LCRI LOW-CARBON RESOURCES INITIATIVE

EPRI

GTI ENERGY

TECHNICAL REPORT

Clean Energy Network Analysis (CENA)

Co-Optimization of Hydrogen and Carbon Dioxide Infrastructure Deployment in a Net-Zero U.S. Economy

THE LOW-CARBON RESOURCES INITIATIVE

This report was published under the Low-Carbon Resources Initiative (LCRI), a joint effort of EPRI and GTI Energy addressing the need to accelerate development and deployment of low- and zero-carbon energy technologies. The LCRI is targeting advances in the production, distribution, and application of low-carbon energy carriers and the cross-cutting technologies that enable their integration at scale. These energy carriers, which include hydrogen, ammonia, synthetic fuels, and biofuels, are needed to enable affordable pathways to economy- wide decarbonization by mid-century. For more information, visit www.LowCarbonLCRI.com.

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ACKNOWLEDGMENTS

GTI Energy prepared this report under the Low Carbon Resources Initiative (LCRI).

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ABSTRACT

Economy-wide decarbonization studies have consistently pointed to large-scale deployment of H_2 and CO_2 infrastructure assets as part of their least-cost pathways to reach net-zero conditions in the U.S. In this Clean Energy Network Analysis (CENA), we evaluated and visualized the potential geospatial deployment of these infrastructure assets with the aim of illuminating new insights that were not previously understood. We developed and applied a novel cost-minimization modeling tool that allows for the evaluation of co-optimized placement of H_2 and CO_2 infrastructure assets. Such infrastructure modeling tools may prove useful in supporting energy transition infrastructure planning efforts by providing a cost-effective means to evaluate a wide range of potential future scenarios and regions of interest. The results of this study highlight a considerable level of infrastructure deployment and system integration. While the results illuminate the potential challenges for infrastructure planning given the high level of system interconnectivity and potential variability, they also highlight the relative feasibility of deploying these systems.

Keywords

Hydrogen
Carbon dioxide
Net-zero
Infrastructure
Network
Pipeline

ACRONYMS

ANL	Argonne National Laboratory
AOI	Area of interest
ARCH2	Appalachian Regional Clean Hydrogen Hub
CC	Carbon capture
CENA	Clean Energy Network Analysis
CO_2	Carbon dioxide
CO_2NCORD	CO_2 National Capture Opportunities and Readiness Data
DOE	U.S. Department of Energy
EER	Evolved Energy Research's Annual Decarbonization Perspective 2023
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GDP	Gross domestic product
H_2	Hydrogen
LCRI	Low-Carbon Resources Initiative's Net-Zero Scenarios 2.0
NG	Natural gas
RNG	Renewable natural gas
SNG	Synthetic natural gas
U.S.	United States
UHS	Underground hydrogen storage

UNITS

Btu	British thermal unit
EJ	Exajoule
km	Kilometer
MMcfd	Million cubic feet per day
Mt	Megatonne or million metric ton
scf	Standard cubic feet
SCFM	Standard cubic feet per minute
t	Tonne or metric ton

INTRODUCTION

In recent years, energy system modelers have investigated what a net-zero United States (U.S.) economy might look like, providing insight into the role of low-carbon resources (Figure 1)[1-3]. The authors of this study conducted a meta-analysis of five such independent U.S. economy-wide net-zero studies ("Meta NZ") [3]. Across these studies, net-zero energy systems consistently leverage large-scale deployment of hydrogen (H_2) and carbon management technologies, involving vast buildout of new infrastructure to move and store H_2 and carbon dioxide (CO_2) [3]. While these economy-wide studies offer valuable insights, they do not convey detailed information regarding the geographic placement and sizing of individual infrastructure assets. In this study, we developed a novel, state-of-the-art modeling approach that provides geographically granular insight regarding the needs and implications of H_2 and CO_2 infrastructure in net-zero energy systems. This modeling capability illuminates new insights and issues related to decarbonization planning that were not previously understood.

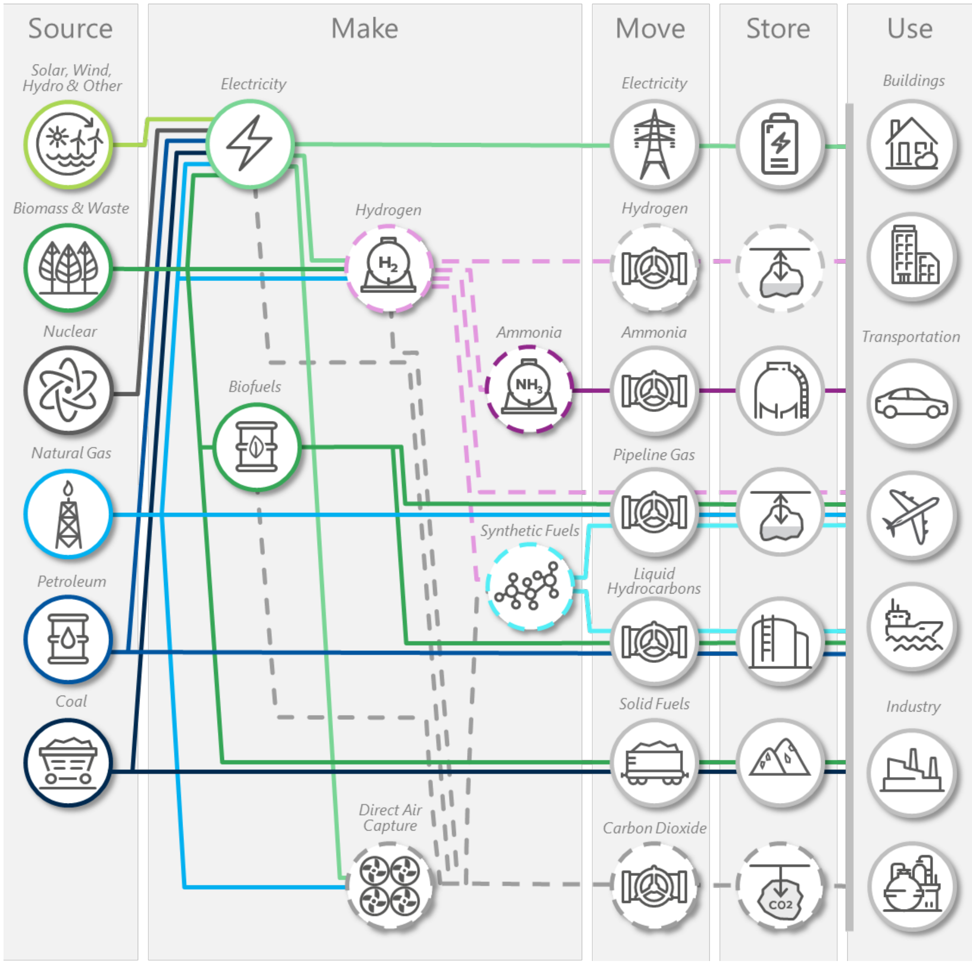

Figure 1. Net-zero energy systems will need new infrastructure to make, move, store, and use hydrogen and carbon dioxide. Figure adapted from Meta NZ [3].

Building upon the results of economy-wide studies, this Clean Energy Network Analysis (CENA) project evaluates the potential geospatial placement and sizing of gas infrastructure for H_2 and CO_2, with respect to existing natural gas (NG) infrastructure, and inclusive of renewable and synthetic natural gas use (RNG and SNG), in net-zero systems. In this CENA project, a novel modeling approach has been developed that enables simultaneous co-optimization of CO_2 and H_2 infrastructure placement and sizing relative to NG infrastructure. While the present study evaluated a single region in the U.S. (Appalachia), the infrastructure co-optimization capability developed in this study can be applied to various geographies and scales. This study offers fresh insight into the needs, challenges, and uncertainties associated with deploying new H_2 and CO_2 infrastructure assets at the scale required to achieve net-zero targets, providing a deeper understanding to support long-term infrastructure planning efforts.

METHODOLOGY

The aim of CENA was to evaluate optimized gas infrastructure asset placement and sizing in deeply decarbonized energy systems. To analyze such decarbonized systems, we adopted the results of two U.S. economy-wide net-zero studies, Evolved Energy Research's Annual Decarbonization Perspective 2023 ("EER") and the Low-Carbon Resources Initiative's Net-Zero Scenarios 2.0 analysis ("LCRI") released in 2024 [4, 5]. We used simulated regional- or state-level 2050 data from two net-zero scenarios from each study and apply it to the Appalachian area of interest (AOI). To determine the optimal placement and sizing of H_2 and CO_2 assets, we applied a bespoke cost minimization model termed "H2-CO2" developed by Carbon Solutions. This model builds upon Carbon Solution's proven capabilities for locating and optimizing the placement and sizing of CO_2 pipelines and storage sites, and proprietary databases such as CO_2 National Capture Opportunities and Readiness Data (CO_2NCORD) and SimCCS^{PRO} [6]. The methodology is visualized in Figure 2.

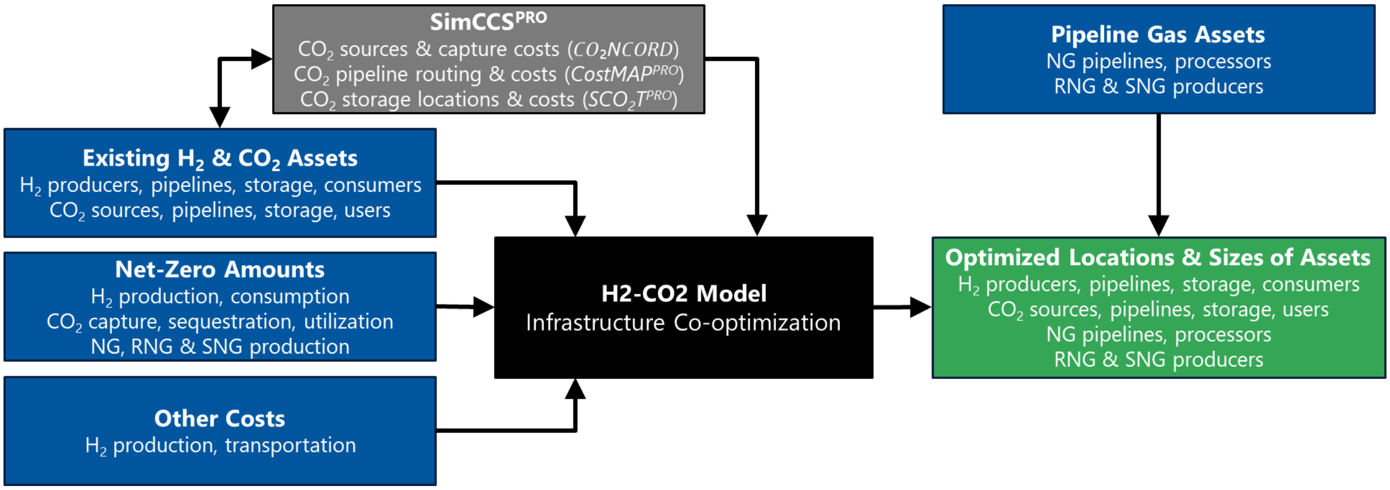

Figure 2. *Analytical approach for CENA.*

The resulting key output is a set of maps displaying optimized placement and sizes of gas infrastructure assets across the AOI:

- Carbon dioxide sources, CO_2 storage sites, CO_2 utilization sites, CO_2 pipelines.
- Hydrogen producers, H_2 consumers, H_2 pipelines, H_2 underground storage sites.
- Natural gas production/processing sites, RNG producers, SNG producers, and NG pipelines.

Analysis Sub-Region Selection and Definition

Given that CENA is a first-of-its-kind analysis, we chose to evaluate a smaller subregion of the U.S. rather than the entirety of the U.S. The Appalachia region was selected due to the following factors:

- The Appalachia region has industries such as steelmaking that could use H_2 as a fuel and feedstock.
- The Appalachia region has many large sources of CO_2 that could be captured.
- The Appalachia region has extensive existing gas infrastructure.
- The Appalachian Regional Clean Hydrogen Hub (ARCH2) was selected as a Regional Clean Hydrogen Hub by the U.S. Department of Energy (DOE) [7].

The AOI chosen is shown in Figure 3. It includes Appalachian counties in four states—Kentucky, Ohio, Pennsylvania, and West Virginia—and overlaps with the ARCH2 region [7].

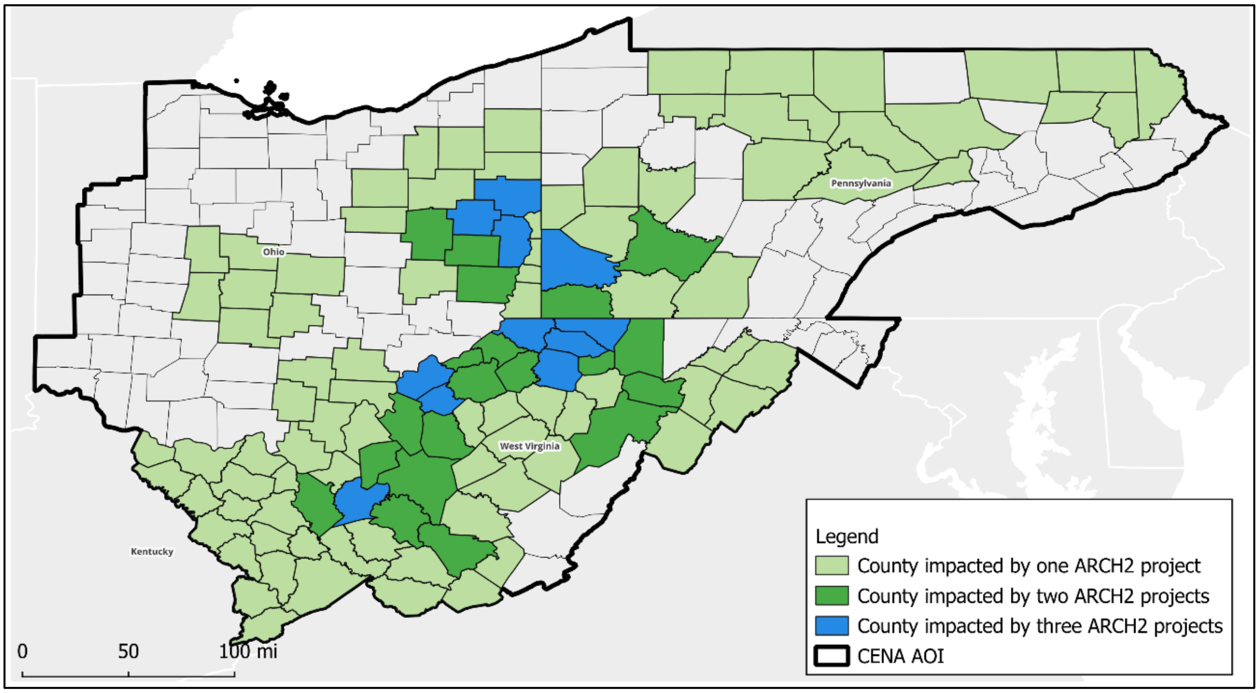

Figure 3. *Map showing the counties and states in the area of interest, highlighting the counties impacted by ARCH2 projects.*

Existing Infrastructure Assets – Compilation of Available Data

Existing Natural Gas, Renewable Natural Gas, and Synthetic Natural Gas Assets

Existing NG production and processing sites (“Gas processors”) were obtained from the U.S. Energy Information Administration (EIA) Energy Atlas and filtered to sites with capacities of 50 million cubic feet per day (MMcfd) or greater [8]. Active NG transmission pipelines were also obtained from the EIA Energy Atlas. There are 73,243 kilometers (km) of existing NG pipelines in the AOI. Existing NG assets in the AOI are shown in Figure 4.

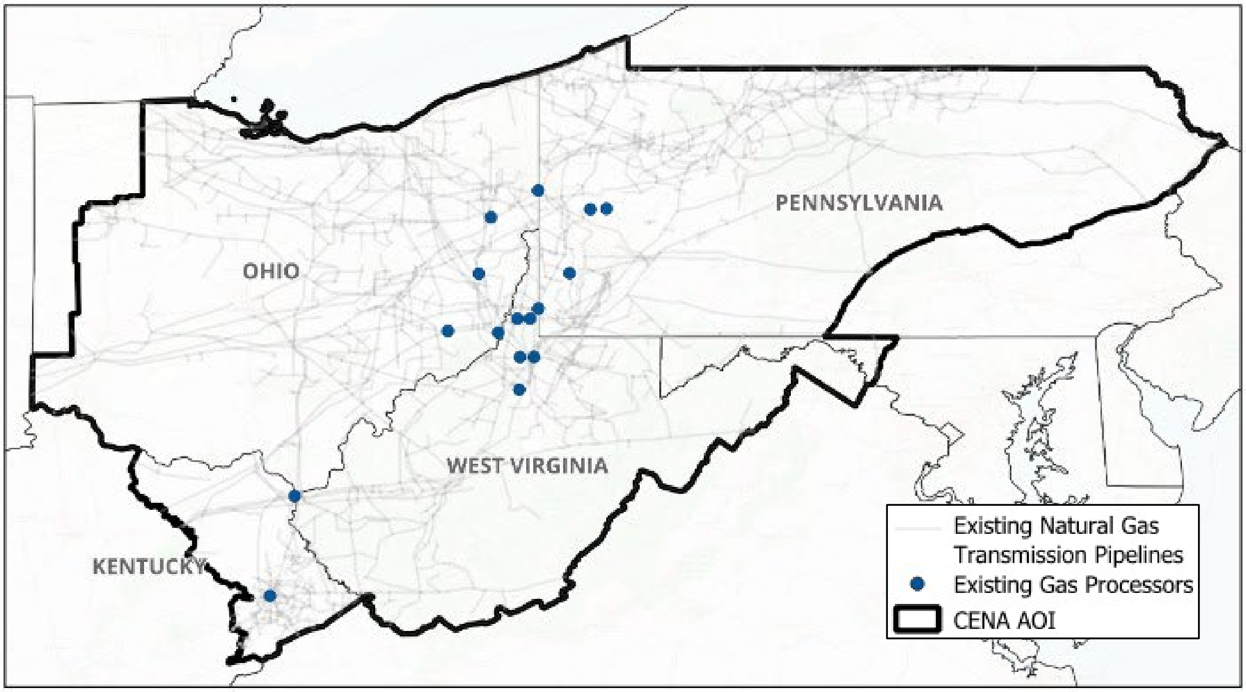

Figure 4. *Existing natural gas assets in the area of interest.*

There are 18 existing RNG production sites in the AOI to date, based on data from the U.S. Environmental Protection Agency (EPA) Landfill Methane Outreach Program, the EPA Livestock Anaerobic Digester Database, and the Argonne National Laboratory (ANL) Renewable Natural Gas Database [9-11]. To date, there are no SNG production sites in the AOI.

Existing Hydrogen Assets

Data on existing H_2 production sites were obtained from Hydrogen Tools, DOE, and the International Energy Agency [12-15]. The AOI has 11 existing H_2 production sites (nine SMRs and two electrolyzers). Existing H_2 consumers in the AOI include refineries and ammonia producers. There are no H_2 pipelines or H_2 storage sites in the AOI to date.

Existing Carbon Dioxide Assets

Carbon Solutions' CO_2NCORD tool was used to identify 252 CO_2 sources in the region that emit at least 0.05 MtCO_2/yr. None of these sources are currently retrofitted with CO_2 capture technology. There are no CO_2 pipelines, CO_2 storage sites, or CO_2 utilization sites in the region to date.

New Assets – Geographical Disaggregation of Net-Zero Scenario Results

Selection of Net-Zero Scenarios

The EER and LCRI studies solved for a least-cost optimization of the U.S. economy to meet net-zero targets by 2050 under various conditions, constraints, and scenarios. These studies provided a range of answers to questions such as, "How much hydrogen might be produced via electrolysis in the U.S. in 2050 under net-zero requirements?". Each study provided the scenario results at a regional level that depended on the geographic granularity of their underlying models. LCRI's US-REGEN model divided the Lower 48 states into 16 regions, enabling an answer to the question at a regional level. EER's EnergyPATHWAYS model divided the entire U.S. into 27 regions but also reported state-level results.

Two net-zero scenarios were selected from each study. These scenarios were chosen so that we could explore the uncertainty associated with many underlying assumptions in the models, summarized below:

1. **LCRI Opt-Tech** explored optimistic assumptions for CO_2 transport and storage, electrolysis, advanced nuclear, and bioenergy.
2. **LCRI Lim-CCS Opt-Nuc** explored optimistic assumptions for electrolysis and nuclear, but limited CO_2 storage.
3. **EER Central** modeled the least-cost pathway for achieving net zero by 2050 using a high electrification demand-side case with the fewest constraints on resources and technologies.
4. **EER Low Land** limited the amount of land available for building energy infrastructure.

The AOI did not align with state boundaries or regions in either of the two studies. We thus had to disaggregate the region- or state-level net-zero data to the AOI. We used county-level real gross domestic product (GDP), an inflation-adjusted indicator of economic activity, as a normalizing parameter for the geographic data disaggregation process. That is, the region- or state-level data from the U.S. economy-wide studies was disaggregated into county-level data based on the fraction of the total real GDP of each county in the AOI. This county-level data was then summed across the AOI to develop total values to be used as inputs and/or constraints for the H2-CO2 model optimization runs. Relevant total values across the AOI are listed in Table 1.

Table 1. *Total level of H_2 consumption and production, CO_2 utilization, sequestration, and capture, RNG production, SNG production, and NG production in the AOI, resulting from the disaggregation analysis using county-level real GDP.*

Physical Quantity	LCRI Opt-Tech	LCRI Lim-CCS Opt-Nuc	EER Central	EER Low Land
H_2 consumption total [Mt/yr]	0.13	0.63	2.43	2.88

Green H_2 production total [Mt/yr]	0.00	0.63	1.38	1.77
Blue H_2 production total [Mt/yr]	0.13	0.00	1.04	1.11
CO_2 capture total [Mt/yr]	92.01	4.91	21.15	32.67
CO_2 sequestration total [Mt/yr]	92.01	0.00	18.59	29.40
CO_2 utilization total [Mt/yr]	0.00	0.00	2.56	3.27
RNG production total [EJ/yr]	0.02	0.03	0.07	0.09
SNG production [EJ/yr]	0.00	0.00	0.00	0.00
NG production total [EJ/yr]	3.71	0.04	3.71	4.99

Existing H_2 and CO_2 assets in the AOI are insufficient to meet the totals listed in Table 1. New assets would need to be sized, located, and built to achieve the H_2 production and CO_2 capture levels shown in Table 1 in support of the U.S. economy-wide net-zero target in these four scenarios. The following subsections summarize the process by which these new assets were defined.

New Natural Gas, Renewable Natural Gas, and Synthetic Natural Gas Assets

The LCRI and EER studies forecasted that total pipeline gas consumption in the AOI would fall below current levels by 2050. Thus, we assumed that no new natural gas production sites or gas pipelines would be built in any of the four net-zero scenarios.

The potential RNG production from 48 additional sites in the AOI was based on estimates from the EPA [9-11]. Assuming all 48 sites could be realized, summing these 48 sites plus the 18 existing sites gave us 66 potential RNG sites in the AOI. The total potential RNG production capacity from these 66 sites in the AOI was 161,592 SCFM or 0.09 EJ/yr.[1] These 66 RNG sites are highlighted in Figure 5, along with NG transmission pipelines. Sixty RNG sites are within 5 km of NG transmission pipelines. Table 1 shows disaggregated RNG production totals for the four 2050 net-zero scenarios. Leveraging the potential RNG production capacity in the AOI would make it possible to meet the RNG totals in all four scenarios.

Table 1 also shows total NG production for the four scenarios across the AOI. In three scenarios, the amount of RNG production is very small compared to the amount of NG production. The values are comparable only in the LCRI Lim-CCS Opt-Nuc scenario, which did not allow CO_2 storage.

Zero SNG production was forecasted in the AOI in the four 2050 net-zero scenarios. Accordingly, no SNG production sites were modeled in this study.

The RNG assets were not included in the H2-CO2 co-optimization analysis, which sought to optimize the location and/or sizing of H_2 and CO_2 assets.

[1] Calculated using an average heating value of 970 Btu/scf from EPA (range 950–990).

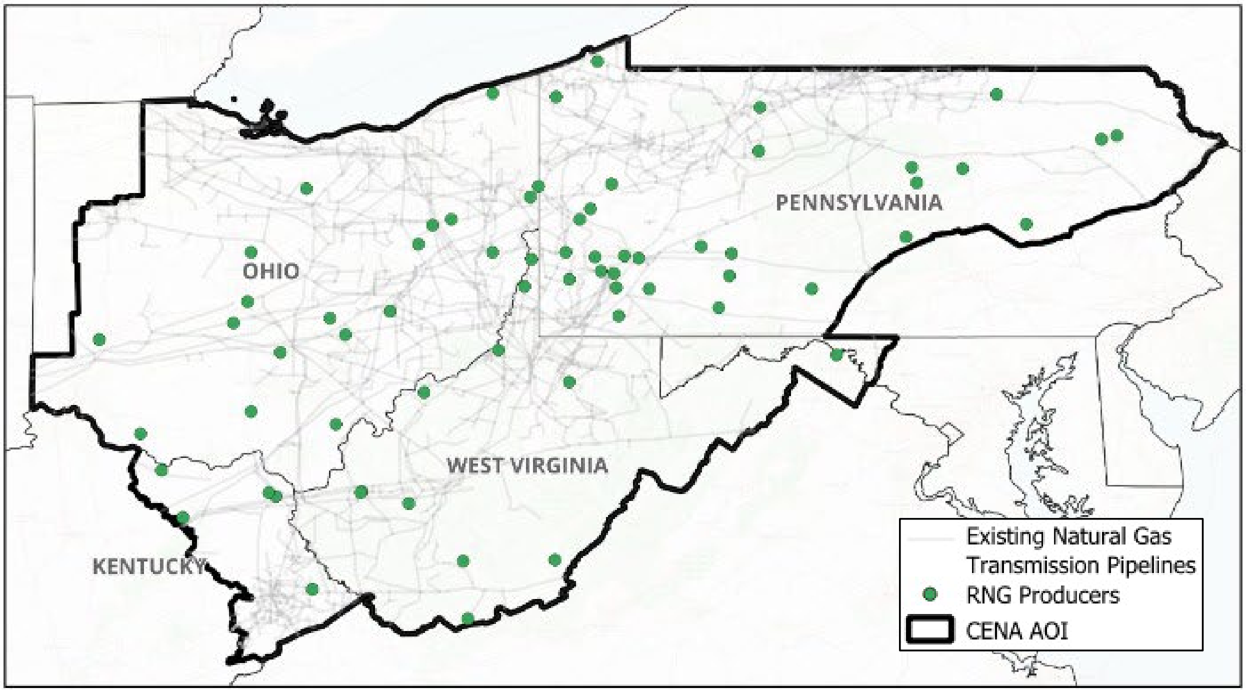

__Figure 5.__ Map showing existing natural gas pipelines and potential renewable natural gas production sites in 2050.

New Hydrogen Assets

The databases used for identifying existing H_2 production sites also included some planned H_2 production sites [12-15]. We assumed that under net-zero conditions, all natural gas reformation sites implement carbon capture (CC) and that these facilities would be constructed on-site to produce H_2.[2] The net-zero scenarios explored in CENA modeled a certain amount of H_2 production via biomass gasification with CC. Since no such facilities currently exist in the AOI, it was assumed that a subset of biomass-based industrial facilities would be converted into H_2 production facilities. To simplify the model, the natural gas reformation and biomass gasification facilities, both with CC, are grouped together as "blue" H_2.

When modeling electrolytic or "green" H_2, we assumed all electrolyzers were proton exchange membranes. New electrolyzers were sited by identifying locations with abundant water availability and proximity to electricity transmission lines. We assumed that all H_2 production sites would have capacities of 300 tonnes (metric tons) per day (t/day) in the LCRI Opt-Tech, LCRI Lim-CCS Opt-Nuc, and EER Central scenarios. However, we assumed capacities of 600 tonnes per day for the EER Low Land scenario to enable the model to solve for fewer sites in this land-constrained scenario. All H_2 production costs were obtained from the underlying net-zero studies and levelized per kilogram of H_2. The resulting estimated costs varied for each type of H_2 production in each scenario.

[2] Natural gas reformation refers to the production of hydrogen from natural gas via either steam methane reforming or autothermal reforming.

We assumed H_2 would be transported from producers to consumers via purpose-built H_2 pipelines. None of the four net-zero scenarios modeled any H_2 blending in NG pipelines, so H_2 blending was excluded from this analysis. Hydrogen pipeline costs were obtained from ANL [16]. We assumed that the EER Low Land scenario would have higher H_2 transportation costs to mimic socio-environmental opposition to building energy infrastructure in this scenario.

We assumed that H_2 would be stored underground in subsurface/geologic depleted oil and gas reservoirs, given the abundance of such sites in the AOI (Figure 6) [17]. We assumed underground hydrogen storage (UHS) sites would always exist along pipelines connecting producers and consumers. Costs associated with UHS were obtained from the Subsurface Hydrogen Assessment, Storage, and Technology Acceleration report [18].

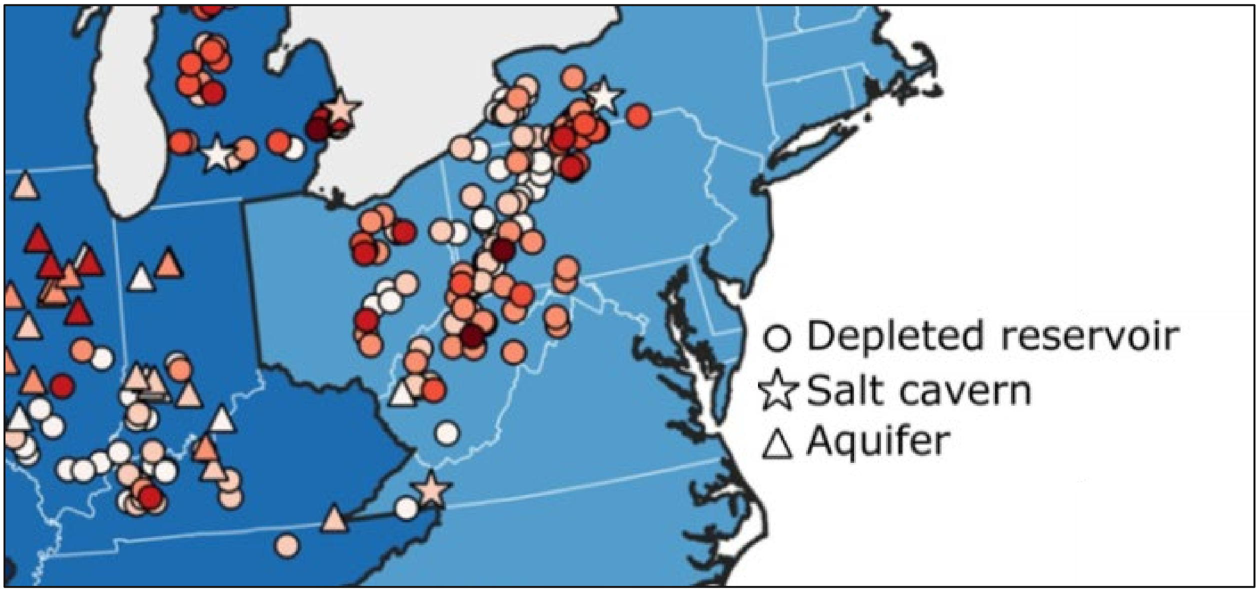

Figure 6. Map showing potential underground hydrogen storage sites. Adapted from Lackey et al. [17].

In the four net-zero scenarios, H_2 was consumed by six industrial off-takers — iron and steel, cement and lime, ammonia, synthetic fuels, refineries, and medium- and heavy-duty transportation.

New Carbon Dioxide Assets

In the four net-zero scenarios, CO_2 is captured from four types of activity—hydrogen production, power plants, cement and lime production, and ethanol production. We assumed that CO_2 would be transported via dedicated pipelines from source to sink (storage or utilization) and sequestered onshore in geologic subsurface formations (Figure 7) as a form of CO_2 storage [19]. Capture, transportation, and sequestration costs were obtained from SimCCS^{PRO} [6]. Synthetic fuel production is assumed to be the only CO_2 utilization pathway in CENA.

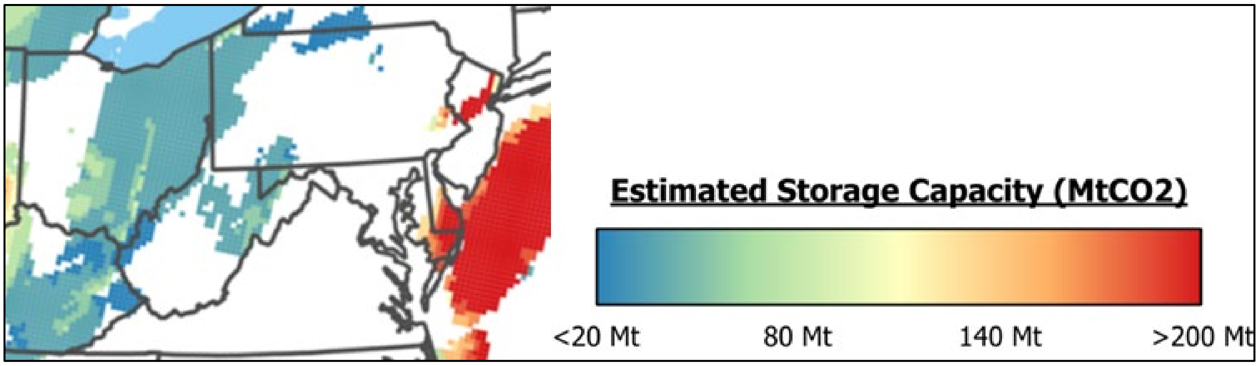

__Figure 7.__ Map showing estimated underground CO_2 storage capacity. Adapted from Carbon Solutions [19].

All potential H_2 and CO_2 assets in 2050 are plotted in Figure 8.

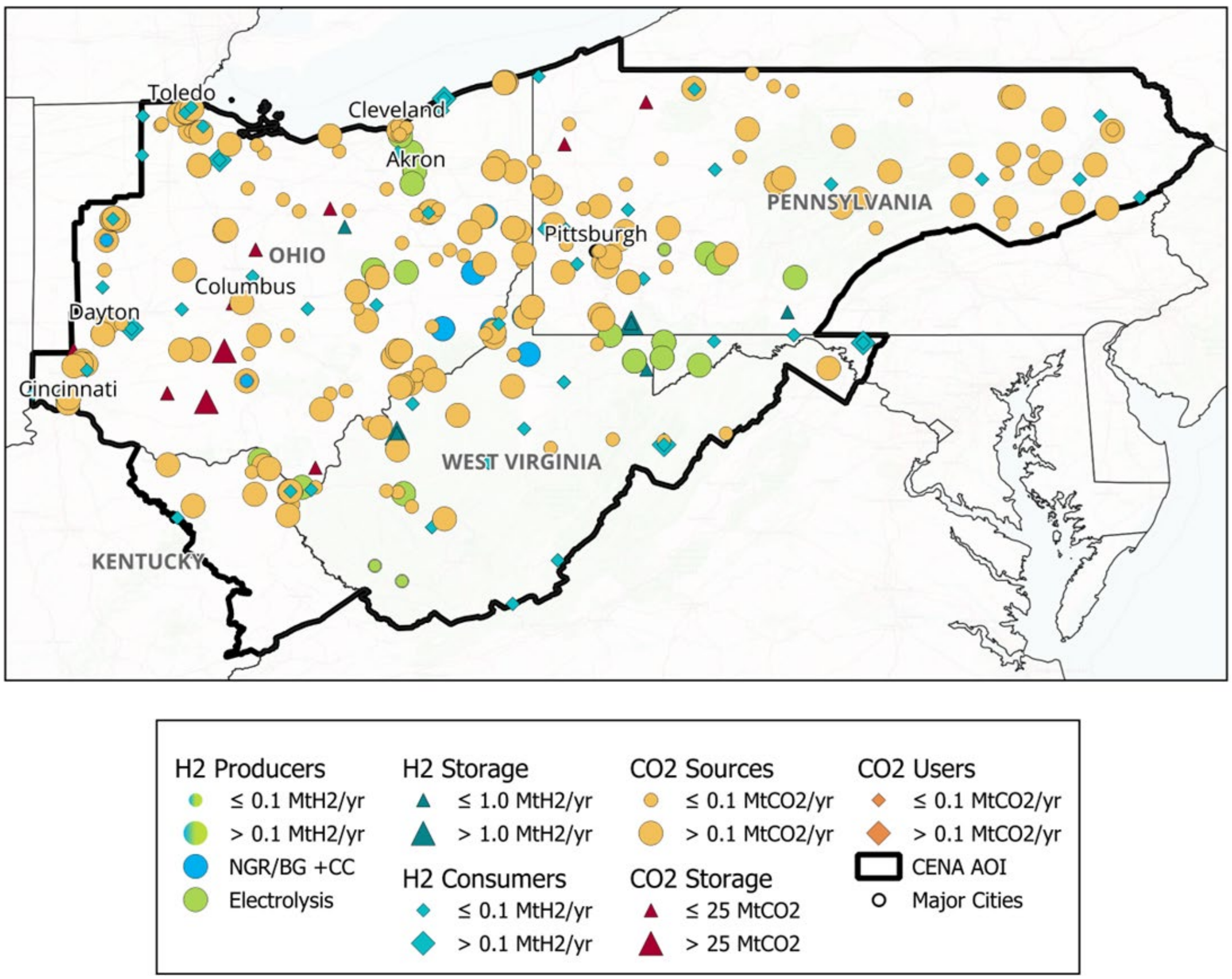

__Figure 8.__ Potential hydrogen and carbon dioxide assets in the area of interest.

Optimization of Potential Assets

The H2-CO2 model was developed, validated, and applied to determine the optimal location, number, and size of H_2 and CO_2 assets in the four net-zero scenarios. The H2-CO2 model used mixed integer linear programming with the CPLEX solver to find the least-cost solution for a scenario. Given the objectives of each scenario (e.g., blue and green H_2 production targets and CO_2 capture targets in 2050), the H2-CO2 model finds the least-cost solution that provides sufficient pipeline and storage infrastructure to transport the H_2 from production facilities to storage sites and consumers and to capture, transport, and utilize or sequester the CO_2. The cost minimization objective function includes the following costs:

- The cost of capturing CO_2 at emission sources.
- The cost of transporting CO_2 to sequestration or utilization sites.
- The cost of injecting or sequestering CO_2 into underground storage sites.
- The cost of blue H_2 production, including the cost of capturing CO_2.
- The cost of green H_2 production.
- The cost of storing H_2 underground.
- The cost of transporting H_2 from production sites to consumption sites via storage sites.

The H2-CO2 model contains multiple constraints, including but not limited to:

- Blue and green H_2 production targets must be met.
- CO_2 capture targets must be met.
- The CO_2 and H_2 flowing through each pipe section behave as expected in terms of flow direction.
- H_2 production at each facility cannot exceed each facility's maximum production capacity.
- CO_2 sequestration cannot exceed the maximum capacity of storage sites.

The H2-CO2 model leverages existing rights-of-way of NG pipelines, when available, while modeling the buildout of new H_2 and CO_2 pipelines. The model also accounts for topographic factors like land gradient. The major outputs and their associated inputs are connected in Table 2.

Table 2. *Key CENA modeled outputs with a brief description of the associated inputs.*

Outputs	Inputs
CO_2 capture sources	The SimCCS database contained the locations and sizes of all existing CO_2 sources and the costs of capturing CO_2 from those sources. The four net-zero scenarios defined the total amounts of CO_2 captured and blue H_2 produced in 2050. CENA was given the locations and sizes of potential blue H_2 producers. The H2-CO2 model solved for the sources from which CO_2 would be captured and the amount captured at each source.
CO_2 utilization facilities	The four net-zero scenarios defined the total amounts of CO_2 utilized, all of which is utilized to produce synthetic fuels. We assumed that synthetic fuel production facilities would be co-located with existing biofuel production facilities, i.e., ethanol producers. CENA was given the

	locations and sizes of existing ethanol producers. The H2-CO2 model solved for the facilities to which CO_2 would be transported for utilization and the amount utilized at each facility.
CO_2 storage	The four net-zero scenarios defined the total amounts of CO_2 stored. The SimCCS database contained the locations, sizes, and costs of all potential CO_2 storage sites. The H2-CO2 model solved for the storage sites and the amount stored at each site.
CO_2 pipelines	The SimCCS database contained the costs of building new CO_2 pipelines based on size, location, and other factors like topography. The H2-CO2 model solved for cost-optimized placement and sizes of pipelines.
H_2 producers	We obtained public data for existing and planned H_2 producers in the AOI. We developed a method to site potential new blue and green H_2 producers. The four net-zero scenarios defined the total amount and cost for each H_2 production method. The H2-CO2 model solved for the sites where H_2 would be produced.
H_2 consumers	Existing H_2 consumers include refineries and ammonia producers. In addition to these two groups, potential H_2 consumers include iron and steel producers, cement and lime producers, synthetic fuel producers, and medium- and heavy-duty transportation. The four net-zero scenarios defined the total amounts of H_2 consumption. We obtained public data for the locations and sizes of all potential H_2 consumers. The H2-CO2 model solved for the sites where H_2 would be delivered and consumed.
H_2 storage	We obtained locations and costs for potential underground H_2 storage sites [17, 18]. We assumed all H_2 pipelines connecting suppliers with consumers would include a storage facility. In other words, H_2 produced at a site must pass through an H_2 storage site before reaching an H_2 consumer. Given the nascency of underground H_2 storage, such simplifying assumptions had to be made. The H2-CO2 model solved for the specific locations for cost-optimized placement, subject to constraints.
H_2 pipelines	There were no existing H_2 pipelines in the AOI. Hydrogen pipeline costs were obtained from ANL [16]. We assumed all H_2 pipelines connecting suppliers with consumers would include a storage facility. This assumption lengthened the H_2 pipelines calculated by the model. The H2-CO2 model solved for specific locations for cost-optimized placement, subject to constraints.

RESULTS

Table 3 summarizes the results of the four net-zero scenarios analyzed using the H2-CO2 model: LCRI Opt-Tech, LCRI Lim-CCS Opt-Nuc, EER Central, and EER Low Land. Table 3 shows the numbers of assets, lengths of H_2 and CO_2 pipelines, annual H_2 and CO_2 amounts, and annual costs (2022$billion/yr). The cost of capturing CO_2 from blue H_2 production facilities was embedded in the blue H_2 production costs. We did not consider the costs of consuming H_2 or utilizing CO_2. Thus, Table 3 does not show any costs associated with these parameters.

Table 3. *Modeled results for each scenario.*

Category	Variable	LCRI Opt-Tech	LCRI Lim-CCS Opt-Nuc	EER Central	EER Low Land
Number of Assets	Blue H_2 Producers	2	0	10	6
	Green H_2 Producers	0	6	13	9
	H_2 Storage Sites	3	1	2	3
	H_2 Consumers	27	45	60	62
	Non-H_2 CO_2 Sources	194	4	9	14
	CO_2 Sequestration Sites	9	0	2	3
	CO_2 Consumers	0	0	6	6
Physical Quantity	Length of H_2 Pipelines (km)	3763	3523	4801	4602
	Length of CO_2 Pipelines (km)	6018	472	1242	1576
	Blue H_2 Produced (MtH_2/yr)	0.1	0.0	1.0	1.1
	Green H_2 Produced (MtH_2/yr)	0.0	0.6	1.4	1.8
	CO_2 Captured at Blue-H_2 Sites ($MtCO_2$/yr)	1.6	0.0	9.7	10.3
	CO_2 Captured at Non-H_2 Sites ($MtCO_2$/yr)	90.4	4.9	11.5	22.4
	CO_2 Sequestered ($MtCO_2$/yr)	92.0	0.0	18.6	29.4
	CO_2 Utilized ($MtCO_2$/yr)	0.0	0.0	2.6	3.3
Annual Cost	Blue H_2 Production (2022$b/yr)	0.2	0.0	1.1	1.1
	Green H_2 Production (2022$b/yr)	0.0	0.7	0.7	1.0
	H_2 Storage (2022$b/yr)	0.1	0.0	0.1	0.1
	H_2 Pipelines (2022$b/yr)	0.5	0.6	0.8	0.8
	Non-H_2 CO_2 Capture (2022$b/yr)	11.9	0.4	1.0	1.9
	CO_2 Pipelines (2022$b/yr)	1.9	0.1	0.3	0.4
	CO_2 Storage (2022$b/yr)	1.4	0.0	0.3	0.5
	Total Annual Cost (2022$b/yr)	*16.1*	*1.8*	*4.2*	*5.8*

LCRI Opt-Tech Scenario

The LCRI Opt-Tech scenario explored optimistic assumptions for CO_2 transport and storage, electrolysis, advanced nuclear, and bioenergy. Given the small amount of blue H_2 produced in this scenario, only two blue H_2 producers were needed. No green H_2 was produced. Hydrogen demand, though small, was spread over 27 H_2 consumption sites scattered across the AOI, as shown in Figure 9. Thus, 3,763 km of H_2 pipelines and three H_2 storage sites were needed for the least-cost solution.

The LCRI Opt-Tech scenario had the highest CO_2 capture total among all scenarios, 92.0 $MtCO_2$/yr. This large requirement necessitated capturing CO_2 from every possible CO_2 source (194 sources) in the AOI, irrespective of cost, leading to a total non-H_2 CO_2 capture cost of \$11.9 billion/yr.[3] Only 1.6 of the 92.0 $MtCO_2$/yr was captured from blue H_2 production sites. All captured CO_2 was sequestered in underground storage sites. No CO_2 was utilized. More than 6000 km of CO_2 pipelines were needed to transport the CO_2 to sequestration sites.

The total annual cost for H_2 and CO_2 production (i.e., capture for CO_2), storage, and transport assets for this scenario was \$16.1 billion/yr (see Table 3).

[3] In other scenarios, the H2-CO2 model could choose to capture CO_2 from the cheaper CO_2 sources, bringing down the total annual costs of the scenario.

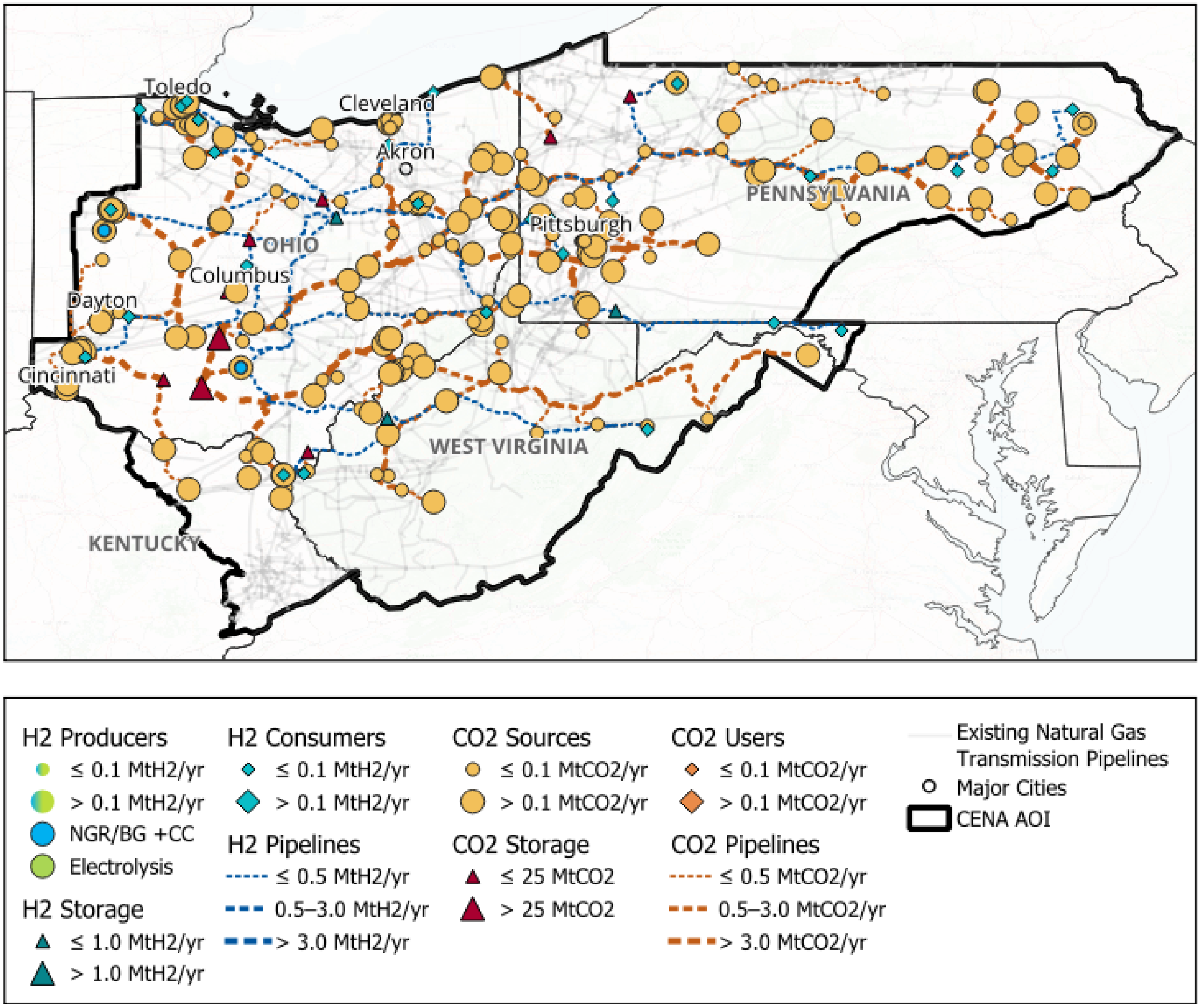

Figure 9. *Map showing co-optimized H_2 and CO_2 infrastructure in the LCRI Opt-Tech scenario.*

LCRI Lim-CCS Opt-Nuc Scenario

The LCRI Lim-CCS Opt-Nuc scenario explored the impacts of not allowing CO_2 storage. There was no blue H_2 production. Hydrogen was produced by six electrolyzers located near each other, as seen in Figure 10. The proximity of these electrolyzers necessitated only one H_2 storage site. However, like the LCRI Opt-Tech scenario, the 45 H_2 consumption sites were scattered around the AOI and thus required more than 3,500 km of H_2 pipelines.

The LCRI Lim-CCS Opt-Nuc scenario did not allow CO_2 storage. Although the scenario allowed CO_2 utilization, none occurred in the AOI. All captured CO_2 (4.9 $MtCO_2$/yr) was exported to neighboring states, as seen in the CO_2 pipeline at the western border of the AOI in Figure 10. The shorter CO_2 pipeline network spanned only 472 km, in contrast to the H_2 pipeline network's length of 3,523 km.

The total annual cost of H_2 and CO_2 infrastructure in this scenario was substantially lower than in the other scenarios, amounting to $1.8 billion/yr.

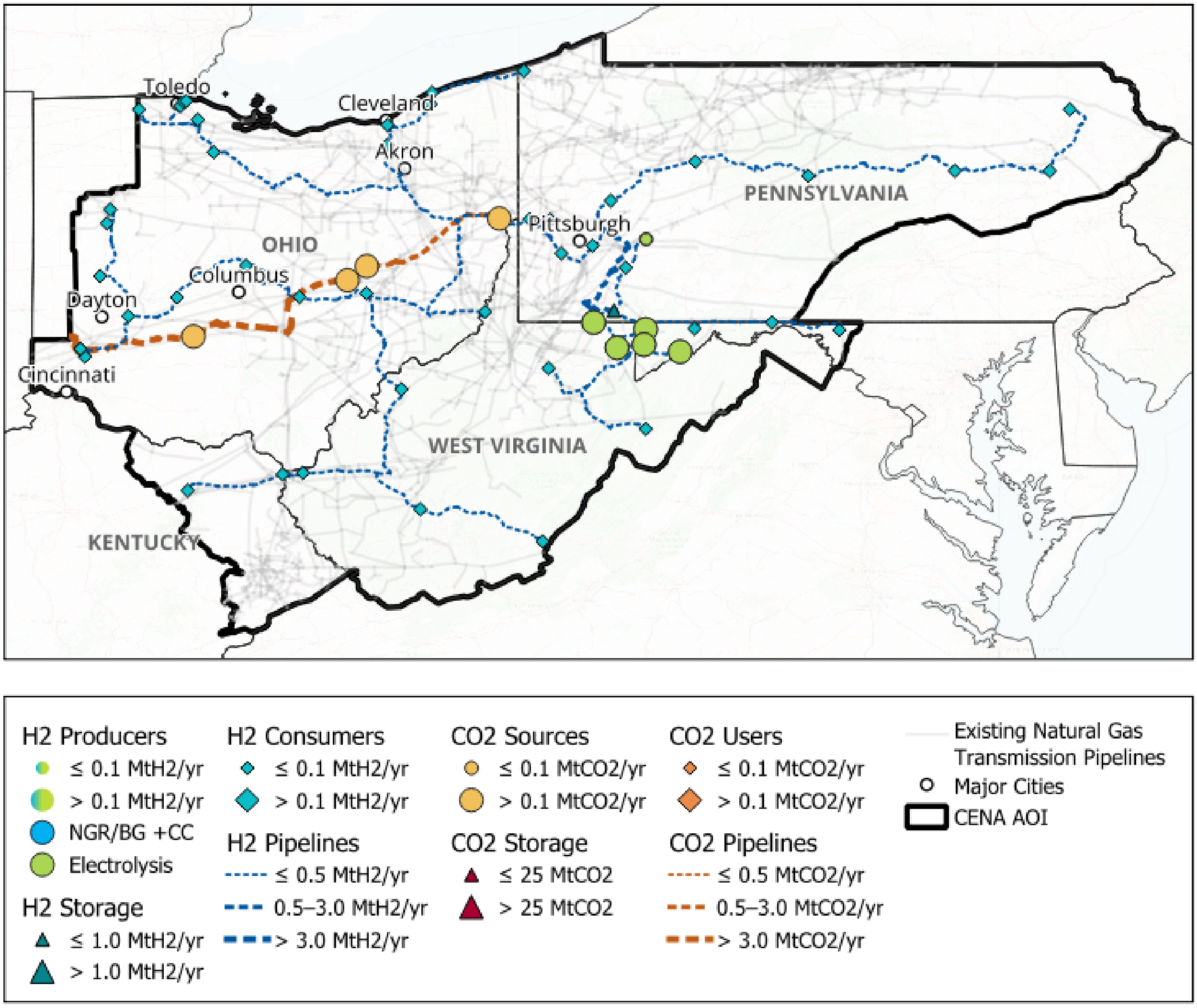

Figure 10. *Map showing co-optimized H_2 and CO_2 infrastructure in the LCRI Lim-CCS Opt-Nuc scenario*

EER Central Scenario

The EER Central scenario modeled the least-cost pathway for achieving net zero by 2050.[4] This scenario had the highest number of blue (10) and green (13) hydrogen production sites, as shown in Figure 11. Most H_2 production sites were located in the middle of the AOI, so only two H_2 storage sites were

[4] The EER Central scenario is the least-cost net-zero scenario in the EER study. Its total cost can be higher or lower than scenarios from other studies like LCRI.

necessary. Approximately 4,800 km of H_2 pipelines, the longest of all scenarios, fed 60 H_2 consumption sites scattered across the AOI.

Around 21 $MtCO_2$/yr was captured from ten blue H_2 sites and nine non-H_2 sources of CO_2. The captured CO_2 was managed by storing 18.6 $MtCO_2$/yr and utilizing 2.6 $MtCO_2$/yr. The CO_2 pipeline network extended 1,242 km.

The total annual cost of H_2 and CO_2 infrastructure in this scenario was $4.2 billion.

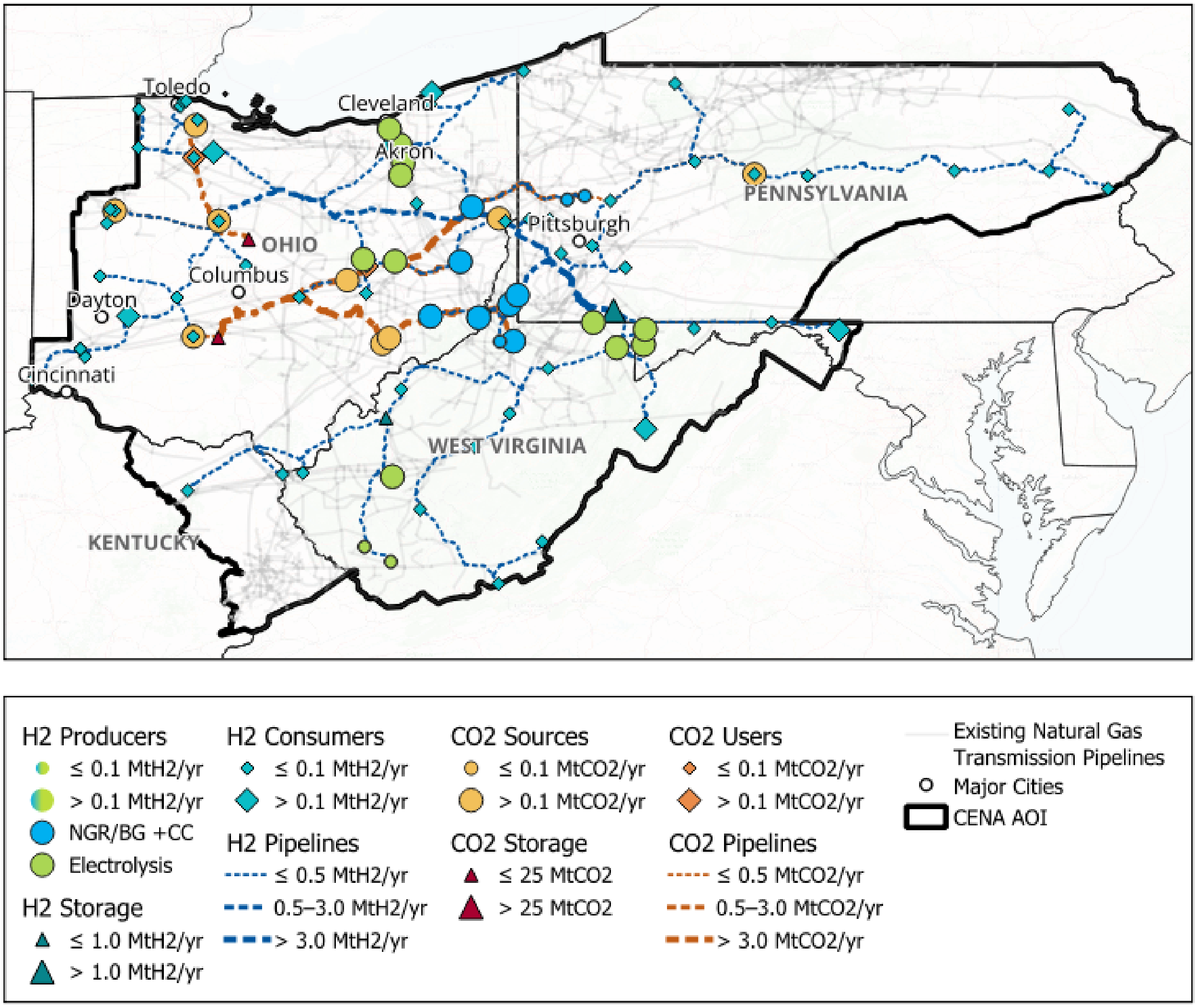

Figure 11. *Map showing co-optimized H_2 and CO_2 infrastructure in the EER Central scenario*

EER Low Land Scenario

The EER Low Land scenario limited the amount of land available for building energy infrastructure. Given this land-use constraint, we allowed this scenario to build larger (and thus fewer) H_2 production facilities.

We also assumed higher costs for H_2 pipelines to simulate the greater difficulty of building infrastructure in this scenario. These assumptions enabled the scenario to meet its H_2 production target with fewer (six blue, nine green) H_2 production facilities (Figure 12) and fewer H_2 pipelines when compared to the EER Central scenario. So, the total length of H_2 pipelines in this scenario (~4,600 km) was less than that in the EER Central scenario. Assumptions regarding H_2 storage were the same as those of other scenarios, and three H_2 storage sites were needed. There were 62 H_2 consumers, more than in any other scenario, because this scenario had the highest H_2 demand.

More CO_2 was captured in the EER Low Land scenario (32.7 $MtCO_2$/yr) than in the EER Central scenario, from 20 CO_2 sources. Roughly 90% of the captured CO_2 was sequestered underground (29.4 $MtCO_2$/yr), and the rest was utilized (3.3 $MtCO_2$/yr) to produce synthetic fuels. The CO_2 pipeline network was 1,576 km long. The focus on mitigating land-use barriers resulted in a smaller H_2 network but a larger CO_2 network than the EER Central scenario.

The total annual cost of H_2 and CO_2 infrastructure in this scenario was $5.8 billion.

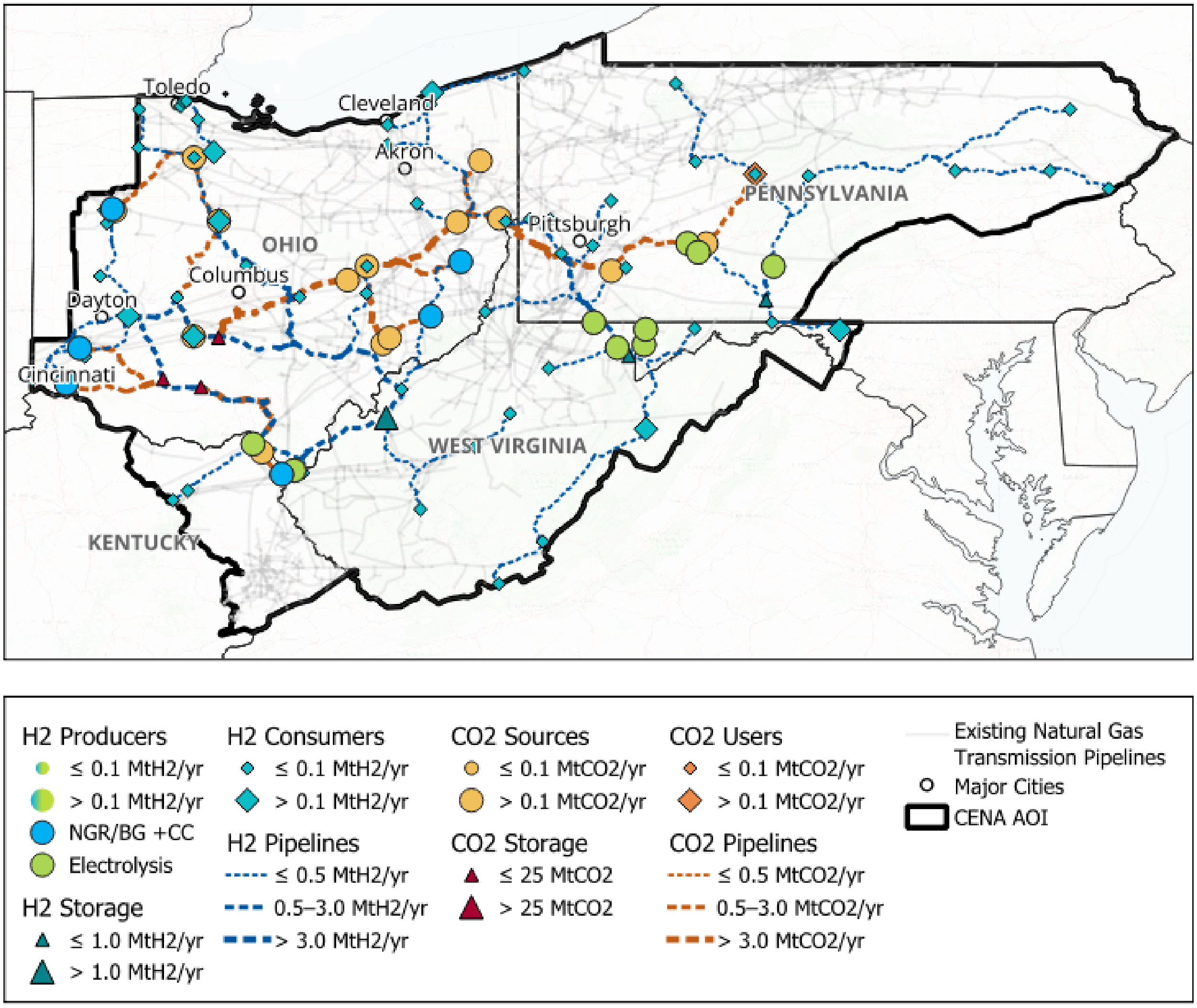

Figure 12. *Map showing co-optimized H_2 and CO_2 infrastructure in the EER Low Land scenario*

Comparison of Costs Across Scenarios

Annual CO_2 pipeline and storage costs were found to be higher for the scenarios with more CO_2 capture, but such additional costs did not scale linearly with the amount of CO_2 captured. Annual CO_2 pipeline and storage costs were much less than annual CO_2 capture costs in all scenarios. Thus, the extent of CO_2 capture required had a more significant impact on total cost of a given scenario than the extent of CO_2 transportation or storage infrastructure. The LCRI Opt-Tech scenario's annual CO_2-related costs exceeded $15 billion, higher than the total annual H_2 and CO_2 costs for the three other scenarios combined. This high annual cost was driven by the high cost of capturing CO_2 from every CO_2 source. When the CO_2 target is so high, the model must tap into every CO_2 source irrespective of capture cost. In the other three scenarios, the model could choose and capture from the cheaper CO_2 sources. However, this observation does not necessarily mean that the LCRI Opt-Tech scenario is less viable than other net-zero scenarios. In other words, the results of this study do not imply anything about the viability of the scenarios.

Annual H_2 production costs in each scenario depended on the amount of each type of H_2 produced because we assumed that each type of H_2 (green or blue) had the same levelized H_2 production costs for all producers of the same type within a scenario.[5] For example, the EER Low Land scenario had the highest annual green H_2 production and the highest annual green H_2 production costs.

Annual H_2 storage and pipeline costs for a scenario can be higher or lower than annual H_2 production costs. The LCRI Opt-Tech scenario had fewer H_2 producers and lower H_2 production amounts and costs than the LCRI Lim-CCS Opt-Nuc scenario. However, the LCRI Opt-Tech scenario needed more H_2 storage sites and H_2 pipelines. Thus, it had higher annual H_2 storage and pipeline costs than the LCRI Lim-CCS Opt-Nuc scenario. The EER Low Land scenario had fewer H_2 pipelines (4,602 km) than the EER Central scenario (4,801 km) but still had the same annual H_2 pipeline cost ($0.8 billion/yr) because we had assumed higher H_2 pipeline costs in EER Low Land.

Our attempt to simulate land-use restrictions in the EER Low Land scenario might have increased the total annual CO_2 and H_2 costs, which were 36% higher in the EER Low Land scenario than in the EER Central scenario. However, isolating this contrast in the results to one input assumption is difficult. Our higher H_2 pipeline cost assumption for the EER Low Land scenario could have led to fewer pipelines being built by the model. Our larger H_2 producer (600 t/day in EER Low Land versus 300 t/day in other scenarios) assumption could have led to fewer H_2 producers and, thus, fewer H_2 pipelines as well. Though we assumed higher H_2 pipeline costs for the EER Low Land scenario, no such assumptions were made for H_2 storage, CO_2 pipelines, or CO_2 storage. Future iterations of the H2-CO2 model could assume higher costs for these three parameters in the EER Low Land scenario to make the analysis more balanced.

H_2 and CO_2 Infrastructure Deployment Relative to NG Infrastructure

It is useful to contextualize the results of this study by comparing the magnitudes and build rates of new H_2 and CO_2 infrastructure with the magnitudes and build rates of NG infrastructure. The total lengths of new H_2 and CO_2 transmission pipelines in the four scenarios are listed in Table 4.

Table 4. *Total lengths of new pipelines in the four scenarios*

Scenario	LCRI Opt-Tech	LCRI Lim-CCS Opt-Nuc	EER Central	EER Low Land
Length of H_2 Pipeline (km)	3,763	3,523	4,801	4,602
Length of CO_2 Pipeline (km)	6,018	472	1,242	1,576
Total Length of New Pipelines (km)	9,781	3,995	6,043	6,178
Build Rate over 25 Years (km/yr)	391	160	242	247

[5] In the real world, different producers would have different levelized costs.

The total length of existing NG transmission pipelines in the AOI is 73,243 km, an order of magnitude more than the total length of new pipelines needed in any scenario. To meet 2050 net-zero targets, the total length of gas pipelines (NG, H_2, and CO_2 pipelines) in the AOI needs to be increased by 5% to 13% in the next 25 years. One-third of these new pipelines could use the rights-of-way of existing NG transmission pipelines, as seen in the underlying gray lines in Figures 9 to 12.

The build rate for new pipelines required to realize at least three of these four net-zero scenarios is less than the current build rates of NG transmission pipelines. Approximately 294 km (183 miles) of NG transmission pipelines were installed in West Virginia alone in 2022 [20]. A 294 km/yr build rate would be sufficient to build more than 7,000 km of new H_2 and CO_2 pipelines across the AOI between 2026 and 2050. This is sufficient to meet the pipeline build requirements for three of the four net-zero scenarios evaluated, with the LCRI Opt-Tech scenario being the notable exception.

DISCUSSION AND CONCLUSION

Economy-wide decarbonization studies have consistently pointed to large-scale deployment of H_2 and CO_2 infrastructure assets as part of their least-cost pathways to reach net-zero conditions in the U.S. [3]. In this study, we sought to evaluate and visualize the potential geospatial deployment of these infrastructure assets with the aim of illuminating new insights that were not previously understood. Through this effort, we developed and applied a novel cost-minimization modeling tool that allows for the evaluation of co-optimized placement of H_2 and CO_2 infrastructure assets.

The visualization results of this study (Figures 9-12) highlight a considerable level of infrastructure deployment and system integration. Within the Appalachian area of interest evaluated in this study, the linkages between production, consumption/utilization, and storage/sequestration assets can span significant distances with multiple interconnection points. The level of interconnection is particularly evident in scenarios with higher levels of carbon management and blue H_2 production.

The scale and interconnectivity in these results highlights the potential challenges for energy infrastructure project development and planning. Infrastructure deployment in the U.S. has often progressed on a project-by-project basis. Given the magnitude of infrastructure build-out and integration in the results of this study (which are based on a least-cost optimization analysis), such project-by-project planning may lead to sub-optimal outcomes. If project developers only consider a small number of producers and off-takers, a narrow geographic region, or a relatively short time horizon, infrastructure planning efforts may fail to leverage potential synergies or position for future opportunities.

While there is value in pursuing infrastructure planning efforts through a wider field of view, this is challenging given the wide range of future possibilities and current uncertainties. For example, all four scenarios in this study had the same target—least-cost pathways to achieve net-zero emissions across the U.S. economy. Despite this common target, the results differ considerably across these four scenarios.

Infrastructure modeling tools such as the one developed and applied in this project may prove useful in supporting energy transition infrastructure planning efforts. Such tools may provide a cost-effective means to evaluate a wide range of potential future scenarios and/or to consider a broader region of interest beyond the immediate producers and/or off-takers of interest. For example, the AOI evaluated in this study was defined with a boundary that extended roughly 100 km beyond the bounds of the proposed ARCH2 hub. All four scenarios evaluated in this study yielded results with infrastructure assets placed beyond the ARCH2 region as part of the least cost solution. Hence, the results of this study highlight that there may be opportunities to leverage synergistic assets (e.g., NG pipeline rights-of-way, industrial clusters, etc.), favorable geology (e.g., CO_2 storage, H_2 storage, etc.), and/or energy demand centers that extend beyond the near-field focus of an individual infrastructure development project.

While the results of this study illuminate the potential challenges for infrastructure planning given the high level of system interconnectivity and potential variability, they also highlight the relative feasibility of deploying these systems. For three of the four scenarios evaluated, the annual build rate of H_2 and CO_2 pipelines (km/yr) required between 2026 and the 2050 net-zero target date is less than the kilometers of natural gas transmission pipelines constructed in West Virginia in 2022 (for the LCRI Opt-Tech scenario, the required build rate was 33% higher than the 2022 build rate in West Virginia). This suggests that, while complex, it is feasible to deploy the level of H_2 and CO_2 infrastructure assets envisioned in these net-zero scenarios, especially when supported by analytically-informed infrastructure modeling tools and planning activities.

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3002033667 **August 2025**

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