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

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 microgrid 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 has motivated many countries to adopt goals to curb damaging carbon emissions, underscored by the 196 signatories of the 2015 Paris Agreement [1]. In 2019, the United States made plans to formally withdraw from the agreement, the only country to do so [2]. In spite of this, individual states and institutions have 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]:

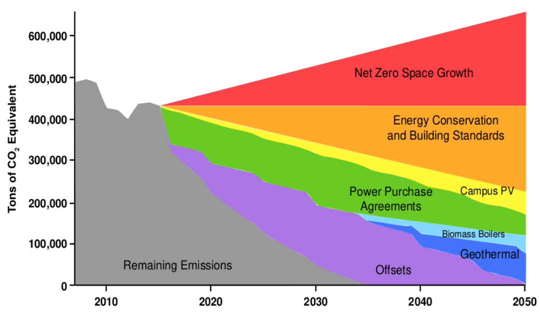

Figure 1: The projected carbon emissions with corresponding policy changes. "Offsets" includes shutting down the Blue Waters Supercomputer. Image originally published in iCAP 2015 [3].

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 emissions goals, they have not been enough to curb emissions as shown in Figure 3.

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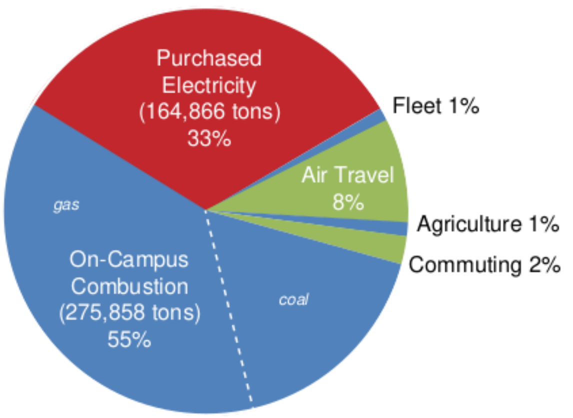

Figure 2: Shows three scopes of university related emissions: on-campus (blue), purchased electricity (red), and off-campus (green). Image originally published in iCAP 2015 [3].

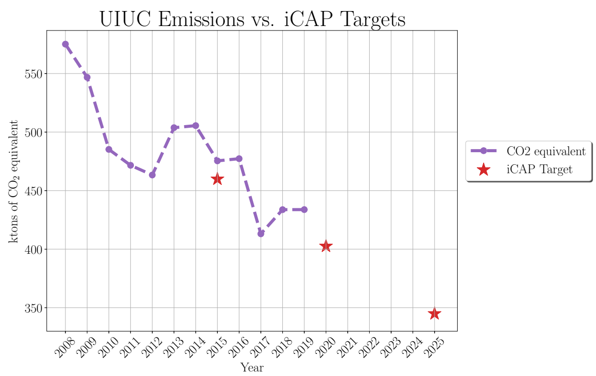

Figure 3: UIUC's actual net emissions compared with iCAP's stated goals. Data taken from the iCAP Sustainability Portal [6].

The struggle to meet these climate goals demonstrates the challenge decision makers face in balancing stakeholder interests, cost, and sustainability goals. 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. Yet the life cycle carbon emissions of a nuclear power plant is rivaled only by on- shore wind power, shown in Figure **??** 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 uninfluenced by 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.

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 where system cost is not perfectly minimized.

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). 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." Mathematically, Temoa solves the following problem:

Minimize

$$C_{tot} = C_{cap} + C_{fix} + C_{var} \tag{1}$$

Subject to:

$$D_i = \sum_{tech} A_{tech} \text{ for } i \in \text{ years} \tag{2}$$

3. Model and Data

The system we modeled in this study is based on the current energy mix of UIUC.

1. Explain the time horizon
   - 2020 is considered a historical year and reflects the current energy mix of the university.
   - The model optimizes years 2021-2030 in single year increments.
   - In this study, one year is divided 6 time slices. 3 seasons, and 2 times of day. Future work will refine this temporal detail.
2. Typical demand for winter, summer, and the spring/fall "inter" season are determined by averaging historical data from 2015-2018.
3. The natural gas plant, "ABBOTT" as a cogeneration plant that produces all of the steam on campus and much of the electricity. In order to capture the cogeneration, we introduced a "TURBINE" technology that produces electricity from steam. The proposed nuclear reactor will also produce steam that "TURBINE" can use to produce electricity. Thus the model assumes that the nuclear reactor will serve as a direct replacement of "ABBOTT" or function alongside "ABBOTT" in an identical way.
4. Natural gas prices.
   The price of natural gas is one of main factors driving the choice of energy production at UIUC. Since 2014, natural gas prices have somewhat steadily declined.
5. Carbon Emissions
   Carbon emissions in the model are captured by using a carbon emission equivalent that matches the strategy adopted by iCAP.
6. Capacity caps
   Solar and wind capacities are both capped by Temoa and reflect the reality of 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 quadrupled in 2022 when the university finishes the planned Solar Farm 2.0.
   - 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.
7. Offsets, Growth, and Building Standards
   This model assumes an energy demand growth of 1% per year. Thus, offsets like shutting down the Blue Waters Supercomputer and improving building standards, which 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.
8. Scenarios
   Describe the modeled scenarios - BAU, 1, 2, 3. Uncertainty analysis is only performed on scenario 3 because scenarios 1 and 2 will be pushed along the same technology trajectory because not limiting the size of the nuclear reactor means demand and emissions constraints can be satisfied arbitrarily. The business as usual scenario is not analyzed for uncertainty because it served as a sanity check to verify that Temoa was giving appropriate results.

4. Results

4.1. Business as Usual

This scenario does two things. First, by comparing the electricity generation over the course of the

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	[17, 18, 19, 3, 7]
Nuclear	`NUCLEAR`	5.945	0.027	-	[20, 21, 22, 17]
Turbine	`TURBINE`	-	0.03	-	
Photovoltaic Solar	`IMPSOL`	1.66	0.196	-	[11, 18]
Wind PPA	`IMPWIND`	-	0.0384	-	[4, 18]
MISO Electricity Imports	`IMPELC`	-	0.13	0.825	[23, 18, 3]

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 4, the `IMPELC-2014` and `TURBINE-2014` bars refer to imported electricity and turbines at Abbott Power Plant (APP) in 2014, respectively.

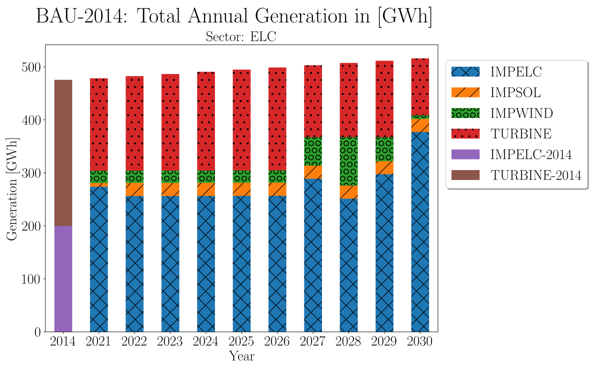

Figure 4: The predicted electric generation in GWh(e) for the next 10 years from Temoa, compared with data from 2014 [3].

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 4. The carbon emissions projected by Temoa are shown in Figure 5 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].

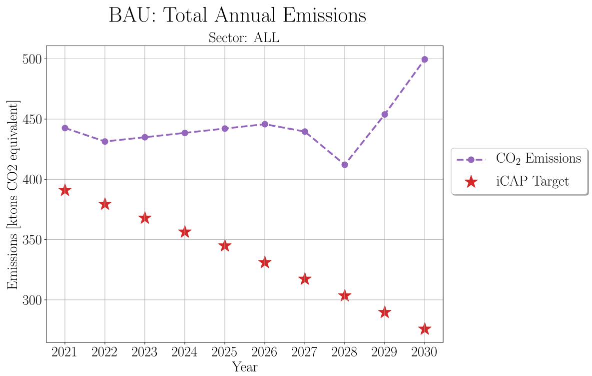

Figure 5: The Temoa projected carbon emissions for the next 10 years if UIUC continues with "business as usual."

4.2. Scenario 1: Zero Capital Cost Nuclear Reactor

This scenario shows an idealized solution for reducing carbon emissions at UIUC if nuclear reactors could be built with no capital cost. For this idealized case, Figure 6 and 7 show that APP would be immediately replaced by a nuclear reactor. Even though Figure 6 shows the nuclear reactor capacity growing to 2000 MW_{th}, Figure 7 shows that this is unecessary and the demand for steam and electricity could be satisfied by a reactor around 375 MW_{th}.

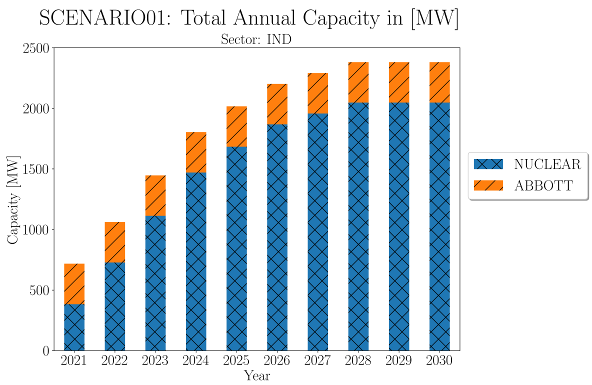

Figure 6: The projected steam generation in MW_{th} for the next 10 years if UIUC could build nuclear reactors at no cost.

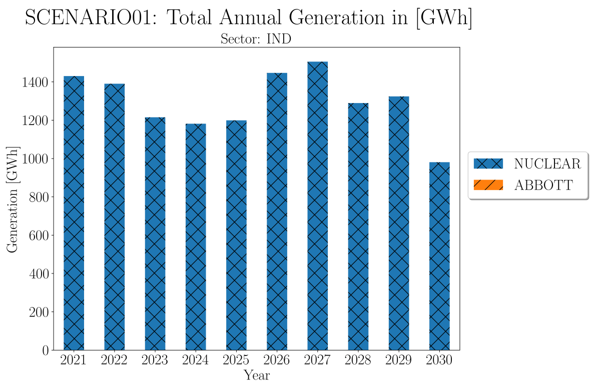

Figure 7: The projected breakdown of steam generation by source in GWh(th) for the next 10 years if UIUC could build nuclear reactors at no cost.

Even though a nuclear reactor is "free" in this scenario, Temoa still uses solar power, wind power, and electricity imports, as shown in Figure 8. In the model description, Temoa must use energy produced 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.

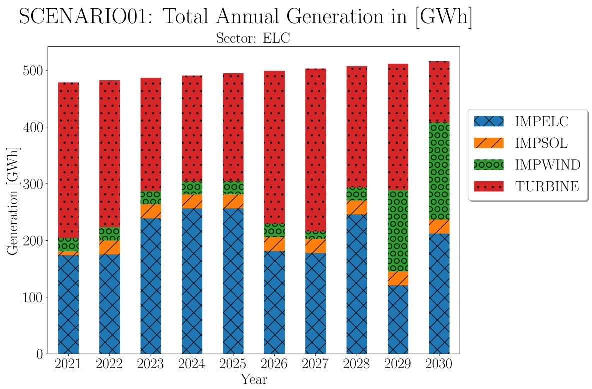

Figure 8: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years if UIUC could build nuclear reactors at no cost.

Since UIUC is still importing electricity in this scenario the projected carbon will not drop to zero. Figure 9 shows that the campus emissions track exactly with the increase or decrease in imported electricity.

4.3. Scenario 2: Nuclear Reactors With Capital Cost

The second scenario is somewhat more realistic because building a reactor includes a capital cost,

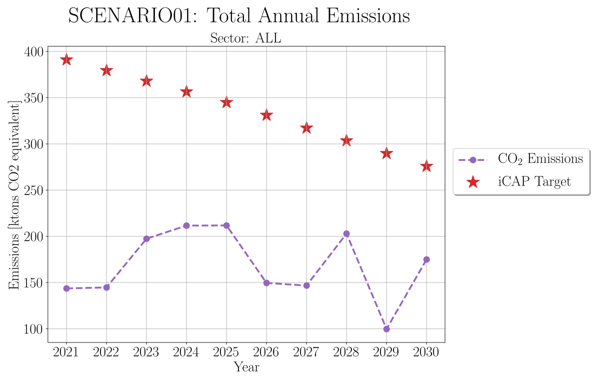

Figure 9: The Temoa projected carbon emissions for the next 10 years if UIUC could build nuclear reactors at no cost.

however, the total capacity is still unconstrained. As in Scenario 1, Figure 10 and Figure 11 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.

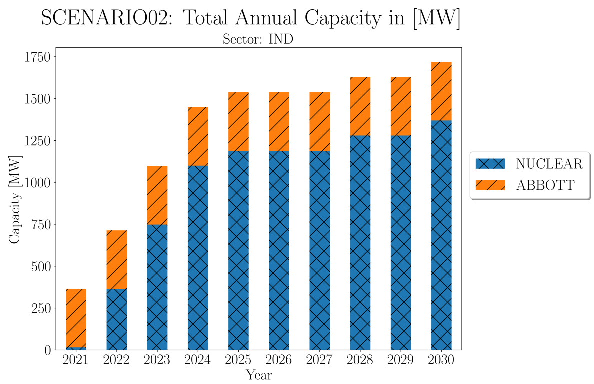

Figure 10: The projected steam capacity in MW_{th} for the next 10 years if UIUC could build nuclear reactors at no cost.

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 12. In addition to electricity imports, Figure 13 shows UIUC expanding it's wind PPA after the current one expires in 2026 [4].

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

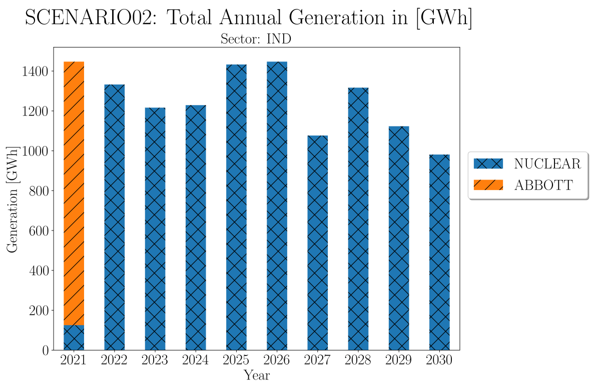

Figure 11: The projected breakdown of steam generation by source in GWh(th) for the next 10 years at UIUC.

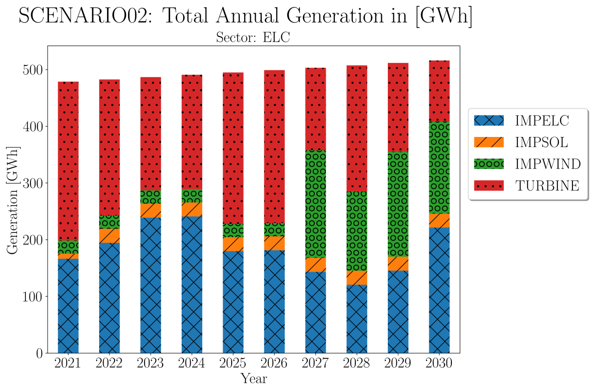

Figure 12: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years at UIUC.

the entire installed capacity of Rail Splitter Wind Farm [4].

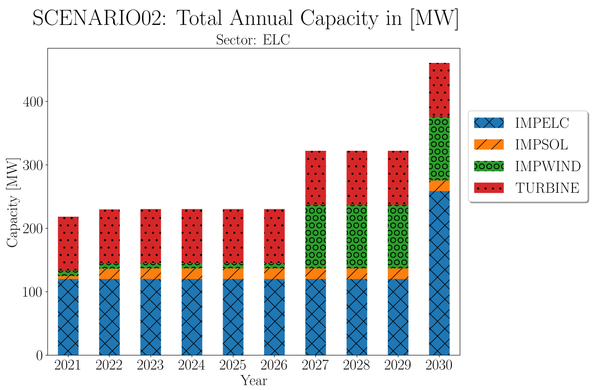

Figure 13: The projected electric capacity in MW_e for the next 10 years at UIUC.

The carbon emissions in this scenario, shown in Figure 14, 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

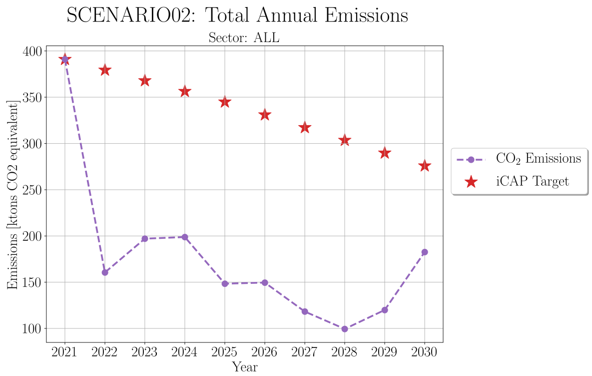

Figure 14: The carbon emissions projected by Temoa for the next 10 years at UIUC.

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 reactor for power production on a university campus will most likely be an SMR. Figure 15 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 16 shows the amount of steam produced by APP and the SMR in GWh(th).

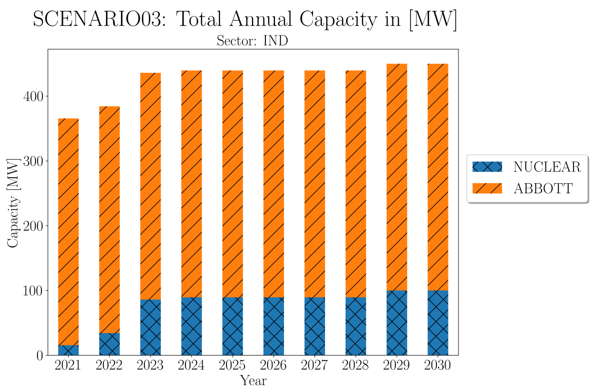

Figure 15: The projected steam capacity in MW_{th} for the next 10 years if UIUC invests in SMRs.

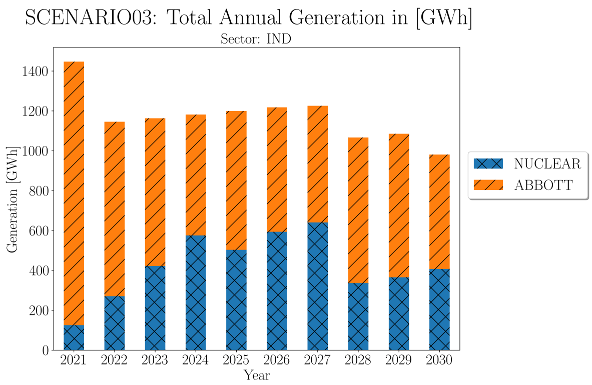

Figure 16: The projected breakdown of steam generation by source in GWh(th) for the next 10 years at UIUC.

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 17. 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.

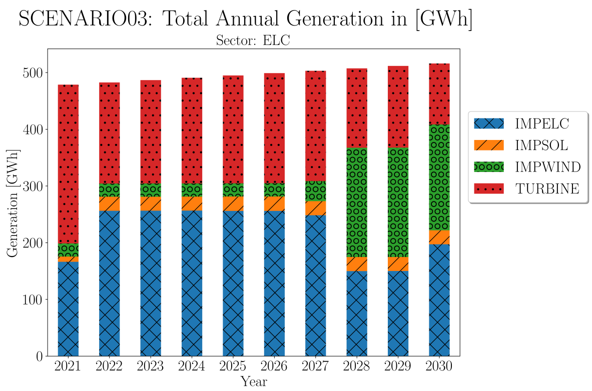

Figure 17: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years at UIUC.

Finally, Figure 18 shows the projected carbon emissions at UIUC until 2030 if the university invests in an SMR up to 100MW$_{th}$ capacity. Further this Figure 18 and Figure 15 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$_{th}$.

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, 24]. In this study,

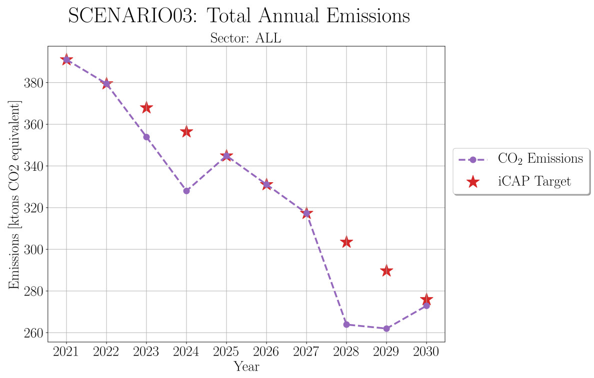

Figure 18: The carbon emissions projected by Temoa for the next 10 years at UIUC with a nuclear reactor up to 100MW$_{th}$.

MGA yielded a single unique alternative that expanded nuclear power and wind PPAs more aggressively than in the optimized case (Scenario 3). Figure 19 shows that the capacity of the SMR reaches the 100 MW$_{th}$ limit after the first year and Figure 20 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.

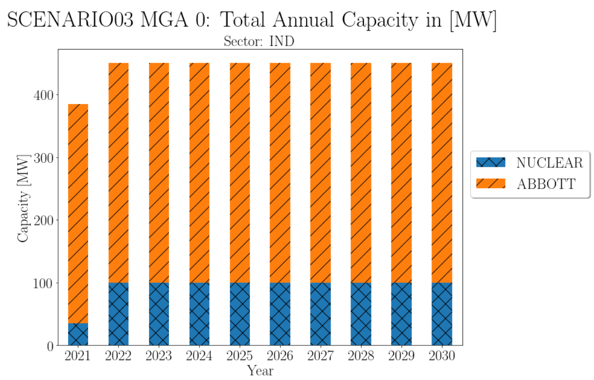

Figure 19: The projected steam capacity in MW$_{th}$ for the next 10 years if UIUC invests in SMRs.

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

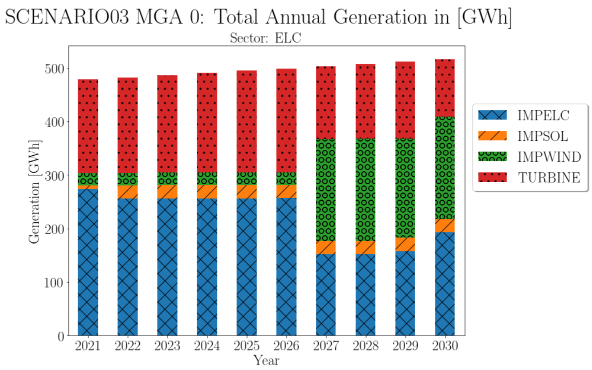

Figure 20: The projected breakdown of electricity generation in GWh(e), by source, for the next 10 years at UIUC.

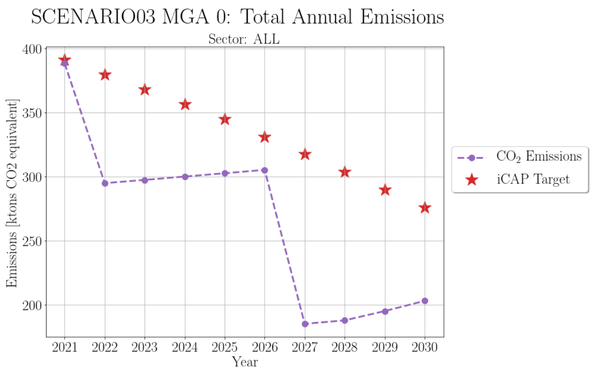

Figure 21: The carbon emissions projected by MGA for the next 10 years at UIUC.

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. 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

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References

[1] The paris agreement | UNFCCC. URL `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`

[2] H. Eshraghi, A. R. de Queiroz, J. F. DeCarolis, US energy-related greenhouse gas emissions in the absence of federal climate policy 52 (17) 9595–9604, publisher: American Chemical Society. `doi:10.1021/acs.est.8b01586`. URL `https://doi.org/10.1021/acs.est.8b01586`

[3] iSEE, Illinois climate action plan (iCAP). URL `https://sustainability.illinois.edu/campus-sustainability/icap/`

[4] S. Breitweiser, Wind power: University of illinois at urbana-champaign. URL `https://www.fs.illinois.edu/docs/default-source/news-docs/newsrelease_windppa___factsheet.pdf?sfvrsn=43aaffea_0`

[5] M. White, Solar farm fact sheet.

[6] Metric: Total campus GHG emissions | iCAP portal | university of illinois. URL `https://icap.sustainability.illinois.edu/metric/total-campus-ghg-emissions`

[7] Affiliated Engineers, Inc, Utilities production and distribution master plan.
URL https://www.fs.illinois.edu/docs/default-source/utilities-energy/utilities-master-plan_.pdf?sfvrsn=16bbfbea_0

[8] M. Allen, O. P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, K. Zickfeld, Framing and context, in: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, p. 46.
URL https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter1_Low_Res.pdf

[9] S. Clemmer, J. Richardson, S. Sattler, D. Lochbaum, The nuclear power dilemma.

[10] V. Nian, S. Zhong, Economic feasibility of flexible energy productions by small modular reactors from the perspective of integrated planning 118 103106. doi:10.1016/j.pnucene.2019.103106.
URL http://www.sciencedirect.com/science/article/pii/S0149197019302070

[11] Solar farm 2.0 (in progress) | iCAP portal | university of illinois.
URL https://icap.sustainability.illinois.edu/project/solar-farm-20

[12] J. DeCarolis, S. Babaee, B. Li, S. Kanungo, Modelling to generate alternatives with an energy system optimization model 79 300–310. doi:10.1016/j.envsoft.2015.11.019.
URL https://linkinghub.elsevier.com/retrieve/pii/S1364815215301080

[13] K. Hunter, S. Sreepathi, J. F. DeCarolis, Modeling for insight using tools for energy model optimization and analysis (temoa) 40 339–349. doi:10.1016/j.eneco.2013.07.014.
URL http://www.sciencedirect.com/science/article/pii/S014098831300159X

[14] B. Li, J. Thomas, A. R. de Queiroz, J. F. DeCarolis, Open source energy system modeling using break-even costs to inform state-level policy: A north carolina case study 54 (2) 665–676. doi:10.1021/acs.est.9b04184.
URL https://pubs.acs.org/doi/10.1021/acs.est.9b04184

[15] J. DeCarolis, K. Hunter, S. Sreepathi, Multi-stage stochastic optimization of a simple energy system 14.

[16] J. DeCarolis, K. Hunter, Tools for energy model optimization and analysis (temoa).

[17] U. D. of Energy, Capital cost estimates for utility scale electricity generating plants 141.

[18] U. F\&S, eDNA billing system: Steam consumption and cost.
URL https://ebs.illinienergy.illinois.edu/EBSwebSecure/default.aspx

[19] E. I. Administration, Electricity data browser - 4.13.a average cost of natural gas delivered for electricity generation by state.
URL https://www.eia.gov/electricity/data/browser/#/topic/15?agg=1,0,2&fuel=1&geo=vvvvvvvvvvvvo&sec=80o&linechart=ELEC.COST_BTU.NG-US-98.M~ELEC.COST_BTU.NG-NEW-98.M~ELEC.COST_BTU.NG-NEW-1.M~ELEC.COST_BTU.NG-NEW-94.M~ELEC.COST_BTU.NG-NY-98.M~~&columnchart=ELEC.COST_BTU.NG-US-98.M&map=ELEC.COST_BTU.NG-US-98.M&freq=M&start=201604&end=202002&ctype=linechart&ltype=sourcekey&rtype=s&maptype=0&rse=0&pin=

[20] H. Desai, Nuclear costs in context.
URL https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/nuclear-costs-context-201810.pdf

[21] WNA, Nuclear economics and project structuring.
URL https://www.world-nuclear.org/getmedia/84082691-786c-414f-8178-a26be866d8da/REPORT_Economics_Report_2017.pdf.aspx

[22] The ETI nuclear cost drivers report.
URL https://www.lucidcatalyst.com/the-eti-nuclear-cost-drivers

[23] Abbott power plant.
URL https://www.fs.illinois.edu/docs/default-source/utilities-energy/abbottbrofinal.pdf?sfvrsn=90b1f9ea_4

[24] J. F. DeCarolis, Using modeling to generate alternatives (MGA) to expand our thinking on energy futures 33 (2) 145–152. doi:10.1016/j.eneco.2010.05.002.
URL http://www.sciencedirect.com/science/article/pii/S0140988310000721