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Life Cycle Assessment for Closed-Loop Pumped Hydropower Energy Storage in the United States

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National Renewable Energy Laboratory (NREL)

July 14, 2022

Outline

- Goal, Scope, and Boundary
- Calculation Methods
- Model Integrations
- Results
- Comparison

NREL Pumped Storage Hydropower (PSH) Life Cycle Assessment (LCA)

***Goal:** Perform a full LCA of new closed-loop PSH in the United States.*

Functional Unit: 1 kilowatt-hour (kWh) of electricity delivered by system to grid substation connection points

Estimated Lifetime: 80–100 years

System Boundary: *Sourcing → construction → operation/maintenance → end of life*

Life Cycle Inventory (LCI) Data: Represents a range of potential prospective U.S. closed-loop PSH with plant data and specifications available

System Round Trip Efficiency (RTE): 80%

Results Presented:

- Global warming potential (Intergovernmental Panel on Climate Change [IPCC] 100a)
- Energy Return on Investment
- Scenario analysis and model sensitivity

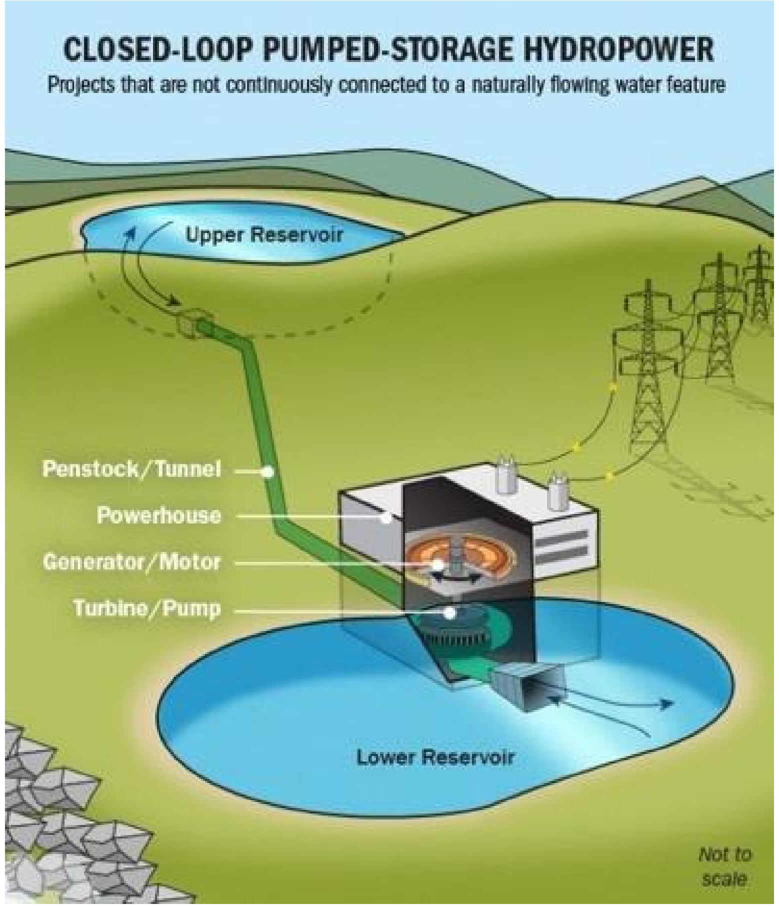


Illustration by John Frenzl, NREL

Closed-Loop PSH

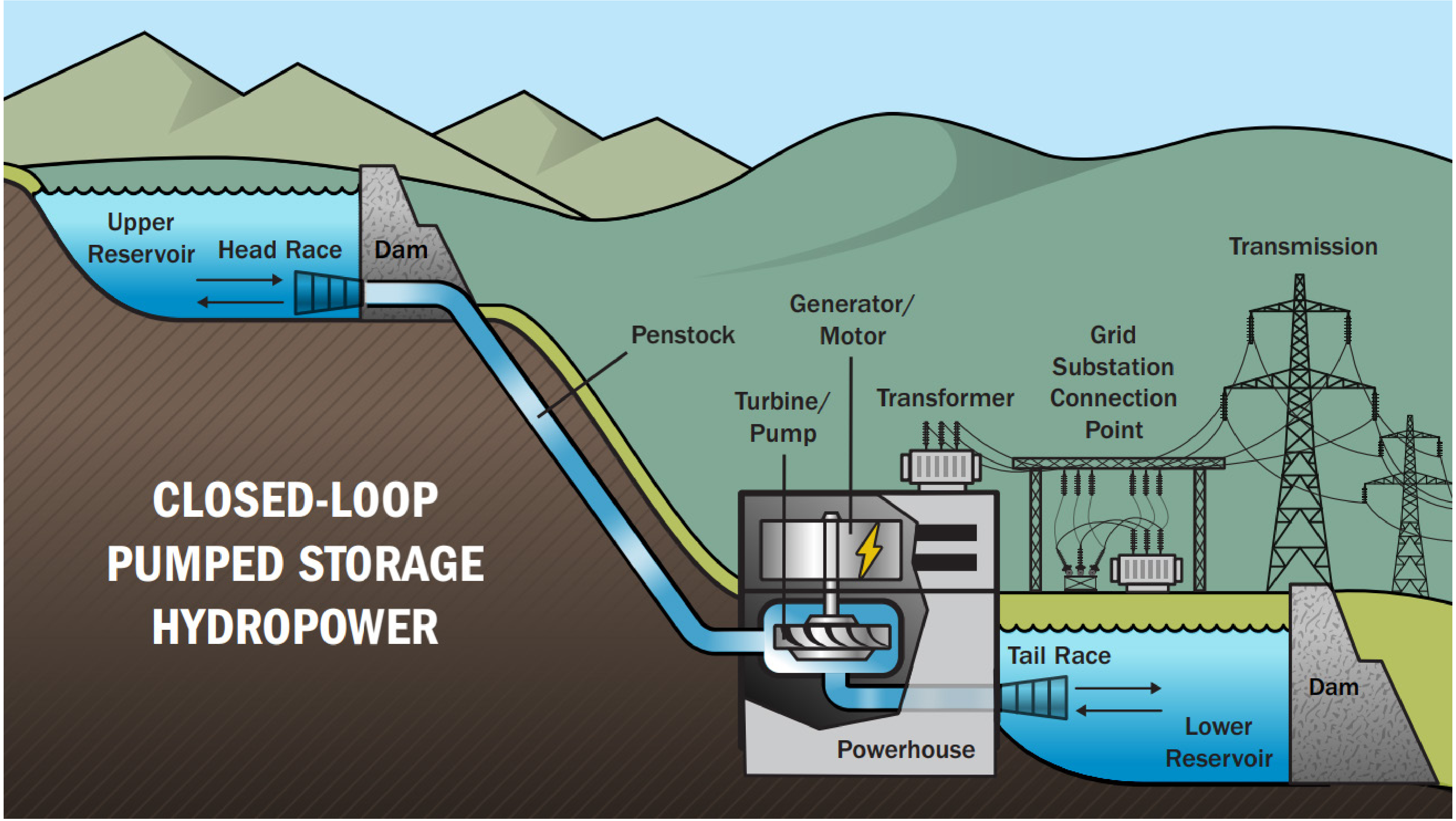


Illustration by John Frenzl, NREL

Scope and Boundary

Operation

- Maintenance (including replacement parts)
- Water refill
- Electricity
- Reservoir greenhouse gas (GHG) emissions
- SF_6 and lubricating oil

Construction

- Dam
- Reservoir
- Tunnels
- Powerhouse w/ inputs
- Turbine/generator
- Transformer
- Electrical equipment
- Penstock
- Transportation of materials
- Reservoir water
- Electricity
- Diesel
- Geotechnical lining

End of Life

Site is typically abandoned, and some machinery has been removed; deconstruction would require large energy inputs and emissions.

Most U.S. sites are still in operation, so good examples of this stage are limited or not available.

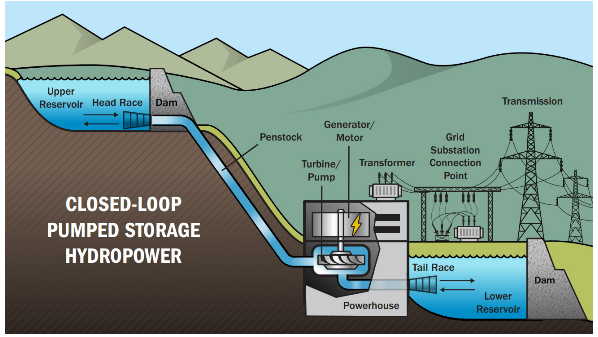
Comparison Technologies

1. Compressed air energy storage
2. Lithium-ion batteries
3. Redox-flow batteries
4. Lead-acid batteries

Scope and Boundary of Analysis

Electricity used to charge system from grid substation

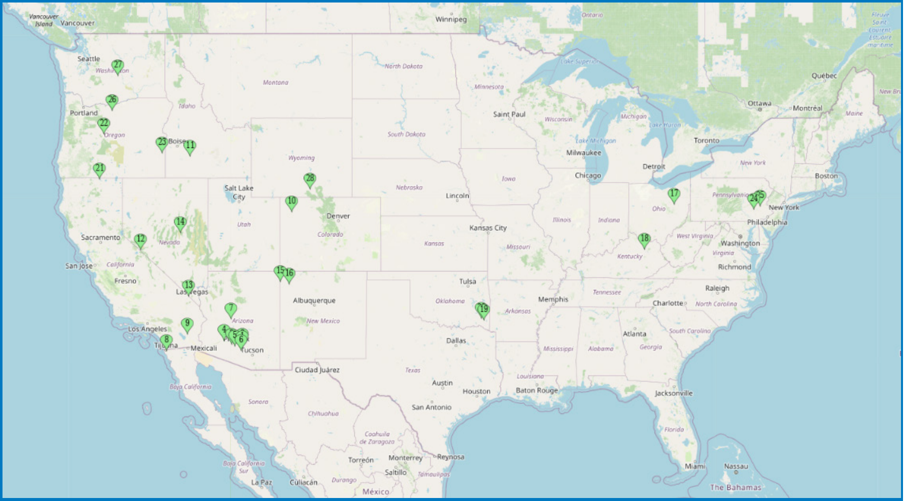
Materials and manufacturing



Energy delivered from PSH to grid substation

Losses due to RTE 80%

Calculation Methods



Green pins are new PSH sites.
Map from MapCustomizer; modified by Timothy Simon, NREL

There are 32 individual sites contributing data; three sites have two complete alternatives included.

- Not all new U.S. closed-loop projects are included, just those with data available.
- Not every location includes data for each construction or operational input.

Project specifications provide basic information about construction and operation.

- Guidelines for the tunnels, dams, powerhouse, and other components are used to find volume/mass inputs.
- All inventory inputs are estimates of what would be required based on project specifications.

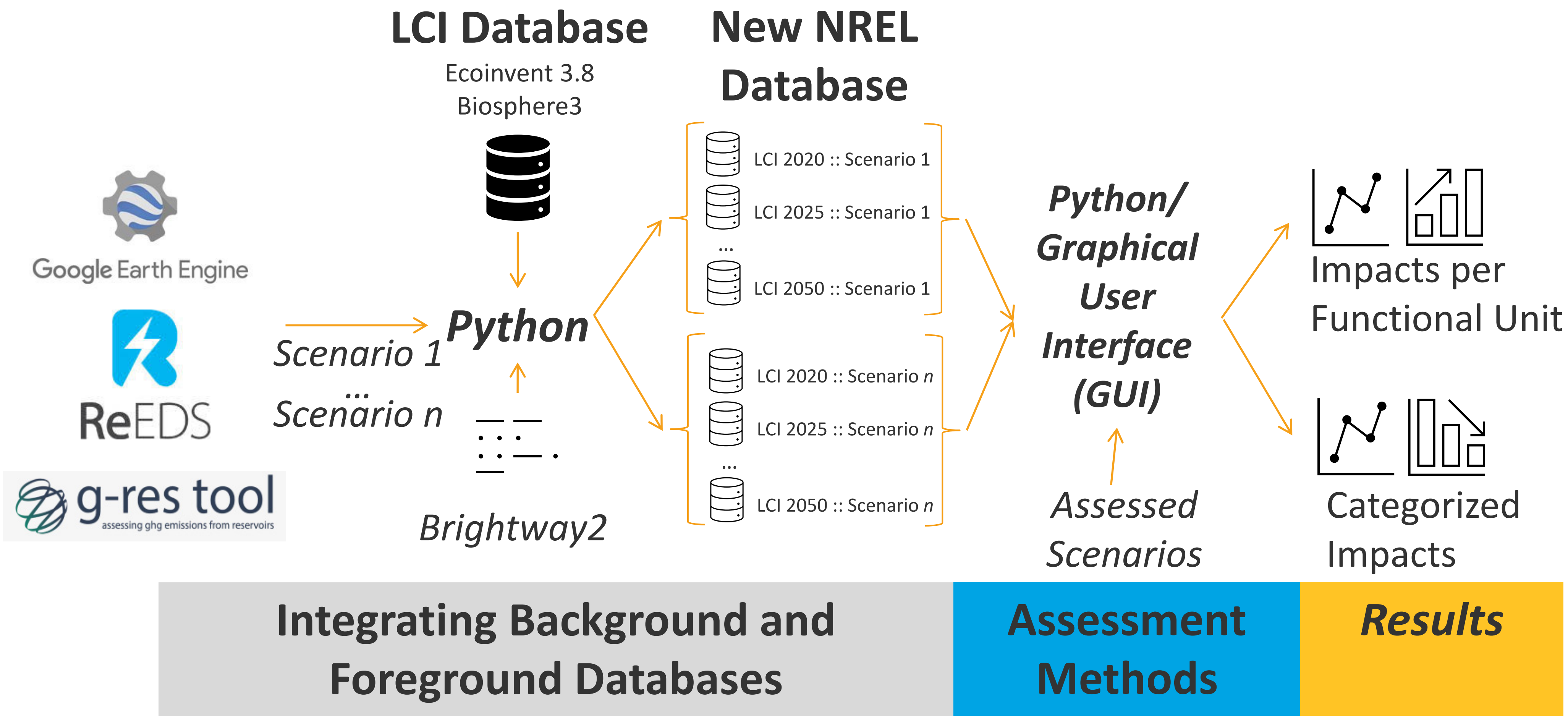
Final input is a weighted average of nonzero values at all sites.

- No data listed means no contribution to the average.
- Weighted by annual electricity delivered (in gigawatt-hours [GWh]).
- The same averaging methods are used for construction and operational inputs.
- Inventory represents the new average closed-loop PSH project, instead of focusing on one/a few locations.

Model Integrations

The G-res Tool, Google Earth Engine, and
Regional Energy Deployment System (ReEDS)

PSH LCA Framework



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The G-res Tool for Reservoir Greenhouse Gas (GHG) Emissions

Emission Pathway	Estimated Pathway Contribution	Primary Variables
1. Diffusion (CO_2 & CH_4)	74%	• Reservoir Age (time) • % Littoral Area (< 3 meters) • Effective Temperature • Reservoir Surface Area • Reservoir Surface Soil C Content • Reservoir Cumulative Global Horizontal Radiance
2. Bubbling (CH_4)	16%	
3. Degassing (CH_4)	10%	

The G-res Tool was developed using an empirical model:

$$Net\ GHG\ Footprint = Postflooding\ Emissions - Preflooding\ Emissions$$

Yves T. P., S. Mercier-Blais, J. A. Harrison, C. Soued, P. del Giorgio, A. Harby, J. Alm, V. Chanudet, and R. Nahas. 2021. “A New Modelling Framework To Assess Biogenic GHG Emissions From Reservoirs: The G-res Tool.” *Environmental Modelling & Software* 143: 105117. https://doi.org/10.1016/j.envsoft.2021.105117.

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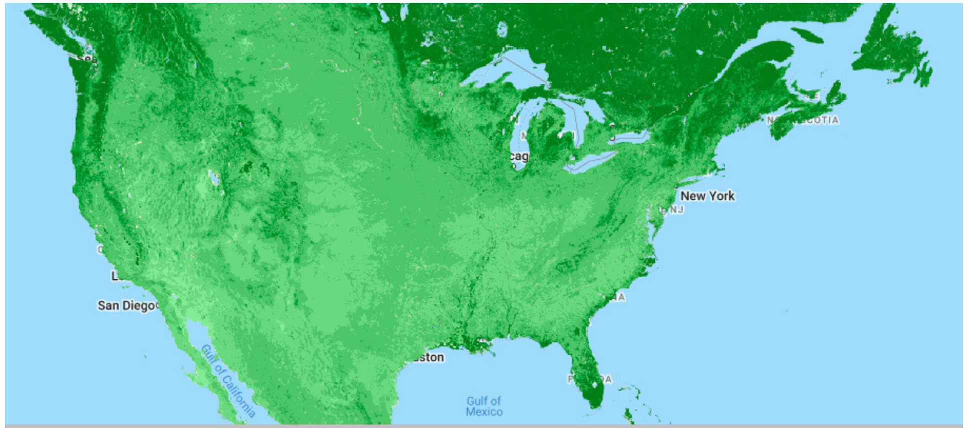
Site-Specific Soil Data 30-Centimeter Depth

Sand Content

Clay Content



Soil Organic Carbon Content

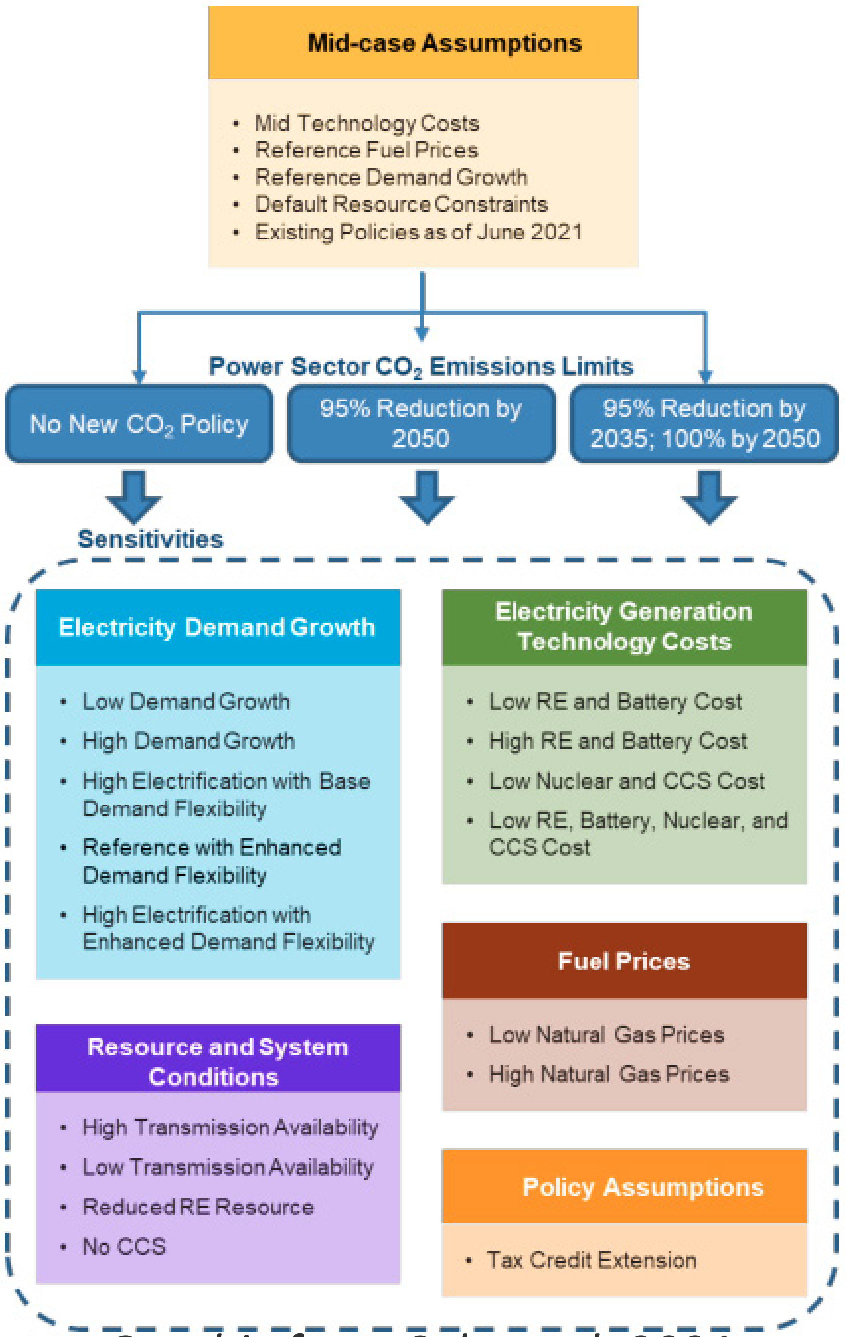
Soil Content	35-Site Combined Average
Sand	45.5%
Clay	21.6%
Silt	32.9%
Soil Organic Carbon	9.0 grams per kilogram

Maps by Timothy Simon, NREL

ReEDS Model Integration

ReEDS Summary of 2021 Standard Scenarios:

- The *midcase* takes the median values of various assumptions made in the model.
- 16 different sensitivities give 50 different scenarios from the midcase.
- Allows for an understanding of how impact on how different drivers affect the midcase.



Graphic from Cole et al. 2021

Cole, W., J. V. Carag, M. Brown, P. Brown, S. Cohen, K. Eurek, W. Frazier, P. Gagnon, N. Grue, J. Ho, A. Lopez, T. Mai, M. Mowers, C. Murphy, B. Sergi, D. Steinberg, and T. Williams. 2021. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-80641. https://www.nrel.gov/docs/fy22osti/80641.pdf.

Results

- Base Case
- Installed Capacity (Small, Medium, Large)
- Greenfield Versus Brownfield
- Liner Comparison (Geomembrane, Concrete, Asphalt, Clay)
- ReEDS (Renewable Storage Versus Full U.S. Grid Mix)

Sensitivity and Scenario Analysis

Base Case

- Geomembrane liner
- Energy stored comprised of renewables i.e., photovoltaics and wind turbines

Installed Capacity

- Small <500 MW
- Medium 500–1,000 MW
- Large >1,000 MW

Greenfield versus Brownfield

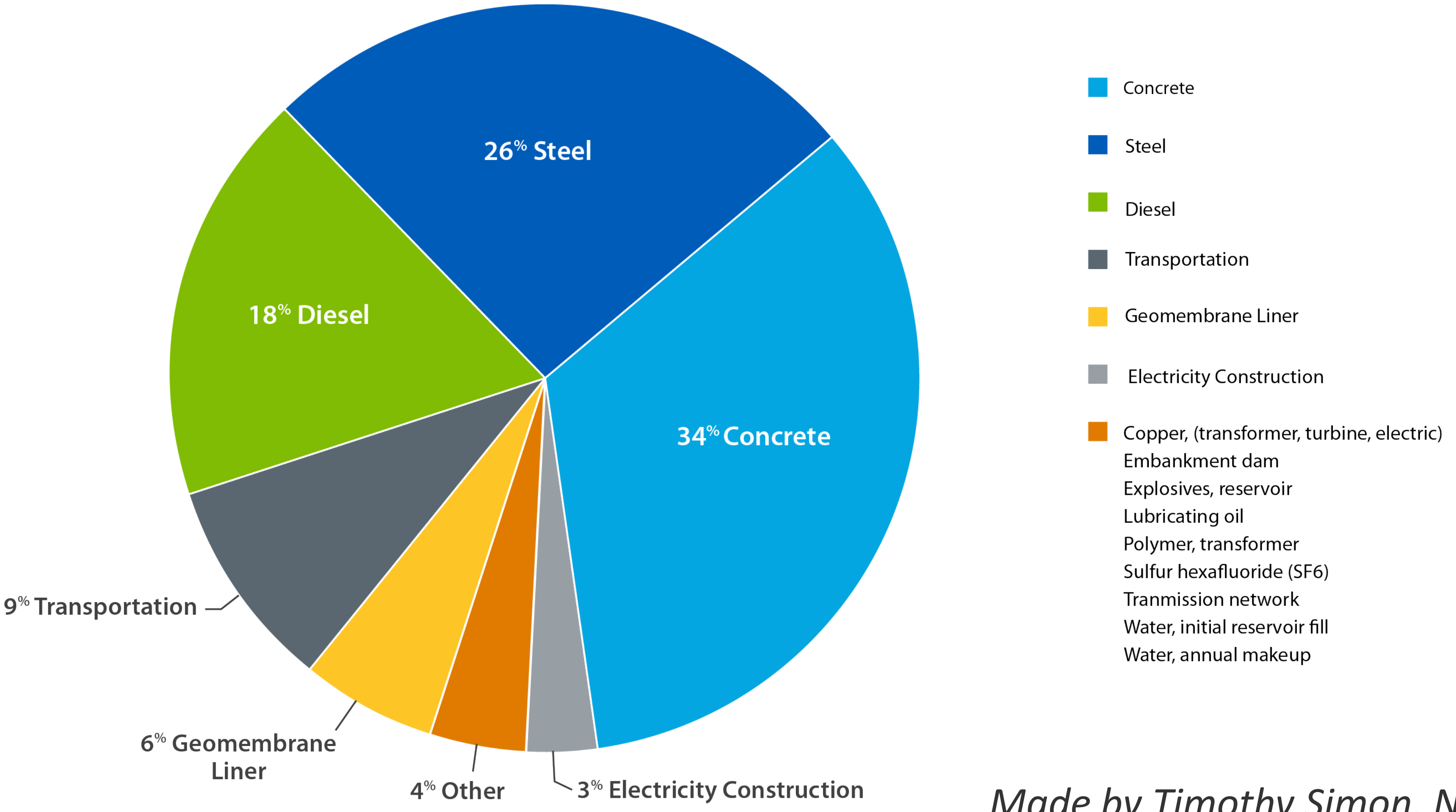
- 27 greenfield sites
- 8 brownfield sites

Liners

- Base case (geomembrane)
- Concrete
- Asphalt
- Clay

ReEDS Full Grid Mix

PSH Base Case GHG Contributions Total GHG: 0.086 Kilograms (kg) CO_2–eqivalent (eq) per Kilowatt-Hour (kWh)Delivered



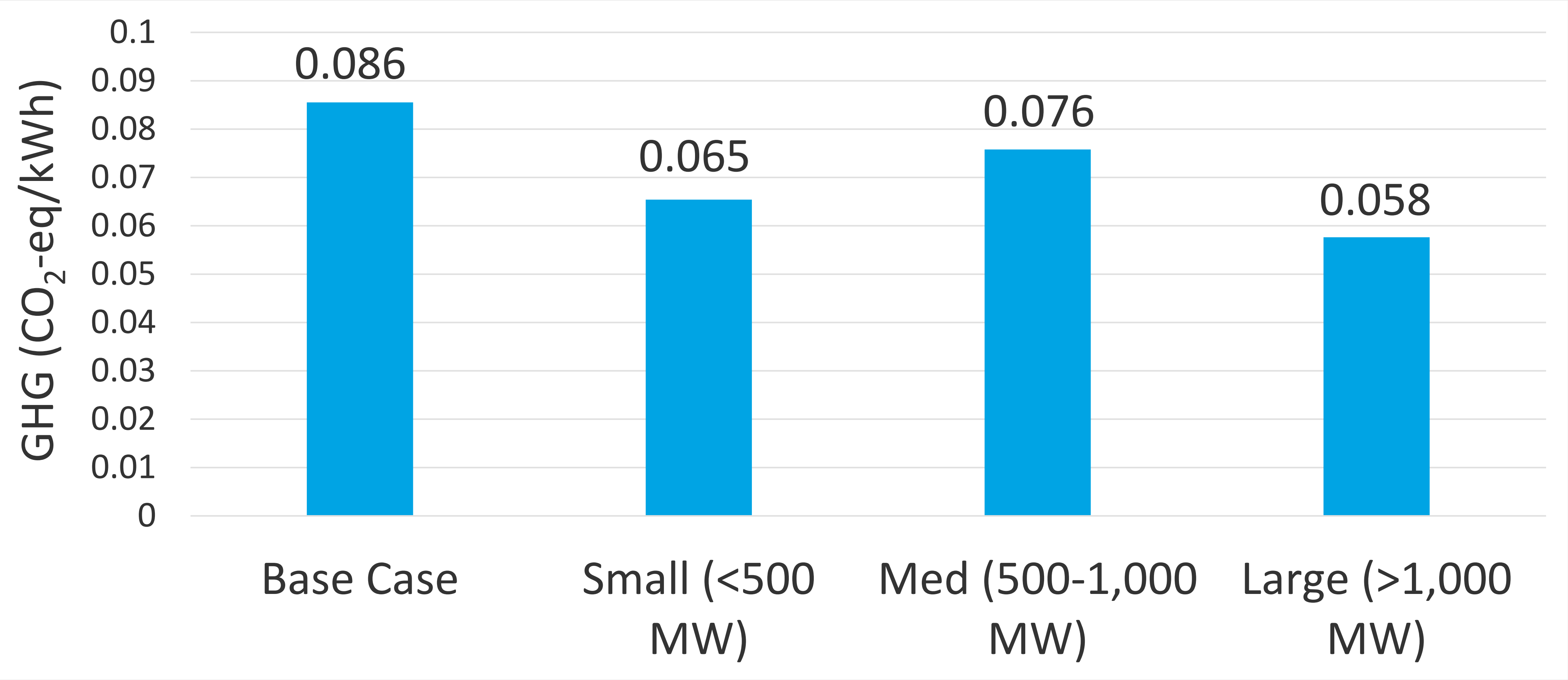
Made by Timothy Simon, NREL

Life Cycle GHG Emissions Sensitivity Results

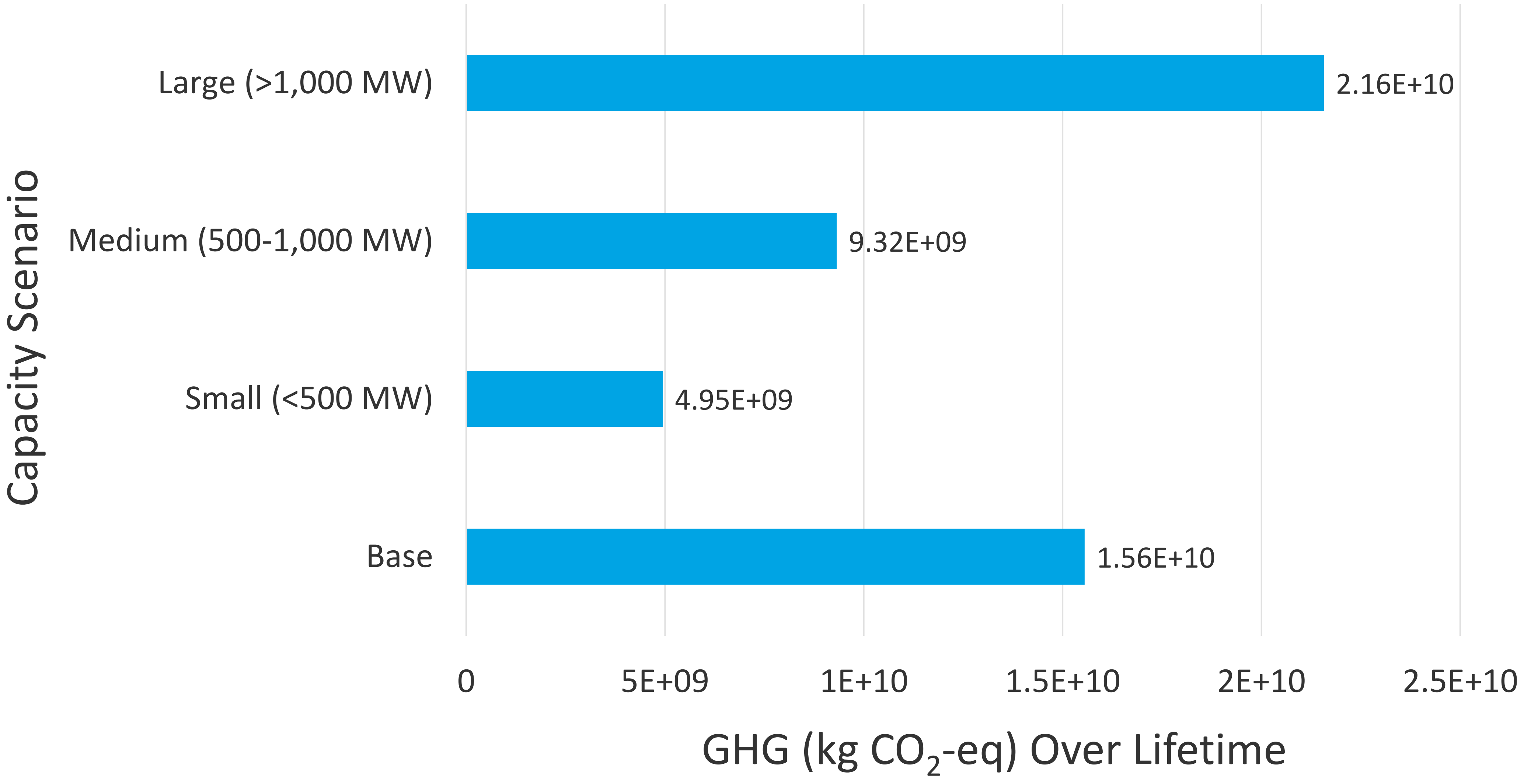
Scenario	GHG (kg CO_2-eq/kWh)
Full Grid Mix	0.53
Greenfield	0.10
Asphalt Liner	0.087
Concrete Liner	0.087
Base Case	0.086
Clay Liner	0.085
Brownfield	0.081
Med (500–1,000 megawatts [MW])	0.076
Small (<500 MW)	0.065
Large (>1,000 MW)	0.058

Variation of Installed Capacity

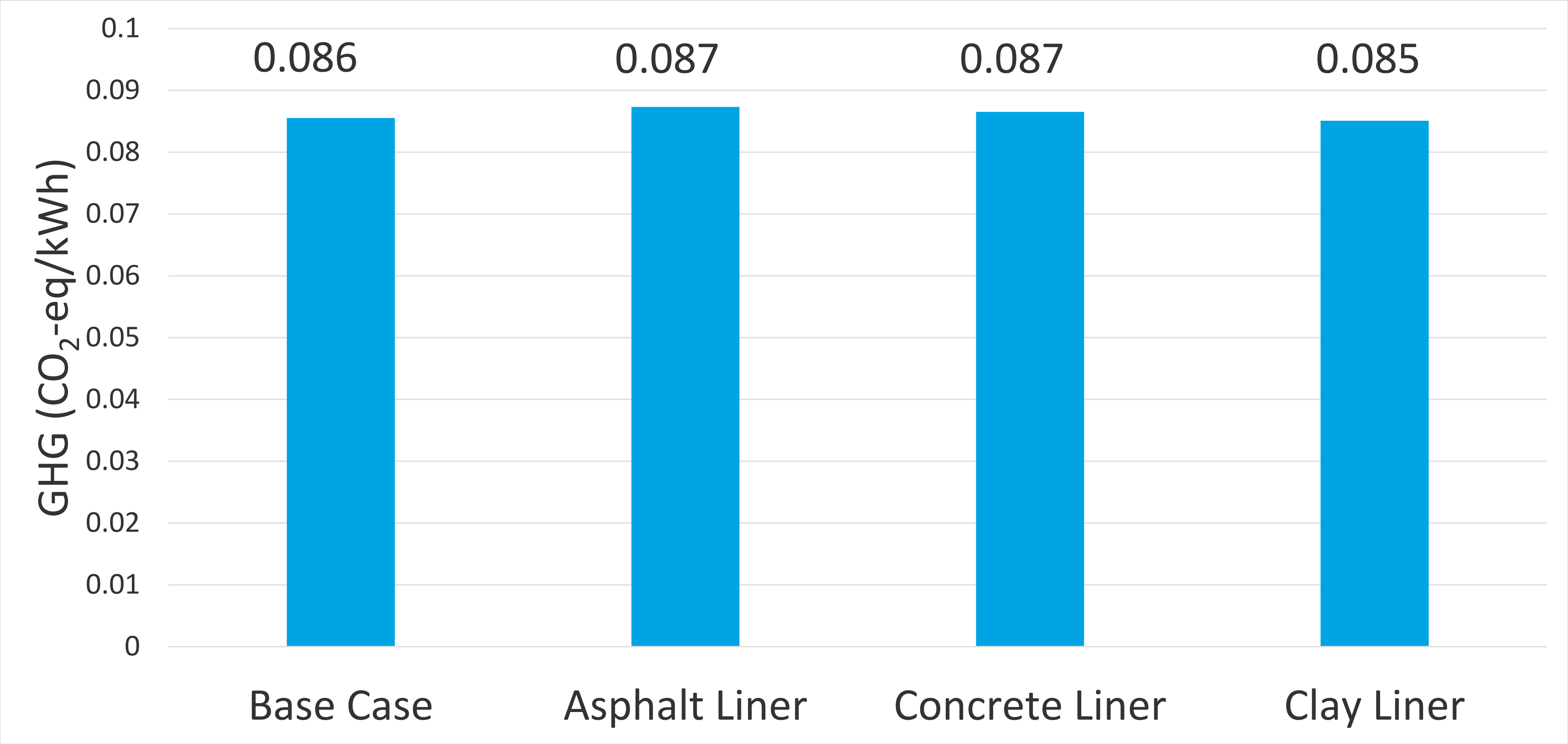
Estimated Annual Energy Delivered (Averages of Each Capacity Set)			
2,082 gigawatt-hours (GWh)	850 GWh	1,394 GWh	4,229 GWh



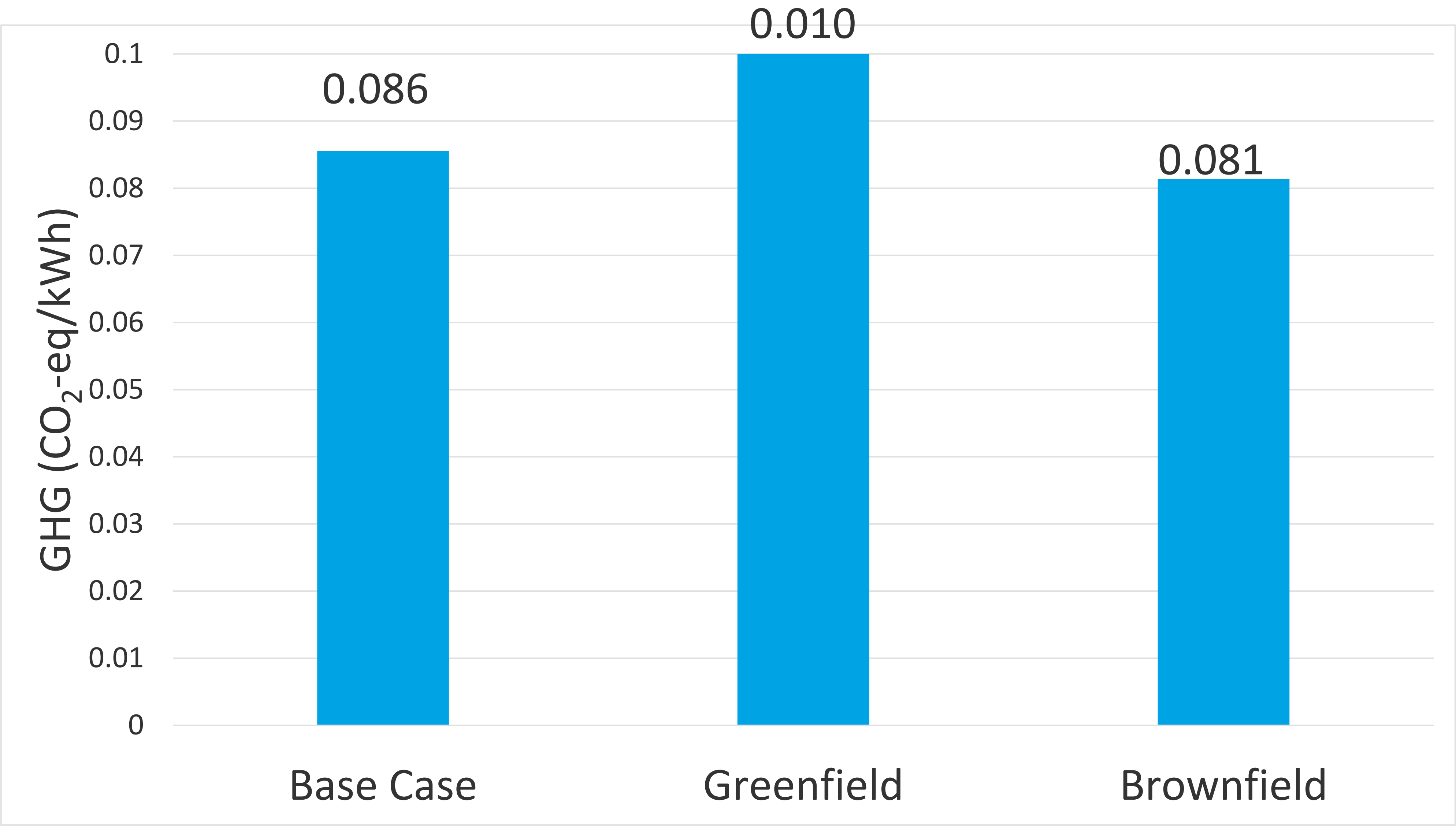
Life Cycle GHG Emissions Over 80-Year Lifetime



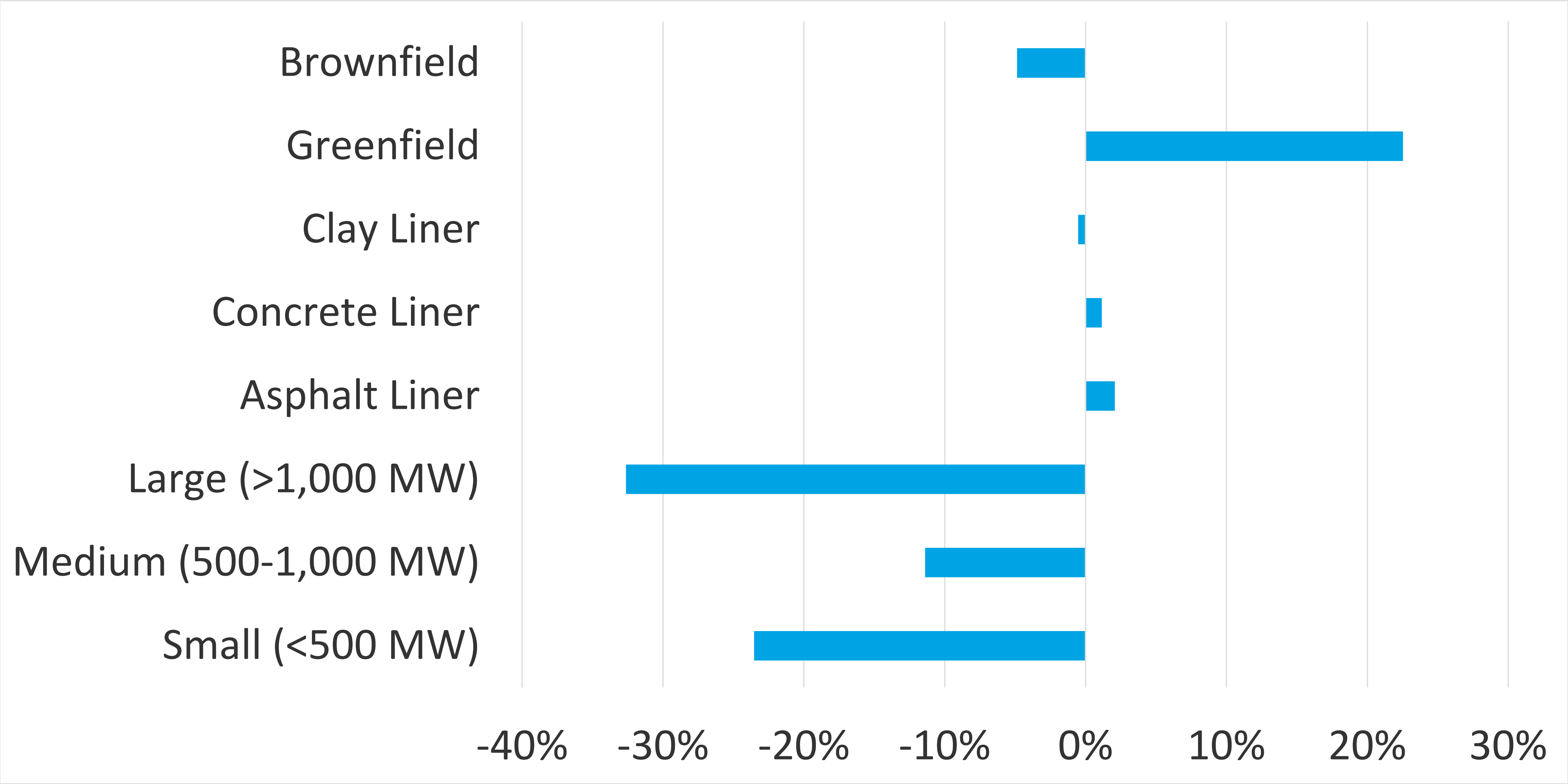
Variation in Reservoir Liners



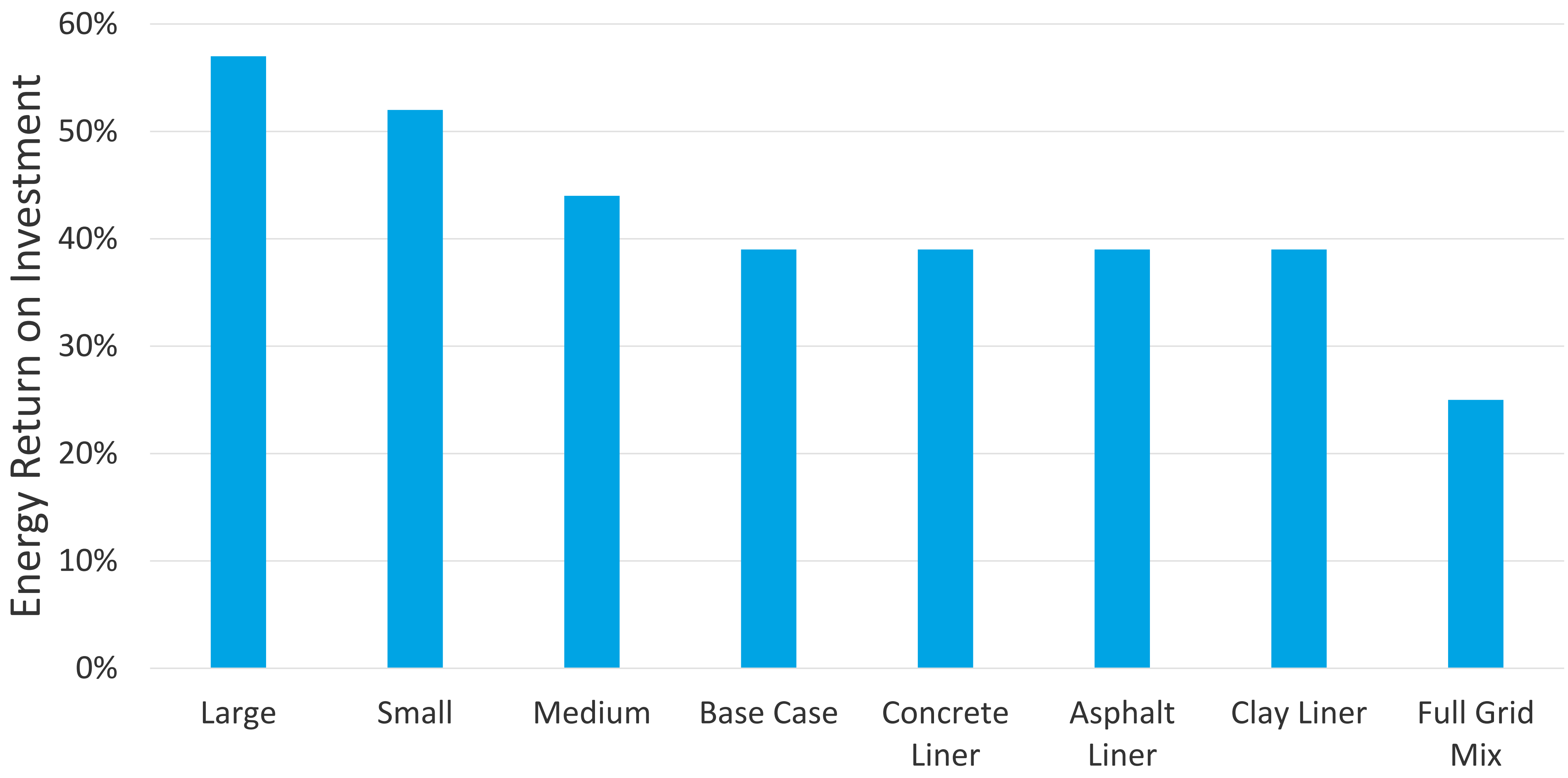
Greenfield Versus Brownfield



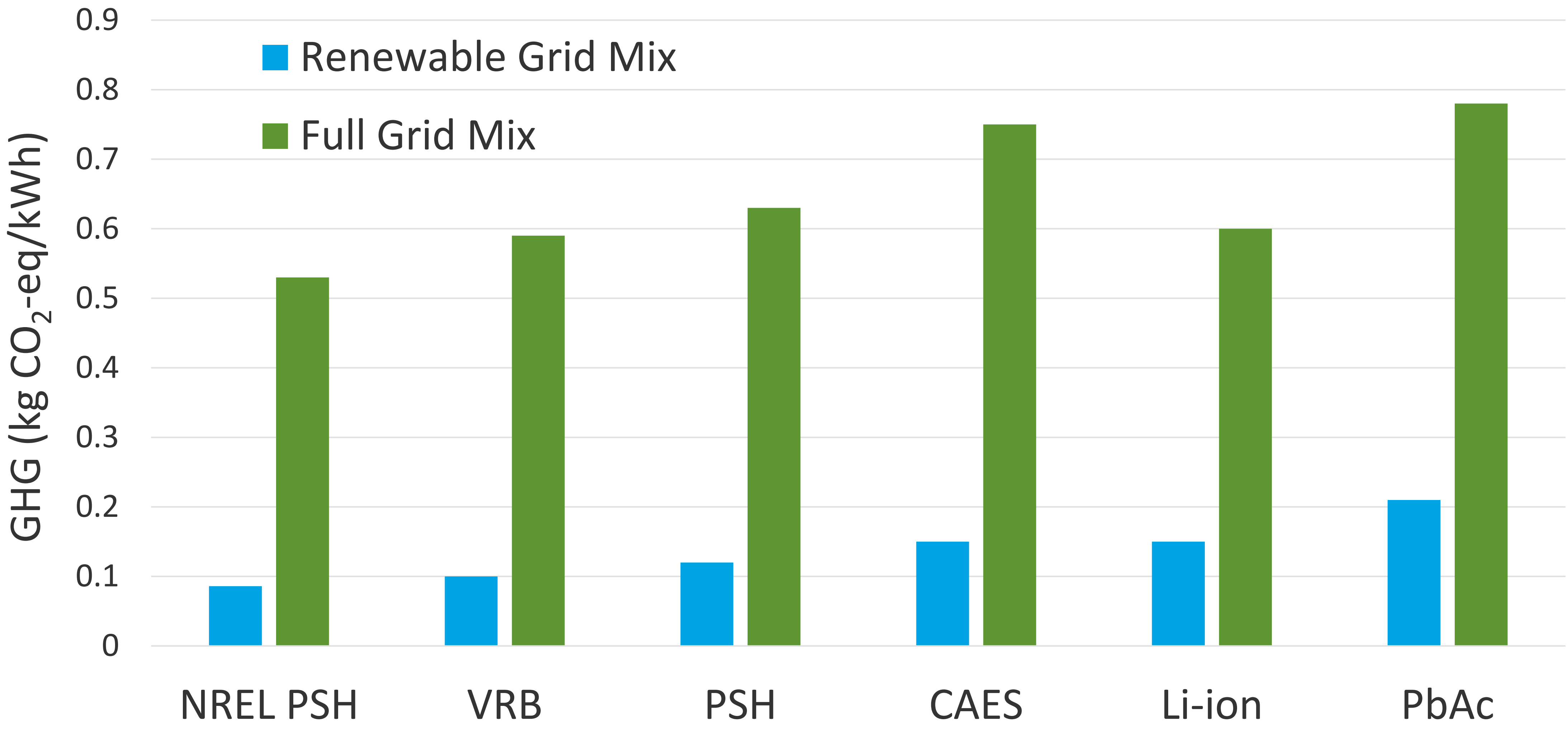
Percent GHG (kg CO_2/kWh) Deviation From Base Case



Energy Return On Investment



Storage Technology Comparison



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Conclusions

- Resulting process GHG contributions are consistent with what has been found in literature.
  1. Concrete: 34%
  2. Steel: 26%
  3. Diesel: 18%
- Variations in GHG emission is minimal when comparing different reservoir liners. This confirms that liner decisions should predominately be made based on cost.
  - GHG emission range: 0.085–0.087 kg CO_2-eq/kWh
- Substantial differences between Greenfield and Brownfield are due to differences in construction needs.
  - Greenfield GHG emissions: 0.010 kg CO_2-eq/kWh
  - Brownfield GHG emissions: 0.081 kg CO_2-eq/kWh
- PSH capacity trends are as expected for overall lifetime emissions but favor larger plants when considering the functional unit of 1 kWh delivered from storage. This functional unit heavily considers estimated energy delivered from the system over its lifetime.

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Supplementary Slides

Storage Technology Comparison

- Reported:
  - PSH favored when coupled with renewable energy systems. Compressed air energy storage has lower net GHG emissions when coupled with fossil generation.
  - PSH and compressed air energy storage uses energy free storage media (water or air) whereas BES electrolytes require energy-intensive mining and ore processing.
  - Turbines, compressors, and generators versus battery electrodes, stacks, and power conversion systems equipment.
- $\frac{Emissions}{year} = \frac{absolute\ emissions\ over\ lifetime}{estimated\ system\ lifetime}$
- Issues:
  - Scaling capacity
  - Grid mix storage
    - Separate by process contributions
    - Grid mix varies by location of study and methodology

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Potential Further Sensitivity

- Concrete mix design:
  - Splitting concrete mix designs by region
- Energy storage mix (ReEDS Data):
  - 95% CO_2 reduction from 2005 levels by 2050
  - 95% CO_2 reduction from 2005 levels by 2035
  - Other ReEDS sensitivities
- Eliminate liner and just use the G-res Tool emission estimates
- System lifetime: 80 versus 100 years

ReEDS Scenario GHG Emission Comparison – Power Sector Limits