Optimal Sizing of a Nuclear Reactor for Microgrid Decarbonization

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Abstract

The abstract goes here. As a general guide, you should provide a concise (150-250 words) summary of your article - introduction, methodology, results, and conclusion. Avoid using abbreviations and acronyms unless the abbreviation/acronym is used repeatedly in the abstract. There should be no references in the abstract.

Keywords: FIXME, key words, go here, like:, simulation, spent nuclear fuel

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1. Introduction

In this work we use an energy system optimization model (ESOM) called Tools for Energy Model Optimization and Analysis (Temoa) to determine the optimal size of a nuclear reactor for a micro-grid system. The optimal reactor capacity satisfies carbon emissions limits and minimizes system cost.

The looming threat of irreversible damage to global ecosystems due to anthropogenic climate change motivated many countries to adopt carbon emissions goals. In 2019, the United States made plans to formally withdraw from the 2015 Paris agreement, the only country to do so [1, 2]. In spite of this, some individual states and institutions created their own climate goals conistent with the aims of the Paris Agreement. The University of Illinois at Urbana-Champaign (UIUC) is one such institution. In 2015 UIUC published the Illinois Climate Action Plan (iCAP) with the goal to become carbon neutral by 2050 or sooner [3]. Emissions projections shown in Figure 1 illustrate the needed policy changes to meet climate goals.

UIUC poses an interesting opportunity to explore options for rapid decarbonization because it: (1) is a mostly self-contained micro-grid (2) has a diverse mix of energy production and (3) relies on steam for district heating which challenges decarbonization efforts.

The iCAP goals for UIUC include several categories [3]:

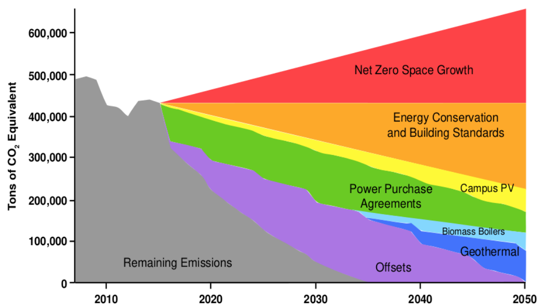

Figure 1: The projected carbon emissions with corresponding policy changes. "Offsets" includes shutting down the Blue Waters Supercomputer. Image originally published in iCAP 2015 [3].

1. Energy conservation and building standards
2. Energy generation, purchasing, and distribution
3. Transportation
4. Water
5. Waste and recycling
6. Agriculture and land use

Energy conservation, generation, and purchasing objectives are of primary interest because these items account for 88% of UIUC's emissions, shown in Figure 2. iCAP 2015 showed that UIUC made progress towards its emissions goals. Further, in 2016 UIUC entered a power purchase agreement (PPA) with Railsplitter Wind Farm [4] and completed Solar Farm 1.0 [5]. Though these investments indicate UIUC's dedication to addressing climate change, they are insufficient to curb emissions as shown in Figure 3.

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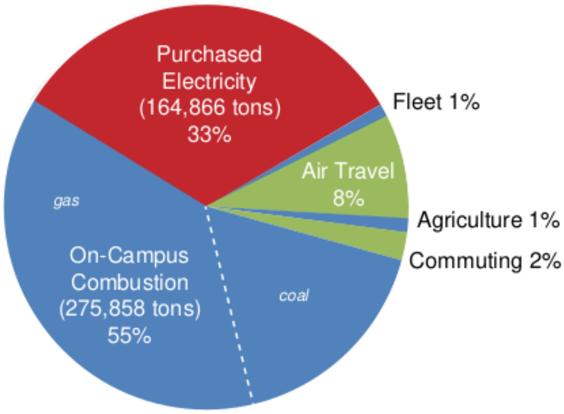

Figure 2: Shows three scopes of university related emissions: on-campus (blue), purchased electricity (red), and off-campus (green). Image originally published in iCAP 2015 [3].

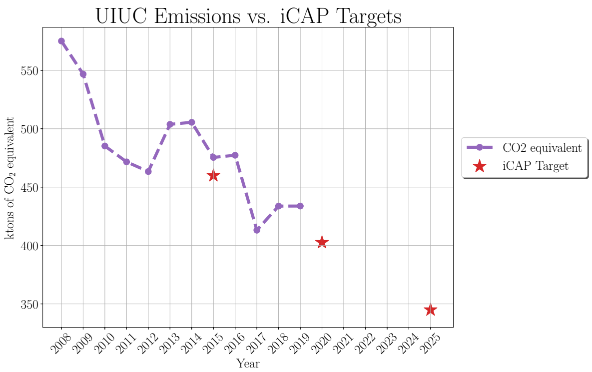

Figure 3: UIUC's actual net emissions compared with iCAP's stated goals. Data taken from the iCAP Sustainability Portal [6].

The struggle to meet these climate goals demonstrates the challenge decision makers face in balancing stakeholder interests, cost, and sustainability. The 2015 Facilities and Services Master Plan, used to define the needs of the UIUC campus, outlined 13 scenarios informed by iCAP [7]. This report found that no combination of existing technologies can achieve the emissions goals developed by iCAP. One of its recommendations was to "investigate additional renewable PPAs or purchasing renewable energy credits."

In order for UIUC to become carbon neutral, it must continue to meet the electricity and steam demand while producing this energy without emissions. Investments in renewable energy through PPAs and solar farm construction will enable carbon free electricity production, but more than half of UIUC's energy demand comes from steam [3] . Renewable energy cannot efficiently produce heat in a manner that is simultaneously cost effective and friendly to the environment.

Nuclear energy was conspicuously absent from the Master Plan's analysis. The life cycle carbon emissions of a nuclear power plant is rivaled only by on- shore wind power, shown in Figure 4, and is capable of producing the high temperature steam required for district heating at UIUC [8]. These two facts alone make nuclear power an ideal candidate for replacing the coal and natural gas boilers in the campus power plant. Additionally, criticisms about nuclear's lack of profitability would not apply to nuclear power at UIUC because the campus operates a micro-grid and is thus insulated from the deregulated energy market in Illinois [9, 10]. The University has already demonstrated its willingness to pay a premium to adopt clean energy for wind and solar [4, 5, 11] which indicates that other premiums might be overlooked in favor of lasting decisions on energy production.

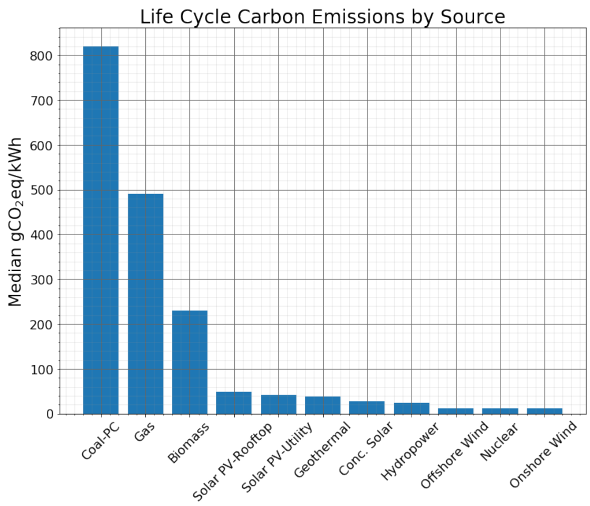

Figure 4: The carbon lifecycle carbon emissions by energy source. Data is from IPCC 2018 Report on Climate Change [8].

ESOMs are useful for exploring different policy scenarios and energy mixes when faced with future uncertainty [12, 13, 14, 15]. In this work, we use an ESOM called Temoa to analyze future energy mixes that will allow UIUC to meet the iCAP goals [16]. This study is unique because we do not consider all possible technologies that could replace natural gas and coal capacity, which have a range of maturity and readiness. Rather, we consider UIUC's existing energy mix and use Temoa to find the minimum capacity of a nuclear power plant that will enable UIUC to satisfy its emissions goals.

We first examine a business-as-usual model to verify that Temoa agrees with the findings in the Master Plan [7]. Then we consider three scenarios that introduce a nuclear power plant to the energy mix. Finally we employ an uncertainty analysis method known as Modeling-to-Generate-Alternatives (MGA) to evaluate futures that also meet the emissions limits for UIUC but do not perfectly minimize system cost.

2. Methodology

Temoa is an open source tool for energy system optimization that formulates and solves a linear optimization problem [16]. A linear optimization problem has two requirements: An objective function and constraints. The objective function in Temoa is total system cost over time horizon of interest and the minimum required constraint is annual demand (and technology options to meet that demand).

Minimize

$$C_{sys} = \sum_{y}^{period} \sum_{t}^{tech} C_{t,y} P_{t,y} F_{t,y} T \tag{1}$$

Subject to

$$\tag{2}$$

$$M_y = \sum_{t}^{tech} M_{t,y} P_{t,y} F_{t,y} T \tag{3}$$

where

$$\tag{4}$$

$$\begin{aligned}
C_{sys} &= \text{system cost, } [\$] \\
C_{t,y} &= \text{technology cost, } \left[\frac{\$}{\text{MWh}}\right] \\
P_{t,y} &= \text{technology capacity, [MW]} \\
F_{t,y} &= \text{technology capacity factor, [-]} \\
T &= \text{time, [hours]} \\
M_y &= \text{emissions for year, } y, \text{ [tons CO}_2\text{eq]} \\
M_{t,y} &= \text{technology emissions, } \left[\frac{\text{CO}_2\text{eq}}{\text{MWh}}\right]
\end{aligned}$$

Users can optionally add other constraints to match the real system being modeled. In our case we added emissions limits based on the carbon goals set by iCAP. At each time step, Temoa must be able to meet the various constraints with the existing capacity, or build be able to build new capacity to do so. If demand and emissions limits cannot be satisfied, then Temoa gives "no solution." A detailed description of Temoa's mathematics can be found at "temoacloud.com." For uncertainty analysis, Temoa implements the Hop-Skip-Jump (HSJ) algorithm for MGA.

3. Model and Data

The system we modeled in this study is based on the current energy mix of UIUC which is summarized in Table 1. Temoa optimizes the years 2021-2030 in single year increments. Each year is divided 6 time slices, three seasons, and a day-night cycle. The seasons are summer, winter, and an "inter" season that represents spring and fall. The typical demand breakdown for each season is determined by averaging historical data from 2015- 2018 [17]. Abbott Power Plant (APP) is a natural gas and coal fired cogeneration plant that fulfills all of the steam demand for UIUC and much of the electricity demand [7]. In order to effectively capture cogeneration from APP in our model, we introduced an intermediate technology, `TURBINE`. Thus, APP can produce a steam "commodity" that is split between campus steam demand and campus electricity demand via `TURBINE`. Introducing this intermediate technology also allowed us to easily plug in new sources of steam to the energy mix, like a nuclear reactor.

The capacities for solar and wind power are both capped in this Temoa model and reflects the real constraints on the UIUC energy mix. The cap on solar energy is due to the maximum capacity of the solar farms on campus. Currently, the solar farm is rated to produce 4.68 MWe, but will be tripled in 2022 when the university finishes the planned Solar Farm 2.0 [11, 5].The cap on wind energy is due to the 10-year power purchase agreement between UIUC and Rail Splitter Wind Farm. This contract ends in 2026, at which point the university can elect to purchase more or not [4]. The current installed capacity of Rail Splitter Wind Farm is 100.5 MW_e so we limited the maximum PPA to 100.5 MW_e.

Carbon emissions are counted as a "CO_2 equivalent" which matches the strategy adopted by iCAP.

Table 1: A summary of the technologies at UIUC

Technology	Name	Capital Cost M$/MW	Variable Cost M$/GWh	Emissions kton-CO_2eq/MW	Citation
Natural Gas & Coal Plant	`ABBOTT`	0.735	0.0553	0.192	[3, 7, 18, 19, 20]
Nuclear	`NUCLEAR`	5.945	0.027	-	[18, 21, 22, 23]
Turbine	`TURBINE`	-	0.03	-	[19, 7]
Photovoltaic Solar	`IMPSOL`	1.66	0.196	-	[11, 19]
Wind PPA	`IMPWIND`	-	0.0384	-	[4, 19]
MISO Electricity Imports	`IMPELC`	-	0.13	0.825	[3, 19, 24]

The limits for each year are also based on the iCAP goals which were only published for three years: 2020, 2025, and 2050. We used linear interpolation to fill in the missing values. In our Temoa model, we only tracked emissions from each unit of energy generated rather than the lifetime carbon emissions. The reason for this is that Temoa will give "no solution" if we include emissions from constructing solar farms, nuclear reactors, or other energy sources because even if UIUC moved toward an energy mix that is based on a purely wind PPA, the steam demand will be left unsatisfied.

This model assumes an energy demand growth of 1% per year. Thus, offsets like shutting down the Blue Waters Supercomputer, zero net-growth on campus, and improving building standards that serve to reduce demand, are not accounted for and assumes the university will carry on with business as usual in every regard except its energy mix. We consider four scenarios, summarized in Table 2. The first scenario maps out the emissions and energy generation for UIUC if the university continues with business as usual. The numbered scenarios include nuclear capacity in the energy mix. Starting with a "free" reactor in Scenario 1, then adding a capital cost in Scenario 2, and finally, limiting the reactor capacity in Scenario 3. We also conducted an MGA uncertainty analysis on Scenario 3 only because the first two scenarios will be pushed along the same technology trajectories when faced with carbon constraints.

4. Results

4.1. Business as Usual

This scenario does two things. First, by comparing the electricity generation over the course of the next 10 years to a reference year, 2014, we can validate the results from Temoa. Second, it motivates the need to include other energy sources. In Figure 5, the `IMPELC-2014` and `TURBINE-2014` bars refer to imported electricity and turbines at APP in 2014, respectively.

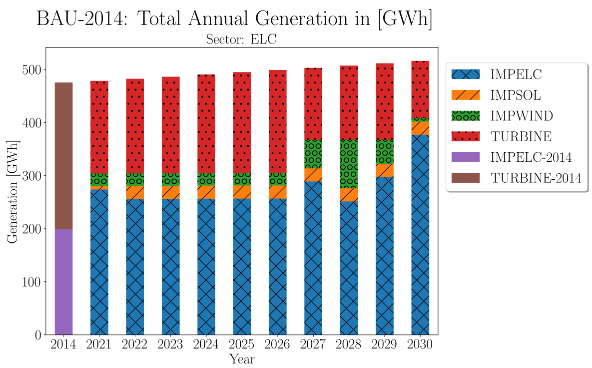

Figure 5: The predicted electric generation in GWh(e) for the next 10 years from Temoa, compared with data from 2014 [3].

UIUC had neither a solar farm nor a PPA with a wind farm in 2015 when iCAP was published. The electricity that those two sources now displace would have been produced by the natural gas plant, APP. The UIUC Master Plan [7] also indicates that increasing electricity imports in the near term will be important for meeting the electricity demands of the university. This recommendation matches the trend shown in Figure 5. The carbon emissions projected by Temoa are shown in Figure 6 also match the carbon emissions in the iCAP document [3], which rises to about 500 ktons of carbon equivalent by 2030. The similarities between the Temoa model and iCAP further validates the model results.

Unless UIUC halts its growing demand for electricity the University will not achieve its carbon goals [3, 7].

4.2. Scenario 1: Zero Capital Cost Nuclear Reactor

This scenario shows an idealized solution for reducing carbon emissions at UIUC if nuclear reactors

Table 2: Summary of Temoa Nuclear Scenarios

Scenario	Nuclear	Variable Cost	Capital Cost	Capacity Limit
BAU	No	-	-	-
1	Yes	Yes	-	-
2	Yes	Yes	Yes	-
3	Yes	Yes	Yes	100 MW_{th}

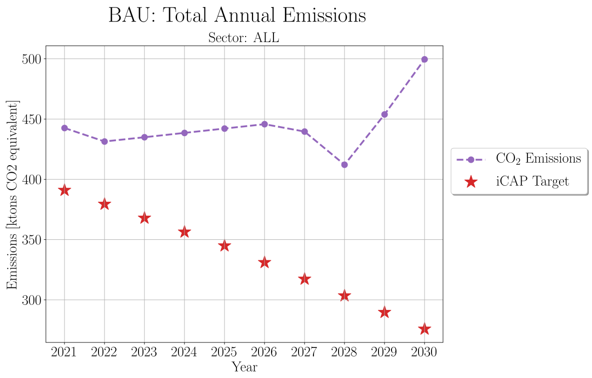

Figure 6: The Temoa projected carbon emissions for the next 10 years if UIUC continues with "business as usual."

could be built with no capital cost. For this idealized case, Figure 7 and 8 show that APP would be immediately replaced by a nuclear reactor. Even though Figure 7 shows the nuclear reactor capacity growing to 2000 MW_{th}, Figure 8 shows that this is unecessary and the demand for steam and electricity could be satisfied by a reactor around 375 MW_{th}.

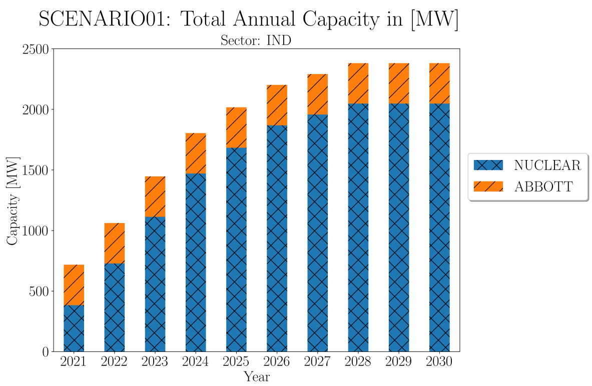

Figure 7: The projected steam generation in MW_{th} for the next 10 years if UIUC could build nuclear reactors at no cost.

Even though a nuclear reactor is "free" in this scenario, Temoa still uses solar power, wind power, and electricity imports, as shown in Figure 9. In the model description, Temoa must use energy produced

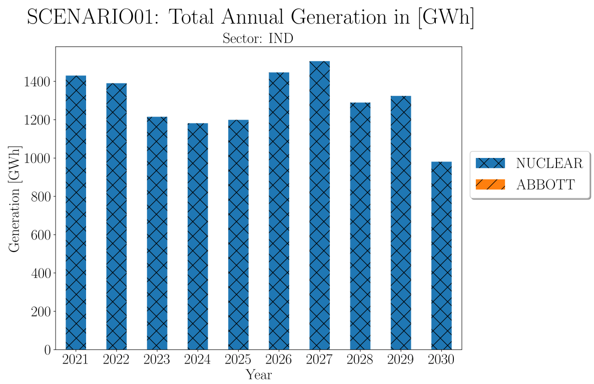

Figure 8: The projected breakdown of steam generation by source in GWh(th) for the next 10 years if UIUC could build nuclear reactors at no cost.

by the solar and wind farms for the duration of those PPAs. Temoa continues to use electricity imports because, in addition to having a carbon constraint, Temoa minimizes the system cost.

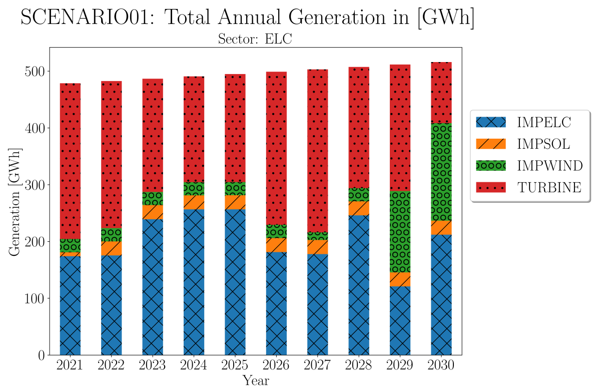

Figure 9: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years if UIUC could build nuclear reactors at no cost.

Since UIUC is still importing electricity in this scenario the projected carbon will not drop to zero. Figure 10 shows that the campus emissions track exactly with the increase or decrease in imported electricity.

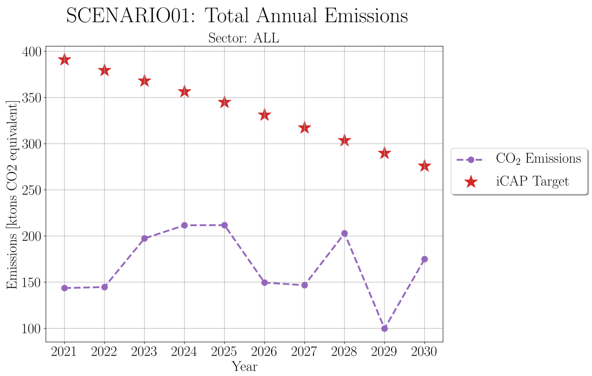

Figure 10: The Temoa projected carbon emissions for the next 10 years if UIUC could build nuclear reactors at no cost.

4.3. Scenario 2: Nuclear Reactors With Capital Cost

The second scenario is somewhat more realistic because building a reactor includes a capital cost, however, the total capacity is still unconstrained. As in Scenario 1, Figure 11 and Figure 12 show that APP is quickly replaced by nuclear capacity. However, Temoa used APP in the first year due to the relatively high carbon allowance in the first year and the capital costs of a nuclear power plant.

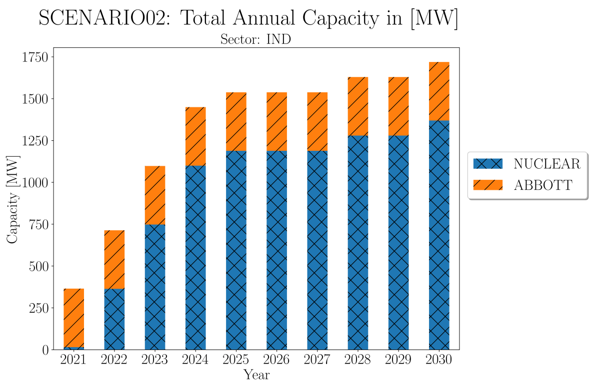

Figure 11: The projected steam capacity in MW_{th} for the next 10 years if UIUC could build nuclear reactors at no cost.

Similar to the results in Scenario 1, Temoa will use the flexibility, or lack thereof, in the carbon limits to determine the lowest cost solution. Since some carbon emissions are allowed, the most cost effective approach is to use imported electricity as shown in Figure 13. In addition to electricity imports, Figure 14 shows UIUC expanding it's wind PPA after the current one expires in 2026 [4].

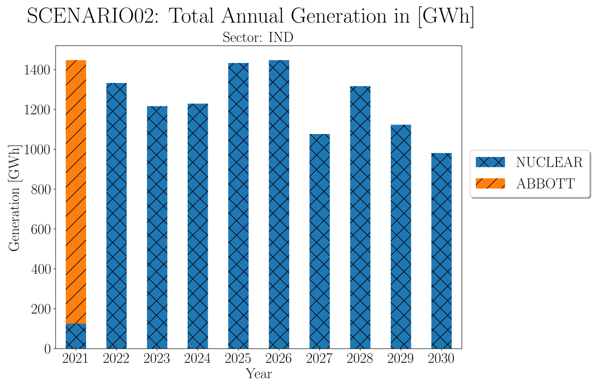

Figure 12: The projected breakdown of steam generation by source in GWh(th) for the next 10 years at UIUC.

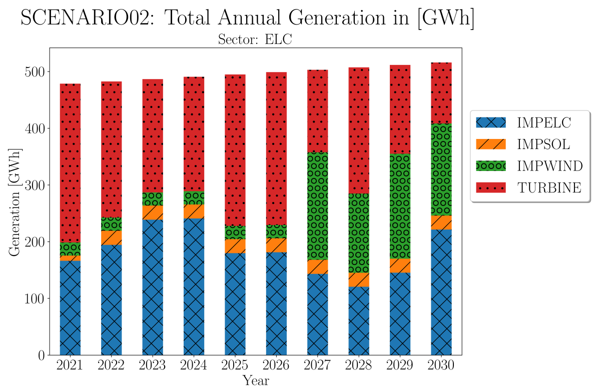

Figure 13: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years at UIUC.

Increasing the amount of electricity purchased from a wind farm is cheaper than building more nuclear capacity because the reactor is responsible for steam demand, while electricity demand can be met through other means. In this scenario, the wind PPA grows to a capacity of 100.5 MW_e, which is the entire installed capacity of Rail Splitter Wind Farm [4].

The carbon emissions in this scenario, shown in Figure 15, also follow a similar trend to Scenario 1. The key difference is in the first year when APP is still being used to produce steam and electricity. In both cases, the campus carbon emissions follow the amount of

These results show that UIUC's carbon goals can be initially met with a slower introduction of nuclear power.

4.4. Scenario 3: Small Modular Reactor

The final scenario limited the capacity of a nuclear reactor to 100 MW_{th} for a small modular reactor (SMR). Due to physical size constraints a nuclear

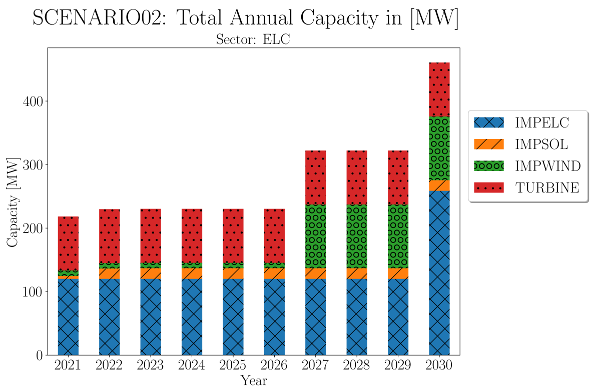

Figure 14: The projected electric capacity in MW_e for the next 10 years at UIUC.

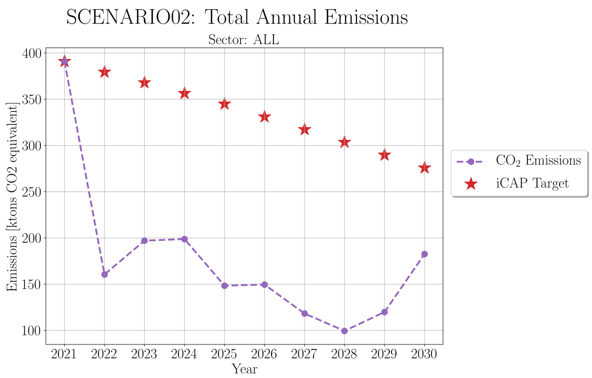

Figure 15: The carbon emissions projected by Temoa for the next 10 years at UIUC.

reactor for power production on a university campus will most likely be an SMR. Figure 16 shows that an SMR is not large enough to replace APP but a reactor with a rated capacity less than 100 MW_th can still help UIUC satisfy the carbon goals outlined in iCAP. Figure 17 shows the amount of steam produced by APP and the SMR in GWh(th).

The share of electricity produced by the `TURBINE` decreases in that last few years of the decade when the wind PPA increases, as illustrated in Figure 18. As in Scenario 2, the wind PPA is a somewhat cheap renewable energy source for UIUC because it requires no capital investment on the part of the university, whereas building another solar farm or nuclear reactor would require some capital cost.

Finally, Figure 19 shows the projected carbon emissions at UIUC until 2030 if the university invests in an SMR up to $100MW_{th}$ capacity. Further this Figure 19 and Figure 16 together show that the iCAP goals for the next ten years can be met with a reactor that has a capacity of less than $100MW_{th}$.

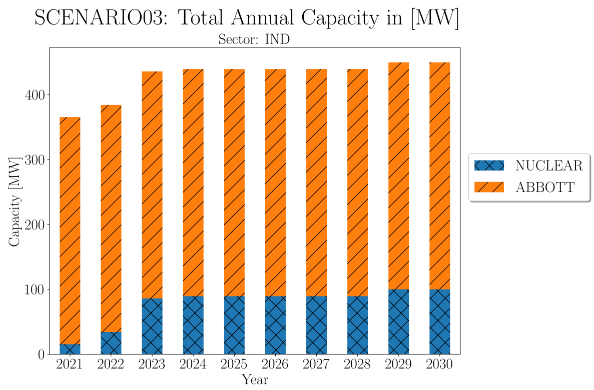

Figure 16: The projected steam capacity in MW_{th} for the next 10 years if UIUC invests in SMRs.

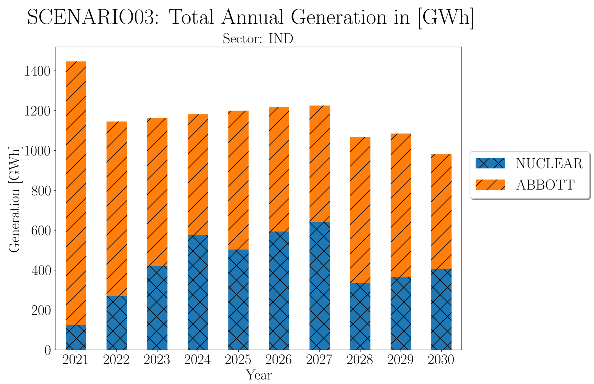

Figure 17: The projected breakdown of steam generation by source in GWh(th) for the next 10 years at UIUC.

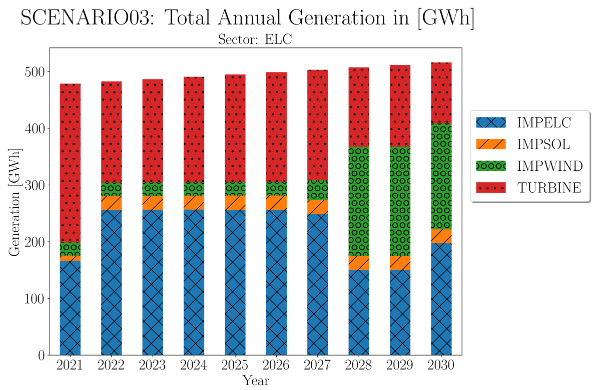

Figure 18: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years at UIUC.

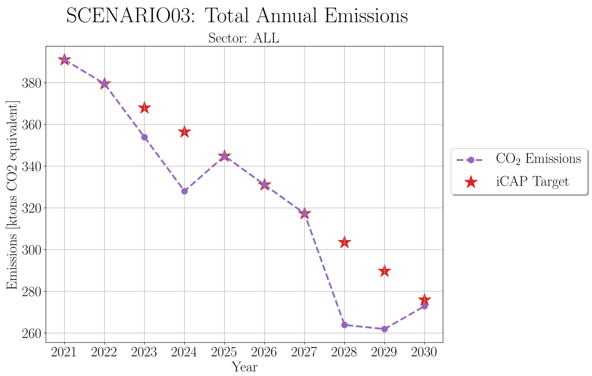

Figure 19: The carbon emissions projected by Temoa for the next 10 years at UIUC with a nuclear reactor up to 100MW_{th}.

4.5. MGA Analysis

The MGA method is useful for capturing solutions that are considered sub-optimal but may be viable alternatives in practice [12, 13, 25]. In this study, MGA yielded a single unique alternative that expanded nuclear power and wind PPAs more aggressively than in the optimized case (Scenario 3). Figure 20 shows that the capacity of the SMR reaches the 100 MW_{th} limit after the first year and Figure 21 shows that the wind PPA increases sooner than in Scenario 3. The result of this aggressive expansion of nuclear power and wind PPAs is that carbon emissions are reduced further and more quickly than in the lowest cost solution.

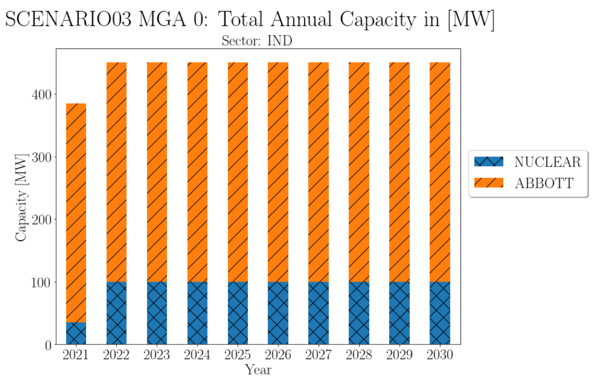

Figure 20: The projected steam capacity in MW_{th} for the next 10 years if UIUC invests in SMRs.

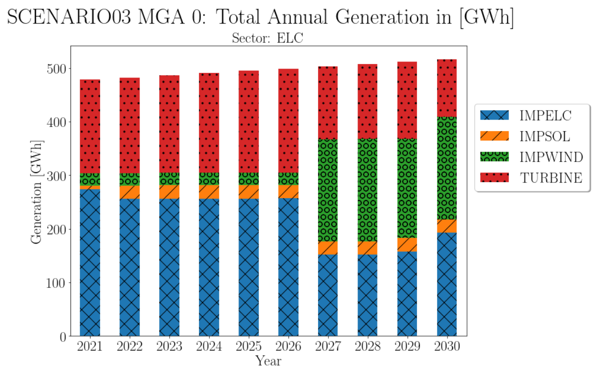

Figure 21: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years at UIUC.

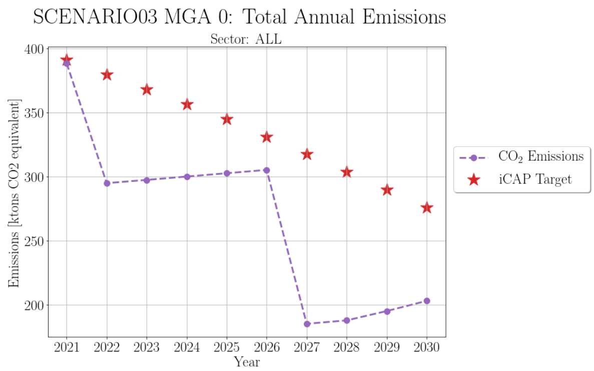

Figure 22: The carbon emissions projected by MGA for the next 10 years at UIUC.

5. Conclusion

In this study we used the ESOM called Temoa to find the optimal size of a nuclear reactor for the UIUC microgrid. We first showed that Temoa gave realistic results that matched predictions from both iCAP and the UIUC Master Plan [3, 7]. Then we considered three scenarios that introduced nuclear capacity to UIUC. The first two scenarios did not constrain the size of the nuclear reactor and thus satisfied the carbon constraints and exceeded the steam and electricity demand requirements by building more nuclear capacity than required. Importantly, Temoa has a tendency to over-build nuclear capacity in the first two scenarios. Steam and electricity demands can be met on campus by simply installing enough capacity to replace APP rather than exceed it substantially. The UIUC Master Plan found that the goals outlined in iCAP could not be achieved with UIUC's current energy mix, which we corroborated in our business-as-usual scenario. We showed in Scenario 3 that the iCAP goals could be met for the next decade by adding a modest capacity for nuclear energy production. The assumptions of the model used in this study include contributions from renewables, but exclude requirements of zero growth, improvements in building efficiency, and other offsets. This gives UIUC the flexibility to continue growing while reducing carbon emissions in other areas. The breakdown of carbon offsets shown in Figure 1 is improved by adding nuclear power to the energy mix. Finally, importing electricity drove the campus carbon emissions in every scenario we examined. If UIUC is serious about decarbonizing by 2050, the University must stop buying electricity from MISO. Unless, that is, energy production throughout MISO also becomes carbon free.

Besides producing emissions free electricity and steam, nuclear power can benefit campuses, like UIUC, in many ways. Future work will explore how nuclear power can help decarbonize campus transportation, the role of energy storage, and peer further into the future.

6. Acknowledgments

This work was made possible with the support from the people at UIUC Facilities & Services. In particular, Morgan White, Mike Marquissee, and Mike Larson. It was also aided by other members of the Advanced Reactors and Fuel Cycles (ARFC) group, in particular, Roberto Fairhurst and David Atwater. This work is supported by the Nuclear Regulatory Commission Fellowship Program. Prof. Huff is supported by the Nuclear Regulatory Commission Faculty Development Program (award NRC-HQ-84-14-G-0054 Program B), the Blue Waters sustained-petascale computing project supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois, the DOE ARPA-E MEITNER Program (award DE-AR0000983), and the DOE H2@Scale Program (Award Number: DE-EE0008832)

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