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Modeling hydrogen markets: Energy system model development status and decarbonization scenario results

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A R T I C L E I N F O

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A B S T R A C T

Hydrogen can be used as an energy carrier and chemical feedstock to reduce greenhouse gas emissions, especially in difficult-to-decarbonize markets such as medium- and heavy-duty vehicles, aviation and maritime, iron and steel, and the production of fuels and chemicals. Significant literature has been accumulated on engineering-based assessments of various hydrogen technologies, and real-world projects are validating technology performance at larger scales and for low-carbon supply chains. While energy system models continue to be updated to track this progress, many are currently limited in their representation of hydrogen, and as a group they tend to generate highly variable results under decarbonization constraints. The present work provides insights into the development status and decarbonization scenario results of 15 energy system models participating in study 37 of the Stanford Energy Modeling Forum (EMF37), focusing on the U.S. energy system. The models and scenario results vary widely in multiple respects: hydrogen technology representation, scope and type of hydrogen end-use markets, relative optimism of hydrogen technology input assumptions, and market uptake results reported for 2050 under various decarbonization assumptions. Most models report hydrogen market uptake increasing with decarbonization constraints, though some models report high carbon prices being required to achieve these increases and some find hydrogen does not compete well when assuming optimistic assumptions for all advanced decarbonization technologies. Across various scenarios, hydrogen market success tends to have an inverse relationship to success with direct air capture (DAC) and carbon capture and storage (CCS) technologies. While most model-scenario combinations predict modest hydrogen uptake by 2050 – <10 million metric tons (MMT) – aggregating the top 10 % of market uptake results across sectors suggests an upper range demand potential of 42–223 MMT. The high degree of variability across both modeling methods and market uptake results suggests that increased harmonization of both input assumptions and subsector competition scope would lead to more consistent results across energy system models. The wide variability in results indicates strongly divergent conclusions on the role of hydrogen in a decarbonized energy future.

1. Introduction and overview

While responses to climate change have been strengthened at local, national, and international levels, progress must accelerate significantly to achieve the systemic change required to meet climate change goals [1]. Hydrogen has been proposed as a means of fundamentally transforming several carbon-intensive markets. Similar to electricity, hydrogen is an energy carrier that can be produced from any primary energy resource and delivered to a wide range of end-use technologies. Traditional markets today are served by hydrogen produced from natural gas. Clean or low-carbon hydrogen is generally produced from renewables, nuclear, or fossil energy with CCS (carbon capture and

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storage). New emerging end-use markets include use as a fuel for fuel cell electric vehicles, in turbines or stationary fuel cells for power generation, to generate heat in industry and buildings, and as a chemical feedstock in the production of iron and steel, sustainable aviation and marine fuels, synfuels, syngas, ammonia, methanol, and other industrial chemicals. Advantageous and complementary characteristics of hydrogen compared to fossil fuels and electricity include high end-use efficiencies in fuel cells, high gravimetric densities for transportation applications, increased supply flexibility and resilience when associated with long-duration storage, and relatively inexpensive delivery and storage costs when delivered over long distances and at high volumes [2–7]. Market development challenges include achieving economies of scale, continued progress with R&D and real-world commercialization projects, financing large CAPEX projects, catalyzing end-use demand, and improvements in harmonization, certification, and standardization [8–10].

Interest in hydrogen has a long history, with enthusiasm fluctuating both before and since the 1973–74 energy crisis. Historical highlights include Sir William Gove developing the first fuel cell in 1842, J.B.S. Haldane proposing wind-based liquid hydrogen pumped via pipeline to cities in England in 1923, the first practical fuel cell demonstrated by Francis T. Bacon in 1959, and the Apollo 11 moon mission in 1969 [11]. Additional waves of both enthusiasm and hype have occurred since the 1990s, especially in response to continued progress with fuel cell technology [12–15]. Current interest and global support for hydrogen are widely recognized as a significant departure from these previous waves, primarily catalyzed by increased urgency to address climate change and strong reductions in the cost of renewable energy [16]. By February 2024, 56 countries had published national hydrogen strategy or roadmap reports [17]. Global decarbonization scenarios from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) estimate hydrogen and hydrogen-based fuels comprising 8 % and 14 % of global final energy by 2050, respectively [10,18]. As of December 2023, the global hydrogen project pipeline included 1400 projects summing to $570 billion in investment, with 45 MMT of clean hydrogen production capacity announced through 2030. Of all announced projects, 7 % had passed final investment decision (FID), including 12 GW of electrolysis capacity [19]. These trends represent unprecedented increases in both national support and commercialization progress over the past 3–5 years.

Demand for hydrogen occurs in traditional and emerging markets. IEA reports major traditional uses, including petroleum refining, ammonia, methanol, and iron and steel production, reaching 95 MMT globally in 2022. Smaller traditional markets, including electronics, glassmaking, and metal processing, sum to about 1 MMT. Success in new emerging markets is expected to expand under decarbonization market conditions. Just over 1000 hydrogen refueling stations (HRS) support about 80,000 fuel cell electric vehicles (FCEVs) globally, 63,000 of which are cars and vans. Korea and Japan make up about 50 % of these vehicles, with the US, China and EU comprising the balance. The installed capacity of stationary fuel cells in buildings comprised 1.2 GW in 2022, while announced projects for hydrogen (or clean-hydrogen-derived ammonia) use in electricity generation sum to 5.8 GW by 2030. Announced off-take agreements for low-emission hydrogen, across a variety of end-uses, could sum to over 2 MMT H2 by 2030 [8].

The U.S. produces about 10 MMT of hydrogen annually, primarily through natural gas steam methane reforming (SMR). Refining is 55 % of this demand, and ammonia and methanol production another 35 %. Additional hydrogen infrastructure and end-uses include 1600 miles of dedicated hydrogen pipeline, three geological storage caverns, approximately 4.5 GW of electrolyzer capacity, 0.5 GW of backup power, 69,000 fuel cell forklifts, 380 fuel cell buses, and 18,000 fuel cell cars [20]. Support provided by recent legislation in the U.S. is expected to significantly accelerate use of hydrogen in both traditional and emerging markets. Most notable are the 45 V hydrogen production tax credit from the Inflation Reduction Act (IRA), with up to $3/kg for very low-carbon hydrogen production facilities, and $8 billion in Hydrogen Hub funding from the Bipartisan Infrastructure Law (BIL). As of October 2023, there were 164 U.S. hydrogen production projects in the IEA Global Database, summing to a total production capacity of 16 MMT. Of this total capacity, 0.7 % was in FID/Construction status and 0.1 % was operational, while 60 % was in concept status and 34 % in feasibility status. Electrolysis projects comprised 62 % of the total capacity, and fossil with CCUS (carbon capture utilization and storage) 38 % ([8]; DOE 2023; 2024). Based on information from early hydrogen hub award selections [21], some 25 MMT CO_2e are expected to be reduced across a wide range of end-uses, including power, industry, and transportation. While some EMF37 models did include incentives and programs authorized by IRA and BIL, government guidelines on 45 V had not yet been published when the EMF37 scenario modeling was performed.

1.1. Hydrogen in energy system models

Hydrogen technologies pose unique challenges for energy modeling because they are diverse in type, interact with multiple other technologies, and involve supply chains crossing multiple sectors. A strength of energy systems models is determining which technologies can be deployed most economically to reduce greenhouse gas (GHG) emissions. Energy system models are uniquely suited for some hydrogen modeling challenges, including consistent and interconnected representation of multiple sectors, endogenous technology learning, representation of policy mechanisms, complexities associated with consumer and/or investor behavior, and competition among multiple technologies and energy types. Representations of early technology learning can be particularly powerful analytically when implemented endogenously, with cost and performance metrics increasing with experience and in response to policy mechanisms or business strategies, such as subsidies, incentives, or financing [22]. Several hydrogen system and market modeling challenges are difficult to capture in energy system models, including temporal and spatial detail, interactions with the electricity grid, accurate depictions of lifecycle metrics, and explicit representation of supply chain dynamics for individual hydrogen pathways [23,24]. These more granular, technology-focused challenges have been addressed through a wide range of detailed techno-economic and market potential studies. Hydrogen production costs have been examined in multiple studies [25–29], supply chain components and optimization methods have been examined extensively and simulated with granular geographic detail [30–33], cross-sector interactions have been optimized for a range of economic conditions [34], long-duration hydrogen storage has been compared to other grid storage options [35–37], and lifecycle models have been used to estimate GHGs across the hydrogen supply chain and for scope 1, 2, and 3 emissions [38–42]. In the U.S., the 45 V version of the Argonne National Laboratory GREET model is being relied upon to determine hydrogen production carbon intensities for the 45 V Hydrogen Production Tax Credit [43].

Most high-profile reports estimating strong future hydrogen market growth have tended to rely on relatively simple scenario development tools and decarbonization targets rather than detailed techno-economic or energy system market simulation models. This article draws on two classes of energy system models, namely bottom-up (BU) and top-down (TD) models, which differ in several key aspects [44,45]. BU models usually describe the energy sector in detail with a comprehensive list of different forms of energy, as well as different (energy) production and demand technologies. In addition to current technologies, they model a variety of alternative technologies that can provide the same energy services more efficiently and/or in a cleaner way. Technologies are explicitly represented by their economic and technical characteristics. BU models account for all energy flows within the energy sector (in physical units), but the demand for energy services (e.g., passenger-km, lumens) is usually provided exogenously. Additionally, BU optimization models can determine an optimal energy sector configuration to satisfy useful energy demand at minimal cost, while meeting constraints such as GHG reduction targets. However, BU models do not provide a complete picture of the entire macro-economy, and they tend to be rather optimistic regarding technology diffusion. Some “hybrid” models include both BU ant TD model characteristics, as discussed by Hourcade et al. [46].

In TD models, a broader equilibrium framework is relied upon to calculate the supply and demand of goods and services in major economic sectors. They capture more interactions between the energy sector and other economic sectors, but generally do not explicitly represent the techno-economic details of energy technologies. Energy consumption is instead determined as the result of an economic equilibrium. Also, they do not consider physical units of energy flows, but rather monetary units. TD models are designed to estimate market reactions to price changes. In particular, they model the relationships between energy prices and energy demand, also considering the impacts on other economic sectors. They generally assume that the interactions between energy and the economy will be the same in the future as in the past, by assuming fixed elasticities of substitution. As such, they tend to be more pessimistic about the diffusion of emerging energy technologies. Attributes of the models discussed here are indicated in Appendix Table A1.

The present work builds upon previous studies of efforts to integrate hydrogen into energy system models. Quarton et al. [47] contend that energy system models have become more complex over time, and that hydrogen abatement options have emerged more strongly as a result. Based upon a review of modeling methods, their general recommendations for improvement include: knowing the limits of models, including appropriate sectors and technologies, having appropriate levels of ambition, and using realistic input data that are subsequently reported in a transparent manner. The need for spatio-temporal detail is also noted as necessary for a more realistic representation of renewable energy systems, which became a stronger focus, along with decarbonization, for energy model development after the 2000s [48]. In examining the role of hydrogen in decarbonization scenarios from both global and national energy models, Hanley et al. [49] found that deeper levels of decarbonization were achieved with inclusion of hydrogen as a technology option, and many scenarios trended towards higher hydrogen market uptake at higher carbon prices ($/tCO2e). Bioenergy and electrification were identified as both competitors and drivers for hydrogen, given that they can serve as either substitutes for hydrogen or sources of hydrogen demand. In another survey of energy system models, Sub-task C of the IEA Hydrogen Technology Collaboration Programme [50] compared hydrogen representations in 10 TIMES models. Of these, one model included hydrogen use in aviation, one included hydrogen use in shipping, three included hydrogen use in rail, and nine included hydrogen use in road transport. Similar variability was also found in the treatment of pressure and purity requirements, the detail and variety of delivery modes, and the diversity of types and capital cost of production technologies.

A taxonomy of hydrogen models developed by Blanco et al. [23] identified nine model archetypes that capture specific hydrogen characteristics.[j] No single model archetype accurately captures all of the attributes and benefits of hydrogen systems. The authors acknowledge that energy system models typically require simplified representations of some characteristics that are best captured by models with a high level of spatial and temporal detail, such as spatial supply chain optimization models or power sector models. Soft-linking between model types is proposed as one approach to overcoming modeling shortcomings. The study identified several challenges for improving hydrogen representations in energy system models: inclusion of learning, uncertainty and innovation, more detailed technology representations, additional market applications, cross-sector dynamics, consumer behavior for vehicle purchases, geographic constraints on hydrogen production, inclusion of secondary products produced from hydrogen (e.g., ammonia), more realistic rates of return on investment, and internalization of external costs. Blanco et al. also emphasize that hydrogen is a relatively new addition for many energy system models, and that diverse modeling methods must be relied upon to properly assess hydrogen markets in a low-carbon future. Moreover, they observe that most modeling efforts emphasize technology and costs, while environmental impacts, technology innovation, consumer acceptance, and market design and policy receive less emphasis.

Table 1
EMF37 scenario names and assumptions.

Scenario Name & Notation		Technology and Policy Assumptions			
Reference Scenarios					
Reference	NT.Ref	No new climate policy after 2022			
Net Zero	0by50.Ref	Reference (All)			
Net Zero +	0by50.Adv	Advanced (All)			
Carbon Management (CMSG)		**CCS**	**H2 Prod**	**DAC**	
CMSG +	CMSG.Adv	Adv	Adv	Adv	
CMSG NoCCS	CMSG1	None	Ref	None	
CMSG AdvCCS	CMSG2	Adv	Ref	Ref	
CMSG AdvH2	CMSG3	Ref	Adv	Ref	
CMSG AdvDAC	CMSG4	Ref	Ref	Adv	
CMSG NoDAC	CMSG6	Ref	Ref	None	
CMSG NoH2	CMSG7	Ref	No New	Ref	
Transportation (TSG)		**Tech**	**Policy**	**Pref**	
TSG +	TSG.Adv	Adv	Adv	Adv	
TSG Tech	TSG.1	Adv	Ref	Ref	
TSG Tech/Pol	TSG.2	Adv	Adv	Ref	
TSG Policy	TSG.3	Ref	Adv	Ref	
TSG Pref	TSG.4	Ref	Ref	Adv	
Industry (ISG)		**EE**	**Mat Eff**	**RE/H2/CCUS**	**Ind Elec**
ISG +	ISG Adv	Adv	Adv	Adv	Adv
ISG EE	ISG.1	Adv	Ref	Ref	Ref
ISG Mat Eff	ISG.2	Ref	Adv	Ref	Ref
ISG RE/H2/CCUS	ISG.3	Ref	Ref	Adv	Ref
ISG Elec	ISG.4	Ref	Ref	Ref	Adv
Buildings (BSG)					
BSG +	BSG.Adv	Advanced market and standards assumptions			

Acronyms: 0by50 = Net Zero GHGs by 2050; Ref = Reference; Adv = Advanced; SG = Study Group; Tech = Technology; Pref = Consumer Preference; EE = Energy Efficiency; Mat Eff = Material Efficiency; RE = Renewable Energy; Ind Elec = Industrial Electrification.

[j] The 9 archetypes include: (1) integrated assessment models (IAMs), (2) energy system models, (3) power models, (4) integration models for variable renewable energy, (5) models focused on cities, (6) islands/off-grid, (7) sectoral analysis, (8) geo-spatial analysis and networks, (9) integrated life cycle assessment (LCA) models.

1.2. EMF scenario design

Table 1 summarizes the EMF37 scenarios most relevant to hydrogen market uptake results. Three reference scenarios can be compared to sets of scenarios focusing on carbon management (CMSG, for carbon management study group), transportation (TSG), industry (ISG), and buildings (BSG). The *Reference* scenario is the only scenario that does not meet the 2050 net zero goal. Both the *Net Zero* and *Net Zero+* scenarios meet this goal, with more advanced technology input assumptions relied upon for the *Net Zero+* scenario. The other scenarios break down input assumptions into categories with various reference and advanced assumptions: CMSG includes variations on CCS, hydrogen production, and direct air capture (DAC); TSG includes technology, policy, and consumer preferences; and ISG includes energy efficiency, material efficiency, a combined category for renewable energy/hydrogen/CCUS, and industrial electrification. Some CMSG scenarios restrict any use, or any new use, of particular technologies, denoted by “None” or “No New” in the table. Variations within BSG scenarios are less relevant to hydrogen results. More complete discussions of all EMF scenarios and sector deep dives are provided by [51]. All results presented here are for the U.S. energy system.

Only some scenario assumptions are designed to provide insight into the role of hydrogen. The *CMSG NoCCS* and *NoDAC* scenarios are expected to favor hydrogen given that CCS and DAC compete with hydrogen under net zero constraints, while the *CMSG NoH2* scenario should provide an advantage to CCS and DAC. Assumptions for TSG and ISG scenarios are more mixed, and do not include cases where hydrogen assumptions are favorable compared to other decarbonization technologies. The *TSG+* and *TSG Tech* scenarios favor all advanced transportation technologies, and the *TSG Tech, TSG Tech/Pol, TSG Policy*, and *TSG Pref* scenario assumptions do not isolate the role of hydrogen in transportation. Similarly, the ISG *RE/H2/CCUS* scenario bundles advanced assumptions for all three competing decarbonization technologies, while the energy efficiency, material efficiency, and industrial electrification assumptions are not intended to influence hydrogen markets directly. These combinations of scenario assumptions therefore provide only limited insight into hydrogen’s decarbonization potential.

Sector and subsector results for the scenarios in Table 1 were reported by modeling teams using a common data template, comprised of multi-tiered data categories. The data tiers and categories used for hydrogen results are summarized in Appendix Table A2. Energy data are provided in Final Energy and Secondary Energy categories (Tier 1). Final Energy results are provided for three sectors in Tier 2 (transportation, industry, and buildings), which are further broken into eight subsectors in Tier 3. Secondary Energy categories include two Tier 2 types: hydrogen production by feedstock type and hydrogen consumed to produce other energy products. The “Total Hydrogen Use” results reported in this paper are the sum of Final Energy results for end-use applications and the Secondary Energy hydrogen consumed to produce other products (e.g., hydrogen consumed to produce e-fuels). Harmonization of EMF data across tiers and sectors is discussed further in Appendix Tables A3 and A4. Raw EMF data have been adjusted to remove demands associated with traditional markets (i.e., petroleum refining and ammonia production) which only EP-RIO and MARKAL-NETL reported as non-zero starting in 2020 (see Figure A1). All hydrogen market growth results therefore refer to new emerging markets.

2. General scenario results

2.1. Hydrogen production results

The technologies relied upon to produce hydrogen vary widely across models and net zero scenarios. Data on twelve types of hydrogen production were collected: electrolysis, conversion of fossil and biomass fuels with and without CCS (for biomass, natural gas, petroleum and coal), thermochemical nuclear, photoelectrochemical, and ethanol conversion. As shown in Fig. 1, EC-MSMR and TEMOA rely exclusively on 100 % electrolysis and biomass, respectively, for all scenarios. All other model-scenario combinations include a mix of production types, with the exception of 100 % electrolysis results for some scenarios from EPA-TIMES, EPS, and US-REGEN. Mixed production outcomes vary by model: EPA-TIMES results include electrolysis and NG w/CCS; EPS results include electrolysis and NG w/o CCS; and GCAM, US-REGEN, and MARKAL-NETL expand this list to include biomass w/CCS, thermochemical production using nuclear energy, and coal w/CCS. Results across scenarios are also mixed, with some tendency for *Net Zero+* results to favor NG with or without CCS and CMSG scenarios favoring electrolytic production. These mixed results in production types reflect fundamental differences in hydrogen decarbonization economics across models. However, due to lack of reported data on fuel and feedstock input prices and hydrogen production prices ($/kg), a consistent comparison of how production results may have influenced market outcomes across models is not possible. Appendix Table A5 provides additional discussion of production trends across models.

2.2. Market uptake results

Table 2 summarizes hydrogen market uptake results in 2050 across all model-scenario combinations. Values indicate total hydrogen use for each model-scenario combination, where zero results indicate that no market uptake occurred in the model-scenario combination, and empty cells indicate combinations that were not modeled.[k] Models are categorized into the 10 main economy-wide models reporting significant hydrogen results, two additional economy-wide models reporting very low nominal results, and three transportation sector models. Six of the main models report results for all three reference scenarios (*Reference, Net Zero, Net Zero+*), four report results for all five TSG scenarios (EPA-TIMES, GCAM, gTech, MARKAL-NETL), and one model reports results for all seven CMSG scenarios (GCAM). While the transportation sector models (MA3T, NREL-TDA, TEMPO) focus on TSG scenarios, other models focus on ISG (EC-MSMR, MARKAL-NETL), CMSG (EPA-TIMES, CGAM, gTech, MARKAL-NETL, AnyMOD), and BSG scenarios (EPA-TIMES, gTech). Of the 16 EMF models, two do not have hydrogen representation and are not indicated in the table (ADAGE, FARM) and USREP ReEDS is not included in the table but reports limited hydrogen results, discussed briefly in Sections 4 and 5.

In Table 2, the total number of scenarios for each model is summed by column and the number of models reporting results for each scenario is summed by row. Average hydrogen market uptake results by model are summed at the bottom, and average results by scenario are shown in the far-right column. Note that these averages must be compared carefully, given that different models provided results for different subsets of all scenarios. The raw average across all combinations is 13 MMT H2, while the average of combinations reporting results greater than 0.1 MMT H2 is 17 MMT H2.[l] The highest 25 % of market uptake results (29 scenarios shown in highlighted cells) range from 15.2 to 155 MMT H2, while the lowest 24 % of market update results (28 scenarios shown in dashed cells) range from 0 to 0.1 MMT H2. EPA-TIMES, EC-MSMR, and NATEM tend to report most of the highest market uptake results, while MARKAL-NETL reports 13 of the 28 lowest market share results (aside from demands in traditional markets, shown in Figure A1). General trends and details of these results are discussed in the sections below, including the three “breakthrough” results (indicated with bold cell

[k] Some ambiguity surrounds the interpretation of zero vs. null results. Modelling teams reporting results equal to zero for hydrogen markets, rather than null, are assumed to have modeled hydrogen competition.

[l] EMF scenario energy data are reported in exajoules (EJ), which are converted to MMT H2 using a lower heating value of 120 MJ/kg H2 (https://h2tools.org).

Fig. 1. Hydrogen production by volume and type in 2050. Circle sizes indicate production volume and colors and patterns indicate production type. * *MARKAL-NETL includes baseline demand.*

borders) discussed in Section 4. Additional trends by scenario type are discussed in Figure A2.

2.3. Reference scenarios: reference, net zero, and net zero+

Hydrogen market uptake trends for the *Reference* scenario are indicated in Fig. 2, with total demand by year shown at left and subsector breakdowns for 2050 shown at right. As indicated in Table 2, uptake results by 2050 cover a wide range of values. On the high end, three models, US-REGEN, TEMOA, and GCAM, estimate relatively consistent and strong growth between 2025 and 2050 and reach 6–8 MMT H2 demand by 2050. NATEM shows strong growth before 2035 followed by slow growth, while EP-RIO and AnyMOD grow to 1 MMT by 2040 before either leveling off (EP-RIO) or declining rapidly (AnyMOD).[m] The gTech and MARKAL-NETL models project ~1 MMT H2 by 2050, but with growth delayed until after 2035. EPA-TIMES also has a late growth trend, with 0.5 MMT of uptake from 2045 to 2050. The remaining models estimate <0.5 MMT H2 by 2050. TEMPO and EPS project no H2 market uptake in *Reference*. AnyMOD is the only model estimating early growth followed by demand declining towards zero by 2050, presumably due to demand from light-duty FCEVs being outcompeted by BEVs after 2040.

The stacked bars on the right side of Fig. 2 break down demand by end-use sector and sub-sector. Most results are reported at Tier 3, while MARKAL-NETL and TEMOA demand results are reported at Tier 2 and EP-RIO at Tier 1. The solid and pattern-filled red bars indicate transportation sector demands, which tend to dominate over the green bars for industry. Freight demand, primarily from MHDVs, is the most common transportation subsector demand. NATEM is the only model projecting significant offroad transportation demand and GCAM is the only model projecting large light-duty vehicle (LDV) demand. Four models, MA3T, AnyMOD, NREL-TDA, and US-REGEN, project low levels of LDV demand, ranging from 0.08 to 0.17 MMT H2, which is sufficient to fuel approximately 0.5–1.0 million light duty FCEVs.[n] Note that Transportation | Passenger demand in NATEM is 100 % rail, and half of the uptake indicated for US-REGEN is passenger rail. The significant transportation demands from MARKAL-NETL and TEMOA are not broken down by subsector, though more recent scenarios reported by MARKAL-NETL suggest significant LDV FCEV market growth [52]. EP-RIO's Tier 1 results do not distinguish between industry and transportation. US-REGEN is the only model estimating building sector demands and the only model with industry demand larger than transportation demand, with all industrial demand in the non-manufacturing subsector.

[m] Two models, EP-RIO and MARKAL-NETL, explicitly model 8-13 MMT of traditional hydrogen demand in 2020 in petroleum refining, production of ammonia, and production of other chemical products. All other models only estimate new market demand growing from 2020. To allow for consistent comparison of new market growth trends, these traditional baseline demands have been subtracted from final energy results for EP-RIO and MARKAL-NETL. Baseline (or traditional) petroleum refining and chemical feedstock demands over time are subtracted from total MARKAL-NETL demands to determine new market growth. Lacking subsector details, total demand in 2020 is subtracted from all future demands to estimate new market growth for EP-RIO (see Figure A1 for baseline trends before these adjustments).

[n] Assuming 0.44 kg per day per FCEV, based upon 12,000 miles per year and 75 miles per kg H2.

Table 2
Hydrogen market update in 2050 by model and EMF37 scenario.

Total Hydrogen (MMT H2 in 2050)	EC-MSMR	EP-RIO*	EPA-TIMES	EPS*	GCAM	gTech	MARKAL-NET	NATEM	TEMOA	US-REGEN**	AnyMOD	FECM-NEMS	MA3T	NREL-TDA	TEMPO	No. Reporting	Ave. (Main only)
Model Category	Main										Additional		Transportation				
Reference	0	1.4	0.5	0	6.0	0.9	1.3	2.7	6.4	7.6	0.2	0.1	0.2	0.2		14	2.7
Net Zero	90.2	31.2	16.9	29.4	7.0	1.2	0	67.9	12.8	11.1	0.2	0.2		0.2		13	26.8
Net Zero+			27.4	0	12.0		0	59.7		15.0						6	19.0
TSG+			24.1	7.1	15.4	4.8	0	56.3					0	1.3	4.2	8	18.0
TSG Tech			19.5		11.4	6.4	3.9						0.1	1.5	5.4	7	10.3
TSG Tech/Pol			24.1		15.2	6.2	0						0		4.3	5	11.4
TSG Policy			24.3		12.6	1.7	0						0.1		0.1	6	9.6
TSG Pref			17.1		7.1	5.2	0						0.1		0	5	7.3
ISG+	100		16.9	0	8.6		0.2	67.5								6	32.2
ISG EE	6.4						0									2	3.2
ISG Mat Eff	58.9															1	58.9
ISG RE/H2/CCUS	155						0.1									2	77.7
ISG Elec							0									1	0.0
CMSG+			23.3	1.4	12.9	1.7	0	68.0	9.8		0.2					8	16.7
CMSG No CCS					8.3					107						2	57.7
CMSG Adv CCS					7.0	2.0	0				0.2					4	3.0
CMSG Adv H2			23.3		16.8	1.9	0.2				0.2					5	10.5
CMSG Adv DAC			16.8		6.2	1.5	0				0.2	0.1				6	6.1
CMSG No DAC					8.0	6.2	12.2									3	8.8
CMSG No New H2			0		0											2	0.0
BSG+			16.6	3.1	7.0		0									4	6.7
0by50.BSG1			15.8			2.2										2	9.0
0by50.BSG2			15.8			2.2										2	9.0
0by50.BSG3						1.8										1	1.8
0by50.BSG6						1.8										1	1.8
Total Scenarios	6	2	16	7	17	16	18	6	3	4	6	3	6	4	5	116	
Average MMT H2	68.5	16.3	17.6	5.8	9.5	3.0	1.0	53.7	9.7	35.2	0.2	0.1	0.1	0.8	2.8		

NOTES: Dashed cell borders indicate lowest 24% of uptake results. Shaded cells indicate highest 25% of uptake results. Bold cell borders indicate breakthrough scenarios. *MARKAL-NETL, EP-RIO, and EPS results shown do not include baseline conventional demands; **US-REGEN use data in CMSG1 includes secondary uses (electricity production, petroleum refining, syngas, and synfuels).

The second reference scenario, *Net Zero*, achieves net zero CO_2 emissions by 2050 under reference scenario assumptions. Most models see an increase in hydrogen market uptake under net zero constraints, though uptake results vary widely by 2050. Note that the vertical axis scale in Fig. 3 is 12X greater than in Fig. 2. Most models do not project strong market growth before 2035. Of the twelve models included in the figure, one third (4 of 12, including gTech, AnyMOD, FECM-NEMS, and NREL-TDA), projects demand at <5 MMT H2 by 2050. Results obscured in Fig. 3 due to scale include AnyMOD results, with trends similar to *Reference*, and gTech results, with very modest demand increases after 2035. Another third of the models (4 of 12) project a relatively low uptake of between 5 and 20 MMT H2 by 2050, with relatively slow rates of growth from 2040 to 2050. Among the remaining third, EPS and EPA-TIMES increase to about 30 MMT by 2050, EPS linearly and EPA-TIMES with more typical s-shaped growth. The last two models, NATEM and EC-MSMR, report much larger demands in 2050, ranging from ~70–90 MMT H2. NATEM exhibits a strong growth trend after 2035, growing at about 4 MMT per year through 2050. In contrast, EC-MSMR does not see strong market growth until after 2040 and increases by over 70 MMT H2 between 2045 and 2050.

Sub-sector demands in 2050 for *Net Zero* are shown on the right-hand side of Fig. 3. Results are more evenly balanced between industry and transportation compared to *Reference*. EP-RIO results are reported at Tier 1, and TEMOA and transportation results from EC-MSMR are

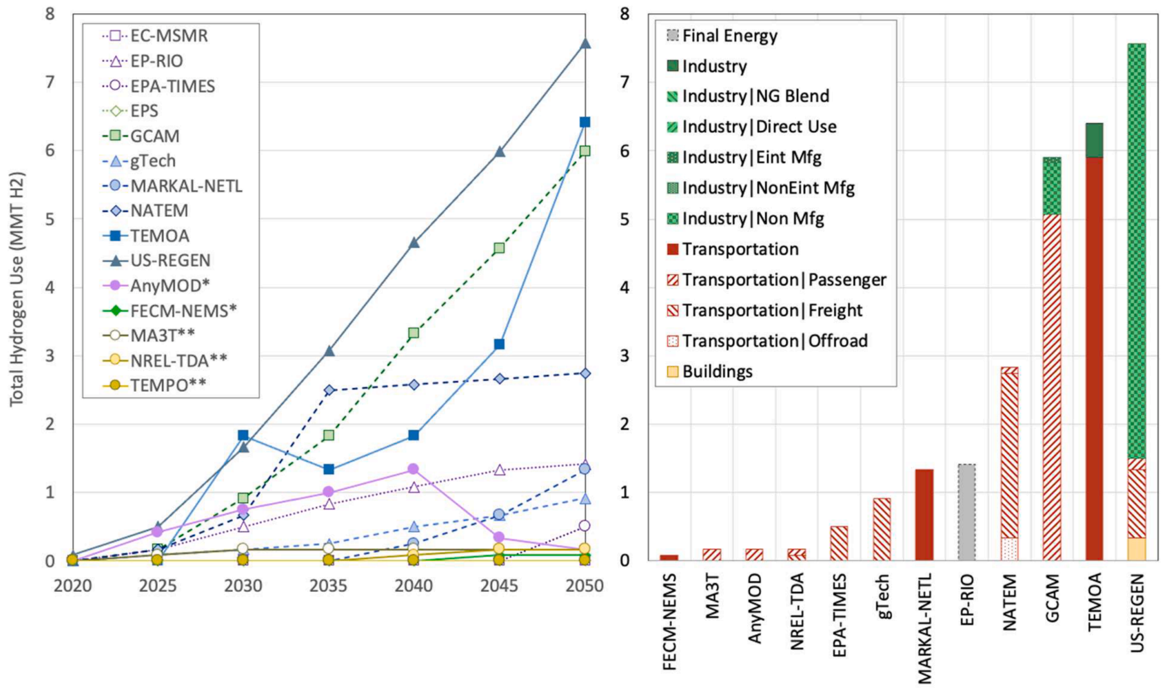

Fig. 2. Reference scenario total hydrogen use by year (left) and by subsector in 2050 (right). **Additional Model, **Transportation model.*

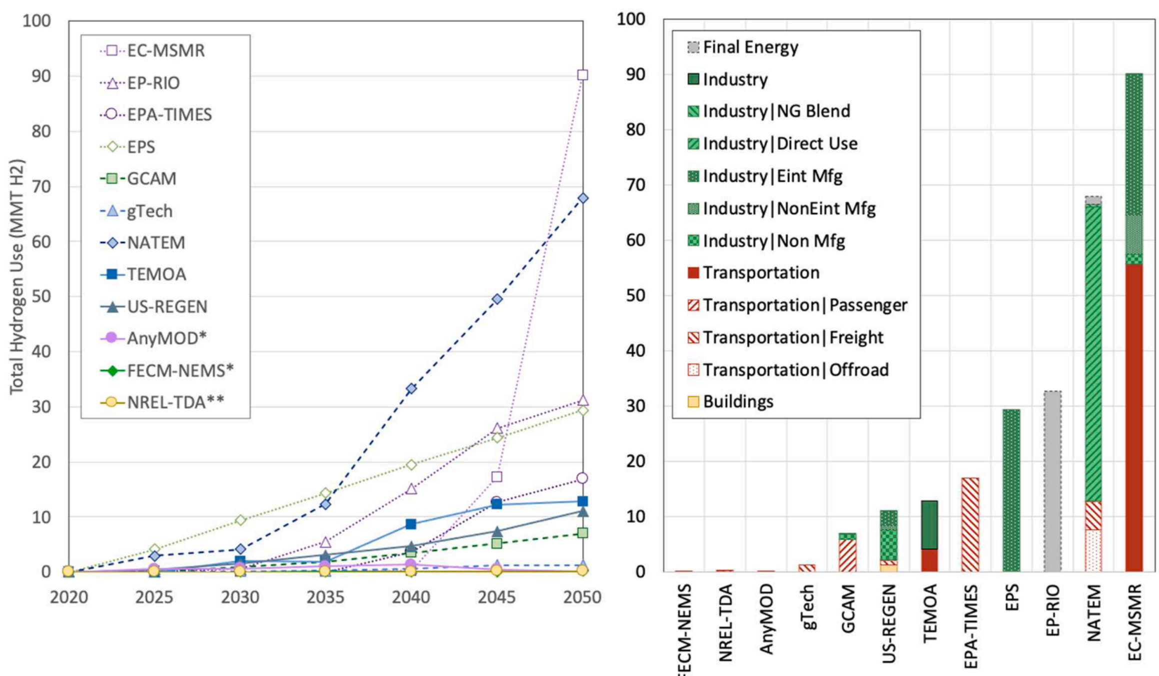

Fig. 3. Net Zero scenario total hydrogen use by year (left) and by subsector in 2050 (right). Note the difference in scale from Fig. 2. *Additional model, **Transportation model.

reported at Tier 2. Subsector transportation shares by model are similar to those in *Reference*, while the larger industry demands in *Net Zero* cover a broad range of sub-sectors, including non-manufacturing (GCAM and US-REGEN), energy-intensive manufacturing (EPS and EC-MSMR), direct use (NATEM), and non-energy-intensive manufacturing (EC-MSMR). US-REGEN projects modest building sector demand.

The third reference scenario, *Net Zero+*, also reaches net zero CO_2 emissions by 2050 but with more optimistic assumptions for all technologies and decarbonization policies. Comparisons between *Net Zero* and *Net Zero+* scenarios therefore indicate the market advantage of hydrogen in the context of all low-carbon technologies improving in technology performance, though the relative progress across different technologies varies by model. Six models report results for both *Net Zero* and *Net Zero+*, allowing for the side-by-side comparison shown in Fig. 4. Of those six models, three (EPA-TIMES, GCAM, and US-REGEN) see increases in hydrogen demand between *Net Zero* and *Net Zero+* scenarios, while NATEM projects slightly less demand, EPS projects no hydrogen demand in *Net Zero+* (i.e., a 100 % reduction by 2050), and

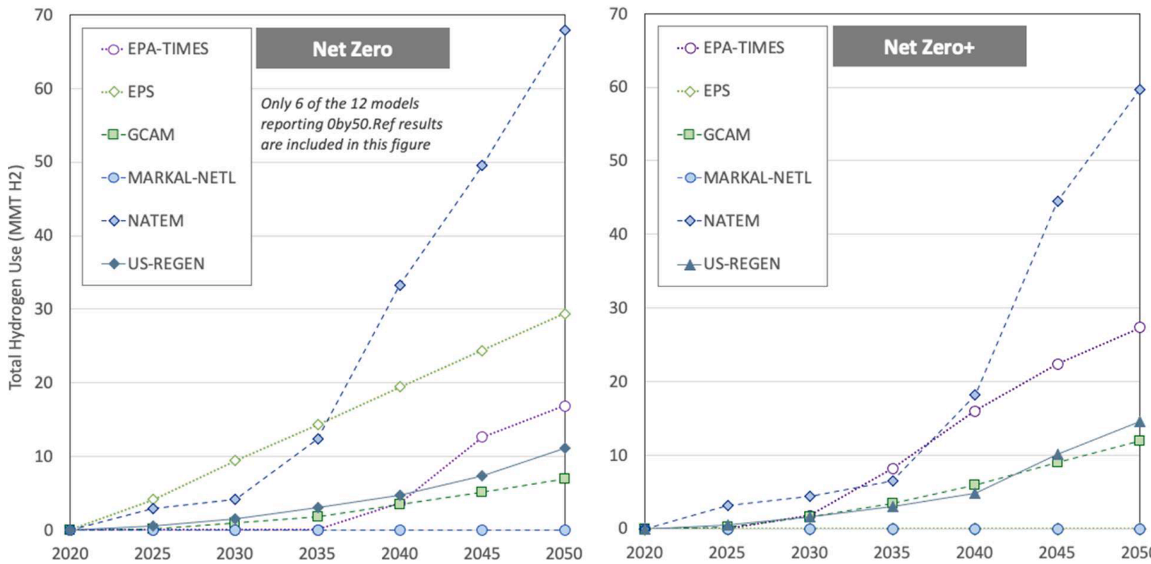

Fig. 4. Hydrogen market uptake from 6 models for *Net Zero* and *Net Zero+* scenarios.

Table 3
Transportation Study Group (TSG) scenario matrix.

Scenario	Description	Examples Model Changes
TSG Tech	Advanced Technology	Vehicle investment cost reductions, technology efficiency improvements, and improvements to charging/refueling infrastructure
TSG Tech/Pol	Advanced Technology and Policy	Combined implementation of the advanced technology and advanced policy strategies used in *TSG Tech* and *TSG Policy*
TSG Policy	Advanced Policy	Limiting the purchase of new gasoline or hybrid technologies in later years, ZEV mandates, and purchase incentives of low carbon technologies
TSG Pref	User's Preference	Behavioral changes or choices including a reduction in the amount of driving of individuals, increases in public transportation use, increased adoption of lower CO2 technologies, and increased freight vehicle loads.
TSG+	All advanced assumptions	Combined implementation of the advanced technology, advanced policy, and user's preference in TSG Tech/Policy/Pref

the MARKAL-NETL model projects no new hydrogen market uptake in either scenario (100 % reduction for both scenarios compared to *Reference*). Comparing final energy in 2050, EPA-TIMES estimates a 62 % increase, GCAM a 71 % increase, and US-REGEN a 32 % increase. Demand estimated by NATEM for 2050 decreases by 12 % but is increasing more rapidly than any other model, at about 3 MMT H2 per year, between 2045 and 2050. Taken together, results from these 6 models offer divergent conclusions on the relative competitiveness of hydrogen when assumptions are favorable for all decarbonization technologies and market conditions. For a discussion of results from additional decarbonization scenarios (CMSG+, TSG+, ISG+ and BSG+), see Figures A3 through A6.

3. Detailed sub-sector results

3.1. Transportation sector details

The *Net Zero* and *Net Zero+* scenario results indicate that hydrogen contributes to transportation decarbonization in most EMF models. In addition, the five TSG transportation-specific scenarios explore the influence advanced transportation technology assumptions, policies, and consumer preferences, as shown in Table 3. The different models implement these scenarios in a variety of ways, with no standard implementation of any of the strategies. For a more complete discussion of the EMF TSG results, see [53]. Three EMF models are transportation sector only models, one of which represented only passenger vehicles (MA3T). Results in Table 2 indicate which of the transportation scenarios each model ran. Four of the main models (EPA-TIMES, GCAM, gTech, and MARKAL-NETL) ran all five TSG scenarios, two ran *TSG+* (EPS and NATEM), and the other four models ran no TSG scenarios. Of the transportation only models, MA3T and TEMPO ran all five TSG scenarios, though MA3T reported very small amounts of hydrogen, <0.5 % of total transportation fuel use. The analysis below will focus more closely on the nine models (7 sector wide, 2 transportation only) that had appreciable amounts of hydrogen use in their results.

An important distinction across models is which transportation subsectors are found to have positive hydrogen market uptake results, as summarized in Table 4. EP-RIO and EPS report no transportation hydrogen results, and are therefore not indicated. MA3T, NREL-TDA, and TEMPO are transportation-specific models, but are limited to on-road applications. As shown, the remaining models vary significantly by sub-sectors with non-zero results. US-REGEN and GCAM report positive market uptake results for the largest number of transportation sub-sectors, 7 and 5, respectively, and are the only models reporting positive results for aviation, shipping, and synthetic liquids.

While the TSG scenarios explore variations on input assumptions for the transportation sector, the largest transportation hydrogen demands are not necessarily seen in the TSG scenarios. This is partly due to TSG scenario designs treating advanced technologies in a unified manner, rather than exploring disparities in technology progress (e.g., assuming hydrogen and fuel cell drivetrain success with modest battery technology progress). Fig. 5 indicates 12 model-scenario combinations with the largest transportation hydrogen demands. Of all models, EC-MSMR and EPA-TIMES have the largest results by 2050, with EC-MSMR's 102 MMT being over three times higher than the Y axis scale in the graph. GCAM, NATEM, and MARKAL-NETL have demands near 13 MMT, while all other models are below 7 MMT by 2050. AnyMOD is the only model with an increasing then declining demand, while several models (gTech, MARKAL-NETL, NATEM, NREL-TDA) indicate demand slowing or leveling off between 2040 and 2050. The types of scenarios generating these highest transportation market results varies widely. Only 4 model-scenario combinations involve TSG scenarios, with the other

Table 4
Models providing non-zero hydrogen market uptake results for transportation sub-sector tier 3 categories.

Subsectors with Non-Zero Final Hydrogen Results (Tiers 2–4, all Scenarios)			EC-MSMR	EPA-TIMES	GCAM	gTech	MARKAL-NETL	NATEM	TEMOA	US-REGEN	AnyMOD	FECM-NEMS	MA3T	NREL-TDA	TEMPO	Number Reported
Model Category			Main								Additional		Transportation			
Transportation			x	x	x	x	x	x	x	x	x	x	x	x	x	13
	Freight			x	x	x		x		x				x	x	7
		Rail		x	x			x		x						4
		Road		x	x			x		x				x	x	6
		Shipping			x											1
	Passenger			x	x	x		x		x	x		x	x		8
		Aviation			x											1
		Rail						x		x						2
		Road		x	x					x			x	x		5
		Shipping								x						1
	Offroad							x		x						2
Secondary Energy	Petroleum Refining						x			x						2
	Synthetic Liquids									x						1

combinations including *Reference, Net Zero, Net Zero+, CMSG*, and *ISG* scenarios.

The left panel of Fig. 6 shows 2050 transportation hydrogen use for ten models comparing *Net Zero, Net Zero+*, and the *TSG* scenarios. With the exception of NATEM, models generally displayed an increase in hydrogen use with advanced technology assumptions, advanced policies, and behavioral changes (*TSG+*). Modeling teams reported implementing lowered FCEV and EV investment costs in this scenario, though the levels of reductions varied among models. For example, EPA-TIMES implemented the deepest reduction in hydrogen costs by implementing the DOE Hydrogen Shot goals.[o] The *TSG Policy* scenario, assuming advanced policies, had the greatest impact in hydrogen use in EPA-TIMES and GCAM. Both models reported implementing policies that allowed no new gasoline, E85, or hybrid LDV and truck sales starting in 2035. The *TSG+, TSG Tech/Policy*, and *Net Zero+* scenarios all included the changes implemented in both *TSG Tech* and *TSG Policy*. The combination led to even greater increases in hydrogen use. Overall, a policy of not allowing carbon emitting technologies had the greatest impact. The *TSG Pref* scenario, with changes in user preference, did not result in an increase in hydrogen use, especially in GCAM and TEMPO, and to a lesser degree in gTech. Modeling teams reported implementing strategies like decrease light-duty demand due to drivers choosing to drive less, increased occupancy in vehicles, increased public transportation use, and decreased freight growth. Methods and amounts to achieve these reductions varied across models. For a comparison of three models (GCAM, EPA-TIMES, and gTech) that reported results for all five TSG scenarios, see Figure A7.

The *CMSG* scenarios also show changes in transportation hydrogen use across models, as shown in the right panel of Fig. 6. Hydrogen technologies in the *CMSG AdvH2* scenario were implemented similarly to how they were implemented in the transportation advanced policies scenario, therefore the resulting hydrogen use is very similar. Only MARKL-NETL and GCAM ran the *CMSG NoDAC* scenario, and for both models this led to increases in hydrogen use, significantly so for MARKAL-NETL (see Section 4). For a breakdown of hydrogen use within transportation subsectors, see Figure A8. For a discussion of how hydrogen in transportation appears to be related to the cost and availability of both non-transportation decarbonization options and negative emission technologies, see Figure A9.

While BEV battery cost and performance are projected to continue to improve over time, consumer choice models incorporating both cost and non-cost vehicle and consumer attributes continue to predict significant FCEV market shares in LDV markets as well as in MHDV markets. A recent dynamic discrete choice model developed at the University of California, Davis, predicts light-duty BEV shares tending to peak in the 2035–2040 timeframe, with FCEVs growth increasing after 2030 to ~30–40 % market share by 2040 under ZEV market constraints [54]. A 2023 study from Julich focused on total cost of ownership and component learning rates finds vehicle application requirements to be critical to relative BEV and FCEV market success, and charging infrastructure having a greater impact on fuel costs than hydrogen refueling infrastructure [55]. TEMPO scenarios with varying degrees of relative technology improvement between BEVs and FCEVs have been explored by Hoehne [56], including increased FCEV LDV market shares associated with 100 % access to hydrogen refueling. Similarly, MA3T and ADOPT have explored sensitivities where FCEVs achieved significantly higher market shares under certain market conditions, especially when assuming pessimistic forecasts for future battery cost reductions [57]. As discussed elsewhere, there are several advantages to improving the representation of consumer choice decisions within energy system models [58]. For a discussion vehicle cost and fuel use data collected

[o] The Hydrogen Shot, the first DOE Energy Earthshot launched on June 7, 2021, is a goal to reduce the cost of clean hydrogen by 80%, to $1 per 1 kilogram, in 1 decade. https://www.energy.gov/eere/fuelcells/hydrogen-shot

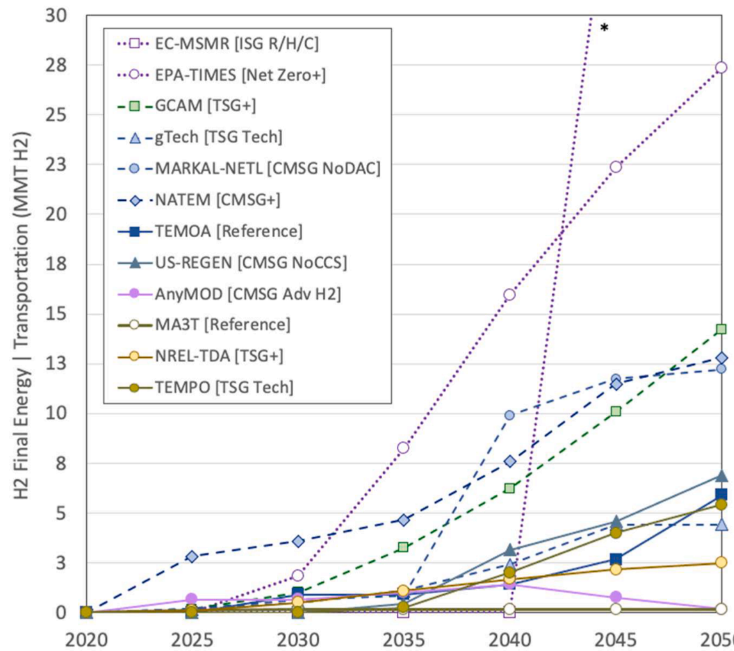

Fig. 5. Maximum hydrogen transportation energy by model and scenario.
*EC-MSMR is 39 MMT in 2045 and 102 MMT in 2050.

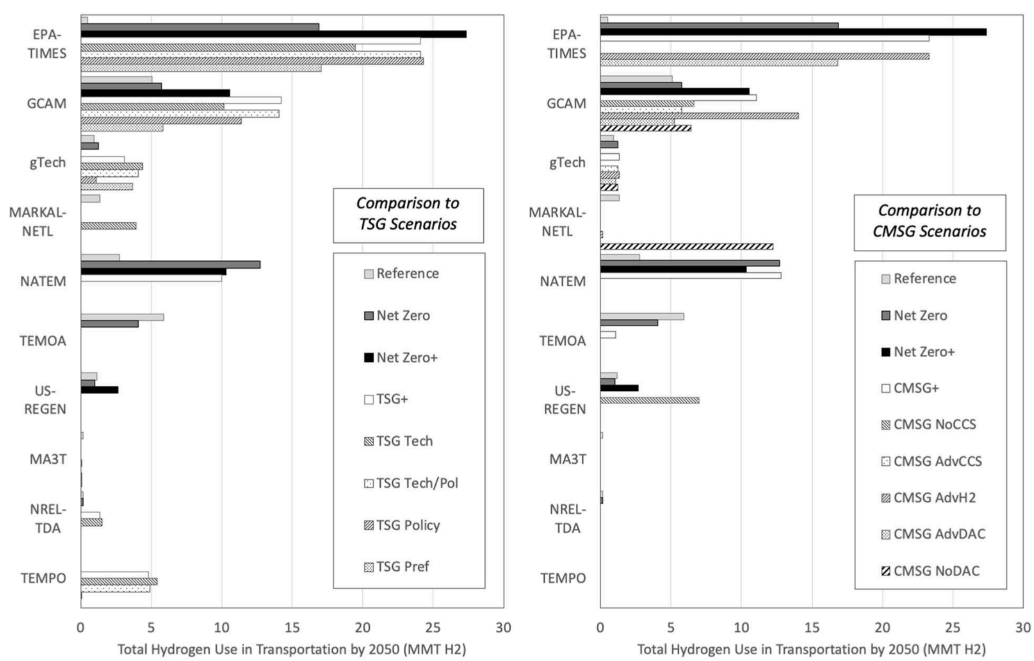

Fig. 6. Transportation hydrogen use in the *Net Zero* and *Net Zero+* scenarios compared to TSG (top) and CMSG (bottom) scenarios.

from EMF models, and a resulting cost per mile driven metric, see Figures A11 and A12.

3.2. Industrial sector details

This section highlights industrial subsector hydrogen demands, which are highly detailed in a subset of EMF models. Maximum industry results by model-scenario combination are shown in Fig. 7. Three of the results are for the *Net Zero* scenario, one for *ISG+*, and two for CMSG variations (*NoCCS* and *AdvH2*). With the exception of EPS, most strong market growth occurs after 2035, and results vary widely by 2050. US-REGEN reports very strong growth between 2040 and 2050, reaching 87 MMT by 2050. EC-MSMR, EPS, and NATEM have more moderate growth trends (1–4 MMT per year), GCAM has very modest demand, and TEMOA has declining demand between 2045 and 2050.

In addition to this wide range by 2050, and corresponding rates of growth or decline, there is significant variability in the industry subsectors comprising demand in each of the maximum growth scenarios, as shown for 4 models in Figure A13. Use of hydrogen in energy-intensive manufacturing (EInt Mfg) makes up 50 % or more for each model except US-REGEN, where Secondary markets comprise nearly 75 % of industry demand. Unique and significant demands by model include aluminum, plastic and rubber, balance of manufacturing, wood products, and other mining for EC-MSMR, cement and lime for EPS,

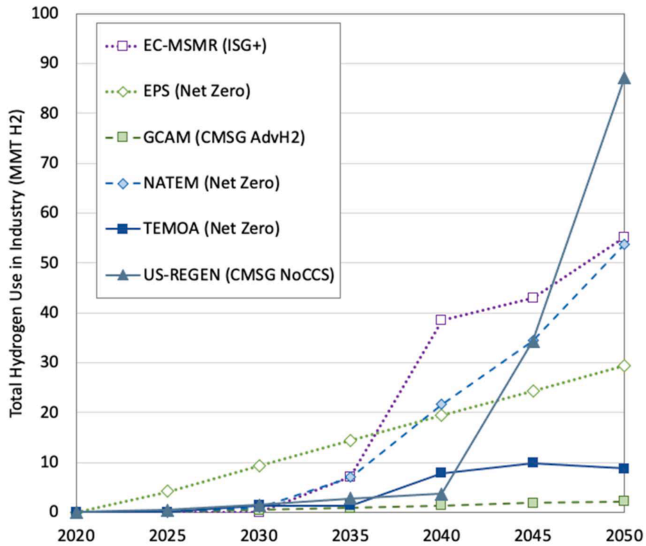

Fig. 7. Total hydrogen use in industry by model for maximum scenarios.

agriculture for GCAM, and secondary uses (synthetic liquids, synthetic gas, and electricity) and paper for US-REGEN. The majority of industrial demand from EPS is categorized as other energy-intensive manufacturing. The variety of end-uses between models, as well as the wide variability in demands, suggests increased harmonization of assumptions across models would likely lead to more consistent results.

4. Hydrogen breakthrough scenarios

Most of the maximum hydrogen demand results discussed in the previous section are only moderately larger than the next largest scenario results reported from the same model. There are three exceptions to this tendency, characterized here as “breakthrough” scenarios given that the demands are 2–5 times larger than the next highest scenario from that model (see the bold bordered values in Table 2). Explanations for these breakthrough results vary by model. In the first case, EPS estimates the largest market uptake for the *Net Zero* scenario (29 MMT), followed by *TSG+* (7 MMT) and *BSG+* (3 MMT). Given that EPS also

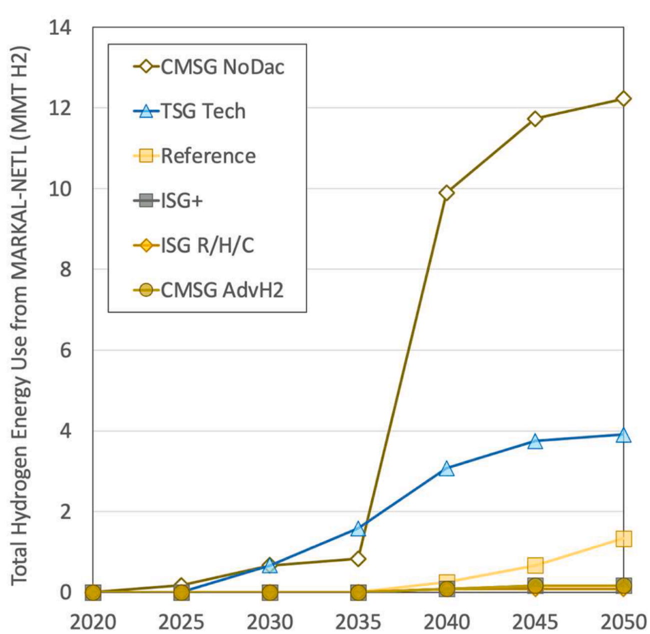

Fig. 8. Total hydrogen use from the MARKAL-NETL model.

modeled the *Net Zero+* scenario, and found no hydrogen market uptake, a likely explanation is that hydrogen technologies do not compete well with other decarbonization options in these scenarios. The hydrogen market breakthrough, in this case, appears to occur if other decarbonization technologies do not improve to the degree seen in *Net Zero+*. However, note that EPS results increase linearly over time between 2020 and 2050 and all hydrogen demand is limited to industry’s energy-intensive manufacturing sub-sector (see Figure A13).

Results from the MARKAL-NETL model for *CMSG NoDAC* represent a different type of breakthrough scenario. For this model, all emerging market results are in the transportation sector, but they are not broken out by transportation sub-sector (see Figure A1).[4] As shown in Fig. 8 for 6 scenarios with non-zero results, MARKAL-NETL reports relatively high hydrogen transportation market uptake in the *Reference* scenario compared to *ISG+, ISG R/H/C*, and *CSMG AdvH2*. This result seems to mirror that from EPS: hydrogen does not compete as well as other advanced transportation decarbonization options across these particular scenarios, which include favorable assumptions for hydrogen in the case of *ISG R/H/C* and *CMSG AdvH2*. The two exceptions to this tendency are the *TSG Tech* scenario, with demand leveling off at 4 MMT H2 by 2050, and in the breakthrough *CMSG NoDAC* scenario, with demand leveling off at 12 MMT H2 by 2050. Without additional subsector details, likely explanations are improved FCEV technology assumptions contributing to the increased demand in *TSG Tech*, and a lack of competitive low-carbon fuel options (e.g., low-carbon synfuels) contributing to increased demand in *CMSG NoDAC*. Note that the *CMSG NoCCS* scenario was found to be infeasible in MARKAL-NETL. While sub-sector details were not reported through the EMF scenario template, subsequent MARKAL-NETL results indicate FCEV market growth as high as 50 % of LDV vehicle miles traveled by 2075 [52].

US-REGEN reports relatively modest hydrogen market uptake in three of four scenarios modeled, as shown in Table 2. In contrast, *CMSG NoCCS* is a strong breakthrough scenario with a >5X increase in hydrogen demand compared to the next highest scenario (*Net Zero+*). Unlike EPS and MARKAL-NETL, US-REGEN reports the lowest hydrogen uptake in the *Reference* scenario, and *Net Zero+* results are larger than *Net Zero*, suggesting that hydrogen options compete well against other decarbonization options with advanced assumptions across all technologies. This scenario is also unique due to strong uptake for secondary uses, including 54 MMT of hydrogen for synfuels and syngas and about 4 MMT of hydrogen for electricity generation. As shown on the right hand side of Fig. 9, while hydrogen demand in *CMSG NoCCS* increases in the same subsectors where growth occurs in *Net Zero* and *Net Zero+*, especially buildings, freight, and energy-intensive manufacturing, the increase in secondary uses is unique to *CMSG NoCCS*. Similar to the transportation demand breakthrough in MARKAL-NETL *CMSG NoDAC*, these breakthrough results are likely associated with a lack of low-carbon fuel alternatives and the lack of CCS options for electricity generation.

The hydrogen use for electricity generation shown in Fig. 9 is the only use of hydrogen in that subsector among the EMF models discussed in this paper. Across other EMF37 models, USREP-ReEDS also predicts significant hydrogen use in electricity generation, with significant increase in hydrogen use between the *Net Zero* scenario (9.8 MMT H2) and the *Net Zero+* scenario (16.5 MMT H2). Both of these reference scenarios have significantly higher use in electricity generation than the 4 MMT from the US-REGEN *CMSG NoCCS* scenario [59].

5. Interactions with carbon management technologies and carbon prices

CMSG scenarios are defined in terms of three levels of technology improvement associated with CCS, hydrogen production, and DAC, as shown in the scenario matrix in Table 1. Scenarios in which hydrogen is expected to have larger market uptake are *CMSG AdvH2, CMSG NoCCS*, and *CMSG NoDAC*. Comparisons to the *CMSG+* scenario should indicate

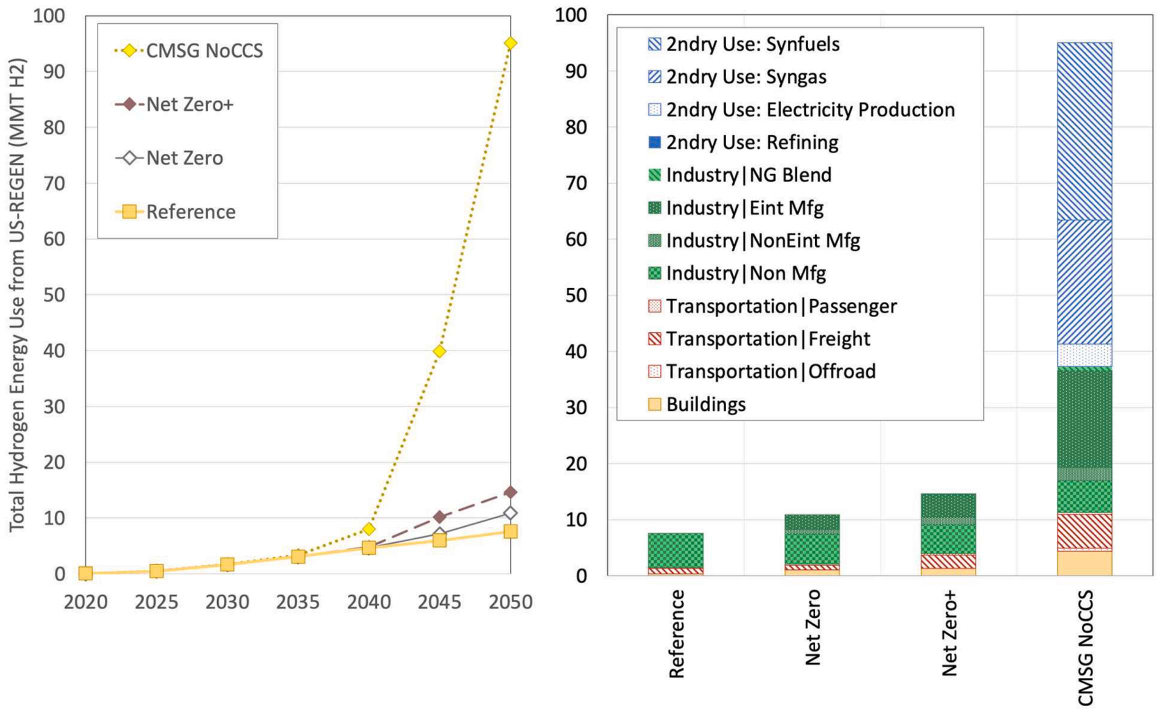

Fig. 9. Total hydrogen energy by year (left) and subsector (right) from US-REGEN.

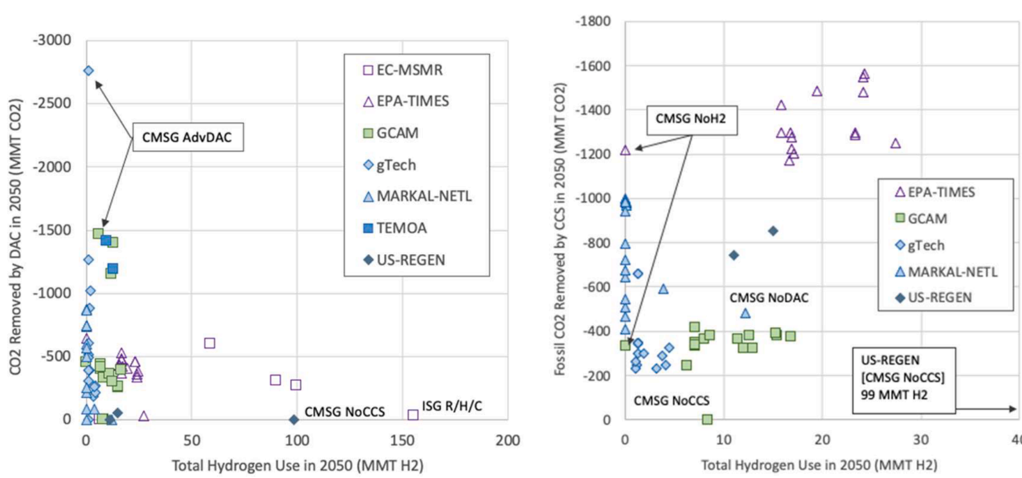

Fig. 10. CO2 removed by DAC (left) and CCS (right) compared to total hydrogen use in 2050.

the degree to which hydrogen competes with CCS and DAC under these alternate technology assumptions. One means of comparing the tradeoff between carbon management and hydrogen as decarbonization options is show on the left-hand side of Fig. 10, with total CO_2 removed by DAC on the vertical axis and hydrogen use on the horizontal axis. A similar tradeoff is shown on the right hand side, with CO_2 removed by CCS on the vertical axis and hydrogen use on the horizontal axis. The tradeoff appears stronger for DAC, where most scenarios with high DAC CO_2 removal have relatively low hydrogen use, and vice versa. Scenario results that tend to defy this tradeoff, falling in the middle of both graphs, are primarily from EPA-TIMES and GCAM, as well as a few scenarios from EC-MSMR. As expected, scenarios that exhibit the strongest tradeoff are *CMSG AdvDAC* with high CO_2 removal and low hydrogen use, and *CMSG NoCCS* and *ISG R/H/C* having the inverse relationship. As indicated, scenario results from EPA-TIMES, GCAM and gTech which strongly adhere to this tradeoff trend include *CMSG AdvDAC, CMSG NoDAC*, and *CMSG NoCCS*.

The relationship between hydrogen use and the price of carbon required to achieve decarbonization, measured in dollars per tCO_2e reduced, can be interpreted in multiple ways depending upon trends seen across the different types of scenarios modeled. These trends are shown in Fig. 11 for seven models where carbon price results were reported. In general, an upward and outward trend moving away from one or more reference scenarios can be interpreted as hydrogen being a more costly but ultimately one of the most economic options under certain scenario constraints, such as the *CMSG NoCCS* or *CMSG NoDAC*

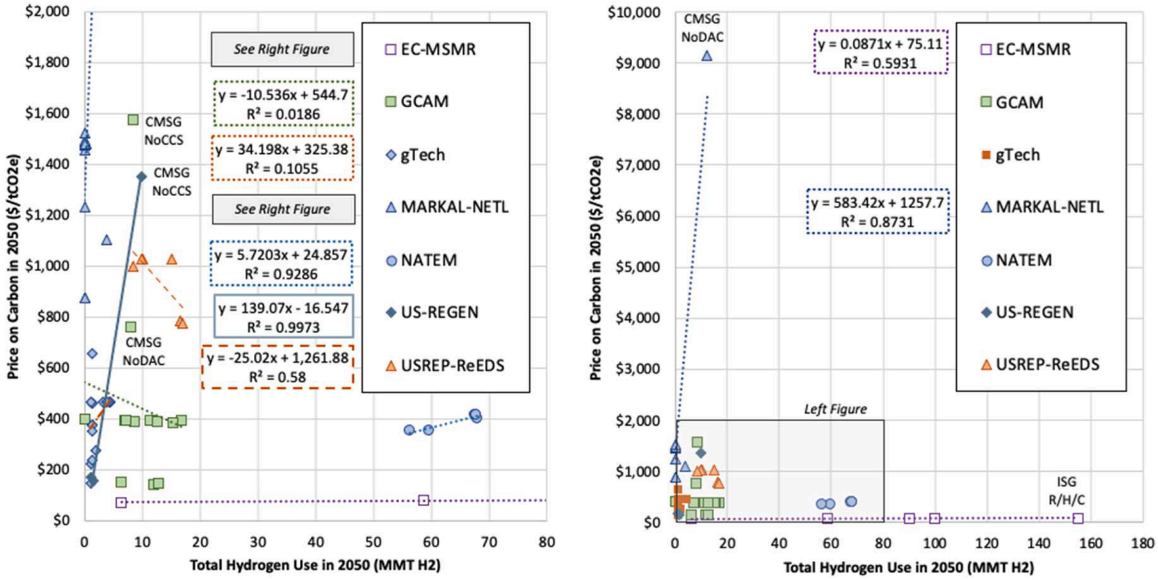

Fig. 11. Price on carbon (vertical axis) compared to total hydrogen use (horizontal axis) in 2050 for all scenarios reported by six models. Left-hand figure is an inset of the right-hand figure.

scenarios. A downward trend away from one or more reference scenarios may be interpreted as hydrogen enabling less costly CO_2 abatement due to improved technology performance or as a result of drivers favorable to hydrogen, such as the *CMSG AdvH2* or various *TSG* scenarios (referred to as TSGX). Note that the cost of carbon outputs result from competition across a mix of decarbonization technologies included in each model, and are not necessarily associated with only the influence of hydrogen on the economics of carbon abatement. More detailed assessments of each model would be required to characterize the precise economic role of hydrogen in decarbonizing the energy system.

In Fig. 11, the carbon price increases strongly with additional hydrogen use in two models, increases at a modest rate in three models, and decreases with additional hydrogen consumption in two models. Linear fits to each set of scenarios indicate the slope and R2 value of the trends, which vary based upon the variation and scatter of scenario results. The very steep upward trends for MARKAL-NETL and US-REGEN are associated with the breakthrough scenarios described in Section 4. These two clear trends adhere to the constraints interpretation: *CMSG NoDAC* and *CMSG NoCCS* scenario assumptions lead to increased hydrogen use due to a lack of alternatives for difficult-to-decarbonize sectors. In contrast, the linear fit for gTech results has a wide scatter (low R2 value), where the upward trend results from modestly higher carbon prices associated with the ~3x increase in hydrogen use for TSG scenarios (from ~1.25 MMT to 3–4.5 MMT H2). For gTech, the *CMSG NoDAC* scenario does increase carbon prices (to ~$660/tCO2) but does not result in increased hydrogen use. Of the seven models, NATEM and EC-MSMR scenarios have the largest total hydrogen use, which occurs in scenarios with relatively low carbon prices (~$400/tCO2 and ~$80/tCO2, respectively), which increase only modestly with additional hydrogen use. EC-MSMR has a very slight upward slope. The downward trend across GCAM scenarios also has a wide scatter, with higher volumes of hydrogen in some scenarios (*ISG+, TSGX, CSMG AdvH2*) and with both higher volumes and lower carbon abatement costs in other scenarios (*Net Zero+, CMSG+*). Similar to gTech, GCAM's *CSMG NoCCS/NoDAC* scenario results have significantly higher carbon prices but only modest increases in hydrogen use relative to *Net Zero*. The second downward trend is seen across the six scenarios reported from USREP-ReEDS, where hydrogen is used for electricity generation. A more detailed examination of trends between particular pairs of scenarios reveals additional insights into the role of hydrogen in reducing GHGs in each model, as discussed for Table A6 and Figures A14 and A15.

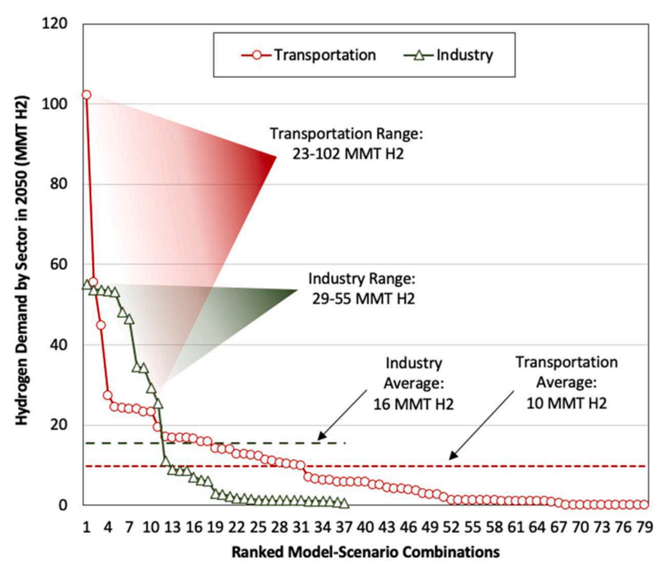

Fig. 12. Ranked 2050 hydrogen market uptake in transportation and industry for all model-scenario combinations. Results for each scenario by sector have been ranked highest to lowest.

Taken together, these results suggest no clear consensus on the economic role of hydrogen in decreasing GHGs across different sectors in response to various technology assumptions.

6. An upper range on hydrogen market potential

Hydrogen market uptake results are strongly clustered towards the lower range of values reported, especially due to a large number of scenarios (28) reporting zero or close to zero results (<0.2 MMT). That being said, 10 scenarios report greater than 50 MMT H2 by 2050. As discussed, hydrogen demands do not only vary widely in magnitude but are also distributed unevenly between sectors and across subsectors (see Table A7 for additional comparisons). To capture the relevance of higher market growth outcomes from individual models, scenario results can be aggregated to characterize a study-specific upper bound hydrogen market potential. To this end, a two-tiered approach is taken to characterize both the highest uptake results and the subsequent “next highest” cluster of results by model and scenario. Fig. 12 ranks hydrogen market uptake results in transportation and industry for all model-scenario combinations. Ranges for the top 10 % of results for both transportation and industry (highest 10 scenarios out of 116 scenarios total) are highlighted, providing a range of 23–102 MMT for transportation and 29–55 MMT for industry. Average values for all non-zero scenarios results are also indicated. In addition to these transportation and industry ranges, drawn from multiple models, the US-REGEN *CMSG NoCCS* scenario provides an upper range for hydrogen demand in buildings (4 MMT) and secondary energy (62 MMT), both of which have a lower bound of zero. Summing the upper and lower bounds gives an aggregate range of 42–223 MMT H2. While Fig. 12 indicates full ranges for industry and transportation, it also indicates a clustering of results near the upper bound for industry and near the lower bound for transportation.[p] As noted previously, the EMF37 scenarios were not designed to explore the role of hydrogen compared to other decarbonization options. This upper range market potential is therefore unique to EMF37 and should not be interpreted as a general response to the question of maximum hydrogen market uptake.

7. Summary results and recommendations

Progress towards commercialization of large-scale hydrogen projects has accelerated at an unprecedented rate over the past 3–5 years. Key drivers include improved economics of renewable energy and increased prioritization of climate change as a global issue by both industry and government. While detailed engineering-based studies have progressed along with technology improvements over time, many energy system models have only recently begun to incorporate detailed and realistic representations of hydrogen technologies and systems. This model development status is reviewed and confirmed based upon an examination of U.S. energy system decarbonization scenarios results provided through the Stanford Energy Modeling Forum study 37 (EMF37). In total, scenario results from 15 models, including 10 main models, 2 additional models, and 3 transportation-sector models, have been examined for one *Reference* scenario and 21 decarbonization scenarios. Wide ranges in variability are observed in both the scope to which hydrogen is represented within models and in the scenario results. This study reviews scenario result trends, articulates observations, proposes explanations, and makes recommendations for future work, all compiled with guidance from the EMF37 Hydrogen Crosscut Working Group (H2 CCWG).

EMF37 scenarios most relevant to hydrogen markets include three reference scenarios: *Reference, Net Zero*, and *Net Zero+*. The *Reference* scenario is the only scenarios that does not achieve 80 % decarbonization goals by 2050, *Net Zero* achieves the goal with reference technology assumptions, and *Net Zero+* achieves the goal with advanced technology assumptions. 18 additional scenarios explore variations in technology and policy assumptions related to carbon management (CMSG, for Carbon Management Study Group), transportation (TSG), industry (ISG) and buildings (BSG). Only three CMSG scenarios explicitly address the role of hydrogen compared to other technologies, especially carbon capture and storage (CCS) and direct air capture (DAC). Assumptions for other scenario variations do not include explicit advantages or disadvantages for hydrogen compared to other decarbonization technologies.

The following are key takeaways from the examination of hydrogen market results reported to EMF37:

- Hydrogen data are reported through the EMF37 data collection template within different tiers and subsectors; these data inconsistencies have been harmonized to portray hydrogen market uptake in new emerging markets in a consistent manner across all models.
- A high level of variability is seen for the 9 models reporting hydrogen production types, with tendencies towards hydrogen production decarbonizing over time through increased reliance on electrolytic production and conversion of natural gas through steam methane reforming (SMR) with carbon capture and storage (CCS).
- Hydrogen market uptake results across 116 model-scenario combinations are skewed towards high volumes by 2050. Uptake results from the lowest quartile of scenarios (28 scenarios) range from 0 to 0.1 MMT H2, while the highest quartile (29 scenarios) range from 15.2 to 155 MMT H2. The raw average across all combinations is 13 MMT H2, while the average of combinations reporting results greater than 0.1 MMT H2 is 17 MMT H2.
- Transportation demands tend to dominate *Reference* scenario results, which range from zero to 7.5 MMT H2 by 2050, predominantly from medium- and heavy-duty trucks.
- For most but not all models, hydrogen market uptake increases moving from *Net Zero* to *Net Zero+*, suggesting that advanced assumptions across technologies tend to favor hydrogen over other decarbonization options. Demands between transportation and industry are more balanced for *Net Zero* and *Net Zero+* scenarios compared to *Reference*, with total uptake ranging from zero to 90 MMT H2.
- While assumptions in TSG scenarios explore drivers for transportation sector decarbonization, relatively large hydrogen market uptake within transportation is found across multiple scenario types, including CMSG scenarios favoring hydrogen technologies by limiting CCS and DAC.
- Hydrogen market uptake within transportation and industry vary widely not only in total amounts, but also across various sub-sectors within each industry. This is largely due to variations in the scope of hydrogen competition within particular models.
- An examination of vehicle cost and fuel economy attributes suggest that cost (e.g., vehicle MSRP) may be less of a driver of market adoption than fuel costs. However, explicit data on hydrogen fuel costs to vehicles was not available across a sufficient enough number of models to substantiate this observation. Additional vehicle, consumer, fuel, or refueling availability attributes may also account for differences in hydrogen vehicle market adoption.
- Two unique “breakthrough” scenarios are observed (MARKAL-NETL’s *CMSG NoDAC* and US-REGEN’s *CMSG NoCCS*) with 3–5x higher hydrogen uptake than the next largest scenario result from each model. The US-REGEN “breakthrough” scenario includes significant hydrogen uptake for synfuels, syngas, and electricity generation.
- Some trends emerge when comparing carbon abatement costs (the dollar per tonne CO_2e reduced price require to achieve decarbonization by 2050) to hydrogen market uptake trends. However, these trends vary, with carbon abatement costs either increasing or decreasing with increased hydrogen market uptake, depending on the model.
- In general, there is a tendency for an inverse relationship between market success of CCS and DAC and hydrogen market success.
- Given the variability in hydrogen market uptake across sectors and subsectors, an aggregated upper bound on hydrogen market potential is identified for the top 10 % of scenario results by sector, with the resulting total uptake ranging from 42 to 223 MMT H2. This range is unique to EMF37 and should not be interpreted as a general characterization of hydrogen’s market potential.

The wide range of results across model-scenario combinations can be explained in large part by the difference in scope and degree to which

[p] Given the highly heterogeneous origin of these market results, they are not amenable to statistical comparison. Moreover, aggregating the highest uptake results at lower data tier levels (e.g., across subsectors within transportation, rather than just transportation and industry) does not significantly change the clustering results characterizing this upper range.

hydrogen representations have been integrated within EMF37 models. In addition, variations in inputs assumptions, such as production type and cost and end-use technology competition, are another important explanatory tendency. These observations lead to the recommendation for increased harmonization in both model representation scope and improved consistency of hydrogen inputs assumptions as a means of increasing alignment on hydrogen's economic role in decarbonization. Additional recommendations for future work, which largely align with recommendations from other related studies [18,23,47], include the following:

- Improve multi-sector interactions with hydrogen systems, especially with the electric grid and bioenergy supply systems, as well as economies of scope across various end-use sectors.
- Expanded assessment and integration of sustainability and lifecycle metrics associated with hydrogen supply chains [42,60].
- Improved resolution and consistency of carbon intensity values across hydrogen supply chains, which will prove critical in assessing existing and future policy mechanisms and international markets [38,39,61].
- Improved scenario development to identify upper bounds on hydrogen market potential under decarbonization conditions, exploring sensitivities that include: (1) successful hydrogen technological progress, and (2) limited progress with competing technologies (such as CCS, DAC, and competing end-use technologies across sectors).
- Alignment of input assumptions with updated techno-economic performance status of commercial projects, as well as future projections of technology performance [62,63].
- Improved electricity grid simulations with high renewables market share, approaching and in excess of 100 % of operational demand, with assessment of novel market designs allowing large scale consumer bidding.

These conclusions are not definitive observations on hydrogen outcomes from models participating in EMF37. Additional studies have been published by MARKAL-NETL, EP-RIO, and GCAM since finalizing the EMF37 scenarios in late 2023 [52,64,65]. As hydrogen representations become more complete, robust, and consistent over time, it is expected that insights will align towards a consensus on hydrogen's role in decarbonization.

CRediT authorship contribution statement

M.W. Melaina: . **C.S. Lenox:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **M. Browning:** Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D.L. McCollum:** Writing – review & editing, Visualization, Investigation, Conceptualization. **O. Bahn:** Writing – original draft, Methodology, Investigation, Conceptualization. **S. Ou:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100153.

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