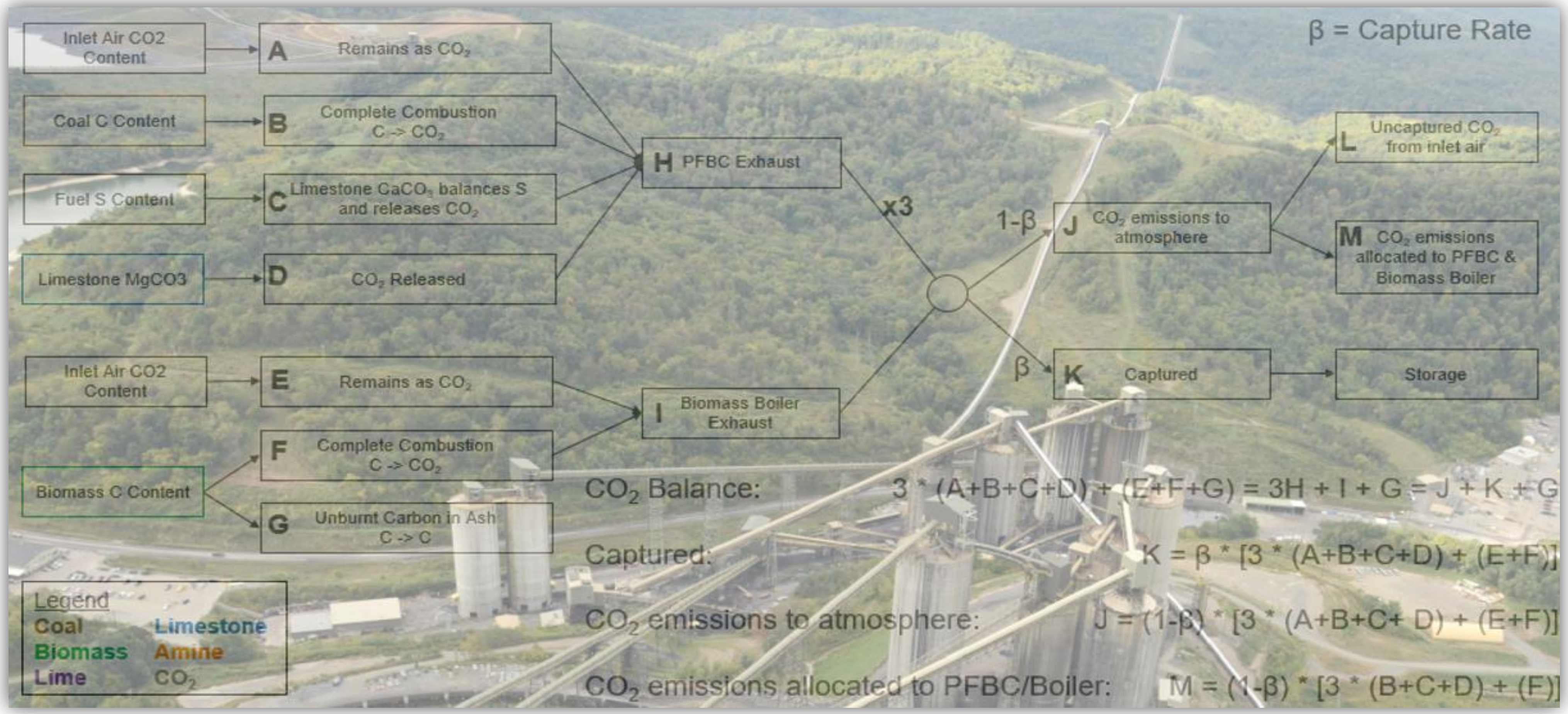
Designing a Carbon-Negative Power Plant: Engineering, Infrastructure, and Storage Considerations

Kevin Ellett, Kat Sale and David Tu

Carbon Solutions Webinar, February 26th, 2025



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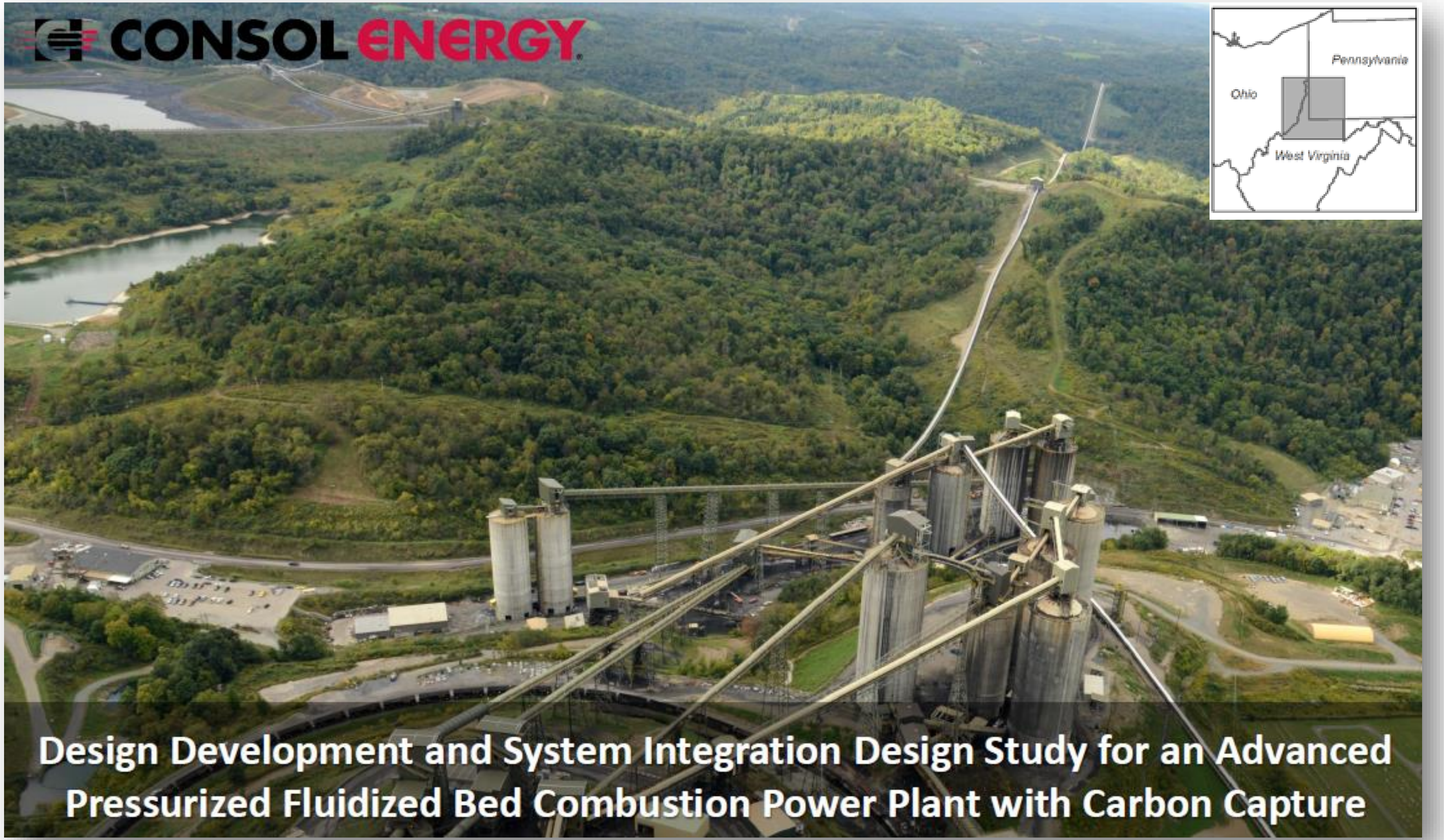
Support site selection and CO_2 disposition plan for the world's first carbon negative power plant that runs on biomass and coal mine waste fuel

Iterative LCA to guide engineering decisions for carbon neutral/ negative operation.

Objectives



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Acknowledgements

- USDOE 21st Century Power Plant Program
  - Award # DE-FE0031998
- R&D Partners: CONSOL Energy (Lead), Worley, Battelle
- Carbon Solutions Team Members
  - *SimCCS^{PRO}* Model Development and Applications
    - Richard Middleton, Carl Talsma, Erin Middleton, Jonathan Ogland-Hand
  - Life Cycle Assessment
    - Andrew Harrison, Marcos Miranda and Tracey Ziev

Learn more at CCUS 2025!
March 3-5, Houston, TX

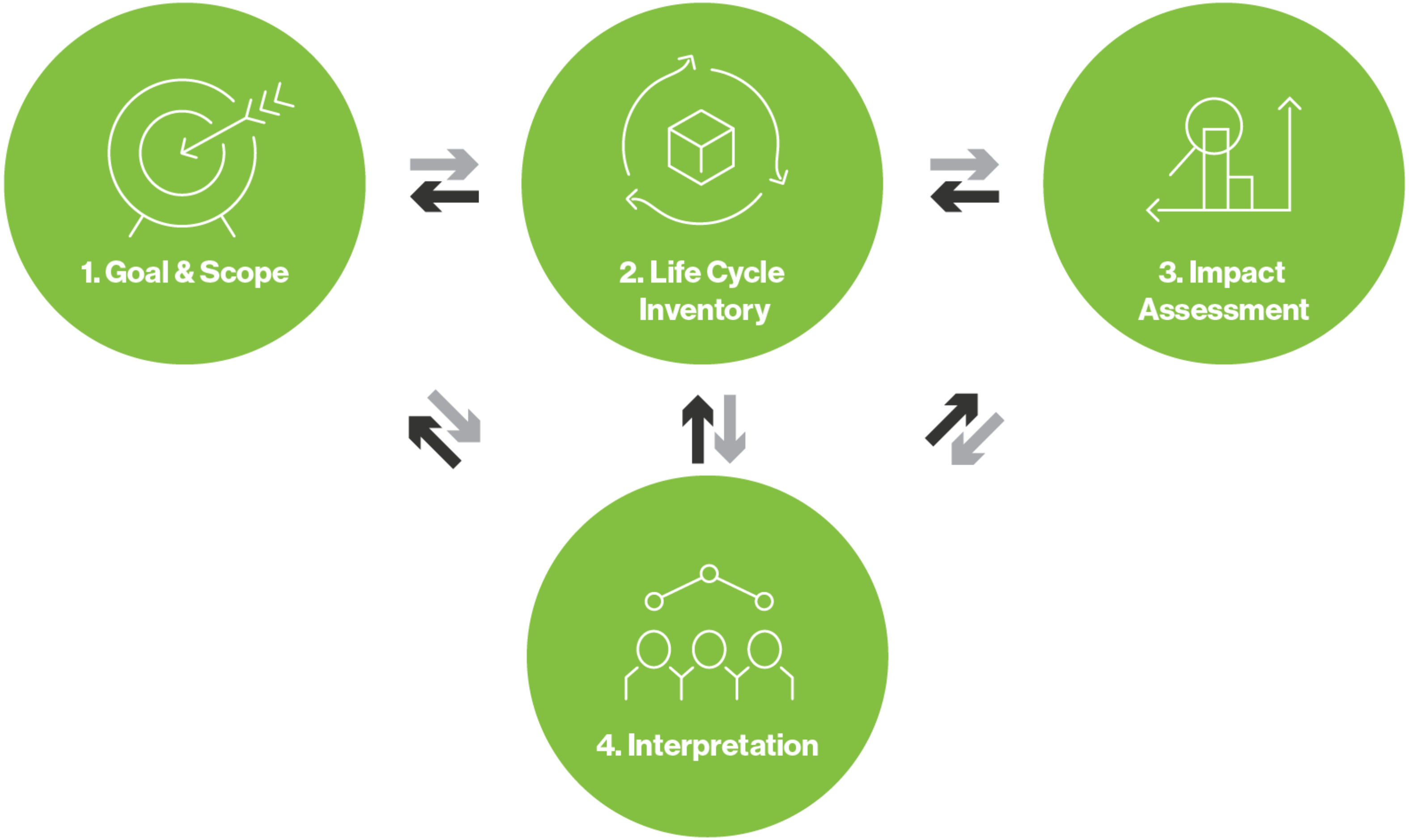
https://ccusevent.org/2025

Webinar Outline

- Iterative Life Cycle Assessment
  - Kat Sale
- Integrated CCS Infrastructure
  - Kevin Ellett
- Alternative Options for Carbon Storage
  - David Tu

Life Cycle Assessment (LCA)

- Iterative process to quantify the impacts of a product or process during its life cycle
- Interpretation at **each step**
- ISO 14040 Compliant



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[What is life cycle assessment (LCA)? | Golisano Institute for Sustainability | RIT]

LCA: Goal

- Intended Audience: CONSOL Energy, stakeholders, general public
- Category of interest: 100-year global warming potential
- Functional Unit: 1 kWh electricity
- Develop a model of a co-fired biomass, waste coal, and virgin coal power facility with carbon capture and storage, that evaluates the 100-yr global warming potential from generating 1 kWh of electricity under different system designs, for use by CONSOL Energy.
- What biomass percentage is needed to achieve carbon neutrality?

LCA: Scope

- Cradle-to-gate analysis for 1 kWh of electricity produced, including:
  - Production and transport of major raw materials
  - On-site emissions
  - Construction
  - Transport and sequestration of CO_2
- Not included: plant decommissioning & demolition → negligible impact
- Evaluated using openLCA 2.2 software, TRACI 2.1 impact assessment, GHG-100 CO_2e
- Data Sources: Industry Partner → NETL 45Q LCI & CO2U Database → GREET 2023, 1.3.0

openLCA

NATIONAL ENERGY TECHNOLOGY LABORATORY

Argonne NATIONAL LABORATORY GREET LIFE-CYCLE MODEL

LCA: System Diagram

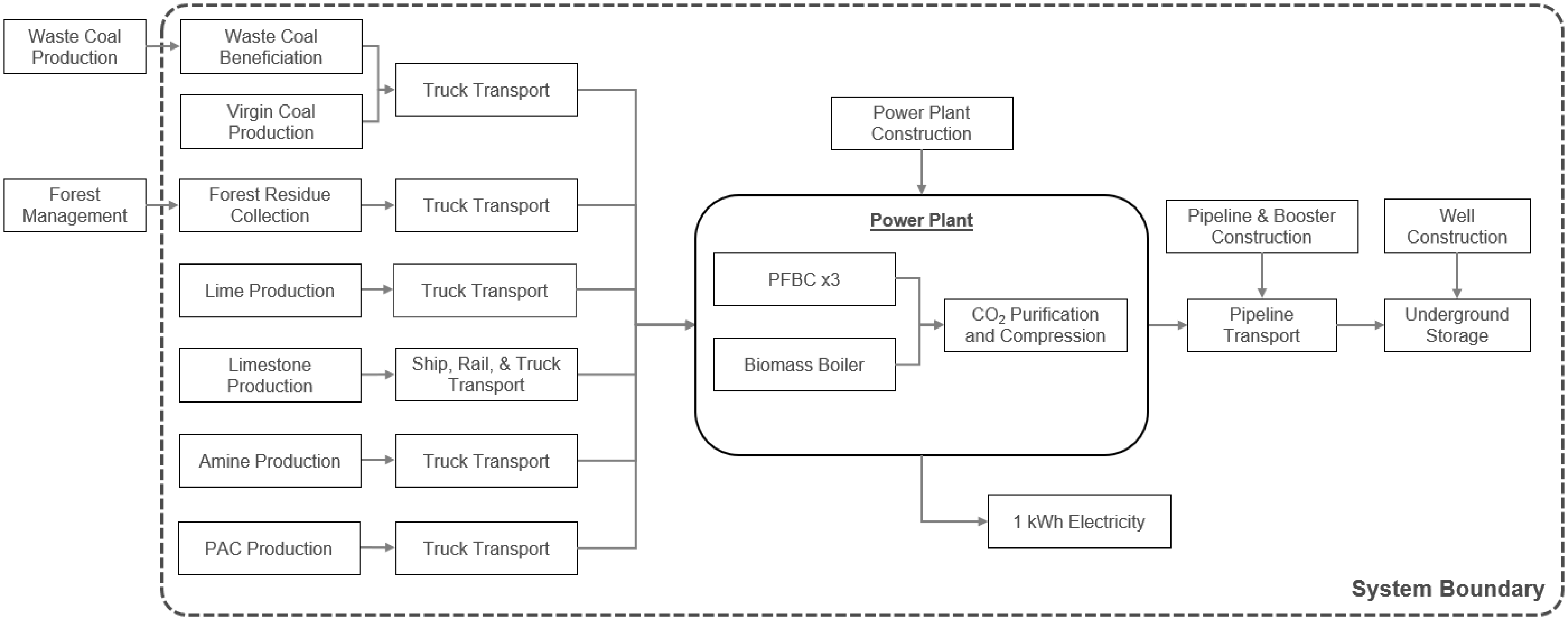

Figure 1. System boundary of the proposed 21 CPP BP2 design

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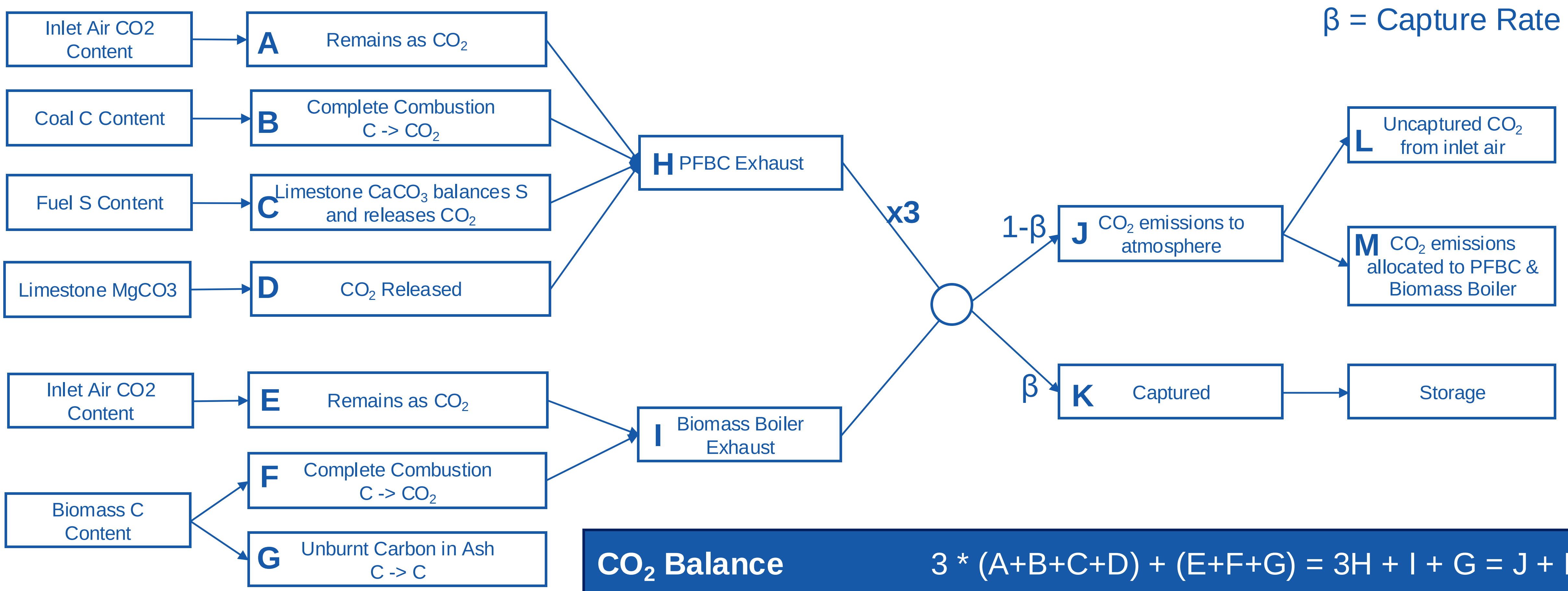
LCA: CO_2 Balance



CO_2 Balance $3 * (A+B+C+D) + (E+F+G) = 3H + I + G = J + K + G$

Captured $K = \beta * [3 * (A+B+C+D) + (E+F)]$

CO_2 emissions to atmosphere $J = (1-\beta) * [3 * (A+B+C+D) + (E+F)]$

CO_2 emissions allocated to PFBC/Boiler $M = (1-\beta) * [3 * (B+C+D) + (F)]$

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Key Model Parameters

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Coal Blend	Virgin & Beneficiated Waste Coal
Coal Blend Energy Content, wet	9,961 Btu/lb
Coal Blend Moisture Content	26.5 wt%
Percentage Waste Coal	50%
Biomass Type	**Forest Residue**
Biomass Energy Content, wet	5,030 Btu/lb
Biomass Moisture Content	30 wt%
Biomass in Feed (Energy-basis)	20%
Capture System and Transport	
CO_2 Capture Rate	97%
Number of CO_2 Compressors	2
CO_2 Pipeline Length	47 miles
Sequestration	
Number of Wells	11
Number of Well Head Compressors	1
Formation Leakage	0.5%

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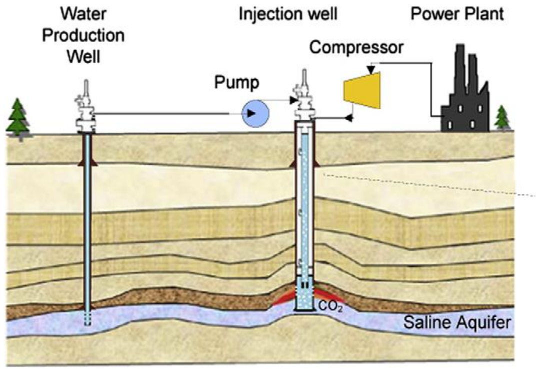

https://doi.org/10.1016/J.ENERGY.2012.07.007

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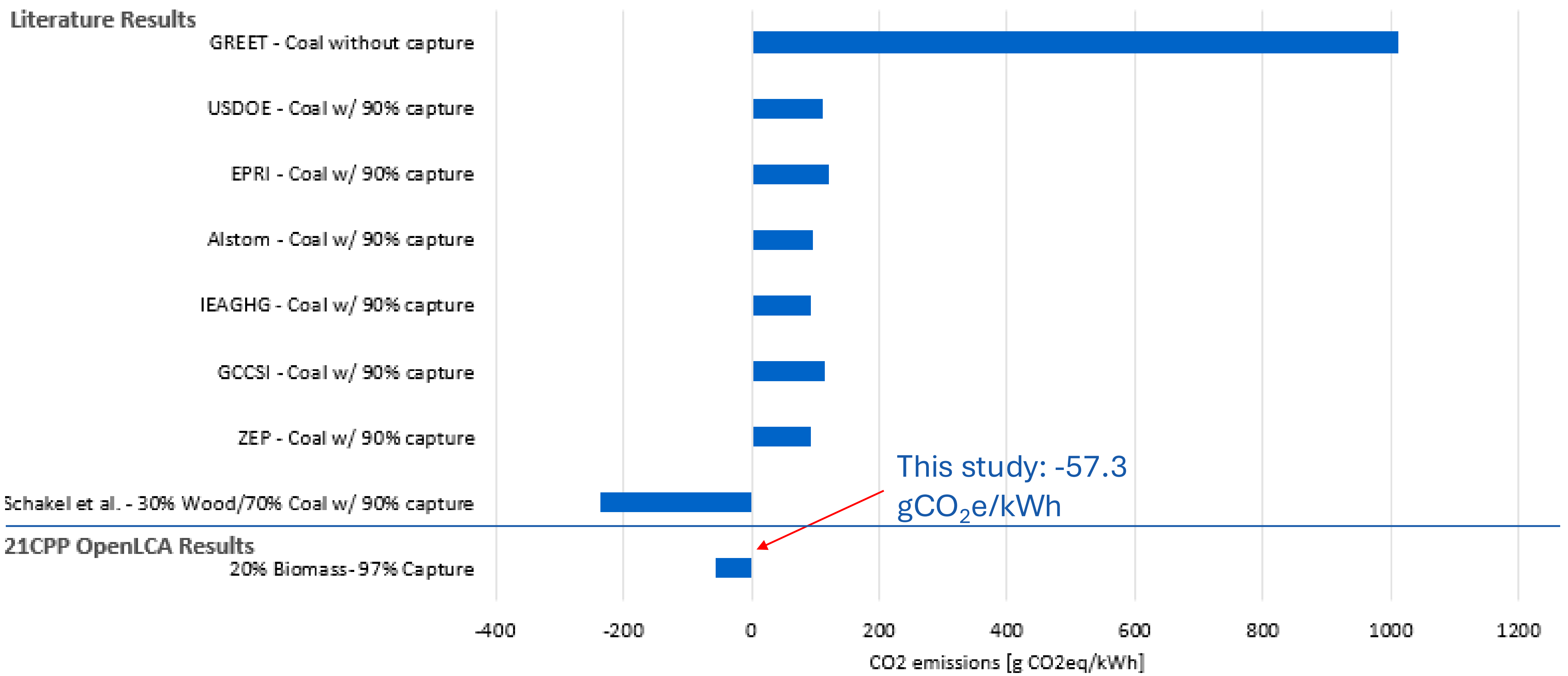
Model Output and Sensitivity Highlights

- Coal power generally produces ~1000 g CO_2e/kWh
- Biomass carbon uptake makes plant's overall GWP negative
  - At least **14% biomass fraction** could achieve carbon neutrality
- Construction of the CO_2 pipeline and its operation have non-negligible effects
  - NETL CO2U transport and storage process: 17.6 g CO_2e/kWh

Process Impact Contributions at Baseline Plant Design

Variable	Value [g CO_2e / kWh]
Biomass Carbon Uptake	-197
Virgin Coal Supply	67.1
Lime, Limestone, Amine, PAC Supply	4.2
Material Transportation	12.5
On-Site Emissions (Combustion)	36.6
Plant Construction	0.8
CO_2 Transport, Storage, and Construction	18.7
TOTAL	**-57.3**

Comparison to Other LCAs



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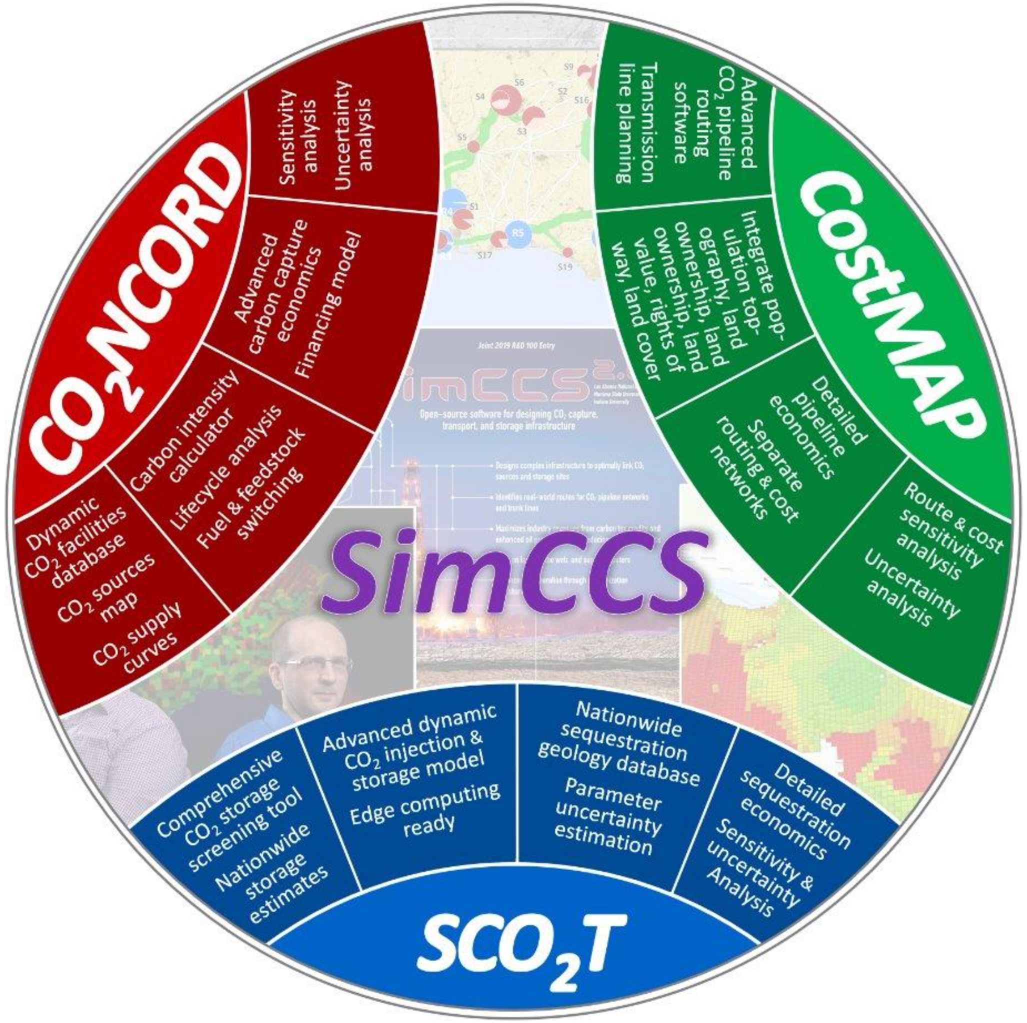
LCA Conclusions

- A cradle-to-gate impact of -57.3 gCO_2e/kWh was calculated for the proposed 21CPP system
- 14% biomass must be combusted on an energy basis for this system to reach expected carbon neutrality
- Integrating LCA into a design process can improve overall system design by identifying key trade-offs and optimizing environmental performance

CO_2 Disposition Plan
Integrated CCS infrastructure for plant siting and regional integration



- SimCCS^{PRO} (system analysis)
  - Decision support across the CCS value chain.
  - Sub-models for CO_2 capture, transport, & storage.
- CO_2NCORD (capture)
  - Dynamic, customizable CO_2 capture database.
  - 10,000+ sources.
- CostMAP^{PRO} (transport)
  - Advanced, multiscale, multi-attribute pipeline routing.
- SCO_2T^{PRO} (storage)
  - World's most advanced tool for dynamic CO_2 storage & costs.

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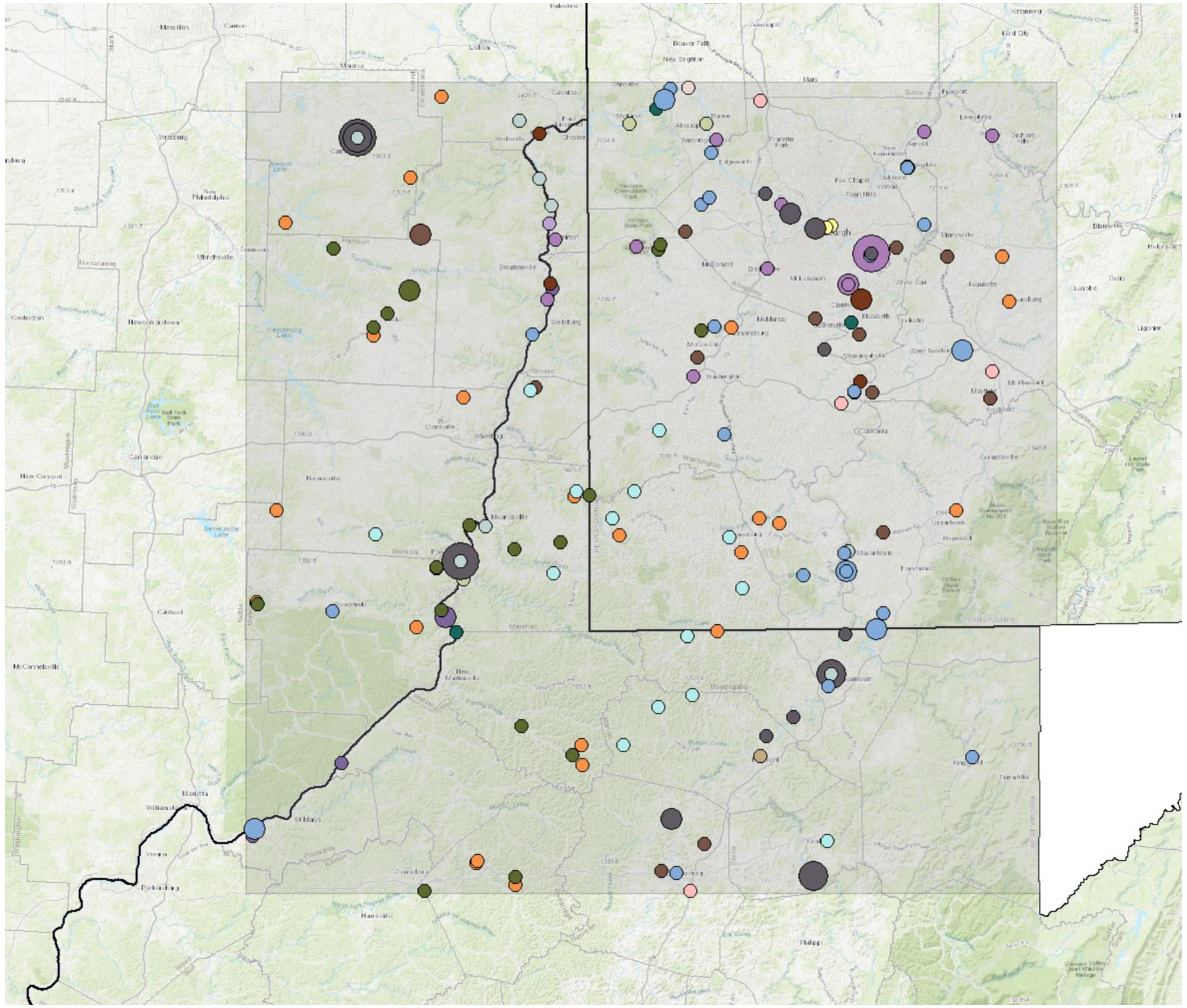
CO_2 DISPOSITION PLAN
INTEGRATED CCS INFRASTRUCTURE FOR PLANT SITING AND REGIONAL INTEGRATION

Potential capturable emissions ($MtCO_2$)

Industry Classifications for Sources of Potential CO_2 Capture

- Fertilizer
- Cement
- Natural Gas
- Ammonia
- Refineries
- Solid Waste
- Coal
- Gypsum
- Mining - Solid Extraction
- Lime Processing
- Mining - Fluid Extraction
- Nat. Gas Processing
- Mining - Other
- Petrochemicals
- Nat. Gas Pipeline Facilities
- Other Manufacturing
- Misc. Institutions

- < 0.5
- 0.51 - 2.5
- 2.51 - 4.5
- > 4.51 (max 9.25)



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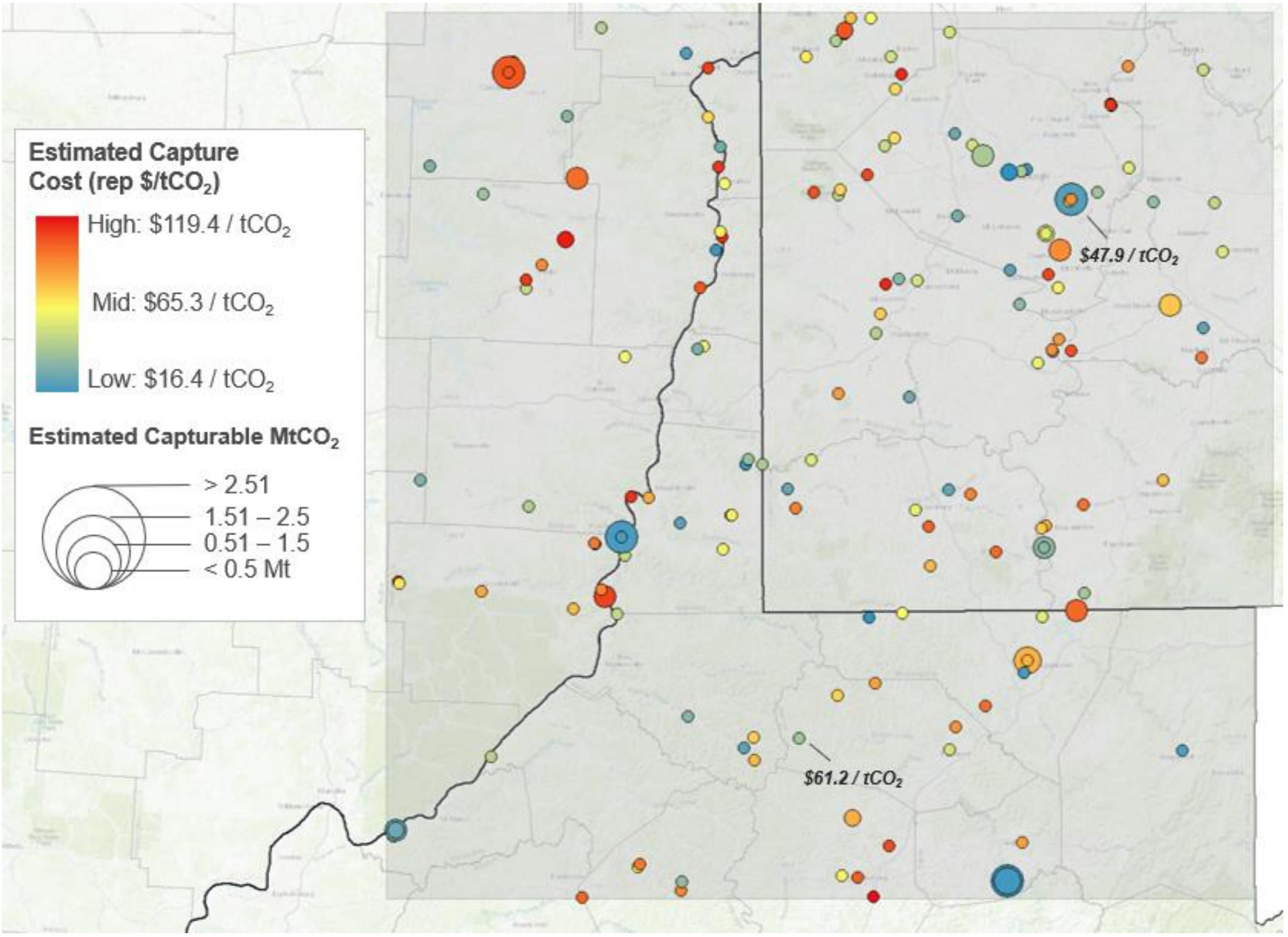
CO_2NCORD Software Application

Estimated Capture Cost ($/tCO$_2$)



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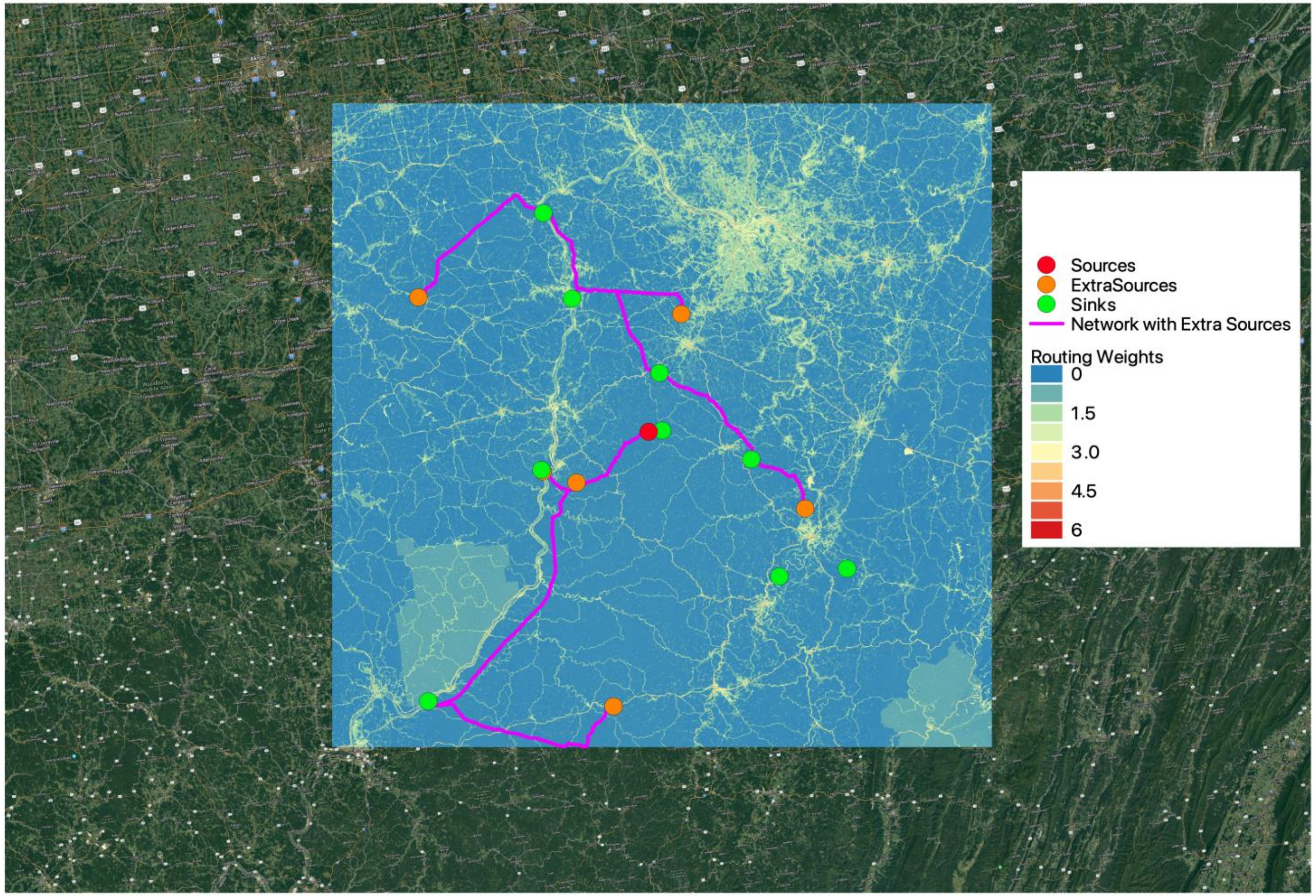
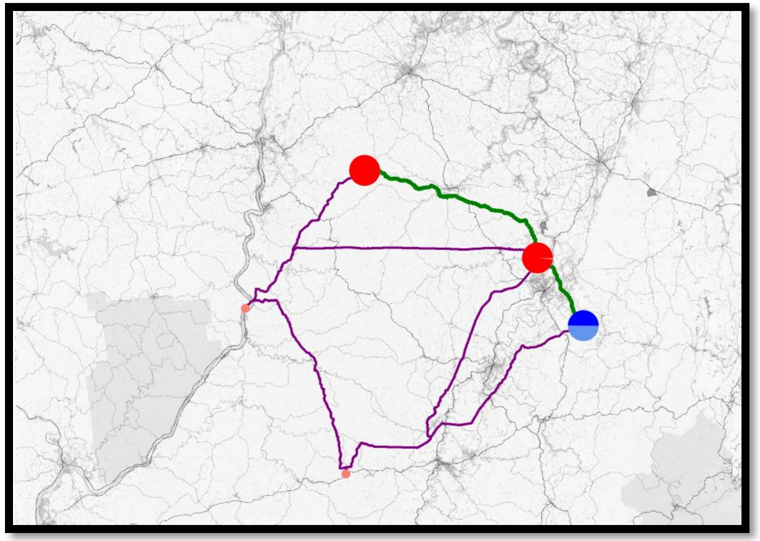
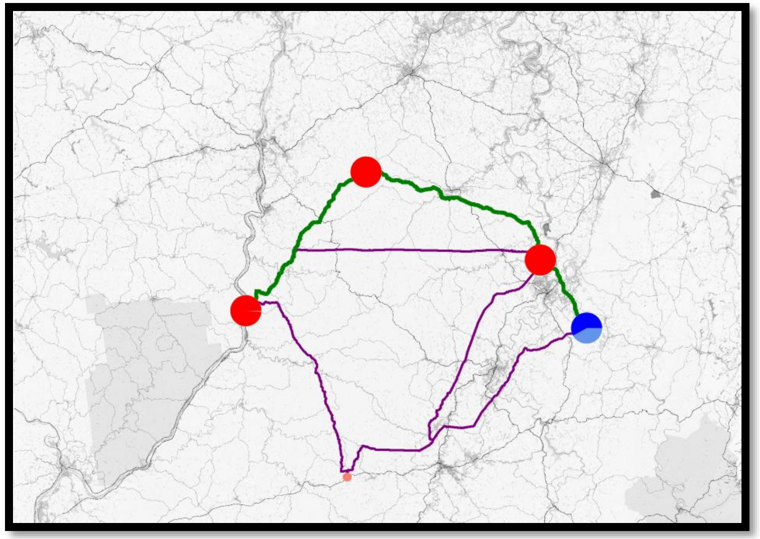
CostMAP and SimCCS^{PRO} Software Applications

Model results indicate opportunity to reduce transport costs by 50%+ via shared pipeline infrastructure







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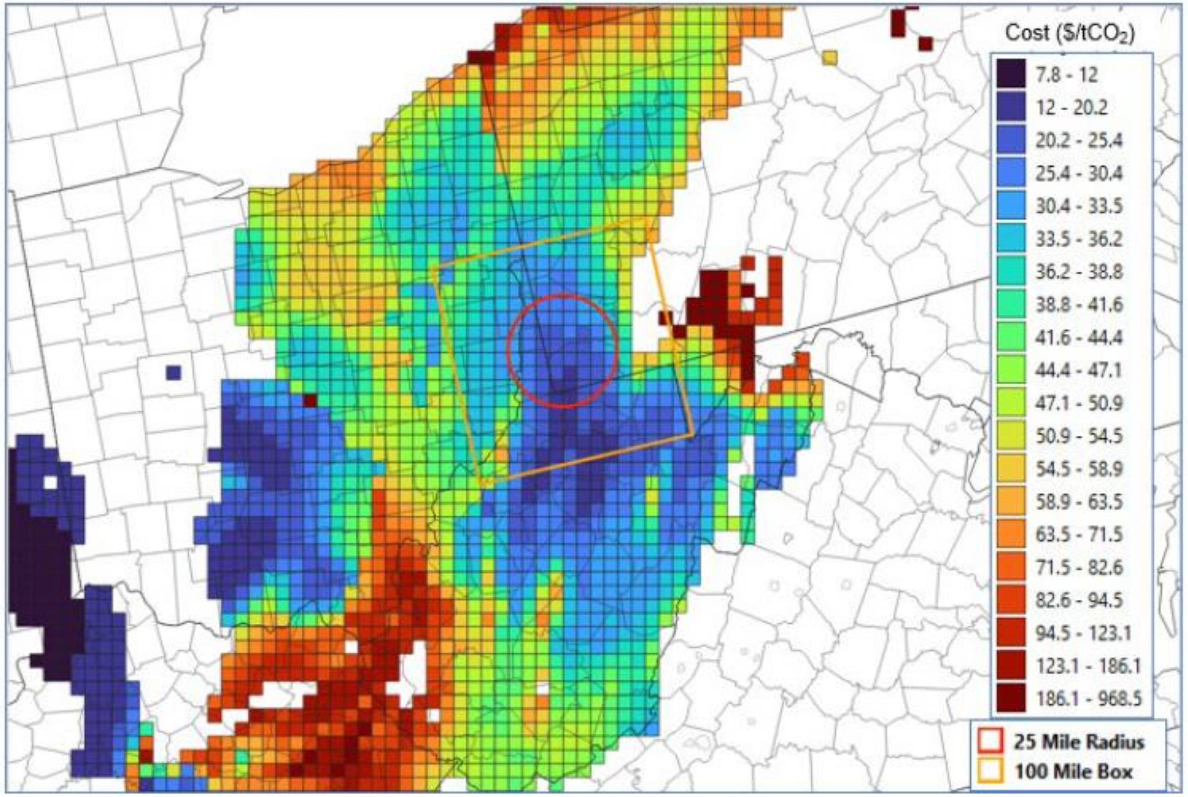
SCO_2T^{PRO} Software Application

Estimated Cost of storage in deep saline formations is relatively high



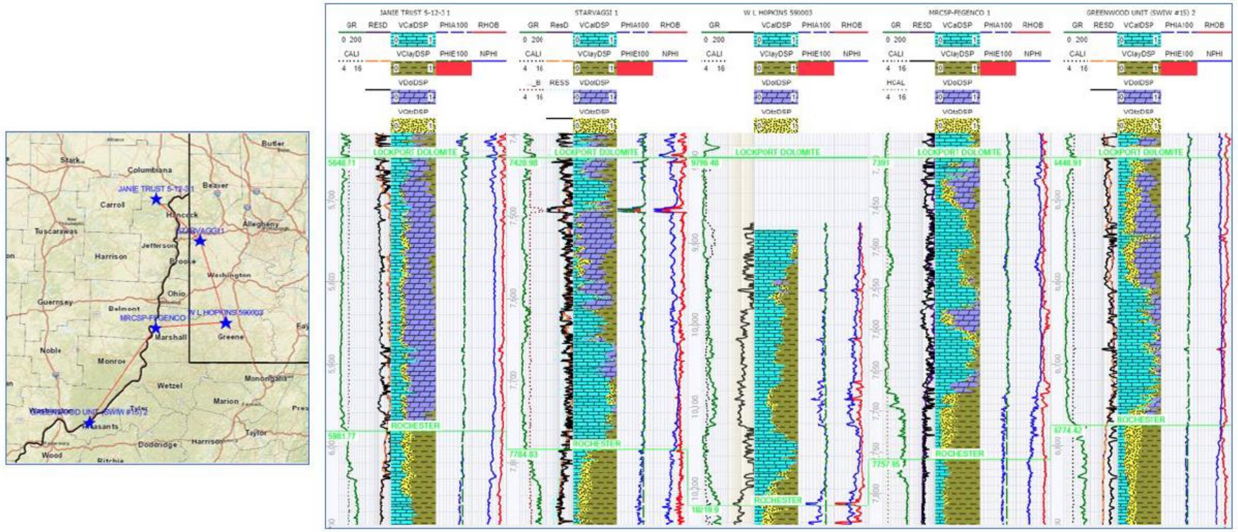
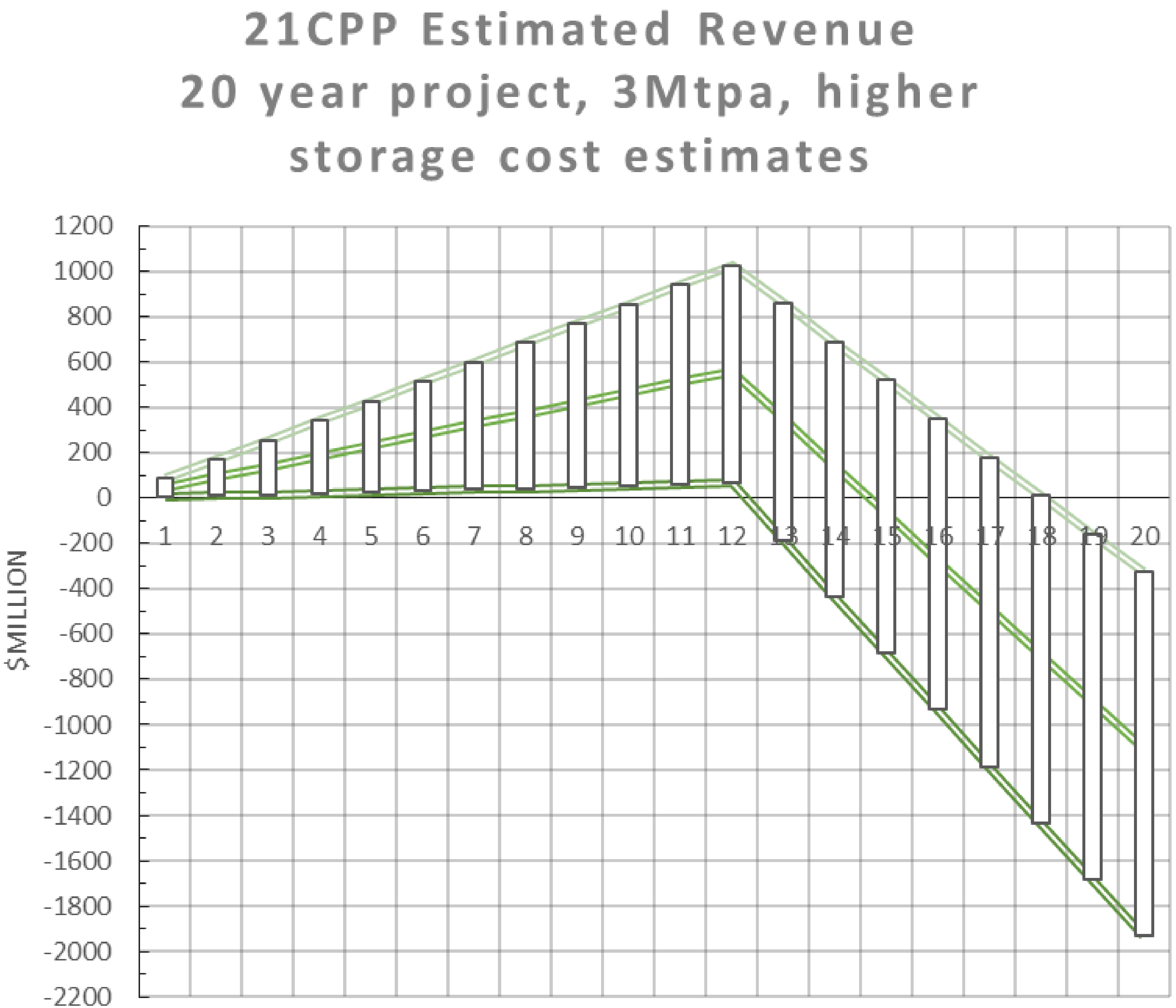


Figure 8: *Detailed assessment of Lockport Dol. using available well data indicated that storage resources are likely limited to thinner reservoir intervals than originally estimated from regional characterization data.*

Uncertainty in storage costs have significant impact on 21CPP's estimated project revenue



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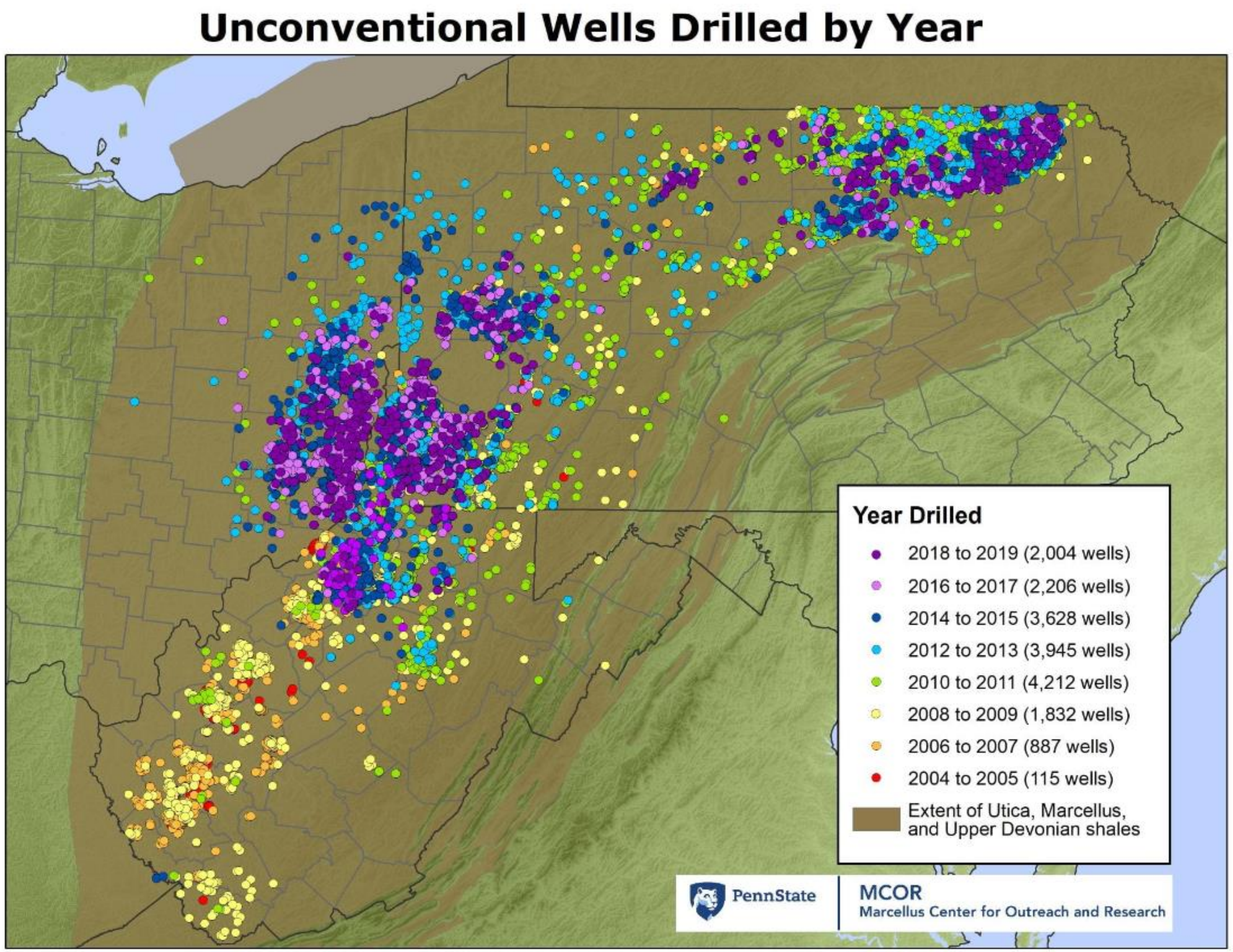
Alternative Storage Options: Conversion of Marcellus production wells into CO_2 storage wells

- Prior work suggests tens of Gigatonnes of potential CO_2 storage capacity in depleted Marcellus Shale gas wells (*Tao and Clarens, 2013; Godec et al., 2013; Bielicki et al., 2018*).
- Storage cost expected to be cheaper than saline storage
  - Existing well infrastructure.
  - Existing fracked reservoirs at reduced pressure.
  - Pipeline rights-of-way.
  - Storage security from adsorption.
  - Smaller AOR for monitoring.
- Wells with 10+ years of production history may be more valuable for CO_2 injection than from continued production



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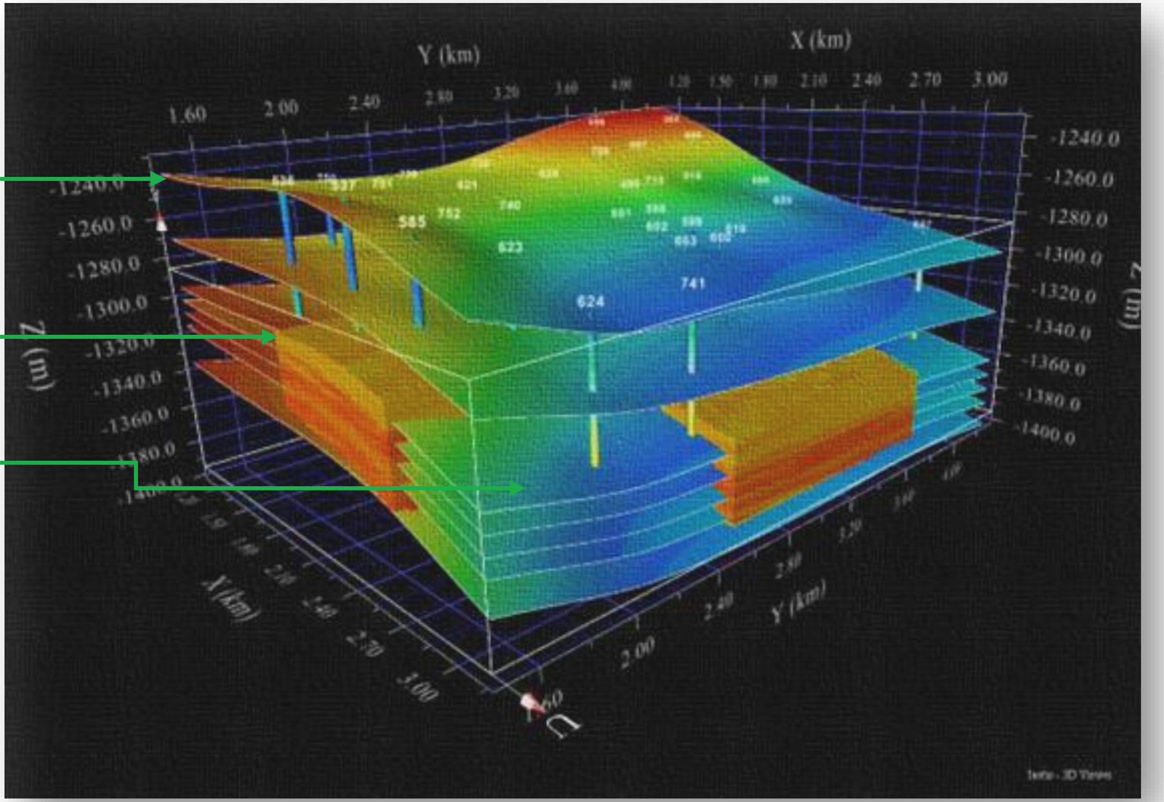
Numerical Modeling and Reservoir Simulation (NMRS)

- What is NMRS?

NMRS is essential for **assessing, planning, monitoring**, and **evaluating** commercial-scale CCS projects. It originated in the oil and gas industry for reservoir development and optimization.

Numerical Modeling is a mathematical representation of the subsurface formations based on available data, including:

- Site Geology
- Rock and Fluids
- Injection Wells



Reservoir Simulation is dynamically emulating rock and fluid physics within porous space.

Numerical Modeling and Reservoir Simulation (NMRS)

- What can NMRS answer?

SCO2TPRO

- Capture complex CO2 storage with **fast-running** models.
- Rapidly **characterize** individual **storage reservoirs**.
- **Regional/national assessment** of CO2 storage **potential**.

Storage Capacity

Ultimate volume can store

How much can the reservoir host?

Injection Capacity

Volume can be stored over a **period**

How fast can the reservoir receive?

NMRS

- **Computational intense** modeling with **detailed** injection plan.
- Closely delineate **geologic features** and impact on selected storage sites.
- **Site-focused** CO2 storage feasibility and **design**.

Numerical Modeling and Reservoir Simulation (NMRS)

- Why is the NMRS study necessary?

Enhanced Confidence:
Optimize the best storage site and reservoir with accurate geologic data

Unlimited Scenarios:
Help create operational plans tailored to the company's financial and development outlook

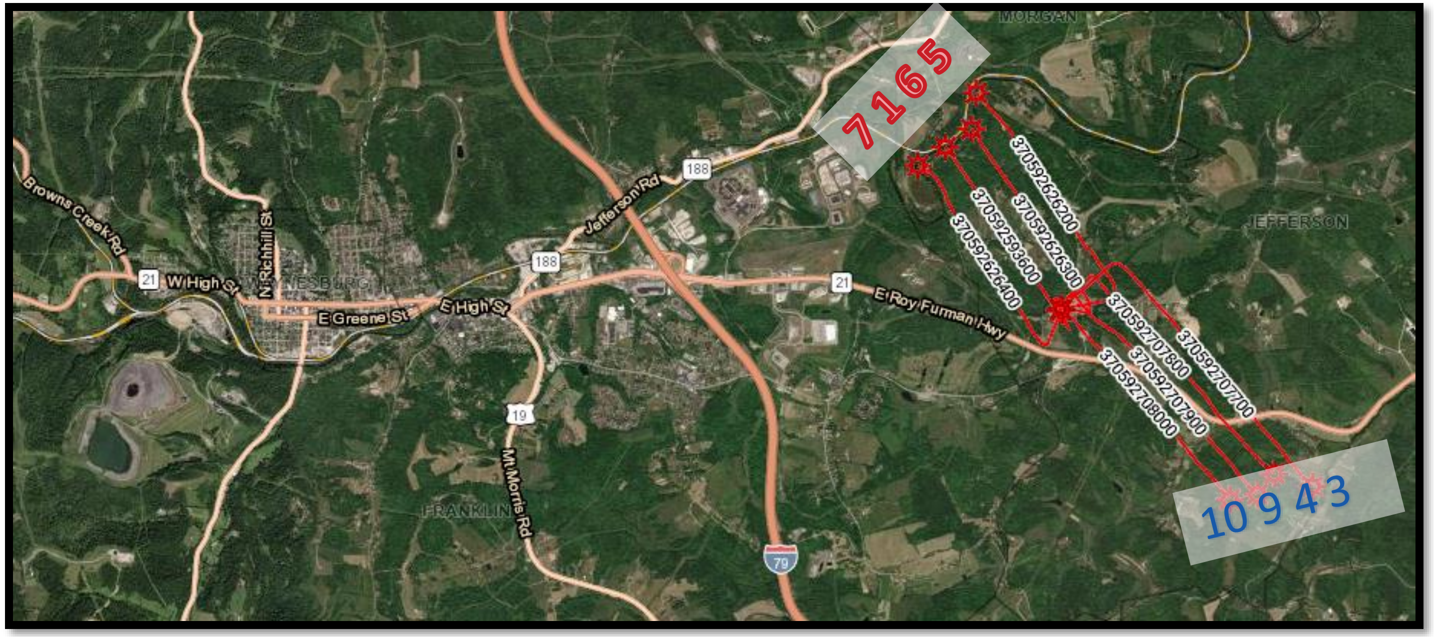
Meet the regulatory requirements:
Help create operational plans tailored to the company's financial and development outlook

- Computational modeling for GS to provide the necessary background for owners or operators, and to assist in understanding and complying with the Class VI Rule.
- The AoR for a Class VI injection project must be delineated using a computational model that accounts for the physical and chemical properties of all phases of the injected carbon dioxide [40 CFR 146.84(a)].
- The Class VI Rule requires that the AoR be delineated using models that include multiphase flow [40 CFR 146.84(a)]

https://www.epa.gov/uic/final-class-vi-guidance-documents

Evaluating potential for CO_2 storage via Marcellus well conversion

-RIDGE ROAD Horizontal Well Cluster Overview



API_UWI	WellName	WellStatus	WelboreType	FirstProdDate	Latitude	Longitude	TVD_FT	MD_FT	LastProdMonth
37-059-26264	RIDGE ROAD 7H	PRODUCING	MULTILATERAL	7/1/2014	39.89594	-80.1008	8047	15020	8/1/2024
37-059-25936	RIDGE ROAD 1H	PRODUCING	MULTILATERAL	12/1/2013	39.89585	-80.1007	8017	14768	8/1/2024
37-059-26263	RIDGE ROAD 6H	INACTIVE PRODUCER	MULTILATERAL	7/1/2014	39.89596	-80.1008	8063	14953	6/1/2017
37-059-26262	RIDGE ROAD 5H	INACTIVE PRODUCER	MULTILATERAL	8/1/2014	39.89598	-80.1007	8060	16020	6/1/2017
37-059-27080	RIDGE ROAD 10H	PRODUCING	SINGLE BORE	9/1/2017	39.89597	-80.1009	8123	16295	8/1/2024
37-059-27079	RIDGE ROAD 9H	PRODUCING	SINGLE BORE	9/1/2017	39.89599	-80.1008	8120	16526	8/1/2024
37-059-27077	RIDGE ROAD 3H	PRODUCING	SINGLE BORE	9/1/2017	39.89604	-80.1007	8175	17739	8/1/2024
37-059-27078	RIDGE ROAD 4H	PRODUCING	SINGLE BORE	9/1/2017	39.89601	-80.1008	8123	16280	8/1/2024

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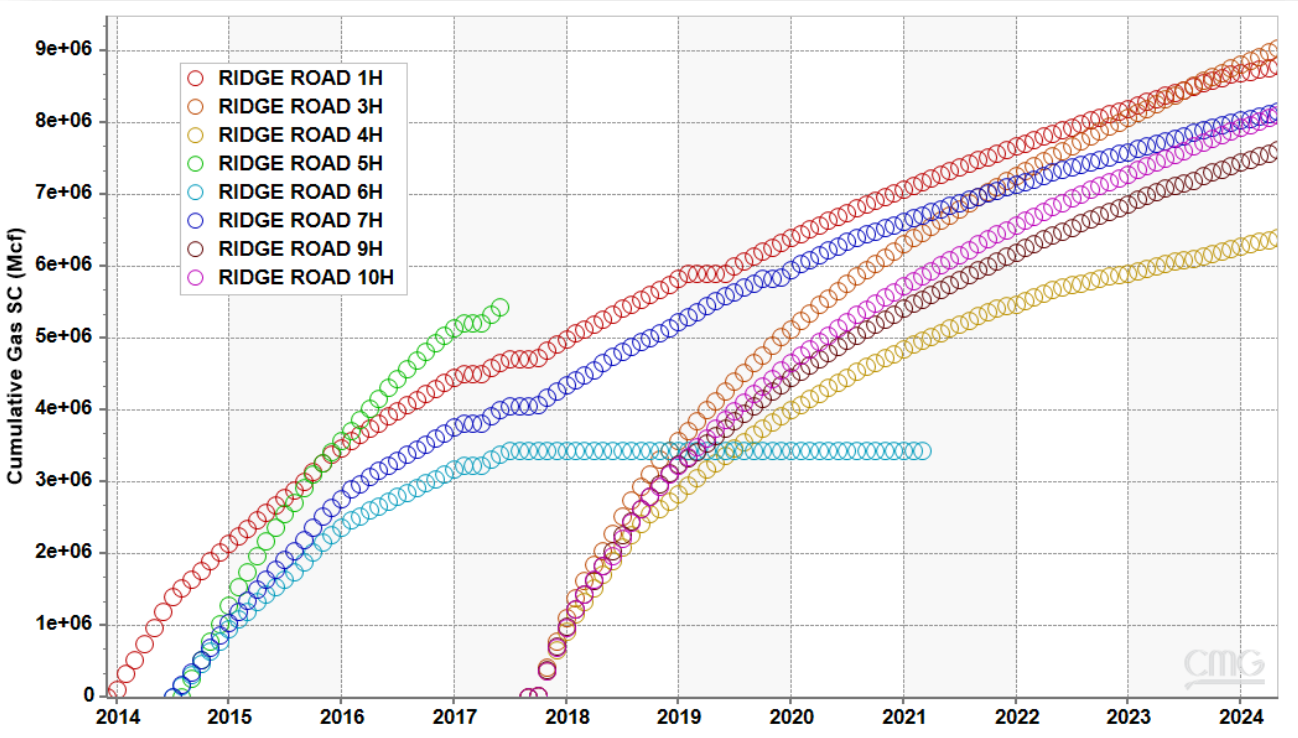
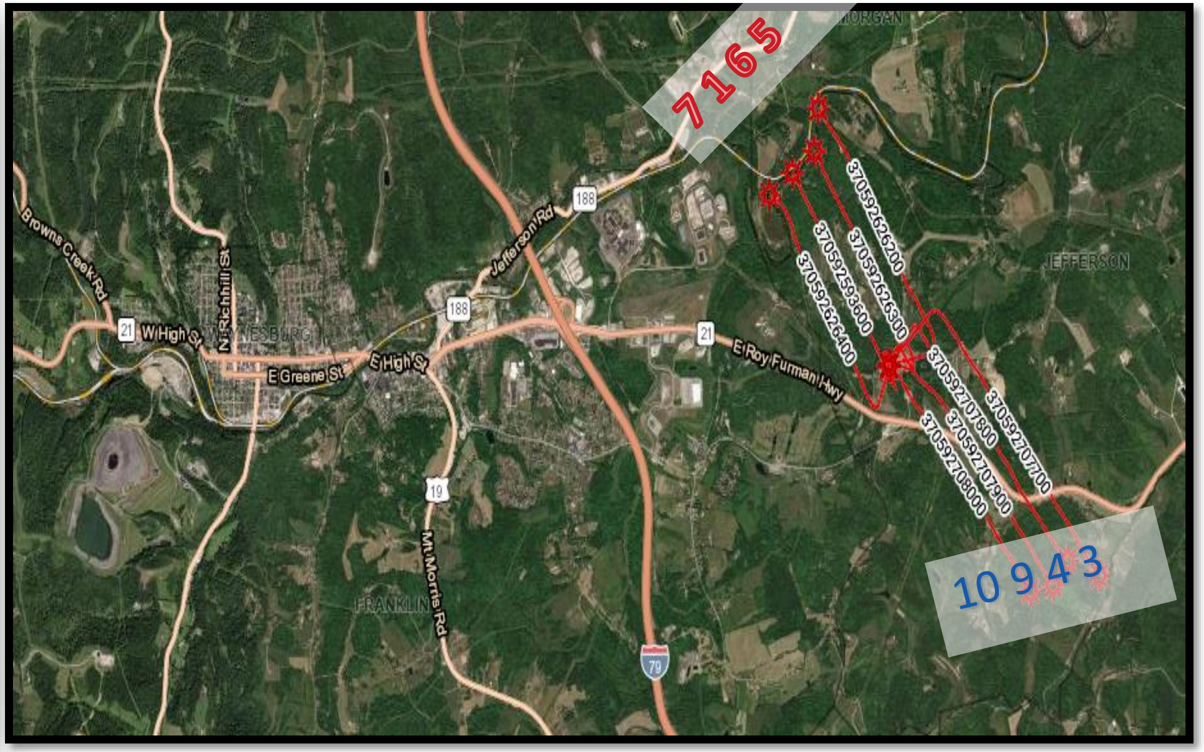
RIDGE ROAD Cluster Model

Field Production History





- *NW wells are comp. btw. 2014 – 2015*
- *SE wells are comp. btw. 2017 - 2018*

***Ridge Road 1,5,6,7 are sampled to construct the cluster model**

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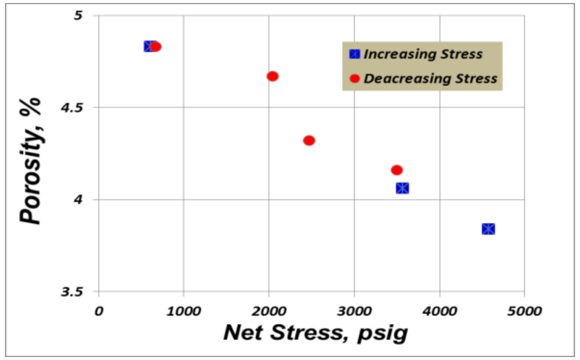
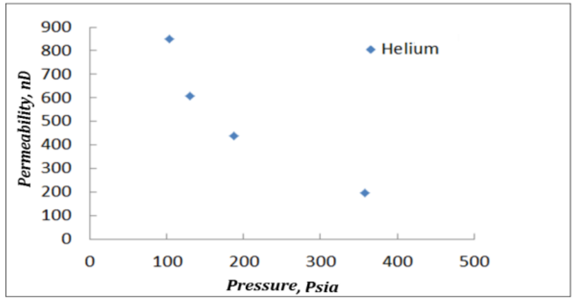
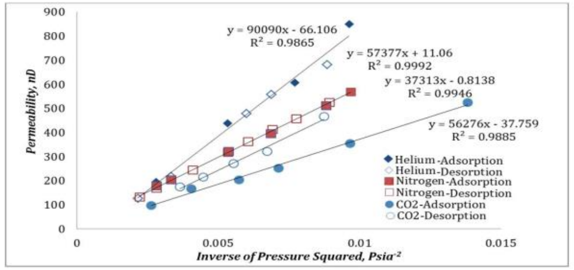
RIDGE ROAD Cluster Model

Model Set up



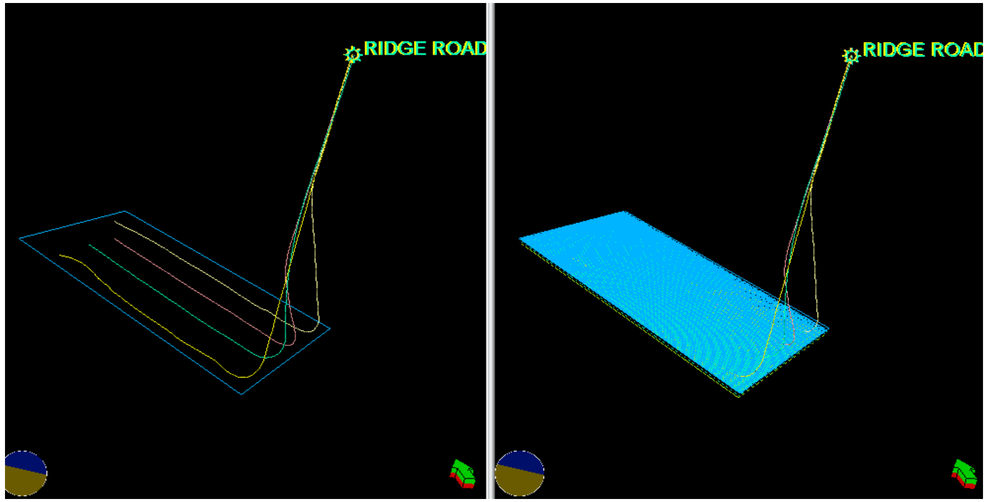




Static Properties	
Aerial Dimension	0.75 x 1.57 mi. sq.
Grid Cells (I, j, k)	163 x 384 x 10
Total number of grid cells	625,920
Avg grid size	50 ft x 50 ft
Marcellus Top	-6552 ft (MSL)
Marcellus Base	-6660 ft (MSL)
Avg thickness	177 ft

Matrix Properties	
Porosity	0.0425
Permeability i, j	0.00015 mD [150 nD]
Permeability k	0.00015 mD [150 nD]

Initial Conditions	
Initial Saturation	1.0 CH4
Irreducible water Sat.	0.25
Reservoir Pressure	5600 psi @ -6600 ft SSTVD
W/G contact	-6750 ft MSL



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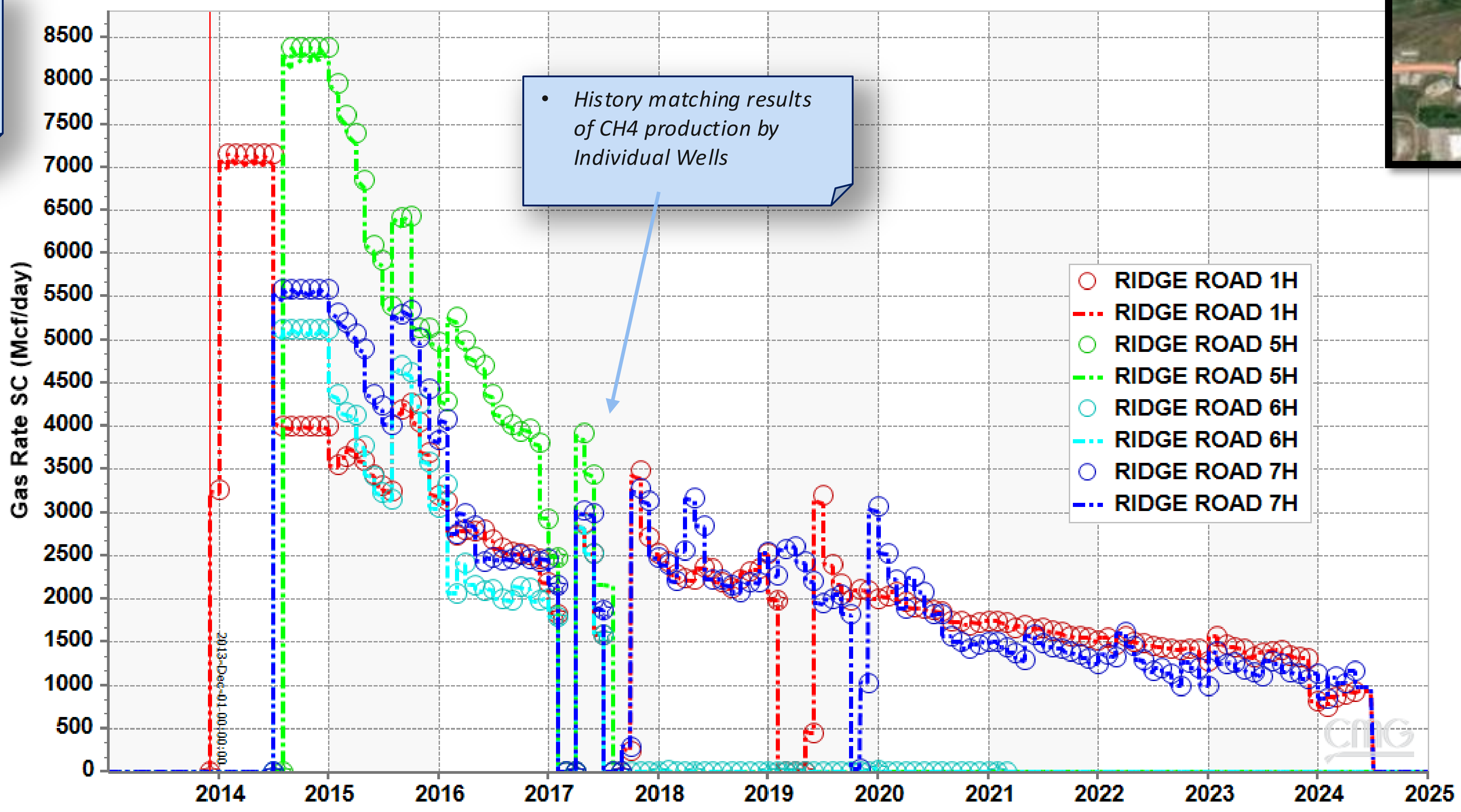
RIDGE ROAD Cluster Model

Field Production History

- *Reservoir properties are modified based on petrophysical lab measurements published by MSEEL*

- *History matching results of CH4 production by Individual Wells*



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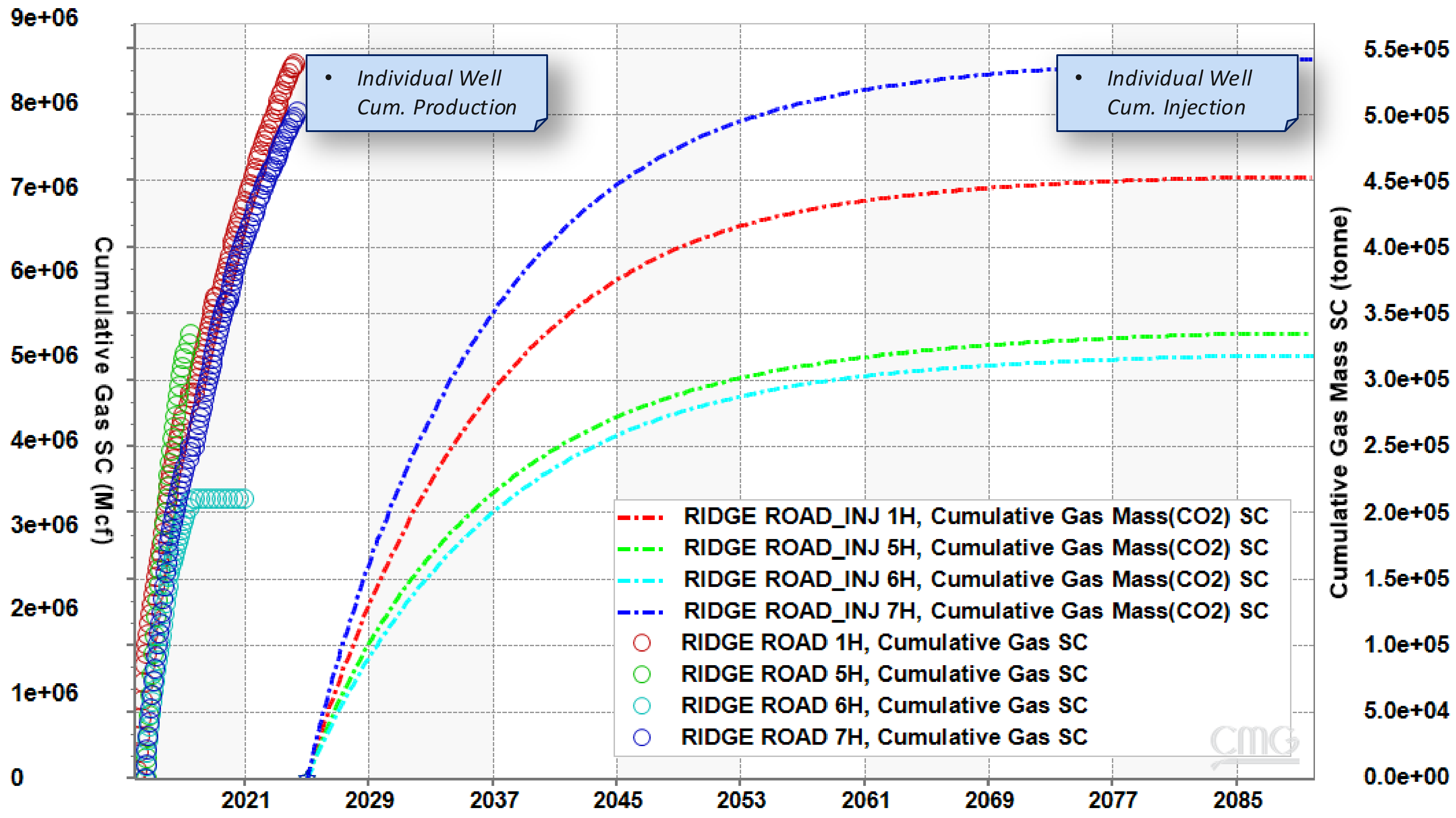
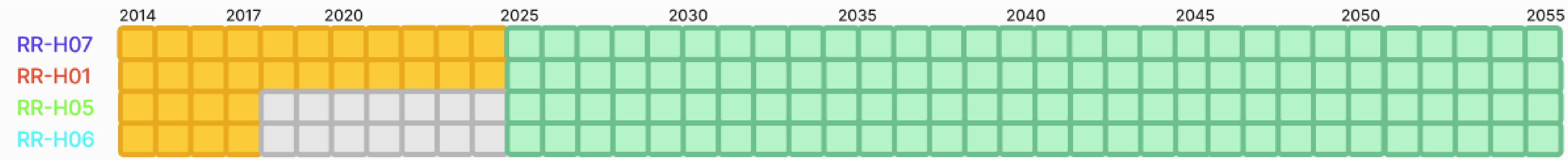
RIDGE ROAD Cluster Model

CO2 Storage





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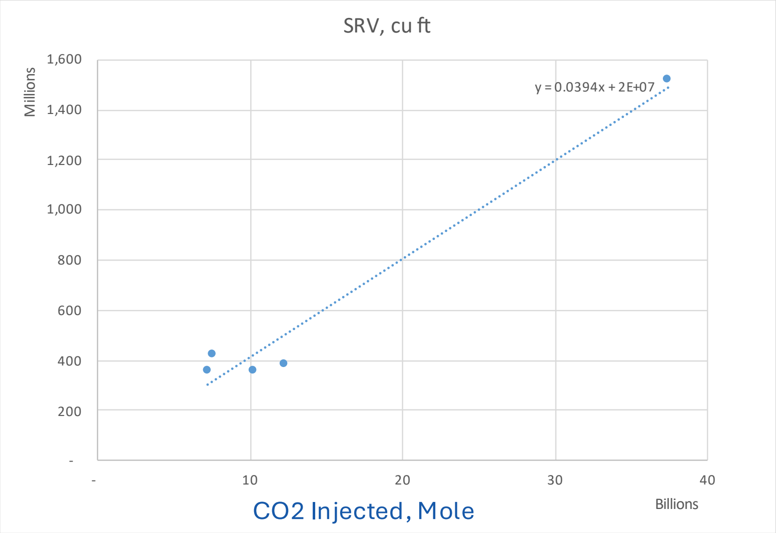
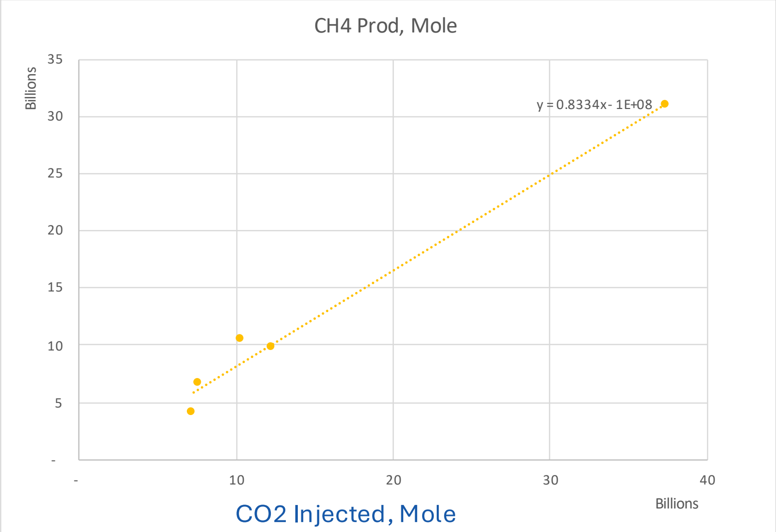
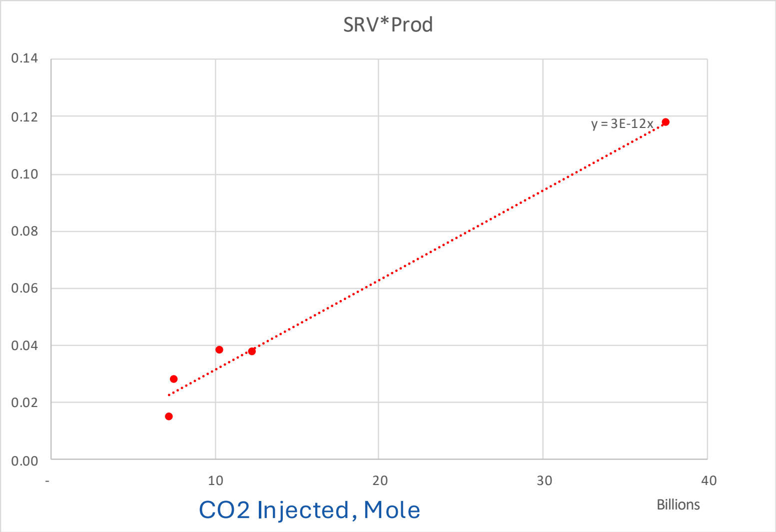
RIDGE ROAD Cluster Model

CO2 Storage by well

Well Names	Heel, ft (MD)	Toe, ft (MD)	Lateral len., ft	Frac Stages	Frac. Den.	SRV, cu ft	CH4 Prod, MMSCF	CO2 Inj, Tonne	CH4 Prod, Mole	CO2 Inj, Mole	SRV*Prod
RIDGE ROAD 1	8,205	14,767	6,562	44	149	**360,579,000**	**8,735**	452,503	10,500,000,000	10,300,000,000	0.04
RIDGE ROAD 5	8,230	16,020	7,790	49	159	**420,675,000**	**5,433**	334,867	6,600,000,000	7,610,000,000	0.03
RIDGE ROAD 6	8,190	14,953	6,763	44	154	**355,254,000**	**3,432**	318,294	4,080,000,000	7,230,000,000	0.01
RIDGE ROAD 7	8,240	15,045	6,805	44	155	**381,874,000**	**8,153**	541,079	9,780,000,000	12,300,000,000	0.04
Total			27,920	181	154	**1,518,382,000**	**25,753**	1,646,743	30,960,000,000	37,440,000,000	0.12

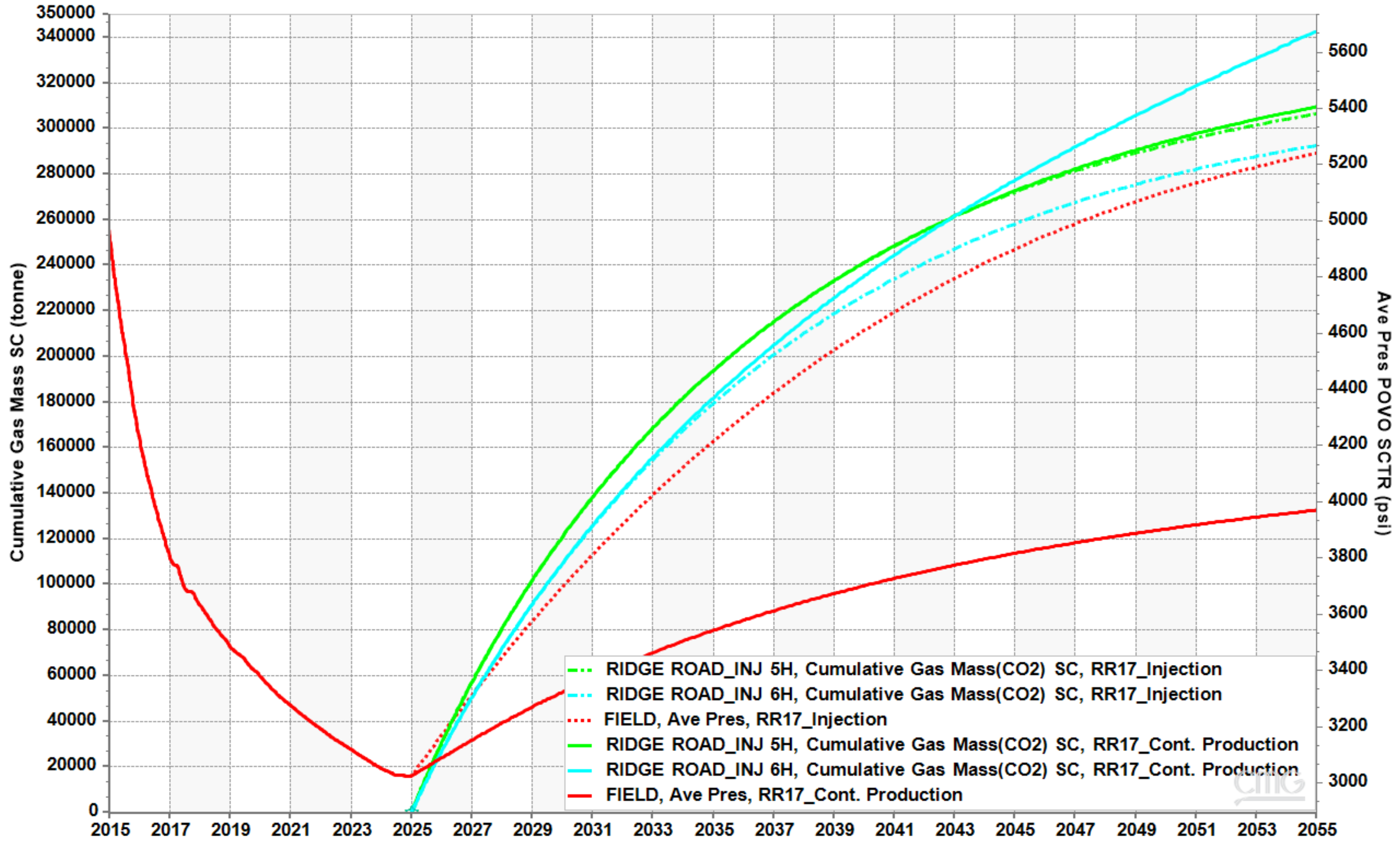




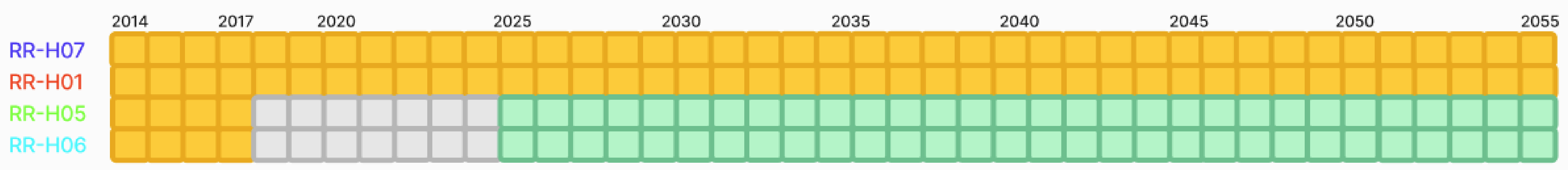


RIDGE ROAD Cluster Model

CO2 Storage



- *Individual Well Cum. Injection*



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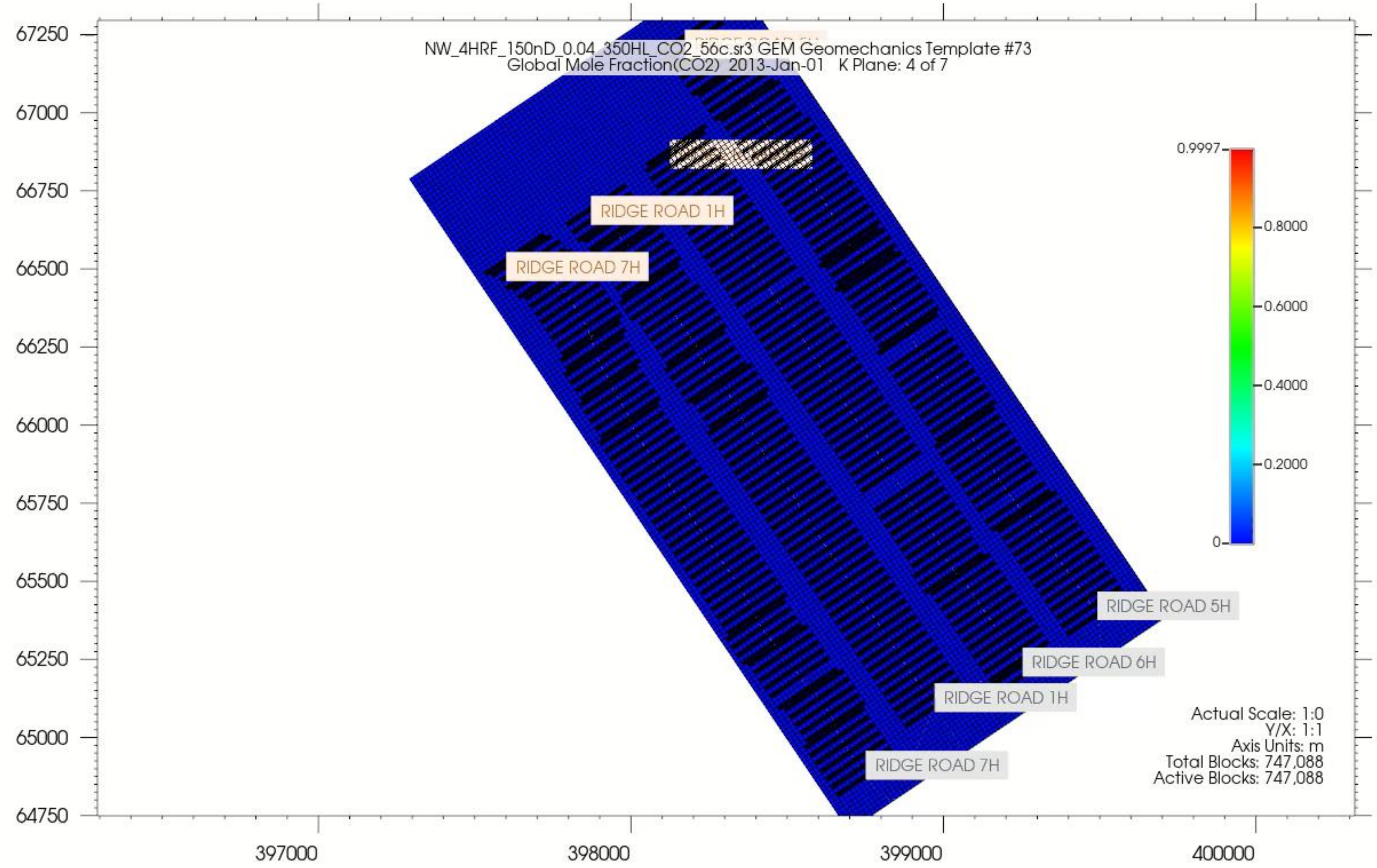
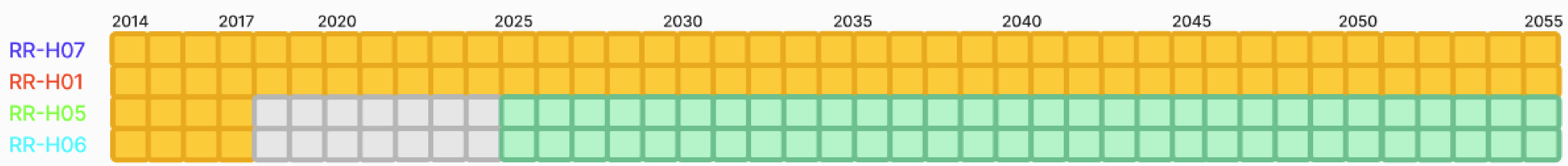
RIDGE ROAD Cluster Model

CO2 Storage



- *Individual Well Cum. Injection*



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Marcellus Well Conversion

- CCS in Marcellus shale formations through depleted multi-stage fracked horizontal wells shows potential of **mega-scale CO_2 storage in cluster patterns**
  - **Model simulations indicate 0.5+ Mt per well, 3+ Mt per multi-well pad**
- Majority of CO_2 storage may be achieved by the early-stage injection
- **Strategic planning of converting** natural gas producers into injectors will maximize the economics by enhance CH_4 production while sequestrating optimal amount of CO_2.

Conclusions

- Integrating LCA into FEED studies can improve overall system design by identifying key trade-offs and optimizing environmental performance
- CONSOL's 21CPP project would be located in a region with favorable opportunities to reduce costs through shared infrastructure
- Cost of storage in deep saline formations is uncertain and likely relatively high but repurposing depleted Marcellus shale gas wells may be a viable option for 21CPP and the region

Q&A

Thanks for your attention…

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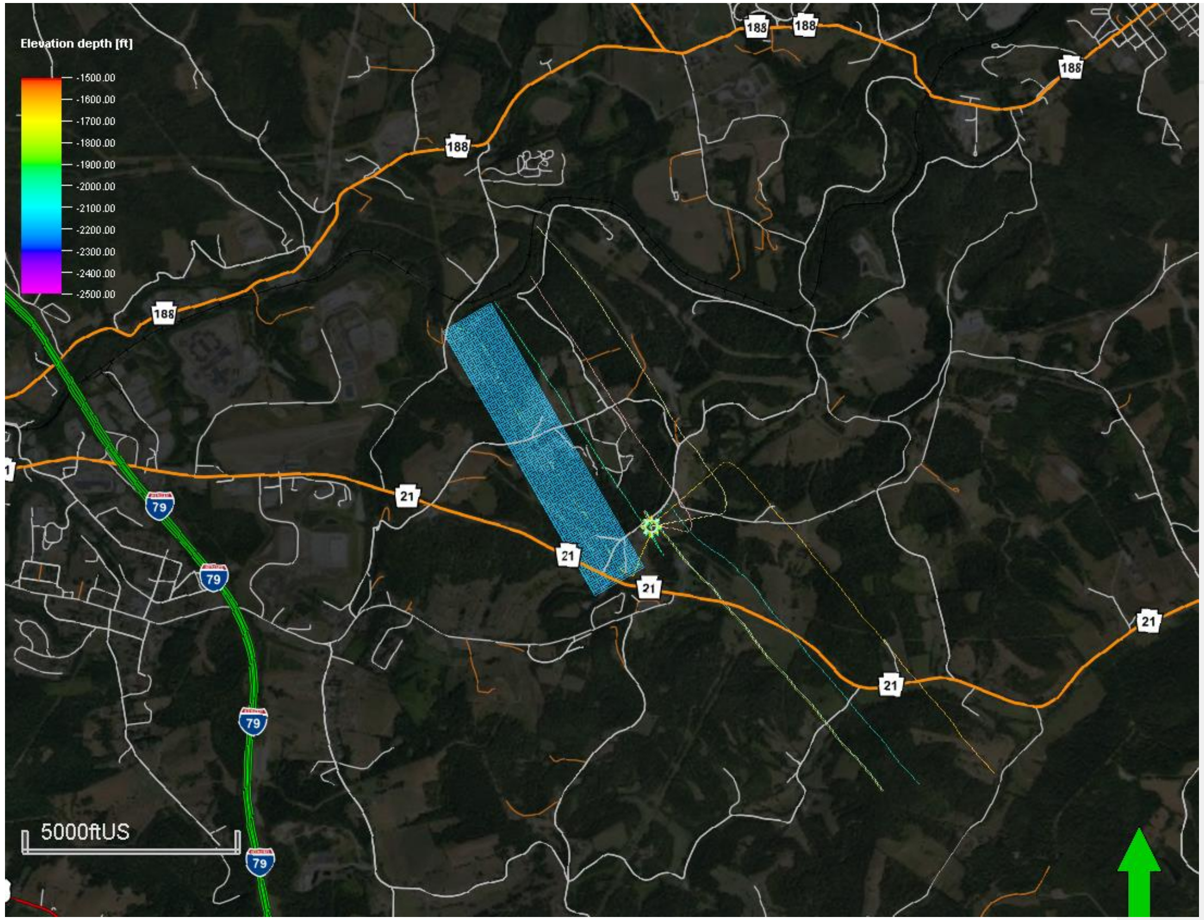
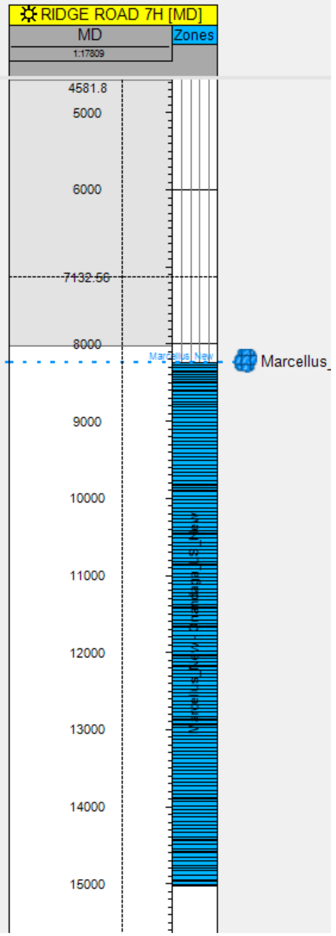
Archive

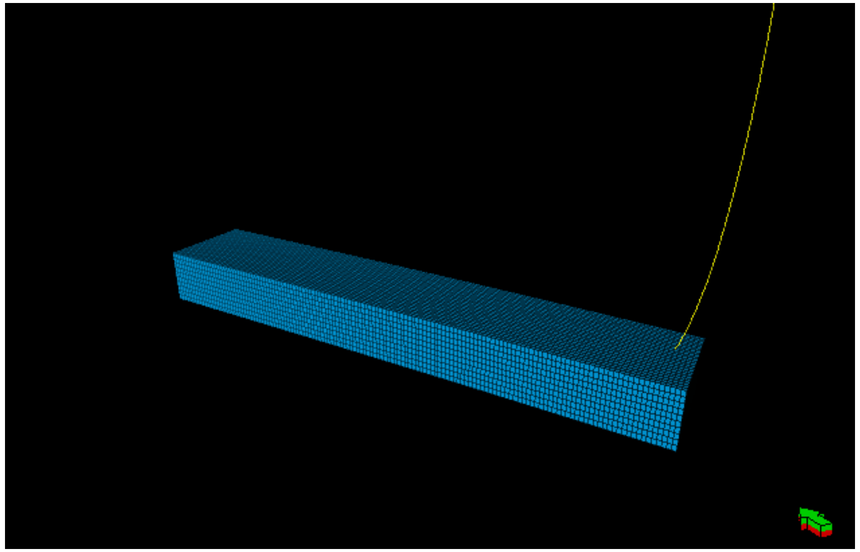
Single Wellbore Model

RIDGE ROAD 07 – Single Wellbore model

Model Setup







Static Properties	
Aerial Dimension	0.25 x 1.35 sq mi
Grid Cells (I, j, k)	25 x 139 x 10
Total number of grid cells	34,750
Avg grid size	50 ft x 50 ft
Marcellus Top	-6552 ft (MSL)
Marcellus Base	-6660 ft (MSL)
Avg thickness	177 ft

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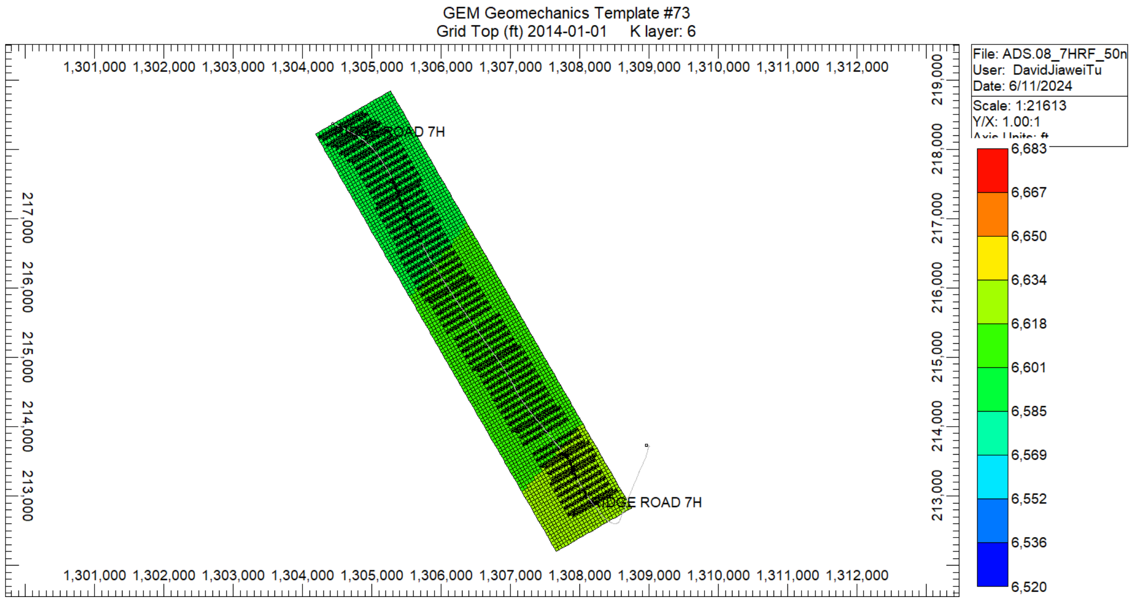
RIDGE ROAD 07 – Single Wellbore model

Grid Properties and Initial Conditions

Matrix Properties	
Porosity	0.04
Permeability i, j	0.00015 mD [150 nD]
Permeability k	0.00015 mD [150 nD]
Initial Conditions	
Initial Saturation	1.0 CH_4
Irreducible water Sat.	0.25
Reservoir Pressure	5600 psi @ -6600 ft MSL
W/G contact	-6750 ft MSL
Adsorption	
$$\omega_i = \frac{\omega_{i,max} B_i y_{ig} p}{1 + p \sum_j B_j y_{ig}}$$	B_i = parameter for Langmuir isotherm relation ω_i = moles of adsorbed component per unit mass or rock $\omega_{i,max}$ = maximum moles of adsorbed component *i* per unit mass of rock p = pressure y_{ig} = molar fraction of adsorbed component *i* in the gas phase
Langmuir isotherm in Fracture	0 1/psi 0 gmole / lb rock
Langmuir isotherm in Matrix	0.001 1/psi 0.08 gmole / lb rock

Fracture Properties	
Fracture Width	0.001 ft
Fracture Half Length	350 ft
Fracture Height	Through the Marcellus shale
Frac Permeability i, j	0.001 mD
Frac Permeability k	0.0001 mD
Frac Porosity	0.001
Total SRV	3.37e8 cu ft



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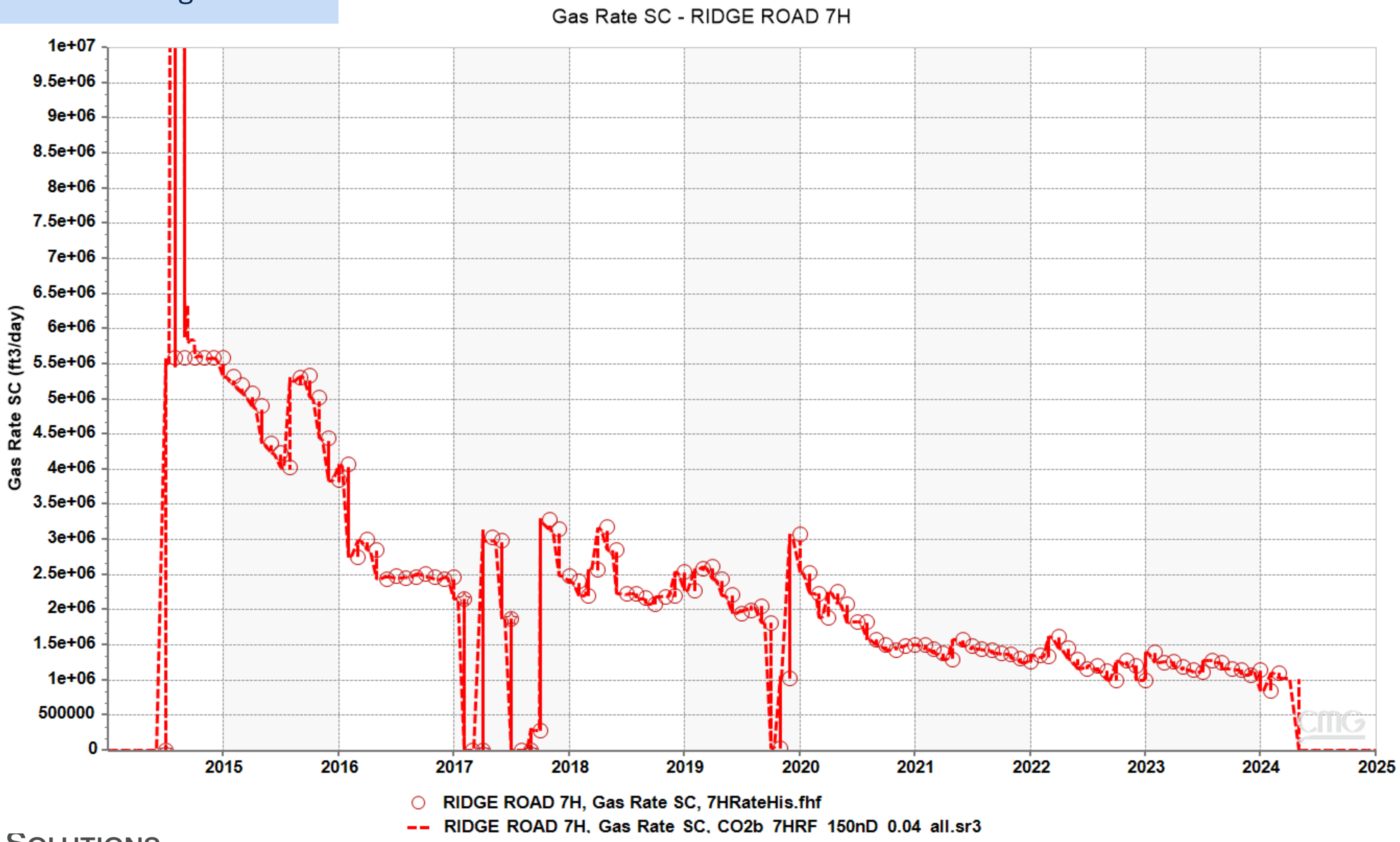
RIDGE ROAD 07 – Single Wellbore model

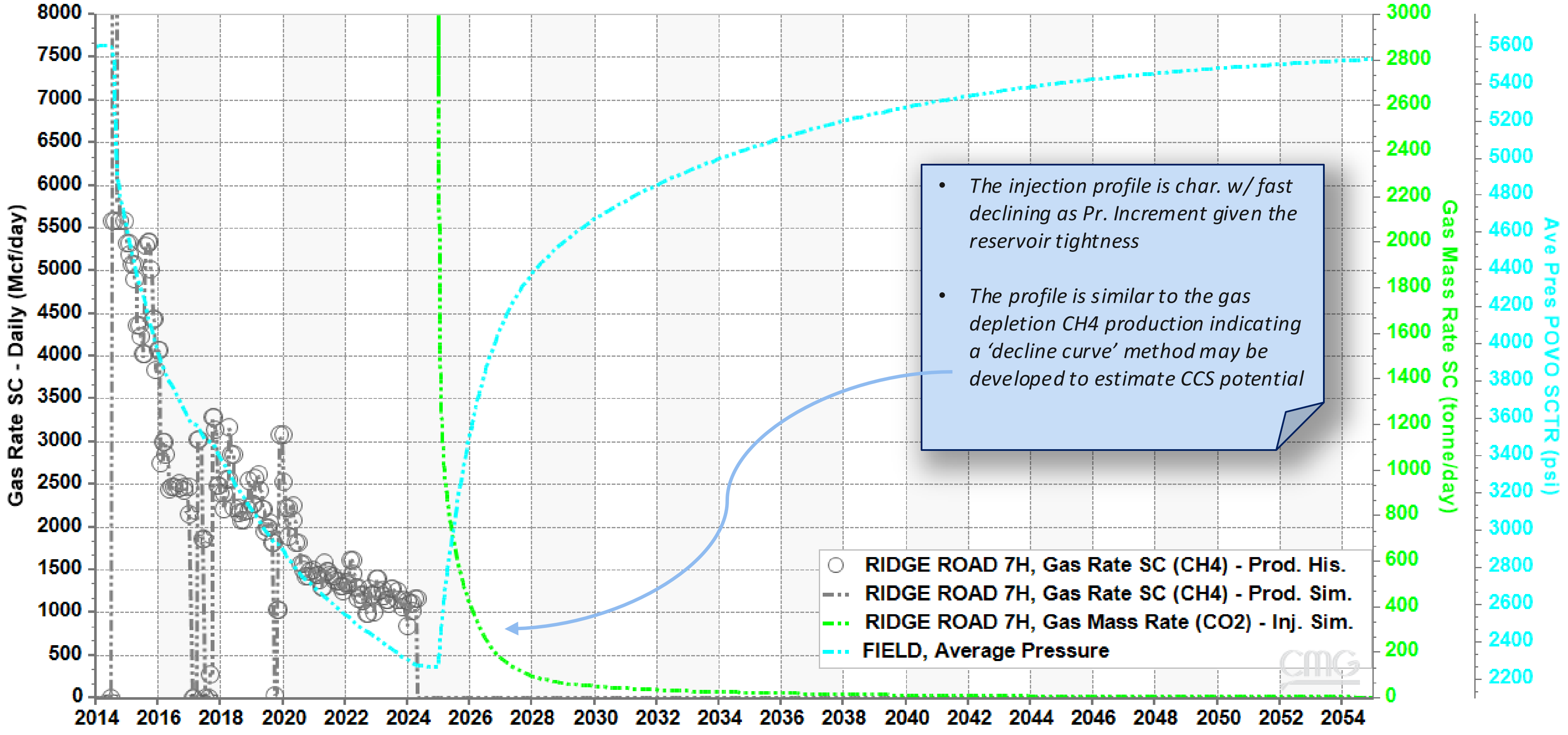
Improved History Matching



RIDGE ROAD 07 – Single Wellbore model

- Continue w/ 30yr - CO_2 Injection following CH_4 production

- The injection rate is set to be controlled by max Reservoir frac. pres.
- The injection limit is set to replenish the initial reservoir avg. pres.



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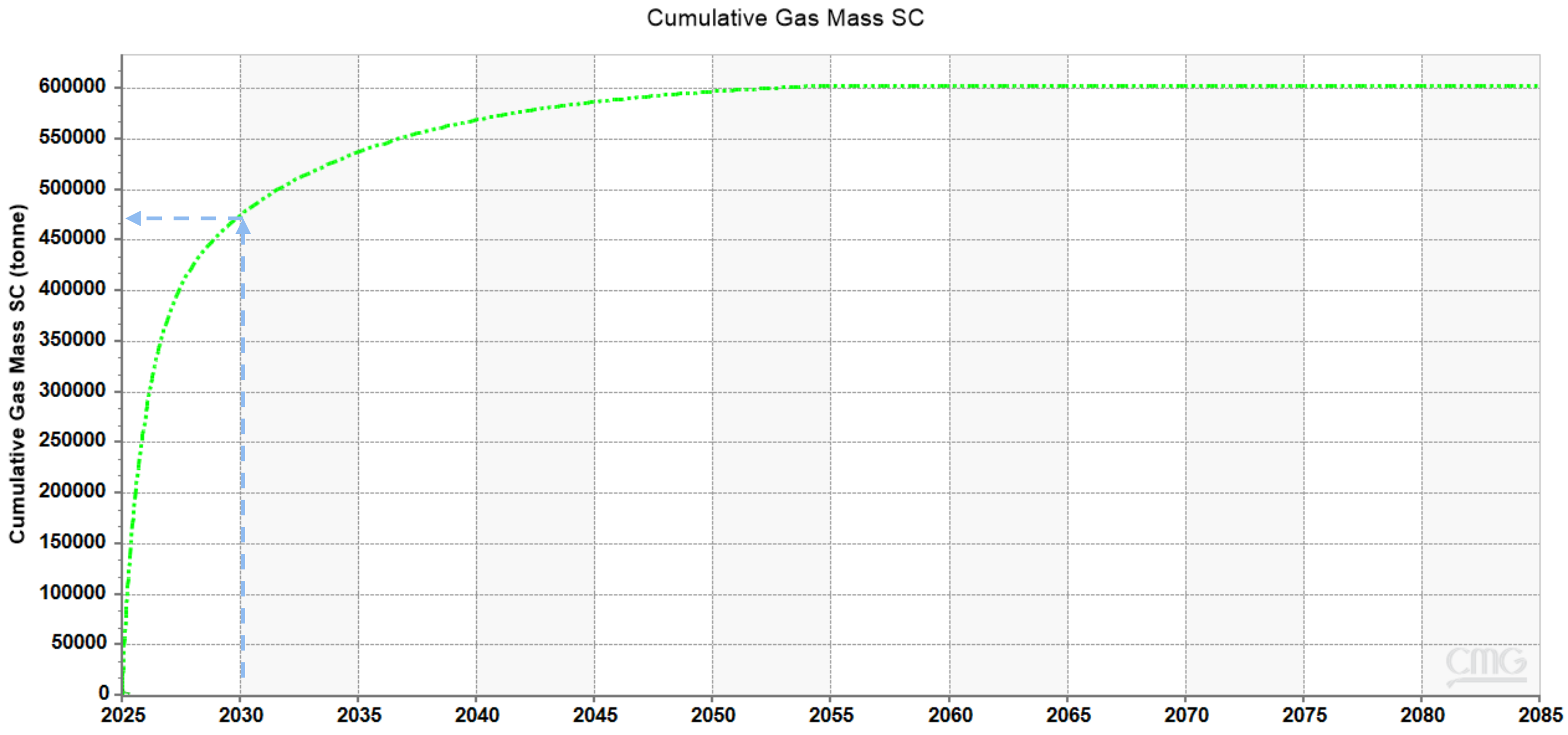
RIDGE ROAD 07 – Single Wellbore model

Key takeaways:

- Dynamic simulation shows in total, cumulatively 0.6 Mt-CO2 was injected over 30 years, in exchange for 8,153 MMSCF CH4.
- 80% stored volume was achieved by the first 5 years of injection.
- The main constraint is pressure built up by low-perm matrix.



Wellbore Properties	
Lateral Length (MD)	6635 ft
Stages of Fractures	44
Perforation Density	40 per stage
Cluster Density	150 ft per stage
Total SRV	3.37e8 cu ft

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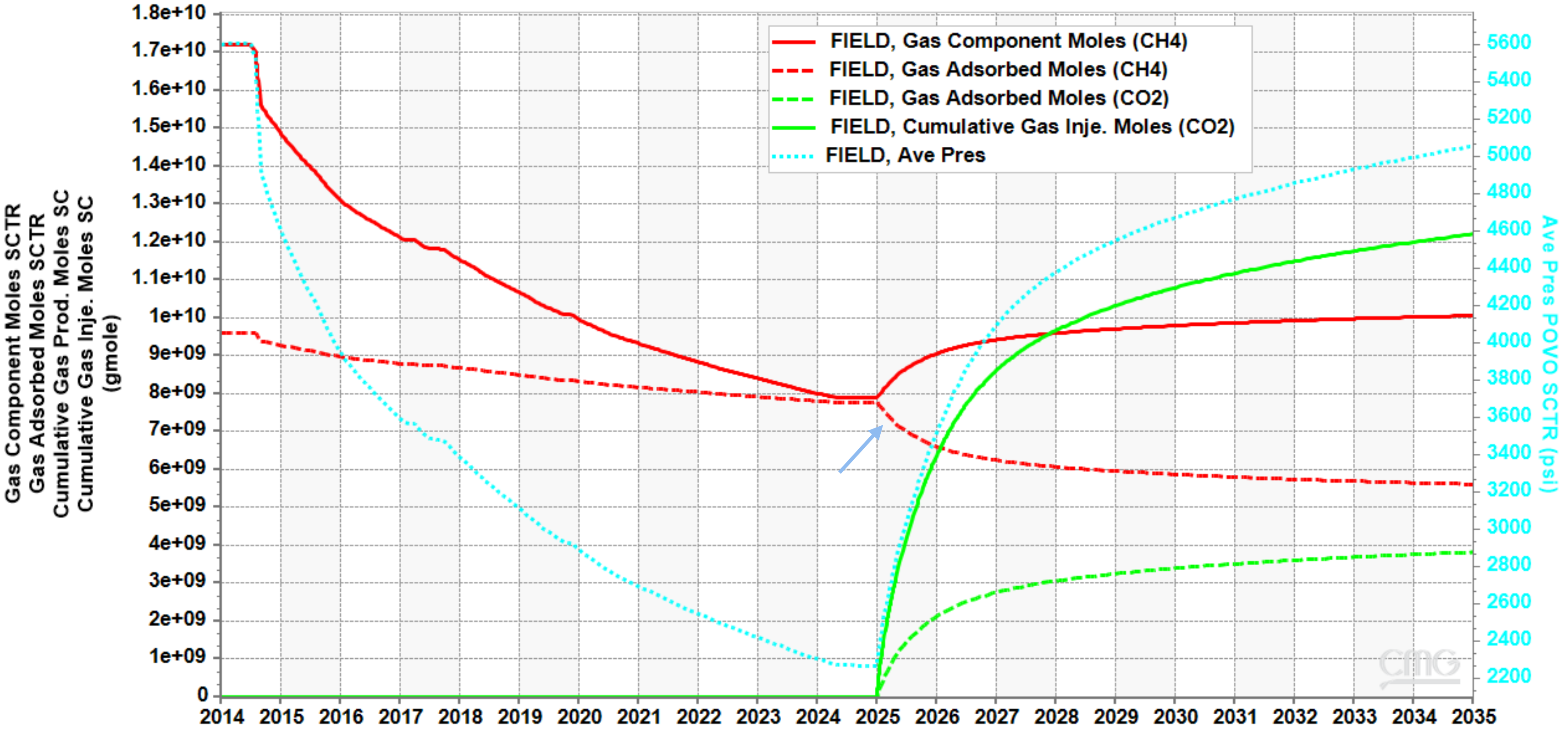
RIDGE ROAD 07 – Single Wellbore model

Key takeaways:

- Desorption of CH4 is expected following gas production as the res. pres. declines.
- The behavior of competition adoption of CO2/CH4 is simulated as the adsorbed CH4 further declined as CO2 injection started despite press. Increase.
- Indicating volumetric calculation of CO2 injection in shale formation can be estimated with improved accuracy.



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