Scalable Energy System Expansion Under Uncertainty Using Multi-stage Stochastic Optimization

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General Infrastructure Expansion Model

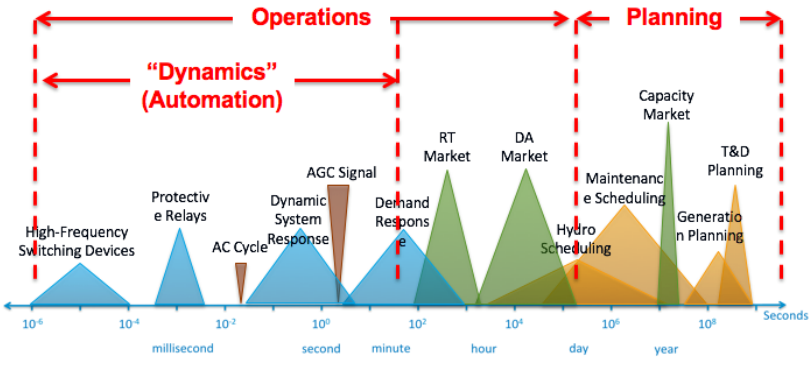
What detail is needed in *O(x)?*

$$\begin{array}{ll} \text{minimize} & C(x) + O(x) \\ \text{subject to} & x \in \mathcal{X} \end{array}$$

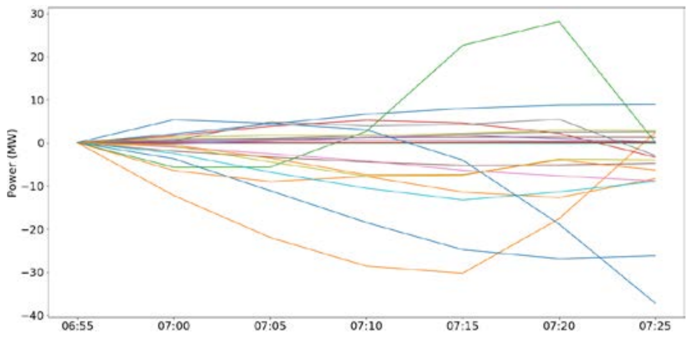
- Where $x \in \mathcal{X}$ represents the build decisions made subject to constraints
- $C(x)$ represents annual payment on assets x built
- $O(x)$ represents the annual cost of operations given assets x are built

Operations Modeling Details

- Temporal resolution
  - Timescale resolution
  - Number of timescales
- Spatial resolution
  - Number of nodes in the network
  - Number of devices on the network
- Representation of Stochastic Quantities
  - Load, wind, solar, hydro, policy
  - Future generation investments
- Representation of System Physics
  - Transport, DCOPF, ACOPF, dynamics



Adapted from A. Von Meier

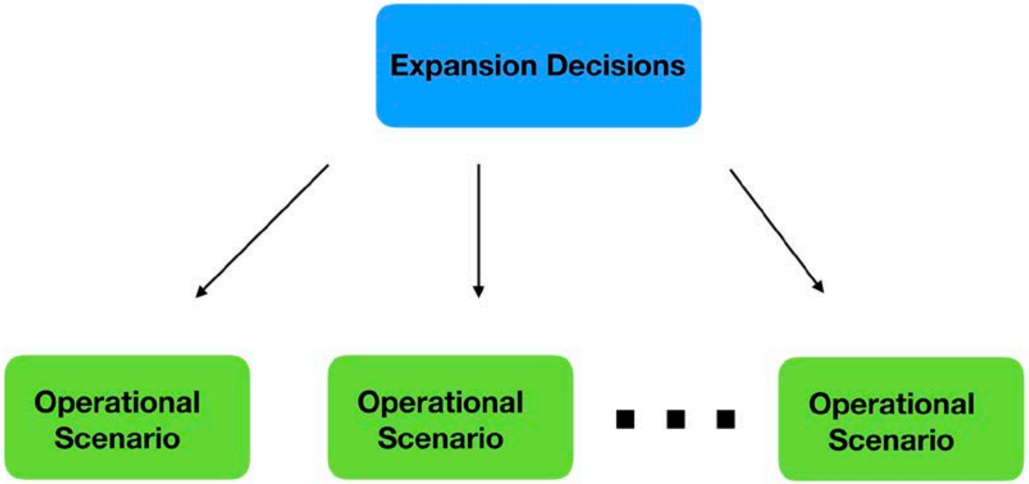


Scenario Based Optimization Under Uncertainty

Infrastructure planning decisions should be co-optimized against many potential operational scenarios

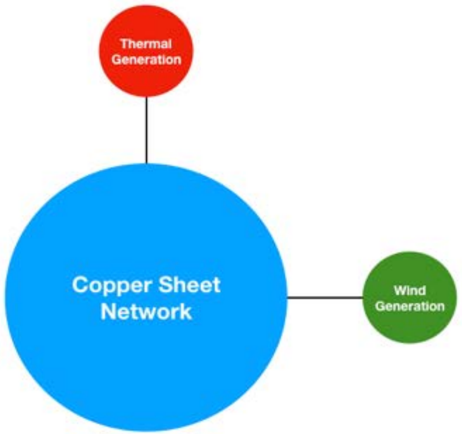
- Allows for planning decisions to be made under uncertainty
- Allows for inclusion of important scenarios when it is not obvious which are the important ones

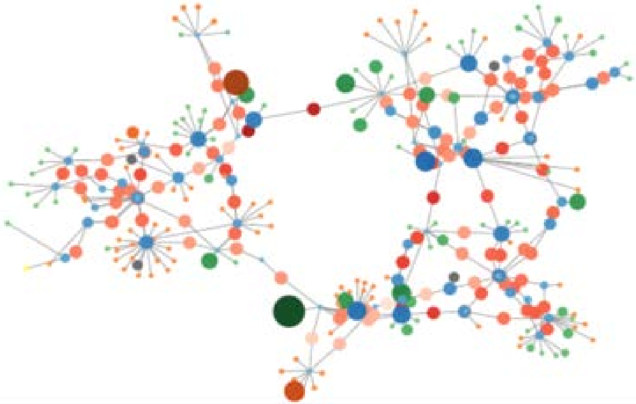
Two Stage Scenario Based Model

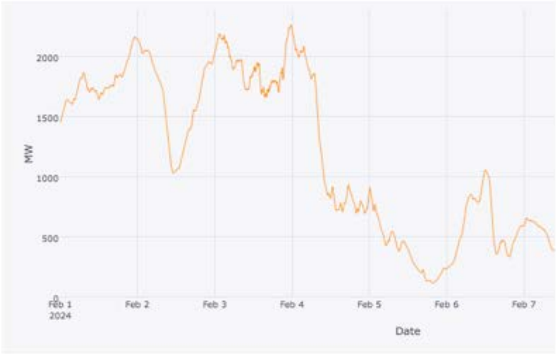


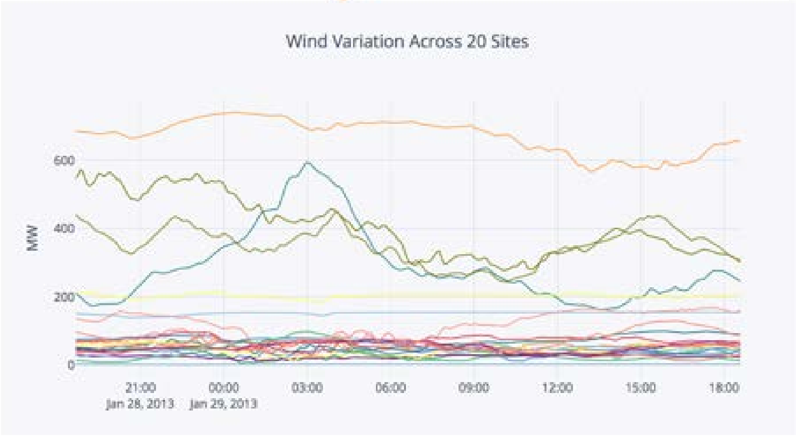
Could have a multi-stage representation of operations

Network Complexity

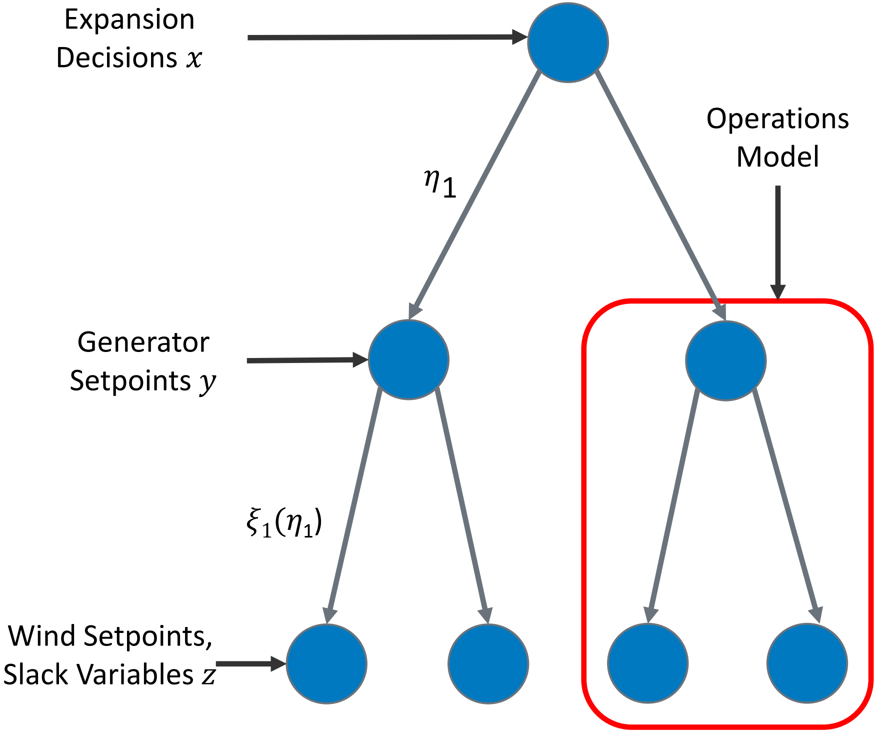








An Expansion Planning Problem



Three-Stage Stochastic Program Formulation.

Variable	Stage	Description
x	First	Wind & Storage Expansion Decisions
y	Second	Thermal Generator Setpoints
z	Third	Loss of Load
η	Second	Possible Day of Systems Operation (determines load)
ξ	Third	Possible fraction of Wind Power Available for Day

- RTS-GMLC test system using DCOPF network
- Wind/Storage Expansion Available at every bus
- Targeted Expansion decisions for load profiles 10 years into the future assuming 3% annual growth
- Day-long Scenarios used
  - 1 operational day from each month (12 used)
  - Time resolutions for operations from 2 hours to 5 minutes
- 1-7 random wind scenarios used for each day

  (https://www.nrel.gov/grid/wind-toolkit.html)

RTS-GMLC

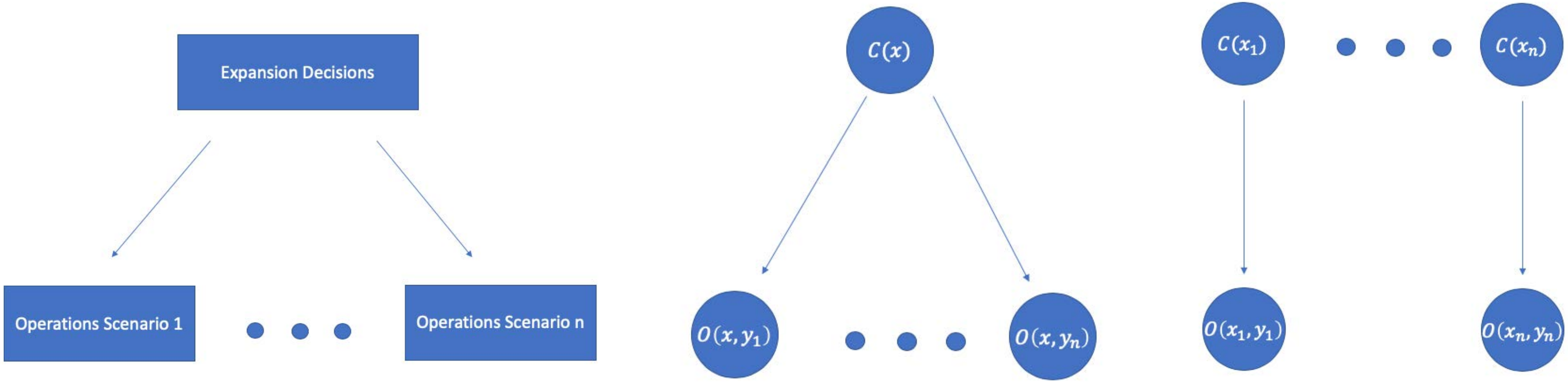
RTS-GMLC is a modernized version of the IEEE Reliability Test System-1996. It was developed to satisfy the need for a standardized data base to test and compare results from different power system reliability evaluation methodologies.

- Buses 73
- Lines 120
- Generators 158
- Three weakly connected regions

https://github.com/GridMod/RTS-GMLC

Progressive Hedging Concept

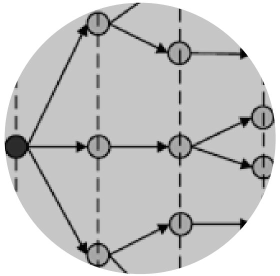
- Horizontal technique for solving multi-stage scenario based stochastic programs
- Solves individual subproblems with penalty terms to force consensus over time amongst the first stage decision variables
- Converges linearly when subproblems are convex



Rockafellar, R. Tyrrell, and Roger J-B. Wets. "Scenarios and policy aggregation in optimization under uncertainty." *Mathematics of operations research* 16, no. 1 (1991): 119-147

Progressive Hedging Implementation

- Implementation of the progressive hedging algorithm in the Julia language
- Uses the Julia Distributed.jl package, an implementation of distributed memory parallel computing
- User provides a function for constructing a JuMP model for an instance of scenario data
- User provides a dictionary of model variables for each stage
- User provides a multi-stage scenario tree with probabilities



ProgressiveHedging.jl

Implements the progressive hedging algorithm in a meta-solver package for decomposition and parallel solution of structured optimization problems. **Jonathan Maack from NREL is the lead developer.**
Jonathan.Maack@NREL.gov

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https://github.com/jump-dev/JuMP.jl

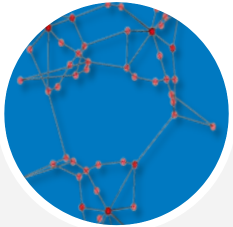
https://github.com/NREL/ProgressiveHedging.jl

SIIP Framework:

An example for electricity systems

Modular, interoperable, modeling components that define infrastructure modeling problems informed by system data

SIIP::Power



PowerSystems.jl

Rigorous data model that defines infrastructure systems

- Collects information required for device level modeling
- Includes parsing capabilities
- Exploits Julia's parametric dispatch for efficient code development
- Agnostic to simulations that will be performed

PowerSimulations.jl

Mathematical formulations and simulation assemblies

- Support for optimization and dynamic simulation models
- Modular problem assembly to enable rapid development and extension
- Includes standard simulations (e.g. UC/ED)
- Deep integration with PowerModels.jl (LANL) to enable non-linear power flow formulations

Extensive Form & Computational Results

- Extensive Form tested on a single 96 GB node, with 32 cores available using Gurobi version 9.0.2 with the default Gurobi settings.
- Failure due to memory or reaching 24-hour limit occurred at order 10^8 nonzero constraint coefficients. This is a problem for both scenarios and time resolution.

Computational Size of Generation Expansion Planning with 12 scenario Days

	1	2	3	4	5	6	7
12	8.3E+06	1.7E+07	2.5E+07	3.3E+07	4.1E+07	5.0E+07	5.8E+07
24	1.7E+07	3.3E+07	5.0E+07	6.6E+07	8.3E+07	9.9E+07	1.2E+08
48	3.3E+07	6.6E+07	9.9E+07	1.3E+08	1.7E+08	2.0E+08	2.3E+08
96	6.6E+07	1.3E+08	2.0E+08	2.6E+08	3.3E+08	4.0E+08	4.6E+08
144	9.9E+07	2.0E+08	3.0E+08	4.0E+08	5.0E+08	6.0E+08	7.0E+08
288	2.0E+08	4.0E+08	6.0E+08	7.9E+08	9.9E+08	1.2E+09	1.4E+09

Cells are the number of nonzero constraint matrix constants, columns are number of wind scenarios, rows are number of time steps

Extensive Form Performance

Success
24h limit
Trial Crash

Results

- Progressive Hedging was then used to solve cases on 12 operational days and 96 timesteps on 6 nodes leveraging Gurobi on each node.

Timesteps	Wind Scenarios	Total Scenarios	EF or PH	Solve Time (s)	Aggregate Wind Build (MW)	Aggregate Storage Build (MWh)
12	1	12	EF	23.99146	46.17201	0
24	1	12	EF	55.36817	41.26791	0
48	1	12	EF	183.1505	35.98531	0
96	1	12	EF	458.0015	36.00186	0
12	4	48	EF	207.7298	46.22417	0
24	4	48	EF	656.0031	38.54937	0
48	4	48	EF	3009.411	37.96231	0.106653
96	4	48	PH	26309.39	38.46644	0.518567
12	7	84	EF	2244.458	43.4028	8.948955
24	7	84	EF	4764.998	34.65826	9.596499
48	7	84	PH	16370.76	30.62677	9.624228
96	7	84	PH	40599.45	31.43219	9.66992

- For a relatively small number of scenarios, the extensive form (EF) can fail to solve the expansion problem. Using Progressive Hedging (PH) across nodes, these problems can be solved in reasonable time assuming maximum parallelization is available (which it was not in these trials).
- The effect of storage builds as the number of scenarios and time resolution illustrates the need for these larger problems.

Summary

- Multi-Stage modeling is a useful tool for infrastructure expansion modeling and it allows for increased detail when representing system operations and uncertainty

- Progressive Hedging provides a useful tool for solving such models at scale and can be effectively run on HPC systems

- Additional stages representing uncertainty do cause different build decisions, and moving forward it might be beneficial to explicitly consider uncertainty in renewables and operations when analyzing expansion decisions

Scalable Integrated
Infrastructure Planning
NREL LDRD

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