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

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NREL/PR-2C00-77099

Overview

- Multi-Stage modeling can be done at scale for power system infrastructure expansion problems
- Multi-Stage modeling allows for detailed representations of 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

ECP
EXASCALE COMPUTING PROJECT

GRID
MODERNIZATION
LABORATORY
CONSORTIUM
U.S. Department of Energy

Scalable Integrated
Infrastructure Planning

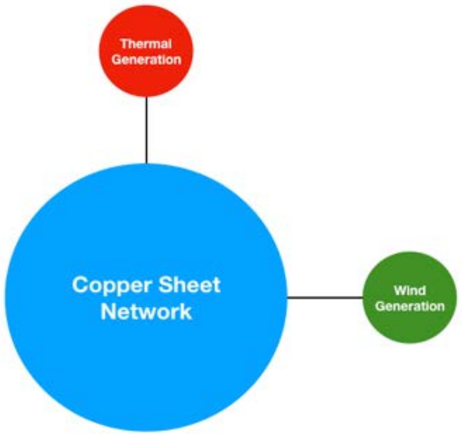
General Infrastructure Expansion Model

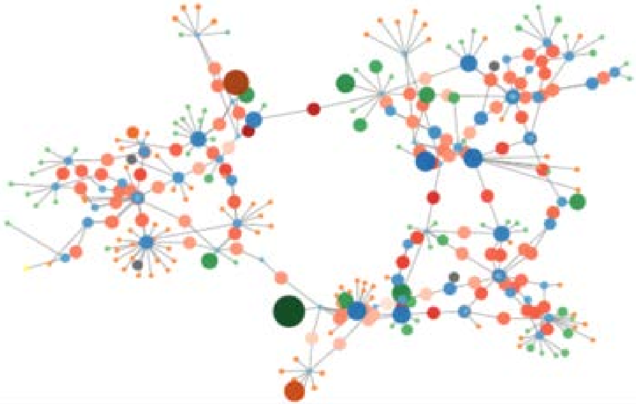
What detail is needed in *O(x)?*

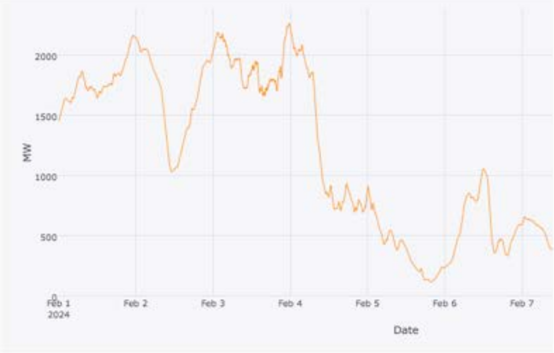
$$\begin{array}{ll} \text{minimize} & C(x) + O(x) \\ \text{subject to} & x \in \mathcal{X} \end{array}$$

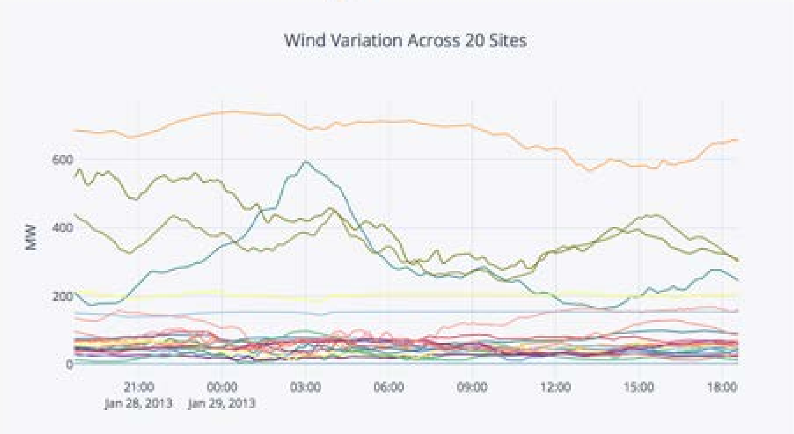
- Where $x \in \mathcal{X}$ represents the build decisions made subject to constraints
- $C(x)$ represents annual payment on assets x built
- $O(x)$ represents the annual cost of operations given assets x are built

Network Complexity







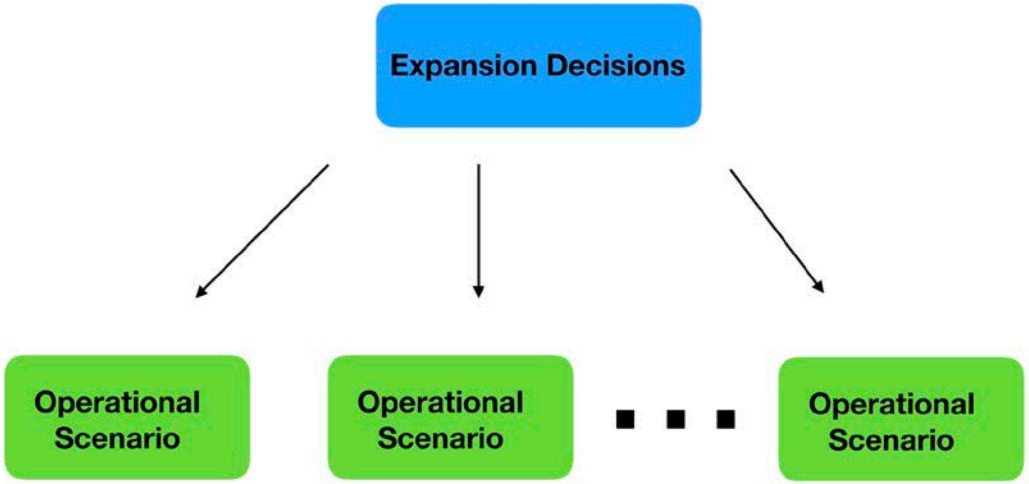


Scenario Based Optimization Under Uncertainty

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

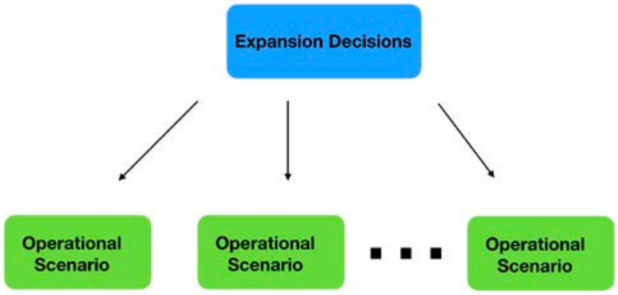
- Allows for planning decisions to be made under uncertainty
- Allows for inclusion of important scenarios when it is not obvious which are the important ones

Two Stage Scenario Based Model



Could have a multi-stage representation of operations

Sparsity Structure



Scalable algorithms exist for solving multi-stage scenario based optimization problems

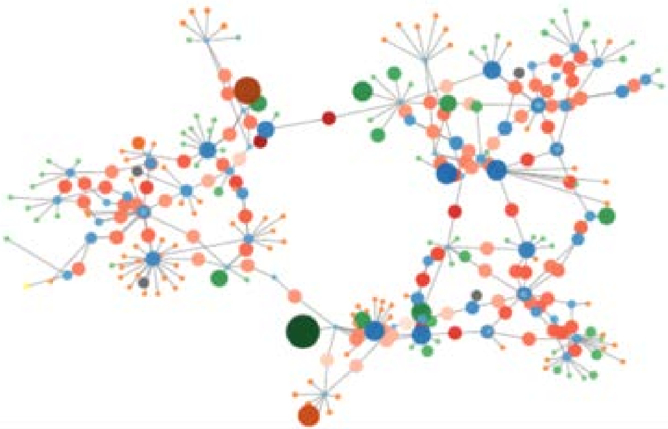
- Progressive Hedging (PySP)
- Schur Complement based iterative methods (IPOPT,PIPSNLP)

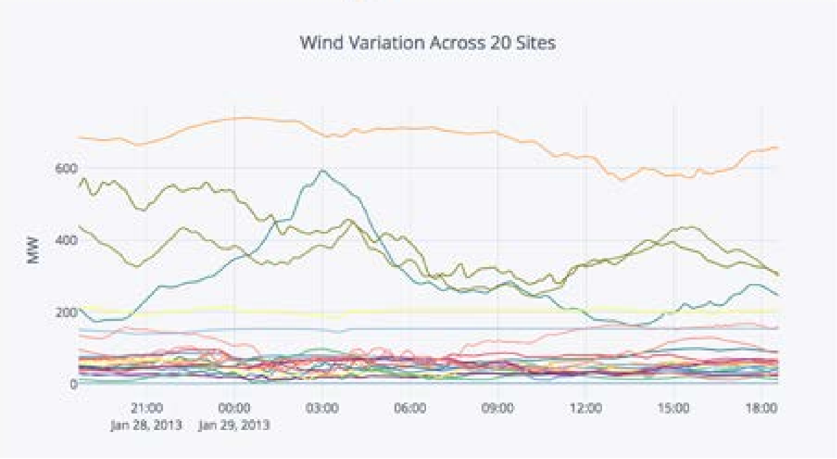
$$\min_{\boldsymbol{x}, \boldsymbol{y}_i i=1,\ldots,N} \quad \boldsymbol{c}^{\mathrm{T}}\boldsymbol{x} \quad + \quad \sum_{i=1}^{N} \boldsymbol{d}_{\xi_i}^{\mathrm{T}} \boldsymbol{y}_i$$

$$\begin{array}{llllllll}
\text{s. t.} & \boldsymbol{A}\boldsymbol{x} & & & & & & = b \\
& \boldsymbol{T}_{\xi_1}\boldsymbol{x} & + & \boldsymbol{W}_{\xi_1}\boldsymbol{y}_1 & & & & = b_{\xi_1} \\
& \boldsymbol{T}_{\xi_2}\boldsymbol{x} & + & & \boldsymbol{W}_{\xi_2}\boldsymbol{y}_2 & & & = b_{\xi_2} \\
& \boldsymbol{T}_{\xi_3}\boldsymbol{x} & + & & & \ddots & & = \vdots \\
& \boldsymbol{T}_{\xi_N}\boldsymbol{x} & + & & & & \boldsymbol{W}_{\xi_N}\boldsymbol{y}_N & = b_{\xi_N} \\
& \boldsymbol{x} \geq \boldsymbol{0}, & & \boldsymbol{y}_1 \geq \boldsymbol{0}, & \boldsymbol{y}_2 \geq \boldsymbol{0}, & \ldots, \boldsymbol{y}_N \geq \boldsymbol{0}. & &
\end{array}$$

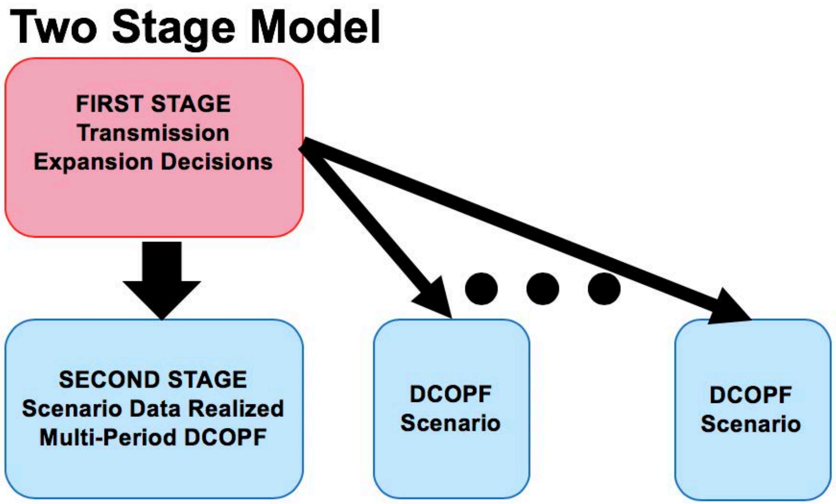
Transmission Expansion Problems

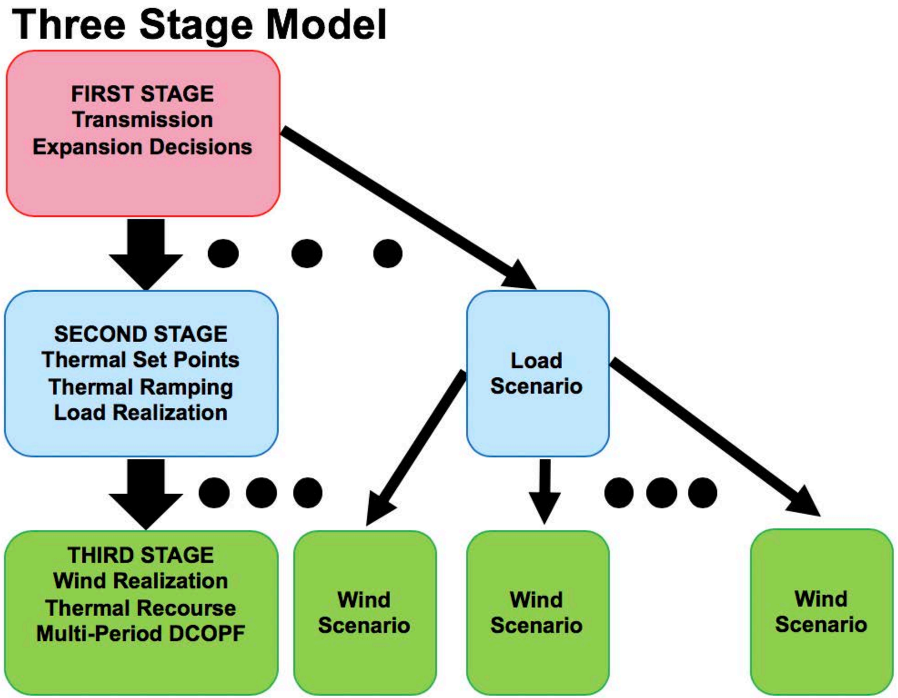
- Traditional solution approaches are limited in the sources and detail of uncertainty they can consider
    - Few operational scenarios are considered
    - Renewable generation forecasts are assumed to be perfect
    - Time scales tend to be either
        - Long
        - Snap shots in time
- What is lost by ignoring various forms of uncertainty?





Two Stage vs. Three Stage Models





Experiment: Effects of Wind Uncertainty

Goal: Understand the effects of uncertainty in wind generation on transmission expansion decisions

2-Stage

$$\begin{array}{ll} \min & c(x) + E_{(\eta,\xi)}\left[o(x, \underbrace{\eta, \xi}_{\text{Load and Wind}})\right] \\ \text{subject to} & x \in \mathcal{X}, \end{array}$$

- Load and wind uncertainty handled simultaneously
- Effectively modeling grid operations only with perfect renewable forecasts
- Builds a system that can operate under many different load profiles when there is no uncertainty in the wind

3-Stage

$$\begin{array}{ll} \min & c(x) + E_{\eta}\left[o(x, \eta) + E_{\xi|\eta}\left[h(x, \eta, \xi)\right]\right] \\ \text{subject to} & x \in \mathcal{X}, \end{array}$$

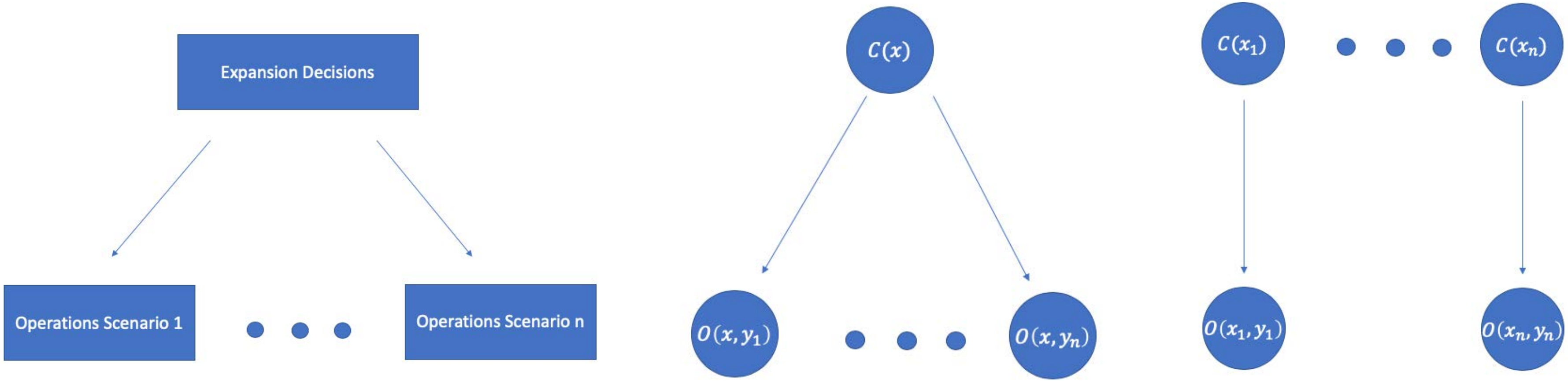
Load

Wind

- Load and wind uncertainty in different stages
- Modeling grid operations with uncertain wind generation
- Leads to decisions informed by more cautious operating decisions

Progressive Hedging Concept

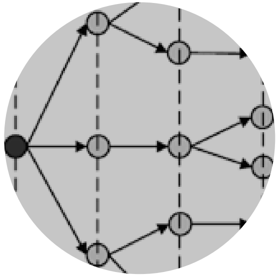
- Horizontal technique for solving multi-stage scenario based stochastic programs
- Solves individual subproblems with penalty terms to force consensus over time amongst the first stage decision variables
- Converges linearly when subproblems are convex



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

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

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

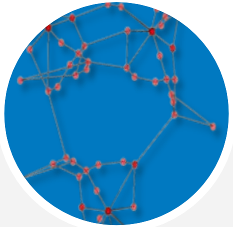
https://github.com/NREL/ProgressiveHedging.jl

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

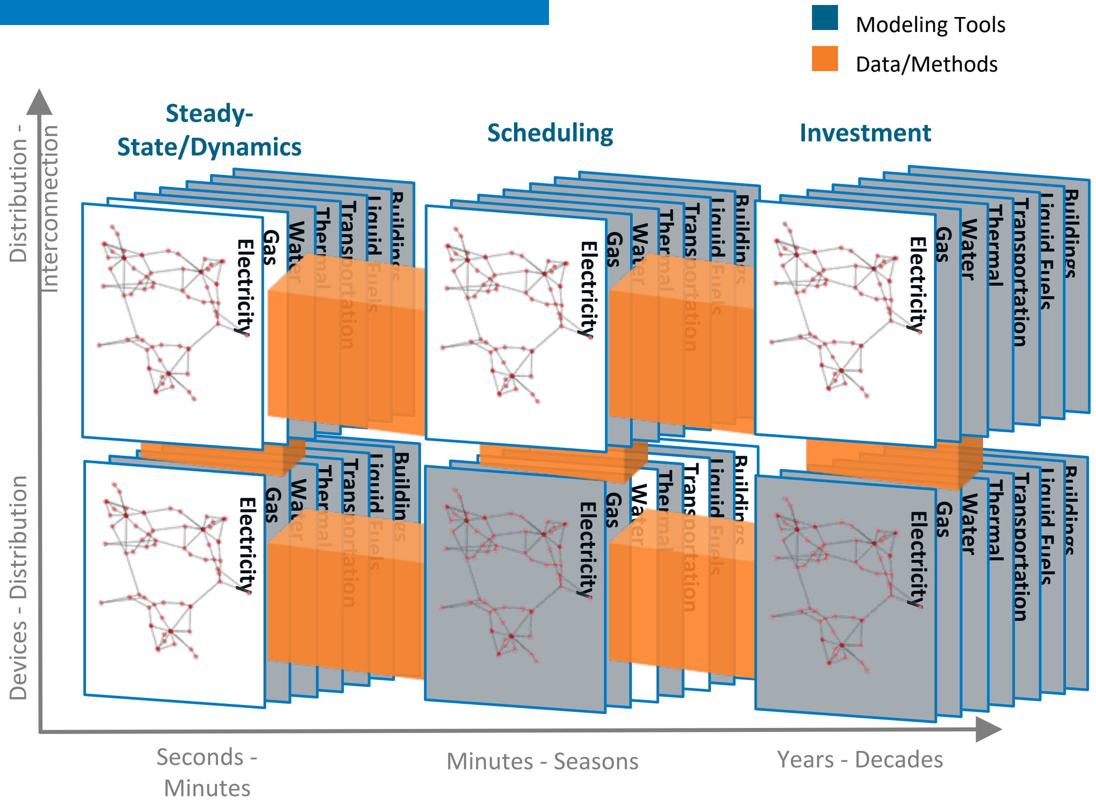
An Integrated Modeling Vision

Framework Design Objectives

Modularity and Accessibility – flexible and transparent problem creation that is easily extensible

Integration – coherency between models representing distinct phenomena

Scalability – address scales that matter through efficient problem simulation and parallelism



Leveraging SIIP

- Use SIIP framework to read data and build models
  - PowerSystems.jl provides needed parsing capabilities
  - PowerSimulations.jl provides model building
- Alter constructed models to fit our formulation
- Reduces debugging time enormously

```
#### Second Stage
ops_model = PowerSimulations.EconomicDispatch(ops_sys,
    PowerSimulations.CopperPlatePowerModel,
    JuMPmodel=model, parameters=false)
delete_1d_constraint(ops_model, :CopperPlateBalance)
```

```
#### Third Stage
(Br_ptdf, Bus_ptdf) = PowerSystems.buildptdf(
    ops_sys.branches, ops_sys.buses)
wind_model = PowerSimulations.EconomicDispatch(wind_sys,
    PowerSimulations.StandardPTDFForm,
    JuMPmodel=model, parameters=false, PTDF=Br_ptdf)

replace_flow_constraints(wind_model, l_OL)
ll_dict, ol_dict = create_slack_variables(
    wind_model, cost_ll*ps_dict["baseMVA"], cost_ol*ps_dict["baseMVA"])
add_thermal_and_slack_to_stage3(ops_model, wind_model,
    ps_stage2["gen"]["Thermal"], ll_dict, ol_dict,
    Br_ptdf)
```

(https://github.com/NREL/PowerSystems.jl and https://github.com/NREL/PowerSimulations.jl)

RTS-GMLC

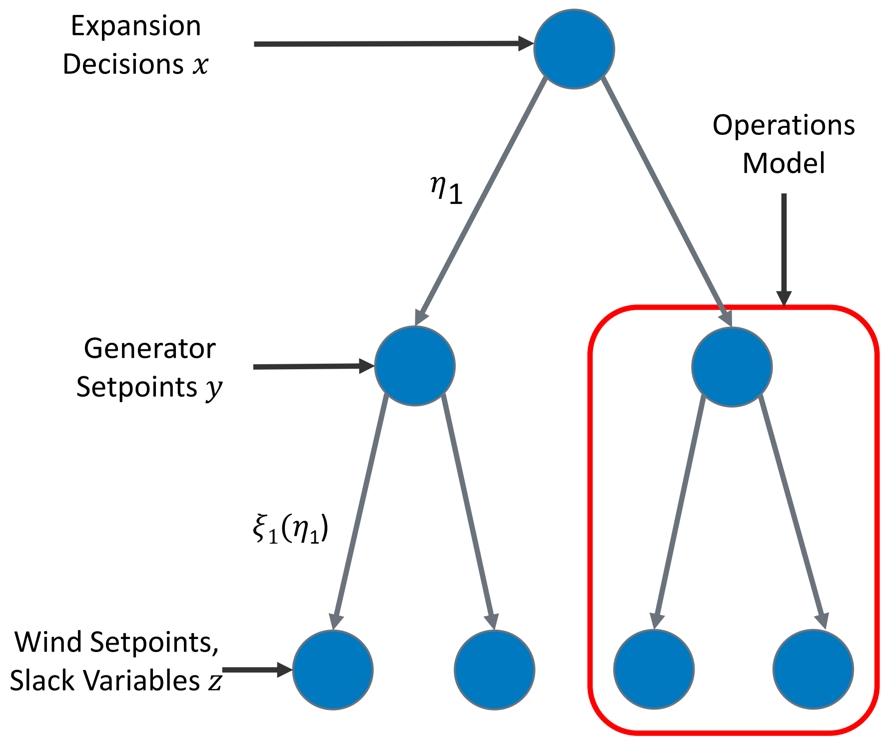
RTS-GMLC is a modernized version of the IEEE Reliability Test System-1996. It was developed to satisfy the need for a standardized data base to test and compare results from different power system reliability evaluation methodologies.

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

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

Problem Setup

Variable	Stage	Description
x	First	Transmission Expansion Decisions
y	Second	Thermal Generator Setpoins
z	Third	Loss of Load
η	Second	Possible Hour of System Operations (determines load)
ξ	Third	Possible Available Wind Power for an Hour



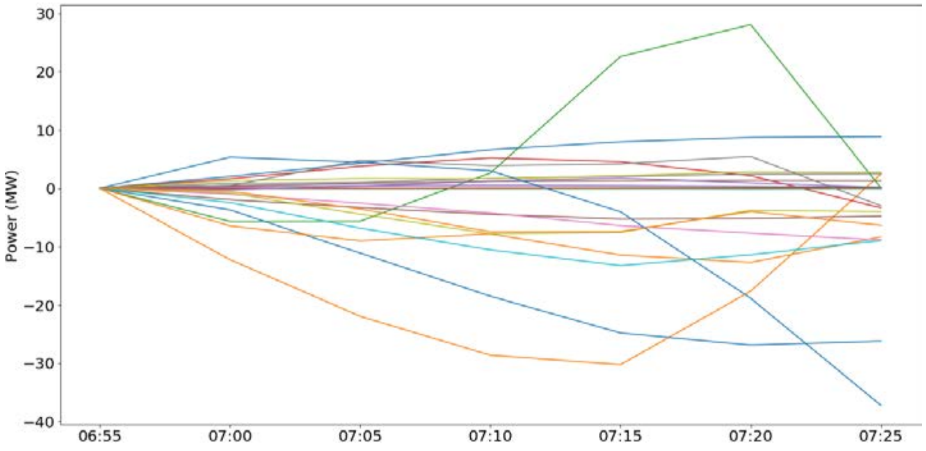
Three-Stage Stochastic Program Formulation.

- RTS-GMLC test system using DCOPF
- 16 hours used
  - 4 days, one from each season
  - 4 times from each day
- 20 wind scenarios for each hour to total 320 scenarios
- Each hour is 12 periods at a 5 minute resolution
- Line flow constraints where modified as follows

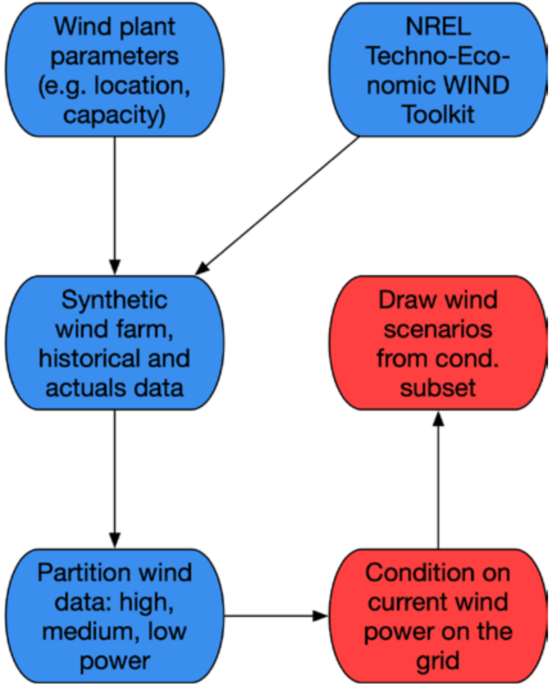
$$-U_l \leq f_l^t \leq U_l \qquad -U_l(1+x_l) \leq f_l^t \leq U_l(1+x_l)$$

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

Realistic Wind Scenarios



Wind Power Scenario for Each of the 22 Wind Farms. These are 6 steps at 5-minute resolution. Scenarios are given as deviations from persistence. Significant changes in wind power occur even for a single wind farm over 30 minutes.



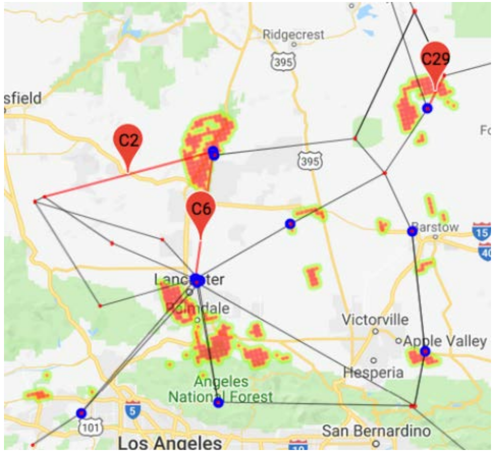
Scenario Selection Process. Blue represents preprocessing while red represents repeated steps for each second stage node. This data driven approach preserves spatiotemporal correlations present in the WTK data.

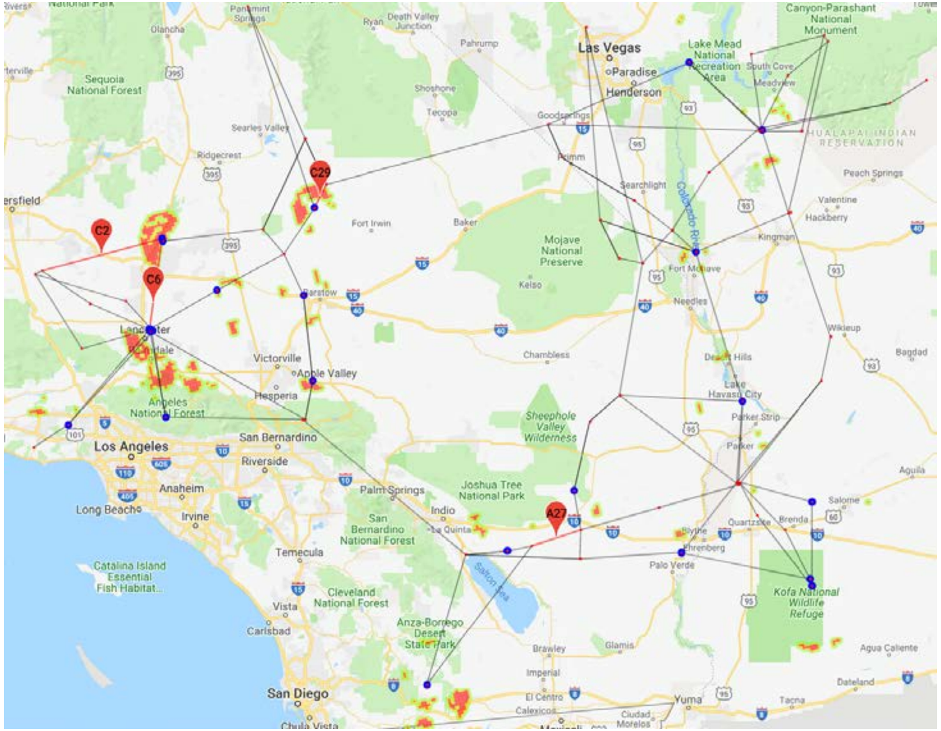
https://www.nrel.gov/grid/wind-toolkit.html

Conference paper on these techniques accept at the 2020 IEEE PES General Meeting

Visualization of Results

The lines that were expanded are all near the large wind resources on the grid. The line that is not still seems to enable a transmission path from a large wind farm.





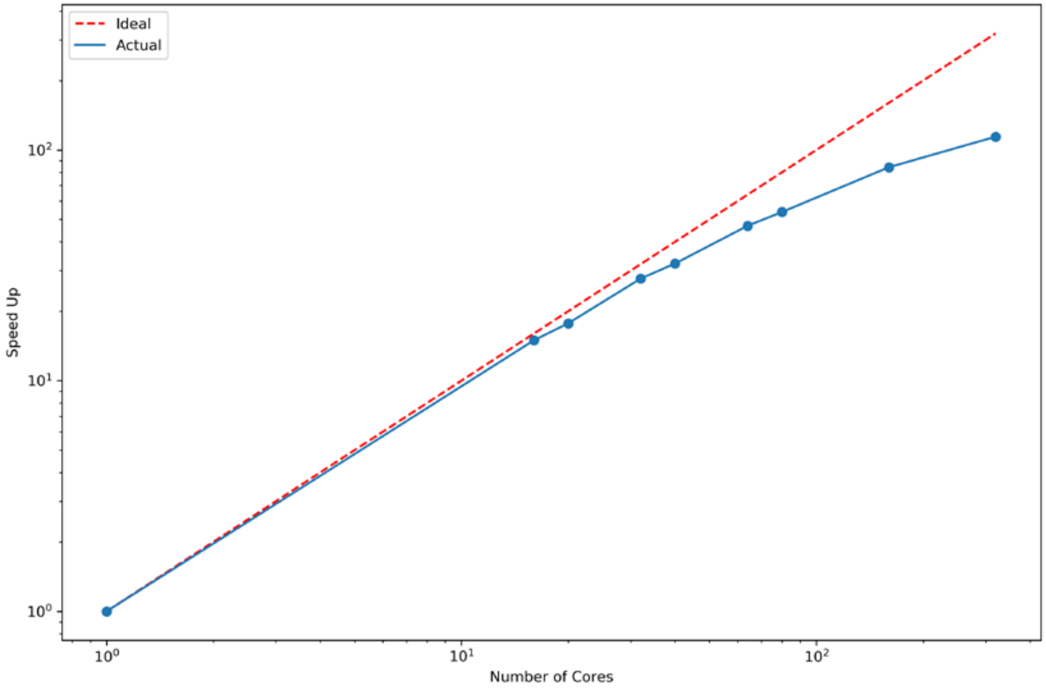
Map of the RTS-GMLC Network. 73 buses (red dots), 22 wind-generating buses (blue circles), 445 WTK wind sites (heat map), 120 transmission lines (black lines), and 4 expansion decisions (red lines)

Results

Branch	Initial (MW)	Model	Expand (%)	Expand (MW)	Final (MW)
A27	375	2 Stage	17.383	65.186	440.186
		3 Stage	15.508	58.156	433.156
C2	131.25	2 Stage	0.098	0.128	131.378
		3 Stage	2.103	2.760	134.010
C29	375	2 Stage	29.213	109.548	484.548
		3 Stage	38.499	144.370	519.370
C6	131.25	2 Stage	22.883	30.034	161.284
		3 Stage	35.567	46.682	177.932

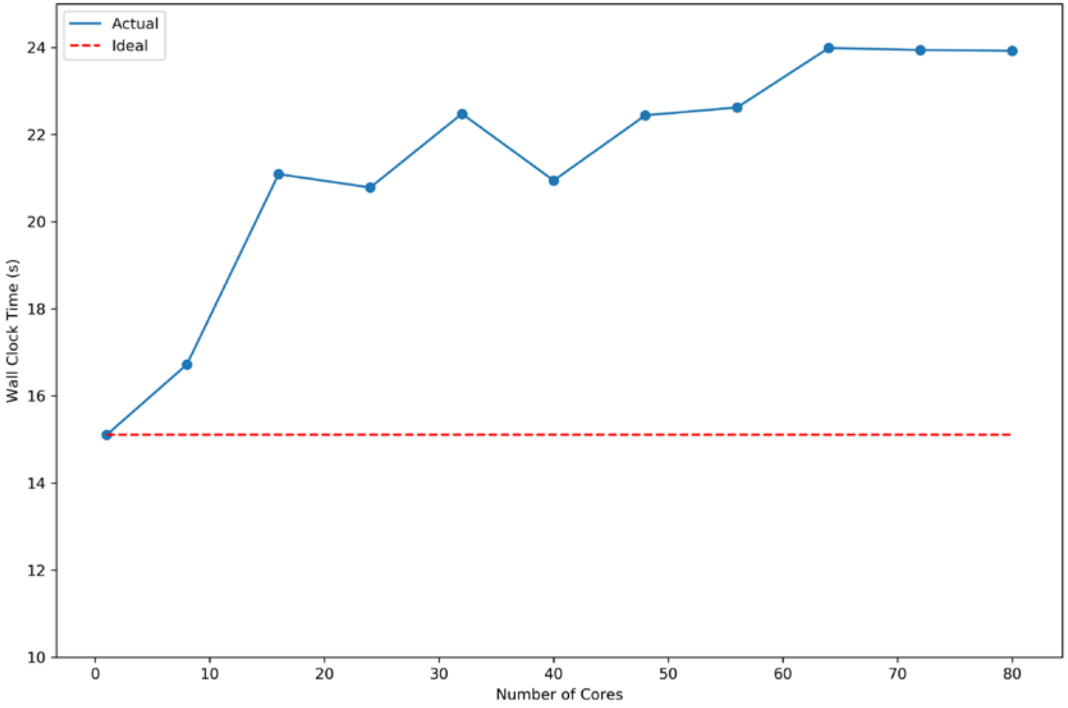
- We compared our 3 stage model expansion decisions with a 2 stage model where in the 2 stage a single wind scenario was considered for each of the 16 load cases
- Large 3 stage model solved in less than 2 hours
- The the same lines were expanded in both cases however in 3 out of 4 lines the 3 stage model chose a larger increase in line capacity

Strong Scaling



Strong Speed Up of ProgressiveHedging.jl. All runs were conducted on Eagle. IPOPT with HSL linear solver MA57 was used for the PH subproblem solutions.

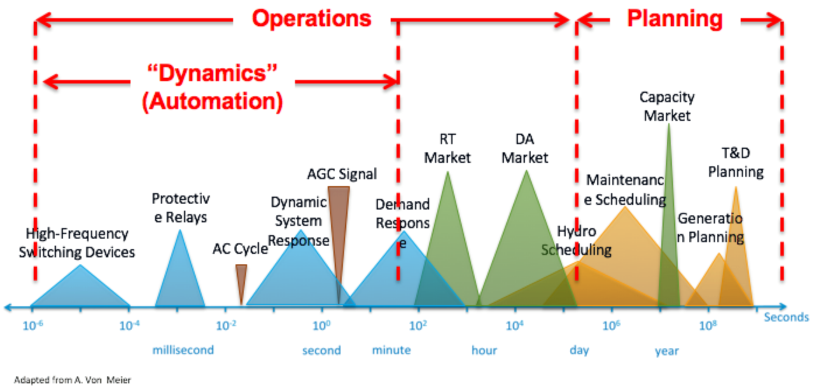
Weak Scaling

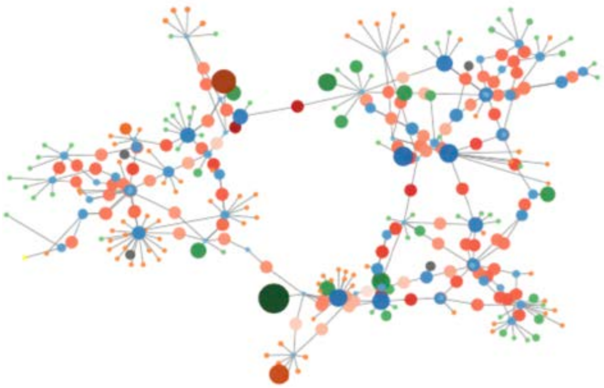


Weak Scaling of ProgressiveHedging.jl. All runs conducted on Eagle. IPOPT with HSL linear solver MA57 was used to solve the subproblems. Wall clock time gives the average time for a PH iteration. Each core solved four subproblems.

Sources of Large Power Systems Models

- 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
  - Optimization Stages
- Representation of System Physics
  - Transport, DCOPF, ACOPF, dynamics





Decomposition on the HPC

- Using Progressive Hedging problems can be formulated in a decomposed manner
- Each scenario is a single JuMP model that can live in memory on its own HPC compute node
- Each scenario then can leverage the memory of the node it is on as well as the cores on that node
- This allows for huge problems to be stored on the HPC across nodes and for the compute resources of each node to be used on each scenario subproblem.
- Allows subproblems to be more detailed in time, space, and physics
- Summary: Large problems, lots of detail, using lots of memory across nodes, and lots computational power on each subproblem

Summary

- Multi-Stage modeling can be done at scale for power systems infrastructure expansion problems
- 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 suggest moving forward it might be beneficial to explicitly consider uncertainty in renewables and operations when making expansion decisions
- Using decomposition techniques allows for extremely large problems to be solved and additional detailed to be added into each scenario when using HPC resources

Sigler, Devon, Jonathan Maack, Ignas Satkauskas, Matthew Reynolds, and Wesley Jones. "Scalable Transmission Expansion Under Uncertainty Using Three-stage Stochastic Optimization." In *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pp. 1-5. IEEE, 2020.

Questions