Design and optimization of natural gas plants with CCS for flexible operation (ARPA-E FLECCS)

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FLECCS Annual Meeting, January 13-14, 2022

GenX open source release

The global electricity system is undergoing a major transformation

In response, researchers at MIT and Princeton have developed **GenX**, a new tool for investment planning in the power sector.

MITei
MIT Energy Initiative

PRINCETON UNIVERSITY
ZERO LAB
Zero-carbon Energy Systems Research and Optimization Laboratory

Powered by: julia + JuMP

Overview: http://genx.mit.edu/

Code and documentation:
https://github.com/GenXProject/GenX

GenX

A new tool for electricity system planning

The MIT Energy Initiative and Princeton University's ZERO Lab have developed an **open-source tool for investment planning in the power sector**, offering improved decision support capabilities for a changing electricity landscape. GenX is **custom-built to model electricity systems in transition** to low- or zero-carbon with increasing shares of wind and solar, energy storage, and novel low-carbon technologies.

GenX is a constrained optimization model that determines the portfolio of electricity generation, storage, transmission, and demand-side resource investments and operational decisions to meet electricity demand in one or more future planning years at lowest cost, while subject to a variety of power system operational constraints, resource availability limits, and other imposed environmental, market design, and policy constraints.

GenX

A flexible & highly configurable tool

A “Swiss Army knife” for electricity system planning:

- Modular and transparent code structure developed in Julia + JuMP
- Adjustable level of technology operating constraints and advanced technology options
- Linear programming (LP) model or mixed integer linear programming model (MILP)
- Co-optimize inter-regional transmission network expansion
- Co-optimize capacity and hourly operations decisions for a full year or representative periods
- Single- or multi-period investment planning
- Produce energy, capacity, and procured ancillary service prices, load payments, generator revenues
- Model a range of policies from emissions caps and clean electricity standards to tax incentives
- Easily connect with other power system data pre-processing tools like PowerGenome
- Modeling to generate alternatives to produce diverse set of near-least-cost portfolios

GenX Release Versions

- **Version 0.0 – May 2021:** First publication of public repository and documentation
- **Version 0.1 – August 2021:** Core functionality and documentation. Julia 1.5x & 1.6x compatibility. Single stage expansion only. Modeling to Generate Alternatives package
- **Version 0.2 – January 2022:** Added Method of Morris package for structured sensitivity analysis. Rearchitected policy modules for future extensibility. Added support for SCIP open source solver.
- **Version 0.3 – February 2022 (*planned*):** Multi-stage expansion planning with either perfect foresight (using decomposition approach for improved tractability) or incremental 'myopic' expansion.
- **Version 0.4 – March 2022 (*planned*):** Multiple advanced technology modules: FLECCS technologies; flexible geothermal systems; solar/wind + storage co-optimization; fusion module; piecewise approximation of non-linear heat rates for thermal generators.

FLECCS Modeling Approach

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FLECCS modeling framework

FLECCS team

- Process flow diagram
- Cost data: Capital, FOM, VOM, start up cost of each subcomponent
- Performance data: heat rate of gas/steam turbine cycle, steam/electricity consumption, capture efficiency, etc.
- Unit commitment data: minimum up/down time, ramp rates, minimum load.

PowerGenome

- Existing generators' capacity
- Cost and performance parameters of existing/future generators
- Hourly power load
- Variable renewable availability
- Fuel price

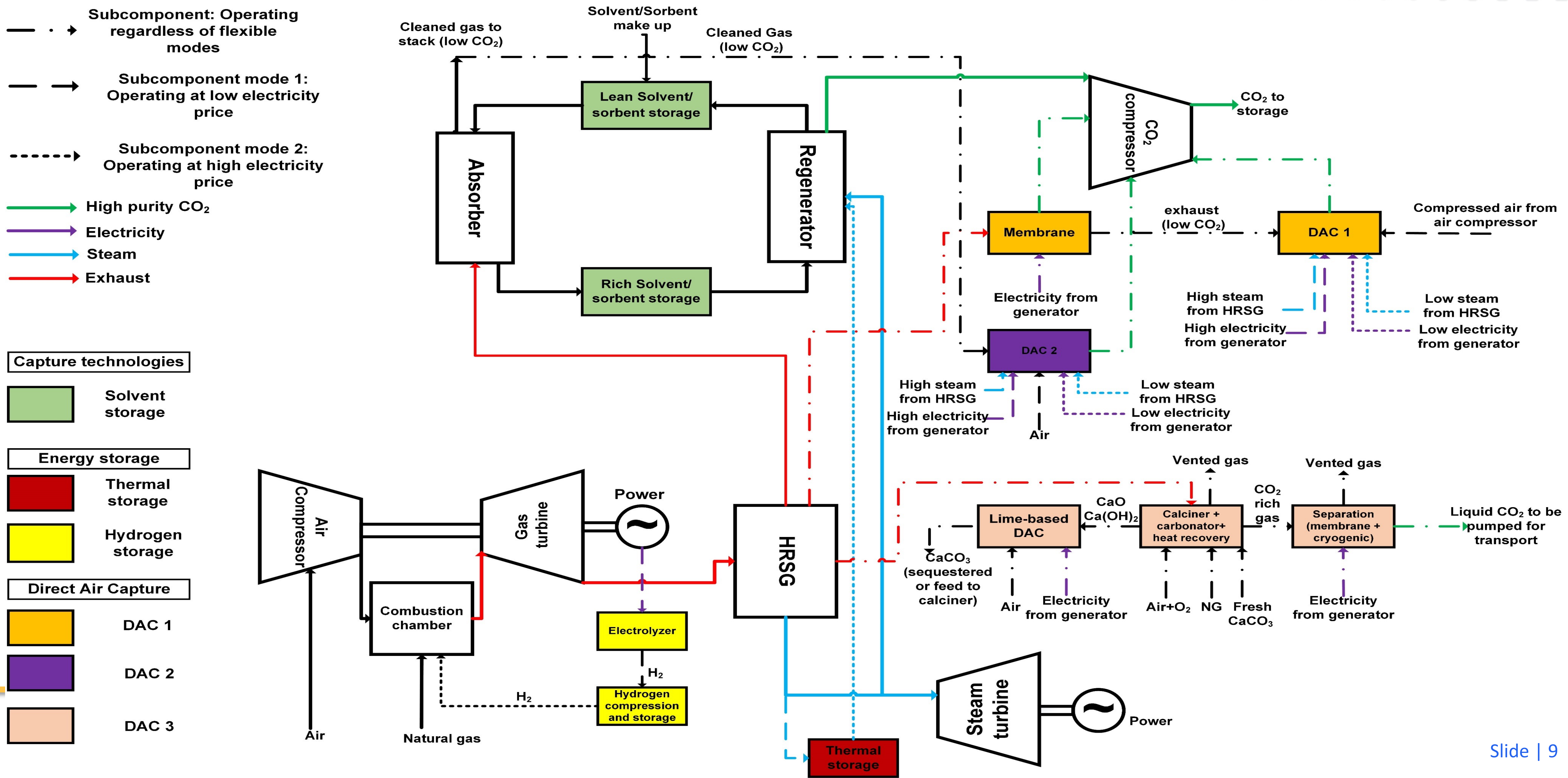
GenX

- Policy (carbon price, RPS, etc.)

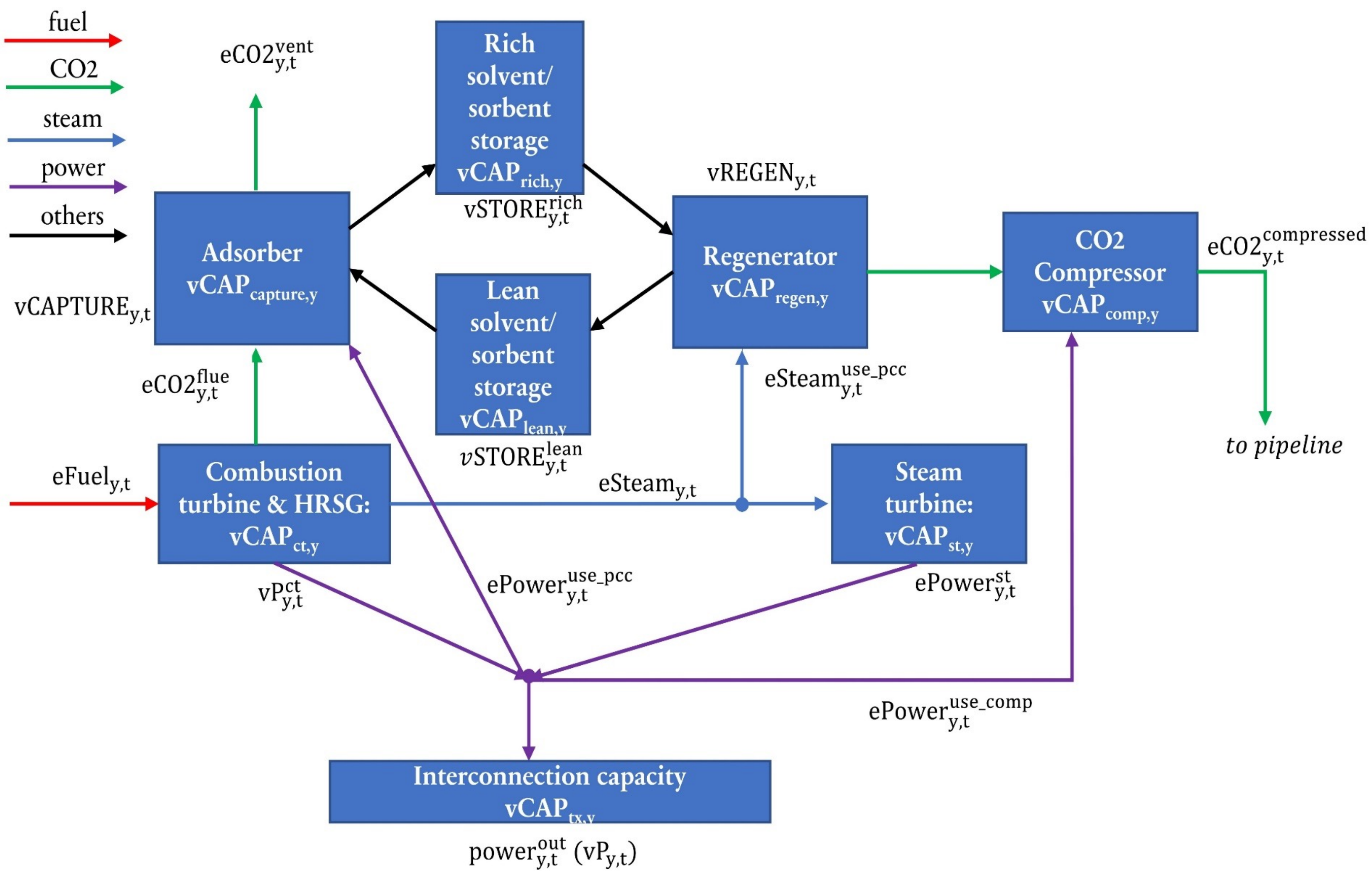
Expected Results

- Hourly price series data under varying future scenarios
- Capacity decisions for all the subcomponents (e.g., gas turbine, steam turbine, flexible components.)
- Hourly operation data of FLECCS systems (e.g., power output, mass and energy flow, etc.)
- The economic and environmental performance of FLECCS systems under varying scenarios

An overview of alternative flexible NGCC-CCS components

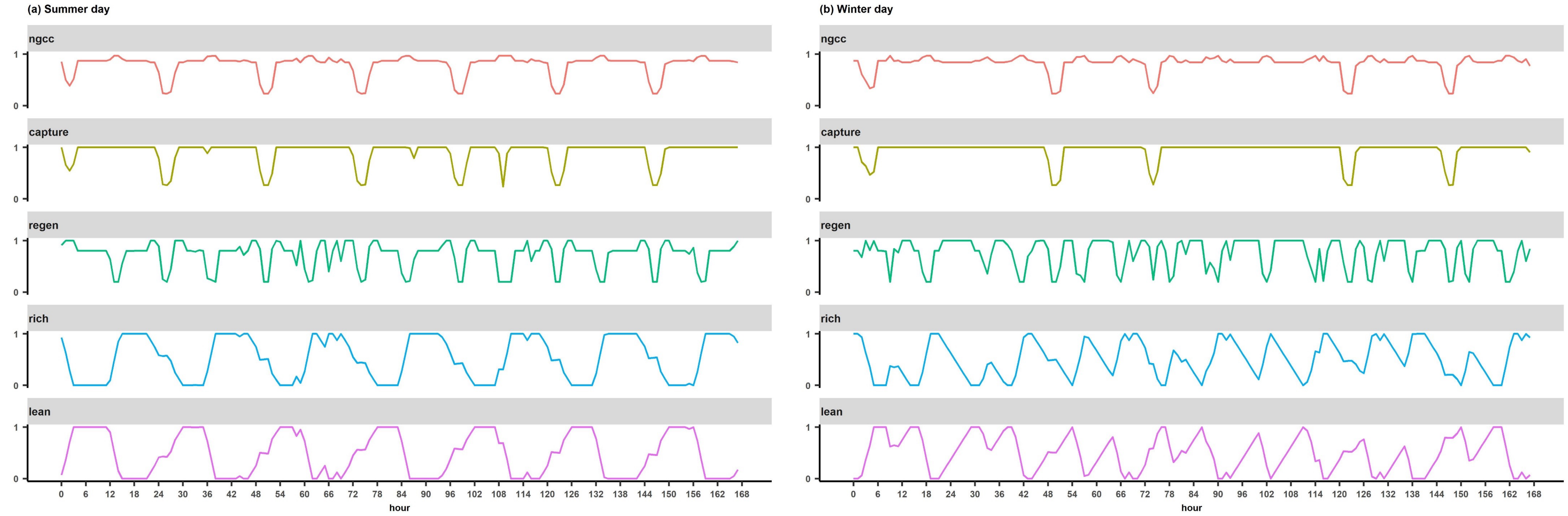


Modeling Approach: breaking down the system into subcomponents that have independent capacity decisions



- An example of NGCC-CCS coupled with flexible solvent/sorbent storage system.
- The system is modeled with major subcomponents that have independent capacity decisions.
- We track the key energy and mass flow between subcomponents and apply linear constraints formulations to enforce the mass and energy balance.
- Those constraints formulations are combined with other functions in GenX to determine the cost and performance of FLECCS systems under varying future scenarios.

Example Outputs: NGCC-CCS w/solvent storage



The outputs are from NGCC-CCS coupled with flexible solvent storage system in a summer and winter week at carbon price = \$80/tCO_2. The fraction represents the hourly generation, the amount of captured CO_2, regenerated CO_2, stored rich solvent, and lean solvent divided by the capacity of the corresponding subcomponents. For solvent storage tanks, 1 means the tank is full and 0 means the tank is empty.

Model Validation: Comparison of values from our modeling approach and the values from NETL report

	Values in our modeling approach	Values from NETL report	Values in our modeling approach	Values from NETL report
	NGCC W/O CCS		NGCC W/ CCS (90% capture rate at steady state)	
Gas turbine power (MW)	477	477	477	477
Steam turbine power (MW)	263	263	213	213
CO_2 capture power (MW)	0	0	10.6	10.6
CO_2 compression power (MW)	0	0	17.09	17.09
Other auxiliaries (MW)	14	14	14	16.37
Total gross power (MW)	740	740	690	690
Net power (MW)	727	727	648	646
Net heat rate (MMBTU/MWh, HHV)	6.362	6.363	7.134	7.159

James III PhD, Robert E., et al. *Cost and performance baseline for fossil energy plants volume 1: bituminous coal and natural gas to electricity*. No. NETL-PUB-22638. NETL, 2019.

FLECCS Test System: "Scale Model" of U.S. System

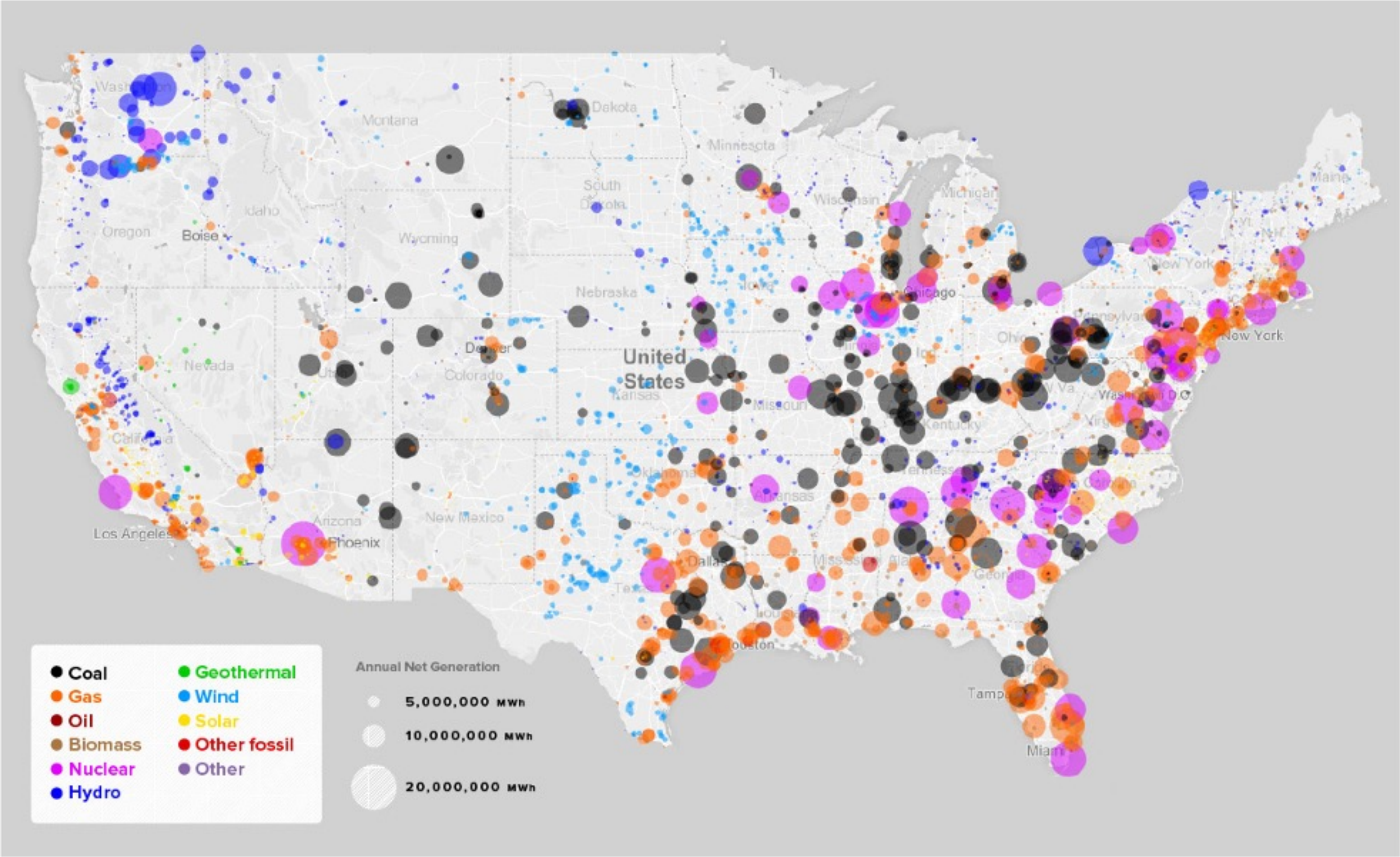


Image source: Daniel V. Schroeder, Physics Department, Weber State University, https://physics.weber.edu/schroeder/energy/PowerPlantsMap.html

- Data on U.S. electricity system from *PowerGenome* data platform (collating data from FERC, EIA, etc.)
- Normalized peak load to 100 GW
- 1/10th scale representation of existing U.S. generation fleet
- Solved with linearized unit commitment for full year at hourly resolution (8,760 hours)
- Transmission constraints ignored.
- Simplified system permits complex representation of FLECCS designs

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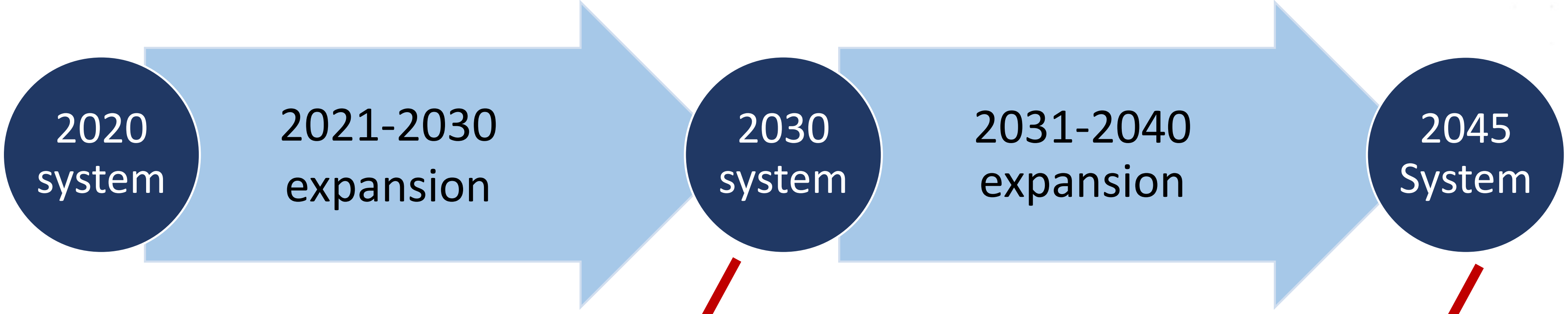
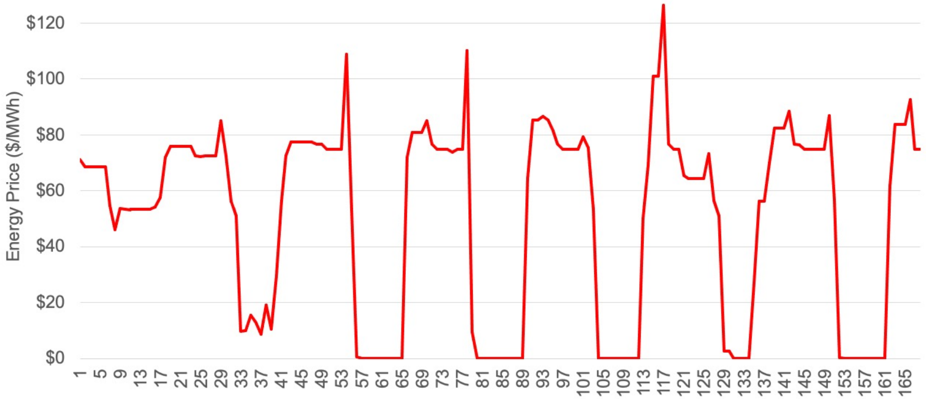
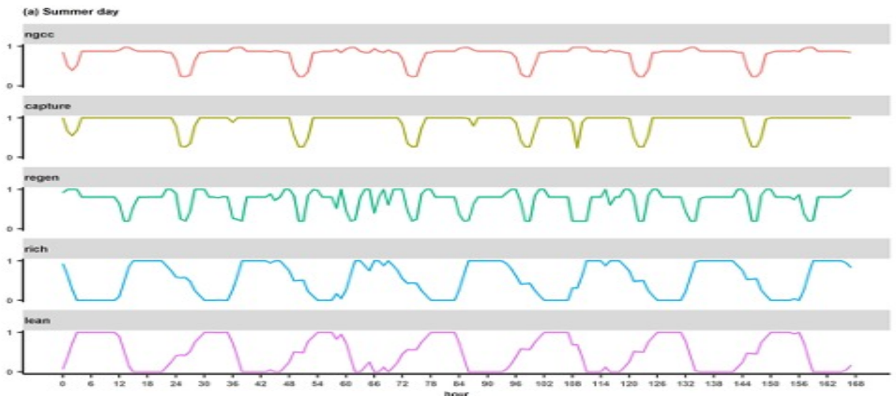
Incremental (Staged) Expansion



Used to produce price series for FLECCS teams (complete)



Used to test and evaluate performance of FLECCS designs (ongoing)



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FLECCS Scenarios

Scenario	Natural Gas Price	Renewable Energy and Battery Cost	Electrification	Competing Technologies (Nuclear, Hydrogen, Bio-CCS, DAC)	Demand Flexibility
Favorable (Best Case)	Low Price $3.2/MMBtu	High Storage: $185/kW / $213/kWh Low Renewables: Wind: $835/kW Solar PV: $621/kW-ac	High 694 GW peak load	Not Available	Moderate Flexibility 189 GW flexible load
Moderate (Reference)	Reference Price $4.2/MMBtu	Mid Storage: $132/kW / $151/kWh Mid Renewables: Wind: ~$1,200/kW Solar: ~$785/kW-ac	Reference 539 GW peak load	Not Available	Moderate Flexibility 189 GW flexible load
Unfavorable (Worst Case)	High Price $6.9/MMBtu	Low Storage: $84/kW / $96/kWh Low Renewables: Wind: $835/kW Solar PV: $621/kW-ac	Reference 539 GW peak load	Available	Enhanced Flexibility 236 GW flexible load

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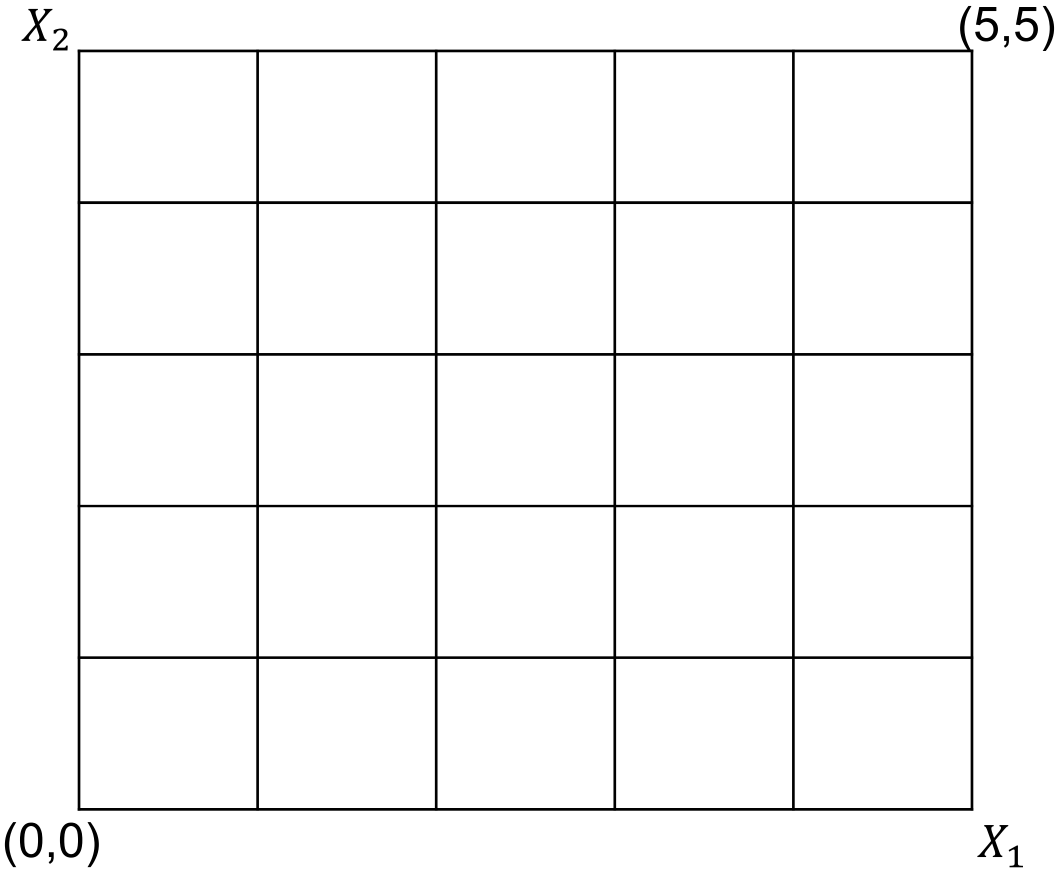
All scenarios run at $150/tCO_2$, $225/tCO_2$, and $300/tCO_2$ (2020 USD)

Method of Morris: structured sensitivity analysis

Consider 2 uncertain parameters that can take on 6 'levels' each
$6^2 = 36$ possible combinations

Combinatoric analysis scales with l^p where:

- p is the number of uncertain parameters
- l is the number of levels each variable can take on and

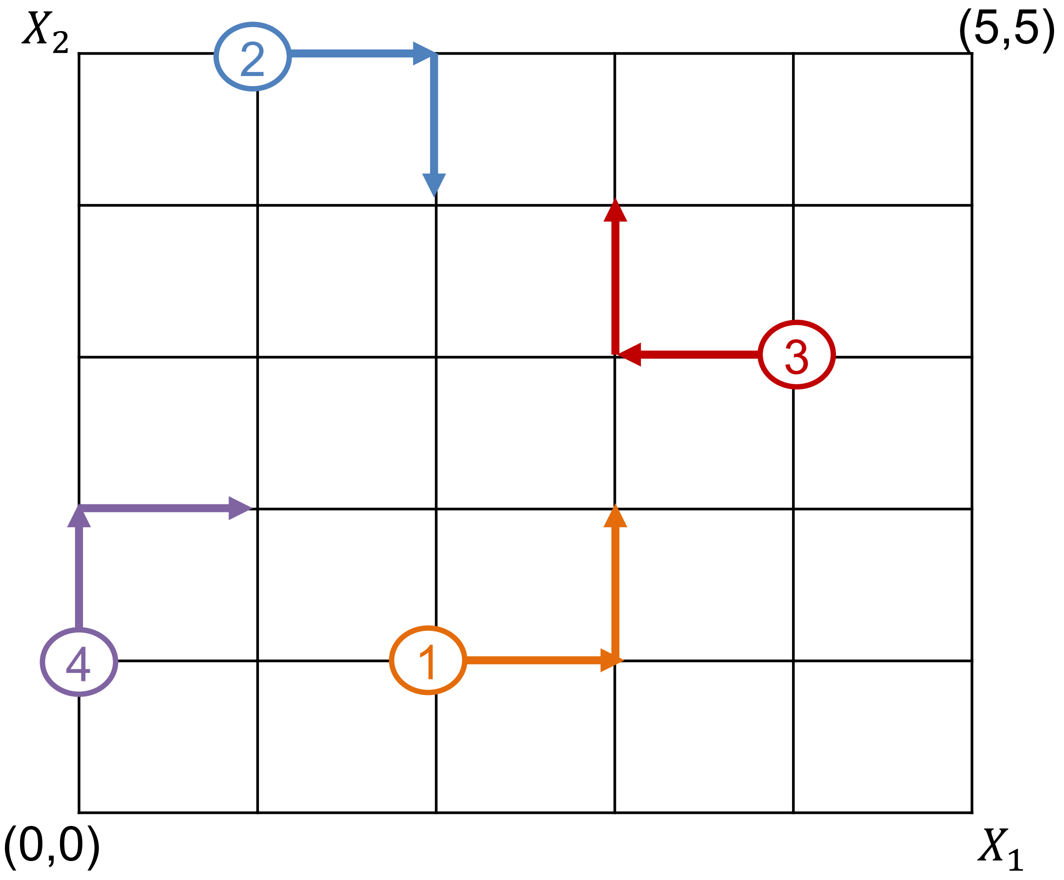


- 5 parameters, 3 levels = 243 combinations
- 5 parameters, 4 levels = 1,024 combinations
- 5 parameters, 5 levels = 3,125 combinations
- 10 parameters, 3 levels = 59,049 combinations
- 10 parameters, 5 levels = 9.8 million cases.

Method of Morris: structured sensitivity analysis

Method of Morris is computationally scalable way to explore uncertainty space and identify most salient parameters for an outcome of interest

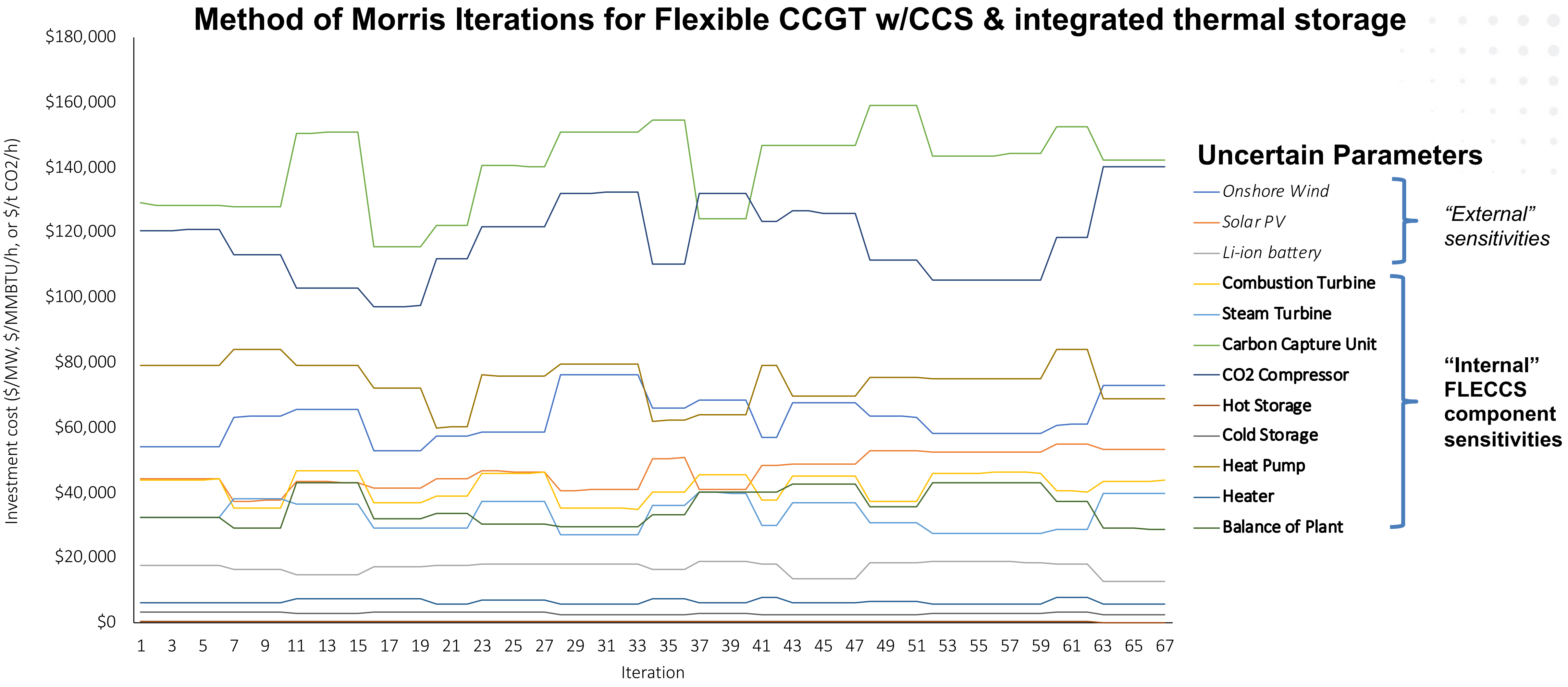
1. Define a set of p uncertain parameters each with l discrete levels.
2. Randomly sample starting values for each uncertain parameter.
3. Select one parameter and randomly increase or decrease value by one 'level', holding all other parameters constant
4. Measure change in outcome of interest.



5. Repeat Steps 2-4 up to p times (e.g. until all parameters are changed once), leaving all prior changes in place at each step.
6. Repeat Steps 2-5 r times, each with a different starting value for each uncertain parameter.
7. Compute avg change in outcome(s) of interest as a result of a per unit change in each parameter and the variance in this change and rank parameters in order of influence on outcome of interest.

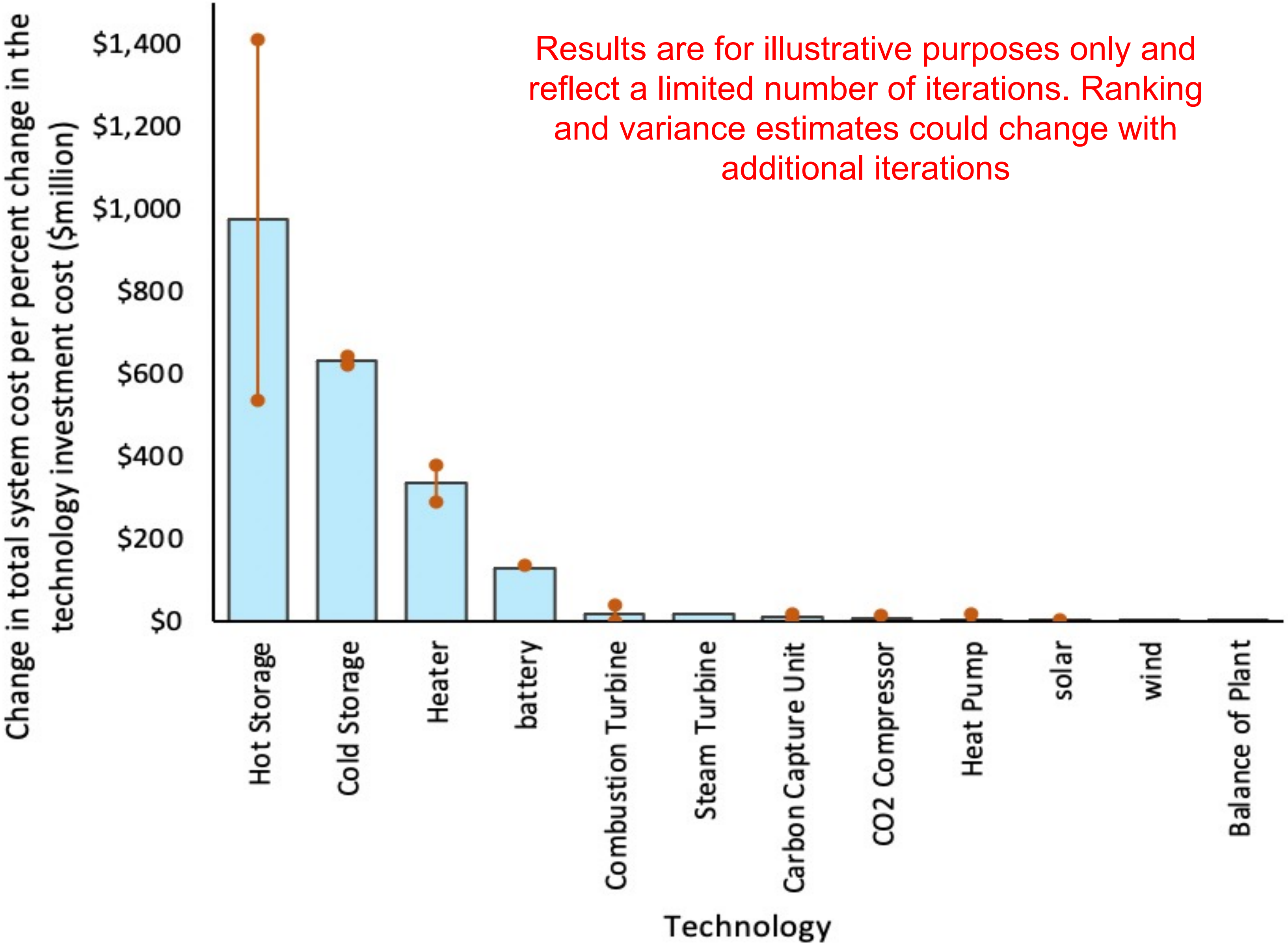
Scales with O($r(p+1)$) total runs. The larger r the more accurate the ranking.

Method of Morris Illustrative Example



Method of Morris Example Results

- **Most important 'internal' and 'external' parameters are identified:**
  - illustrative results indicate importance of thermal storage cost components and competing battery costs
- **Variance metric indicates which parameters interact non-linearly with other uncertain parameters:**
  - high variance = significant non-linearity; low variance = linear effects.



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