27% of the methane leakage, which can be caused by gas diffusing out, value and pipe leakage. Drilling and extraction contribute to 28% emissions, which can be due to flaring of gases and does not meet the required standard and leakage from the pipelines [14,15].

Instead of compressing the methane and transporting it for H_2 production from SMR, the H_2 can be produced regionally by co-locating the SMR process close to the methane gas extraction location. It will also provide an easy opportunity for CO_2 sequestration. However, the energy density of H_2 is around 3 times lower compared to methane (11.5 $MJ_{H2,STP}/m^3$ and 35.5 $MJ_{CH4,STP}/m^3$). This increases the parasitic pumping energy requirement from 4% for methane to 15% for H_2. Additionally, with the H_2 being a much lighter fluid compared to methane, it will have higher leakage (in range of 1.5-3 times higher compared to methane). In this analysis, we assumed the H_2 leak rate to be 2.5 times that of methane. Also, H_2 has a global warming potential of 19 and 5 for 20-year and 100-year lifetimes [19].

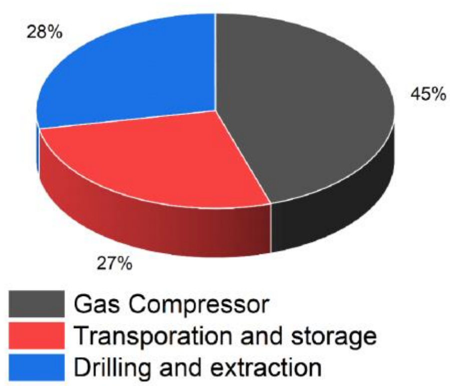

Figure A4: Methane leakage breakdown [14,15].

As shown in Figure A5, with regional H_2 production the net CO_2 emission from blue H_2 is 60% lower compared to direct methane burning. For a methane lifetime of 20 years, and for methane leakage >3.5%, even regional gray H_2 gives superior performance compared to direct methane burning. Therefore, co-locating the methane extraction process with the SMR process can significantly reduce CO_2 emissions. Turquoise H_2 can reduce net CO_2 emissions by 80% compared to direct methane burning.

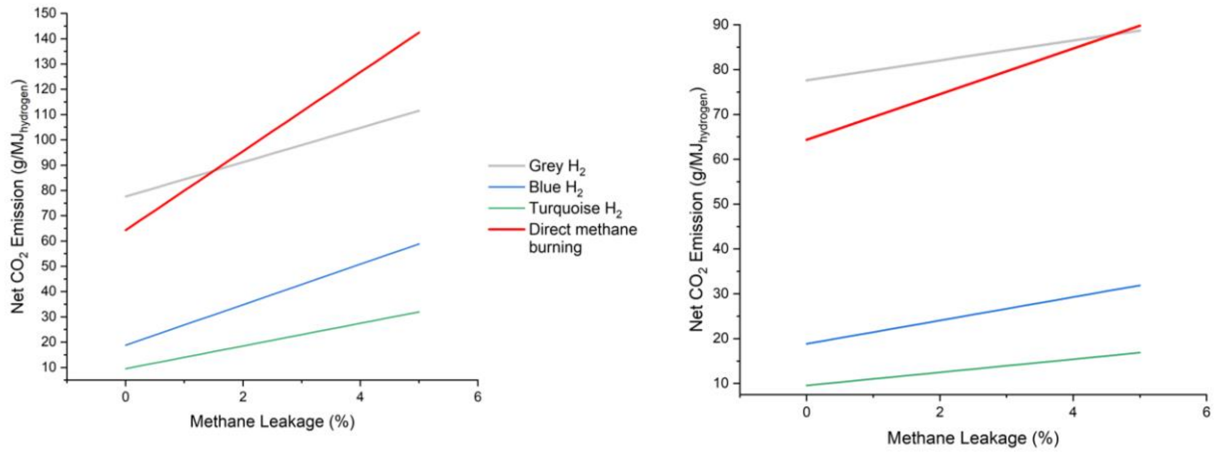

Figure A5: Net CO_2 emissions for regional H_2 as a function of methane leakage for a methane lifetime of (a) 20 years and (b) 100 years, while the SMR energy requirement, carbon capture efficiency and energy requirement are kept constant at 2.25 kWh/m^3, and 85%.