Optimal Sizing of a Nuclear Reactor for Embedded Grid Systems

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ILLINOIS

Outline

1. Motivation
   - Illinois Climate Action Plan (iCAP)
   - Need for Nuclear
   - Framing the Question
2. Methods
   - Overview
   - Methods for RAVEN
   - Methods for Temoa
3. Grid Characterization: RAVEN
4. Optimal Sizing: Temoa
   - Temoa: Business As Usual
   - Temoa: Nuclear Scenarios
   - Scenario 1: Zero Capital Costs
   - Scenario 2: No Capacity Limit
   - Scenario 3: Small Modular Reactor
5. Conclusion
6. Future Work

iCAP Goal and Obstacles

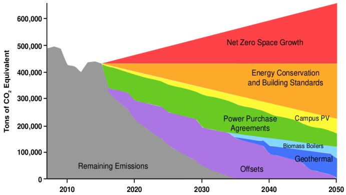

Figure: Shows projected CO_2 emissions for UIUC [9]. Offsets include shutdown of the Blue Waters Supercomputer.

Goal:
Carbon neutrality by 2050 or sooner.

Obstacles:

1. Requires *zero net space growth*.
2. Campus depends on a system of steam tunnels for heating.
3. and more...

The Nuclear Option

Nuclear energy...

1. ...produces almost no carbon emissions [8].
2. ...can produce high-temperature steam.
3. ...requires little physical space*.

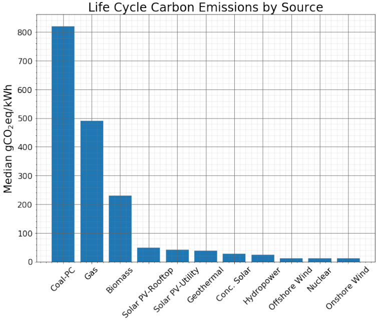

Figure: Lifetime carbon-equivalent emissions by energy source from IPCC findings [8].

*compared to solar and wind.

Small Modular and Micro-reactors

- 20 MWth (micro) to 300 MWth (small modular)
- Fewer resource requirements (area, shielding, operations)

Features:

- Factory fabricated
- Transportable (especially for micro-reactors)
- Walk-away safe
- Potential for dispatchability

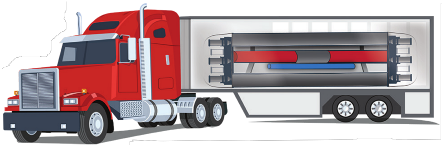

Figure: Transportable reactor concept. Image reproduced from US-DOE Nuclear Fast Facts [11].

What is the optimal size for a nuclear reactor on the UIUC grid?

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To answer this question we considered two modeling approaches:

1. RAVEN (INL) - Risk Analysis and Virtual Environment [2][6]
2. TEMOA (NCSU) - Tools for Energy Model Optimization and Analysis [3][4][7]

Both modeling tools are open source and use publicly available version control software, Git, to track changes.

The analysis in RAVEN requires some external modules that are not currently available to the public.

Workflow in RAVEN

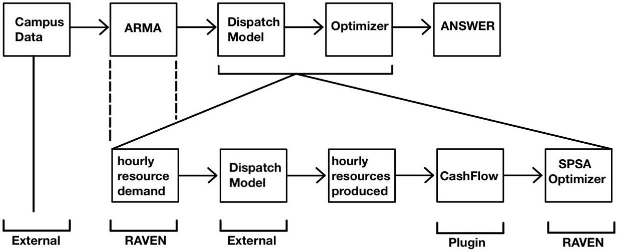

Figure: A general optimization workflow in RAVEN. Only the ARMA step was used to characterize the UIUC grid.

Temoa Implementation

Temoa uses linear optimization to search decision space [7].

1. Objective Function (minimizes system cost)
2. Constraints
   1. Demand must be satisfied at each time step (always).
   2. Carbon limits must be satisfied at each time step (optionally).
3. Variables
   1. Cost
   2. Generation
   3. Capacity

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Step 1: Generate Synthetic Histories

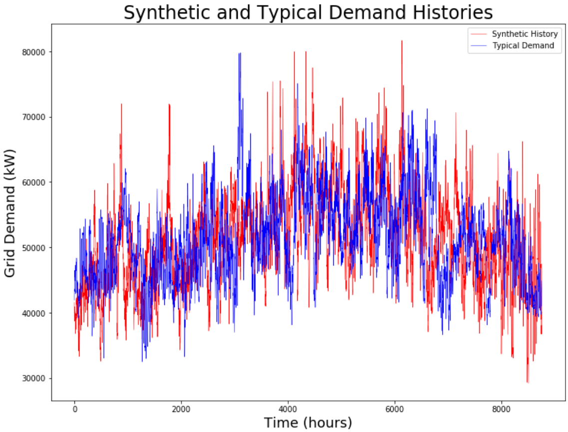

Figure: Shows the synthetic (red) vs typical (blue) hourly electricity demand at UIUC.

Step 1: Generate Synthetic Histories (continued)

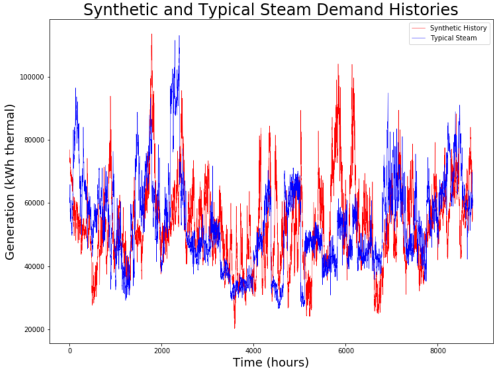

Figure: Shows the synthetic (red) vs typical (blue) hourly steam demand at UIUC.

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BAU: Grid Model

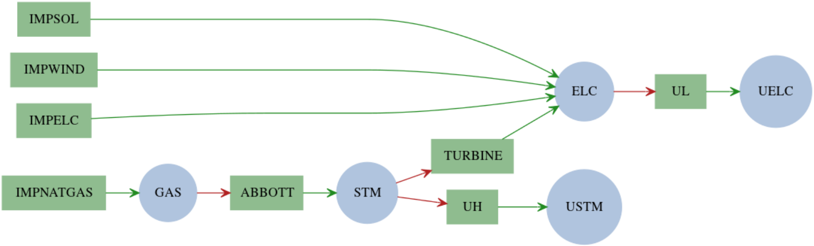


Figure: Graph representation of the UIUC embedded grid.

BAU: Generation

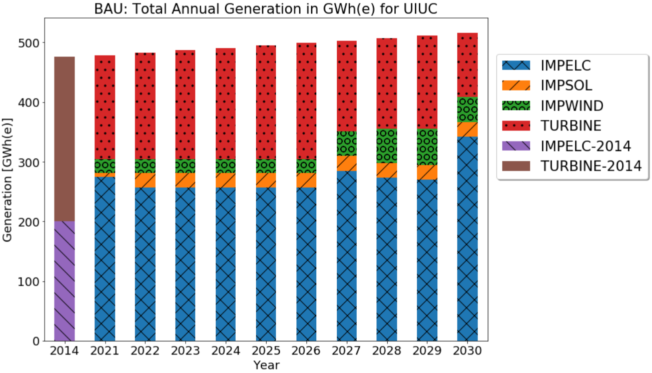
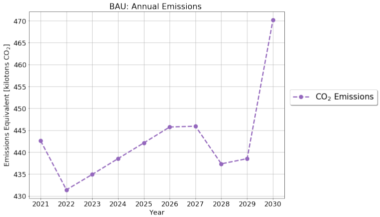


Figure: The change in activity from each energy source from 2020-2030. Assuming 1% demand growth each year

BAU: Emissions



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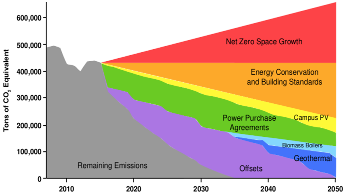

Figure: Predicted growth in emissions from iCAP [9].

Nuclear Scenarios

1. Scenario 1: Zero Capital Costs
2. Scenario 2: No Capacity Limit
3. Scenario 3: Limited to Small Modular Reactor (100MWth)

Table: Summary of Nuclear Scenarios. Costs from EIA and NEI reports [5][10]. Assumes thermal efficiency of 33%.

Scenario	Operation Costs [$/MWh(th)]	Capital Costs [M$/MWth]	Maximum Capacity [MWth]
1	8.91	-	-
2	8.91	1.982	-
3	8.91	1.982	100

Assumptions

1. Assumes fixed capital and variable costs throughout the model time horizon.
2. Nuclear Reactor
   - Assumes LWR due to availability of cost estimates.
   - Assumes 92% capacity factor.
3. Wind Power
   - Assumes 31% capacity factor.
4. Solar Power
   - Assumes capacity factor of 16.8%, based on the UIUC solar farm data [1].

Nuclear Scenarios: Grid Model

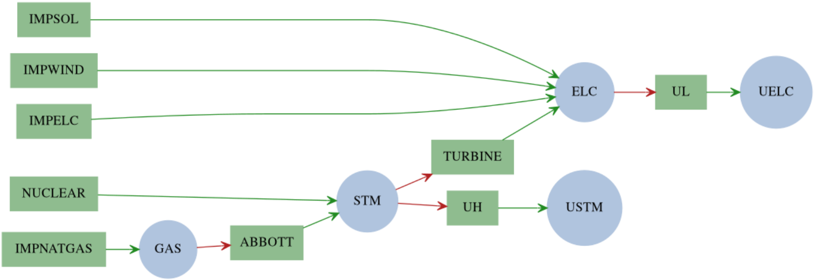

Figure: Graph representation of the UIUC grid with nuclear reactor.

Scenario 1: Generation

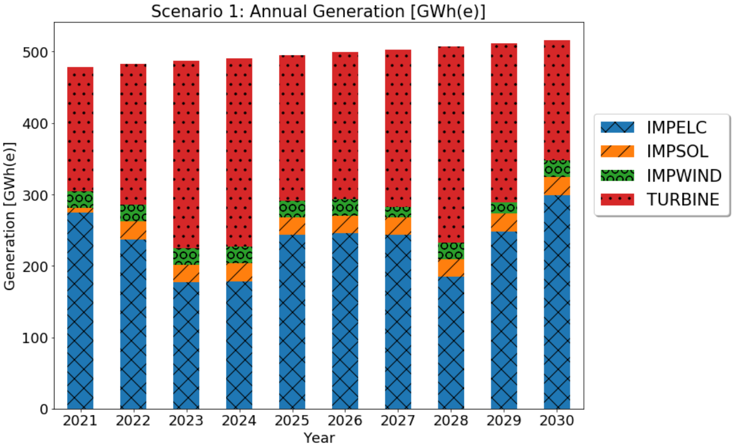

Figure: The electric generation without a cost constraint on nuclear

Scenario 1: Emissions

Figure: The carbon equivalent emissions without a cost constraint on nuclear

Scenario 2: Generation

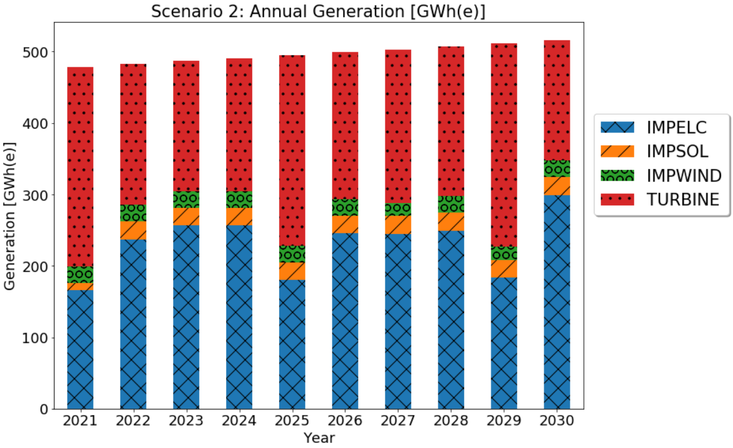

Figure: The electric generation without a size constraint on nuclear

Scenario 2: Emissions

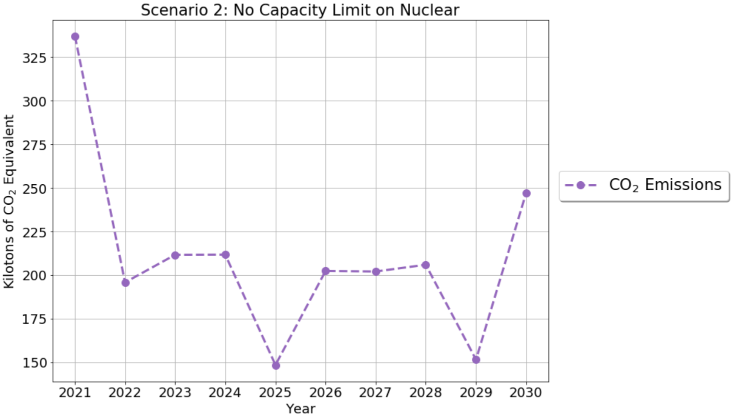

Figure: The carbon equivalent emissions without a size constraint on nuclear

Scenario 3: Generation

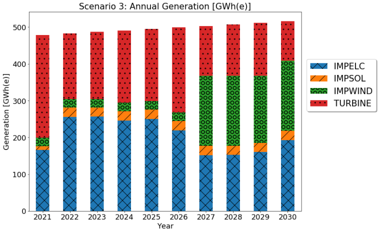

Figure: The electric generation with constrained nuclear.

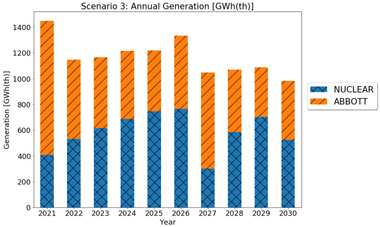

Figure: The steam generation with constrained nuclear

Scenario 3: Generation

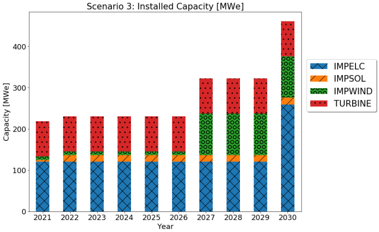

Figure: The electric capacity with constrained nuclear.

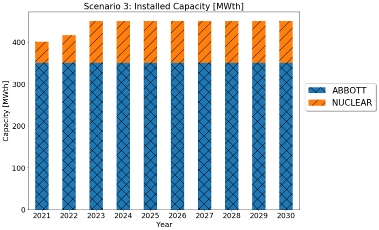

Figure: The steam capacity with constrained nuclear.

Scenario 3: Emissions

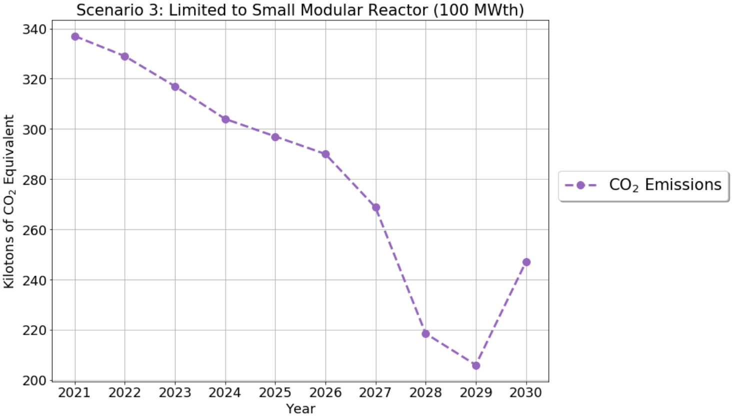

Figure: The carbon equivalent emissions without a cost constraint on nuclear

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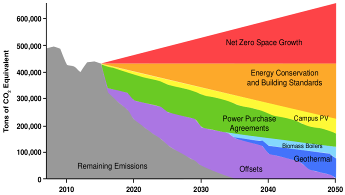
Conclusion

1. Replacing "ABBOTT" with nuclear would resolve all of the Universities carbon goals, *regardless of other offsets and building growth.*
2. Adding, even limited, nuclear capacity will cost effectively meet carbon goals until mid-decade.
3. This model is agnostic to implementation:
   - One 100 MWth small modular reactor
   - Series of 20 MWth micro-reactors



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Future Work

1. Explore parametric uncertainty in `Temoa` with
   - Monte Carlo sampling
   - Stochastic Optimization

   particularly for natural gas prices and nuclear capital costs.
2. Explore structural uncertainty in `Temoa` using Modeling-to-Generate-Alternatives.
3. Explore unmodeled markets and potential cash flows by developing a dispatch model for `RAVEN`.

Acknowledgement

This work was made possible with data provided by UIUC Facilities and Services, in particular, Morgan White, Mike Marquissee, and Mike Larson.
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References I

[1] AlsoEnergy.
University of illinois solar farm dashboard.
http://s35695.mini.alsoenergy.com/Dashboard/2a5669735065572f4a42454b772b714d3d.

[2] T. E. Baker, A. S. Epiney, C. Rabiti, and E. Shittu.
Optimal sizing of flexible nuclear hybrid energy system components considering wind volatility.
212:498–508.

[3] J.F. DeCarolis, S. Babaee, B. Li, and S. Kanungo.
Modelling to generate alternatives with an energy system optimization model.
79:300–310.

[4] Joseph DeCarolis, Kevin Hunter, and Sarat Sreepathi.
The TEMOA project: tools for energy model optimization and analysis.

[5] Harsh Desai.
Nuclear costs in context.

[6] Aaron Epiney, Cristian Rabiti, Andrea Alfonsi, Paul Talbot, and Francesco Ganda.
Report on the economic optimization of a demonstration case for a static n-r HES configuration using RAVEN.

References II

[7] Kevin Hunter, Sarat Sreepathi, and Joseph F. DeCarolis.
Modeling for insight using tools for energy model optimization and analysis (temoa).
40:339–349.

[8] Intergovernmental Panel on Climate Change.
Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Cambridge University Press.

[9] iSEE.
Illinois climate action plan (iCAP).

[10] U.S. Department of Energy.
Capital cost estimates for utility scale electricity generating plants.
page 141.

[11] US-DOE.
The ultimate fast facts guide to nuclear energy.
https://www.energy.gov/ne/downloads/ultimate-fast-facts-guide-nuclear-energy.

Questions?

Mathematics of Temoa

Minimize

$$C_{total} = \sum_{t,v} C_{t,v} \quad (1)$$

Subject to

$$D_{s,p} = \sum_{s,p} G_{s,p}$$

$$L_p = \sum_{t,p} \hat{R}_{CO_2,\{t,p\}}$$

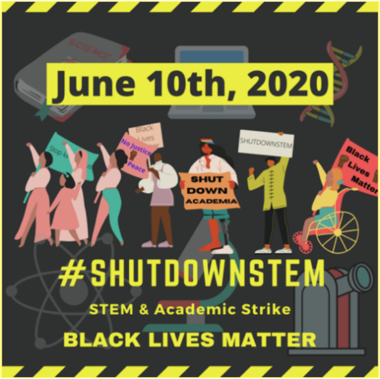
Where

$$C_{total} = \text{total cost}$$
$$D_{s,p} = \text{energy demand by sector, time period}$$
$$G_{s,p} = \text{energy generation by sector, time period}$$
$$L_p = \text{emission limits by time period}$$
$$\hat{R}_{CO_2,\{t,p\}} = \text{emissions by technology, time period}$$

FAQ

- *What does "TURBINE" mean?*
  The "TURBINE" technology simply converts steam to electricity since Abbott power plant is actually a cogeneration plant. We assumed that a nuclear reactor that could replace Abbott would also be used for cogeneration.
- *Can this analysis be applied to other universities or energy systems?*
  Yes. While the University of Illinois is unique in its self-reliance, the idea that nuclear power fulfills a role in the energy mix that is not easily satisfied by renewables is not.

#ShutDownSTEM



This lecture has been pre-recorded.
Questions can be directed to:
Samuel G. Dotson
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Thank you.