Economic and Carbon Impacts of Potential Illinois Nuclear Plant Closures

The Cost of Closures

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1 Summary

On August 27, 2020, Exelon Generation announced planned premature closures of two Illinois nuclear plants (4 reactor units), which compete economically with fossil fueled plants within the Pennsylvania-New Jersey-Maryland (PJM) interconnection [1]. This report quantitatively explores how these closures would undermine economic and decarbonization goals in the state of Illinois, such as an aggressive target to achieve a zero carbon electric grid by 2030.

Previous energy systems research has shown that such clean energy goals cannot be reached if nuclear plants prematurely retire [2, 3, 4]. In particular, the February 2021 National Academy of Sciences, Engineering, and Medicine consensus report, "Accelerating Decarbonization of the U.S. Energy System," determined unequivocally that U.S. decarbonization will require keeping existing nuclear plants open [2]. Consistent with that literature, our simulations indicate that decarbonization in Illinois will require not only maintenance but expansion of nuclear energy capacity. **The simulations in this report minimize future Illinois electric system cost in the context of potential policy constraints and demonstrate that:**

- nuclear energy is necessary to reach Illinois' carbon reduction goals;
- without existing nuclear power, reaching zero carbon would require solar deployments to displace $10,000 km^2$ of critical Illinois farmland;
- and deploying new advanced nuclear generation is the least expensive way to allow Illinois farmland to remain farmland while reaching zero-carbon by 2030.

These simulations also revealed many specific, complementary conclusions, such as:

- Keeping Illinois' existing nuclear plants open through 2050 avoids 25 million metric tons of life-cycle CO_2 emissions and 600,000 metric tons of e-waste.
- Even if advanced nuclear deployments experienced 200% capital cost overruns, total system cost impacts would be negligible.
- Deploying advanced nuclear avoids approximately 900,000 metric tons of e-waste.

- Extraordinary, possibly infeasible, grid-scale battery storage capacity is required to meet any zero-carbon target with significant renewable penetration.

2 Introduction

Eleven (11) emissions-free nuclear reactors at six (6) sites produce the majority of electricity in Illinois and critically underpin its clean energy future. Four (4) of these reactors, representing over 4GWe of electric capacity, are at the Byron and Dresden plants, which face premature closure. This report quantitatively demonstrates the role nuclear energy must play in minimizing cost while meeting Illinois' carbon goals through 2050, with a particular focus on those plants.

We have modeled the Illinois electric grid and conducted optimization simulations of key policy scenarios. These simulations establish the least costly energy generation mixtures with and without the at-risk plants in the context of various policy factors, such as zero-emissions targets. With these solutions, we compared the economic and carbon implications of these energy futures. In addition to emissions, this report also considers other environmental impacts of available energy choices, such as land use and solid waste generation. Other recent work has reviewed the potential health impacts of these closures [5].

We built a computational model of Illinois' electric system that leverages high fidelity data from a variety of sources to explore various potential policy scenarios in the 2020-2050 time frame. Comparison among optimal solutions quantified the economic and emissions impacts of decisions such as: prematurely closing nuclear plants, capping emissions, aggressively installing renewable generation, or deploying advanced nuclear reactors. The following sections describe the methods, data, and assumptions used in the modeled scenarios (Section 3), the resulting optimal solutions (Section 4), and a discussion of the key findings (Section 5). Details of the models and calculations are further described in Appendix A

3 Methods

This work collected data from multiple sources to populate a model of the Illinois electric grid, including existing generation capacities, potential generation technologies, the costs and wastes associated with each, and the electricity demand profile. This simulated representation of the state of

Illinois relies on the Temoa framework, an open source tool built by researchers at North Carolina State University (NCSU), which enables energy system optimization and techno-economic analysis [6, 7, 8].

The technology models in Temoa representing energy source are configured with data regarding fundamental techno-economic parameters such as their capacity, capacity factors, seasonal generation profiles, auxiliary products, waste generation metrics, and costs (fixed, capital, variable, and otherwise). The Appendix A describe the key assumptions about electricity generation and storage technologies in the Illinois model built for this report.

3.1 Optimization Analysis

This work established optimal solutions to various scenarios which illuminate the potential impact of nuclear plant closures and other policy options on the cost of power in Illinois. These simulations also explore Illinois' ability to meet aggressive proposed carbon goals with and without maintenance and expansion of nuclear power capacity.

Assumptions and constraints in these simulated scenarios differentiate them. Each optimized scenario is the solution to a linear programming problem comprised of two key components. First, the *objective function* minimizes the total system cost of the energy grid in the state of Illinois. Such an objective function is stated thus:

minimize

$$\sum_{g=1}^{G} \int_{t=2020}^{t=2050} c_g(t) \tag{1}$$

where

$$
\begin{aligned}
G &= \text{number of generation technologies} \\
x_g(t) &= \text{capacity of technology g in year t } [TW] \\
c_g(t) &= \text{total cost of technology g in year t } \left[\frac{\$}{TW}\right] \\
&= (l_g(t) + f_g(t) + v_g(t)cf_g(t)t)x_g(t) \\
l_g(t) &= \text{loan cost of technology g in year t } \left[\frac{\$}{TW}\right] \\
f_g(t) &= \text{fixed cost of technology g in year t } \left[\frac{\$}{TW}\right] \\
v_g(t) &= \text{variable cost of technology g in year t } \left[\frac{\$}{TW - year}\right] \\
cf_g(t) &= \text{capacity factor of technology g in year t } [\%].
\end{aligned}
$$

Second, a set of constraints limit the model solutions. In this case, such constraints include balancing electric supply with electric demand, reducing carbon to zero by 2030, specifying renewable energy and energy storage deployment speeds, and limiting land use based on availability. All begin with the same initial condition which reflects the present energy generation infrastructure in Illinois. Then, optimization proceeds by varying all free parameters within the scope of the defined constraints in order to meet the objective. Ultimately, the simulation solution gives the energy generation mix, $\vec{x_g}$, for the Illinois electric grid that minimizes system cost. In this case, Temoa varies the deployed ratio of generation technologies on the Illinois electric grid, within the constraints of various policies, to minimize cost. The simulations each begin in the year 2020 and proceed through 2050. The initial condition in 2020 represents the true 2020 electricity generation mix in the state of Illinois.

3.2 Data

Robust data from a variety of national and regional databases populate the model of Illinois' electric generation in the Temoa framework. Primarily, this work relied on federal and international databases from the Energy Information Administration [9, 10, 11, 12], the U.S. Geological Survey [13], International Energy Agency [14], the Nuclear Energy Agency [15], the Nuclear Regulatory Commission [16], the Intergovernmental Panel on

Climate Change [17, 18, 19, 20], the Interstate Renewable Energy Council [21, 22, 23, 24, 25, 26, 27], the Department of Energy's EERE and NE offices [28], and the National Renewable Energy Laboratory [29, 30]. Industry sources included the World Nuclear Association [31] , the Nuclear Energy Institute [32, 33, 34, 35], Rockland Capital Generation [36], Sargent & Lundy [37], Lazard [38], and others [39, 40, 41].

In particular, the costs assumed in the model configuration for each technology drove the cost optimization. Table 1 shows the cost assumptions in the models while Table 2 shows the emissions assumptions.

Table 1: Cost Data for Each Technology

Technology	Investment (M$ /MW)	Fixed (M$ /GW-year)	Variable (M$ /GWh)	Source
Coal (Existing)	3.6663	40.7032	0.0213	[29]
Coal (New)	6.0353	59.0197	0.0366	[29]
Natural Gas (Existing)	0.9596	11.1934	0.0224	[29]
Natural Gas (New)	2.7129	27.4747	0.0275	[29]
Nuclear (Existing)	0.0500	177.7374	0.0058	[33]
Nuclear (New)	6.2326	121.0922	0.0092	[29]
Solar (Utility)	1.5935	19.3340	0.0	[29]
Solar (Residential)	3.1077	22.3868	0.0	[29]
Wind (Utility)	1.8780	43.7560	0.0	[29]
Storage (Li-Battery)	1.6080	34.1100	0	[29]

This work was conducted in the open under a BSD-3 open-source license by the Advanced Reactors and Fuel Cycles group at the University of Illinois. All data, models, and assumptions used in his work can all

Table 2: Emissions Data for Each Technology

Technology	SO_2 $\left[\frac{MT}{GWh}\right]$	NO_x $\left[\frac{MT}{GWh}\right]$	CO_2 $\left[\frac{MT}{GWh}\right]$	Hg $\left[\frac{MT}{GWh}\right]$	CO2eq $\left[\frac{MT}{GWh}\right]$	Source
Coal (Existing)	1.5477E-10	1.2382E-10	3.2594E-07	6.7496E-15	8.2000E-04	[37, 17]
Coal (New)	8.5898E-11	1.3155E-10	3.2656E-08	6.7496E-16	2.2000E-04	[37, 17]
Nat. Gas (Existing)	5.1074E-12	3.0954E-11	1.8108E-07	0.0	4.9000E-04	[37, 17]
Nat. Gas (New)	5.1074E-12	3.0954E-11	1.8108E-08	0.0	1.7000E-04	[37, 17]
Nuclear (Existing)	0.0	0.0	0.0	0.0	1.2000E-05	[37, 17]
Nuclear (New)	0.0	0.0	0.0	0.0	1.2000E-05	[37, 17]
Solar (Utility)	0.0	0.0	0.0	0.0	4.8000E-05	[37, 17]
Solar (Residential)	0.0	0.0	0.0	0.0	4.1000E-05	[37, 17]
Wind (Utility)	0.0	0.0	0.0	0.0	1.1000E-05	[37, 17]
Storage (Li-Battery)	0.0	0.0	0.0	0.0	2.3164E-05	[37, 17, 42]

be found and explored at open source repository at `https://github.com/arfc/2021-04-nm-illinois`.

3.3 Scenarios Simulated

Table 3 describes the scenarios we conducted. All share the same objective function, which seeks to minimize total system cost. They are clustered in four major categories. First, the business-as-usual (BAU) cases assume no carbon limit, while the constrained carbon (CC) cases assume a zero carbon target in 2030. Comparing these two simulation categories reveals the potential impact of carbon limits and premature nuclear energy closure on the minimum achievable cost. These simulations make conservative assumptions about the cost and availability of advanced nuclear power.

To explore the importance of these assumptions, two additional classes of simulations were explored. In the expensive nuclear (XN) cases, advanced nuclear reactors are assumed to be twice as expensive to build than the best conservative estimates. In the zero advanced nuclear (ZN) cases, advanced nuclear power is not available in time to contribute to carbon reductions in Illinois before 2050. These scenarios are summarized in Table 3.

ID	**Byron & Dresden Closures**	**Other Nuclear Closures**	**Zero Carbon Target**	**Renewable Growth Rate**
BAU1	premature	scheduled	none	limited
BAU2	scheduled	scheduled	none	limited
BAU3	none	none	none	limited
CC1	premature	scheduled	2030	optimistic
CC2	scheduled	scheduled	2030	optimistic
CC3	none	none	2030	optimistic
XN1	premature	scheduled	2030	optimistic
XN2	scheduled	scheduled	2030	optimistic
XN3	none	none	2030	optimistic
ZN1	premature	scheduled	2030	unlimited
ZN2	scheduled	scheduled	2030	unlimited
ZN3	none	none	2030	unlimited

Table 3: A summary of the scenarios simulated in this work, differentiated by their primary constraints.

3.4 Constraints

Some constraints are shared among all scenarios:

- The initial conditions reflect the true 2020 energy mix in Illinois.
- Power supply must meet power demand in each time step.
- Strategic planning reserve must be greater than 15% of demand.
- Technology models are identical across all simulations with the exception of the capital cost of advanced nuclear, which is altered for the XN scenarios.

The simulations diverge due to their differing treatment of constraints related to the timing of nuclear plant closures, inclusion of carbon targets, and land-use limits for the growth of renewables.

3.4.1 Byron and Dresden Closures

In each family of scenarios, the impact of closing Byron & Dresden was explored by assuming one of three assumptions. The two plants either:

- close prematurely, in 2021,
- close as scheduled, when their current licenses expire in 20 and 10 years, or
- receive license extensions and continue operating through 2050.

3.4.2 Other Existing Nuclear

In each family of scenarios, the other existing nuclear power plants in Illinois were either:

- decommissioned as scheduled according to their current licenses, or
- awarded license extensions and continue operating through 2050.

3.4.3 Zero Carbon Target

In the business as usual cases (BAU1-3), the simulations were not carbon limited. In all other simulations, a linear reduction in carbon emissions beginning in 2020 and reaching zero carbon emissions by 2030. This constrains energy deployment options in those simulations.

3.4.4 Renewable Growth Rate

In the business-as-usual cases, the growth rate for renewable energy is limited by economics, primarily. In the carbon constrained and expensive nuclear scenarios, an optimistic growth rate is enabled. In those cases, utility scale solar is allowed to grow to 10 GWe by 2030, reflecting the aggressive and optimistic build out proposed in the Illinois Clean Energy Jobs Act. Similarly, wind turbine deployments grow to 13.8 GWe by 2030. Finally, residential solar is allowed to increase at a steady rate, but is capped at 75% of the technical resource availability to reflect deployment on 75% of Illinois buildings [43].

Without preserving existing nuclear or deploying advanced reactors, the required land use for solar and wind generation is infeasible, since the Illinois land appropriate for wind and solar is already in use as vital farmland. The southern and central regions of Illinois most suitable for solar power installations are the same regions the nation currently relies on for 15% of its corn and 14% of its soybeans [44].

Specifically, strategies which allow nuclear plants to close before 2050 require 10,000km^2 of this land to be dedicated to solar as well as 4% of Illinois' land area in use for rooftop solar. Keeping the nuclear plants open through 2050 halves this requirement. The constraints on utility scale wind and solar are lifted. It is not possible to achieve zero carbon without advanced nuclear under the above constraints.

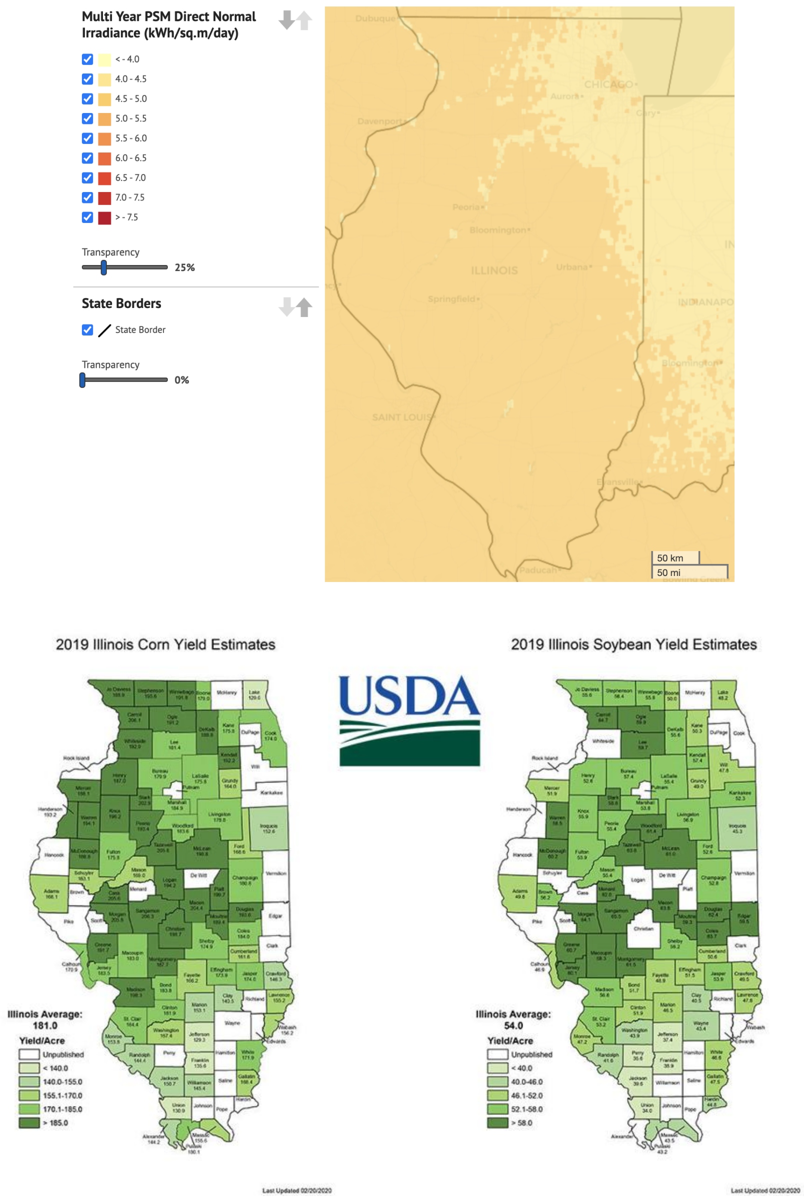

Figure 1: Corn (bottom left) and soybean (bottom right) crops in Illinois lie predominantly in the same portion of the state corresponding to the region of highest solar panel suitability (top) [44, 45, 30].

3.5 Demand Model

Illinois electricity demand has remained steady at approximately 140.7 TWh per year for the last decade [12]. All scenarios simulated in this report assume that this demand remains steady annually. If Illinois transportation is fully electrified by 2050, this assumption will not be valid. However, postulating such growth scenarios is beyond the scope of this report.

As part of model configuration, the Temoa framework accepts demand profiles capturing seasonal and daily fluctuations. The typical Illinois hourly demand profile and seasonal variation in hourly demand were both retrieved from the U.S. Energy Information Administration (EIA) [12]. Figure 2 shows the variation in hourly demand. In our simulations, the demand is seasonally modulated by this information.

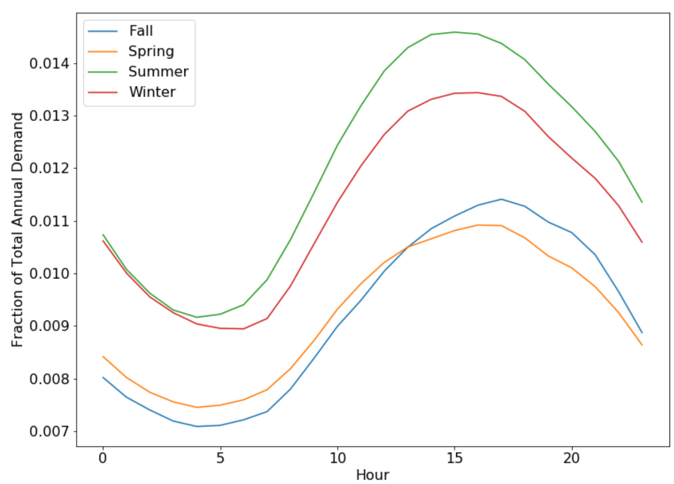

Figure 2: The seasonal variation in hourly demand in Illinois was retrieved from the EIA [12] and loaded into Temoa [7].

4 Results

We report the deployed generation mixes that minimize cost, cumulative carbon equivalent emissions, cumulative solid waste produced, and total land use change for each of the twelve scenarios considered. Figure 3 shows the mixture of Illinois electricity resources in 2050, the final year of each simulation.

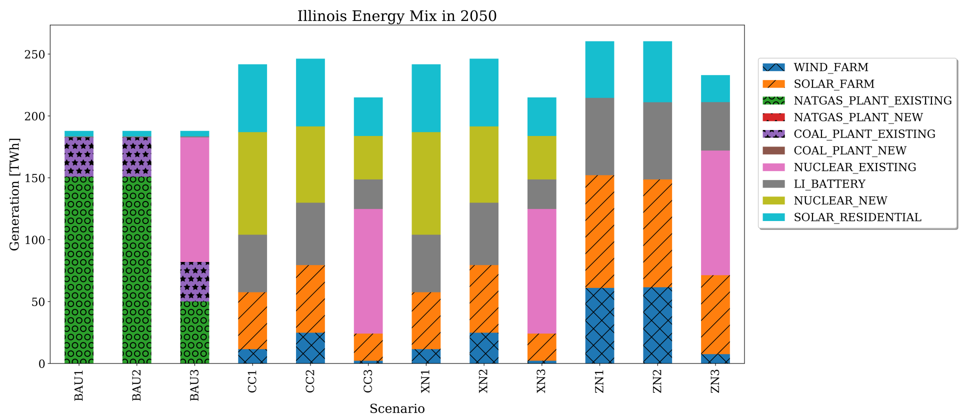

Figure 3: The mixture of electric generation in Illinois by 2050 for each scenario.

In the first two scenarios, BAU1 and BAU2, existing nuclear capacity is phased out by 2050 and replaced almost entirely by natural gas capacity, without carbon capture. 2.7 GW of rooftop solar further displaces coal generation. Existing wind turbines are also phased out by 2045 in these scenarios. In scenario BAU3, all existing nuclear plants are maintained through 2050, halving the required natural gas capacity.

Scenarios CC1, CC2, CC3, XN1, XN2, and XN3, simulate a strong climate policy by forcing zero carbon emissions from electricity generation in 2030 and aggressively pursuing renewable energy per the goals of the Clean Energy Jobs Act [46]. However, even optimistic deployment of renewable energy sources is insufficient to replace all of the current coal and natural gas generation, let alone generation lost from retiring nuclear plants. Advanced nuclear technology is required to achieve net- zero carbon electricity generation by 2030 in each of these scenarios.

The final three scenarios, ZN1, ZN2, and ZN3, show the solar, wind, and battery capacity required to replace electricity generation from all other technologies. If the existing Illinois nuclear fleet is phased out, Illinois will have to build 34 GW of rooftop solar, 77 percent of the technical limit [43], along with 56 GW of utility scale solar by 2030.

In every scenario, Illinois will need, at minimum, 45.7 GW of 4.87 hour duration energy storage to ensure grid reliability according to NERC recommendations [47]. With zero firm capacity from nuclear generation, 65.2 GW of battery storage is required. Since the current total utility-scale batter storage capacity in the US is just over 1.5GW, such battery storage capacity deployment is unrealistic.

In these optimization simulations, all of the carbon-constrained scenarios were more expensive than business-as-usual. In scenarios XN1, XN2, and XN3, which simulated significant cost overruns for advanced nuclear technology, the total system cost was, at most, 0.06% higher than in CC1, CC2, and CC3. Thus, the effect of cost overruns in new nuclear builds is negligible. The ZNx scenarios were at most 5.5% percent cheaper than scenarios with advanced nuclear, which is well within uncertainty for these analyses.

4.1 CO_2 Equivalent Emissions

The lifecycle carbon equivalent emissions for each year in the simulation is shown in Figure 4 and the cumulative lifecycle emissions for each scenario are shown in Figure 5

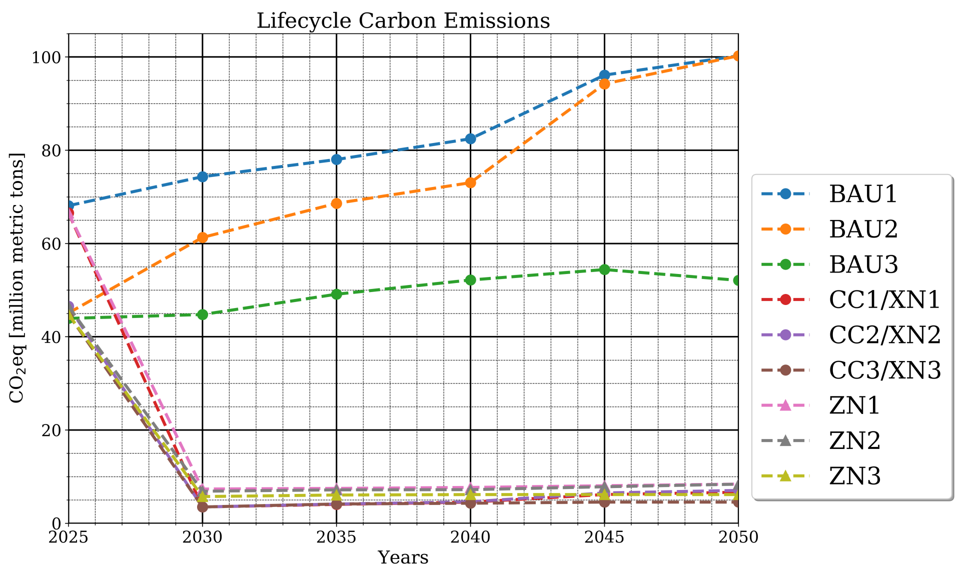

Figure 4: A comparison of the lifecycle carbon equivalent emissions for each simulation year and across all scenarios.

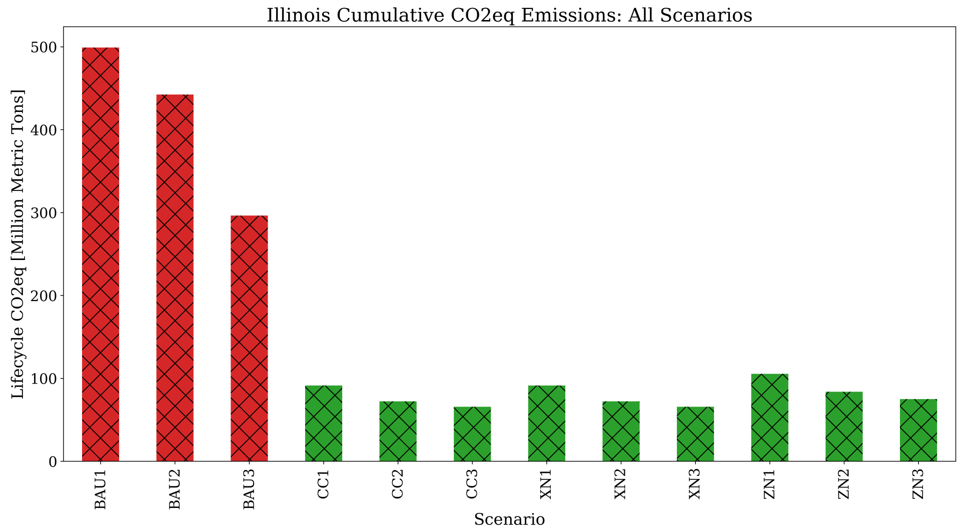

Figure 5: A comparison of the total lifecycle carbon emissions in each scenario. Red bars denote scenarios without a carbon constraint. Green bars denote scenarios that constrained carbon emissions during operation.

Table 4 shows that keeping existing nuclear plants open while investing in both advanced nuclear technology and renewable energy generates the lowest lifecycle carbon emissions. The scenario with the lowest carbon emissions is listed in bold in Table 4.

Table 4: Cumulative Lifecycle CO_2eq Emissions

Scenario	CO_2eq [Million Tons]	Existing Nuclear Closures
BAU1	499.25	Premature
BAU2	442.50	Scheduled
BAU3	296.51	After 2050
CC1/XN1	91.46	Premature
CC2/XN2	72.32	Scheduled
CC3/XN3	**65.83**	**After 2050**
ZN1	105.54	Premature
ZN2	84.00	Scheduled
ZN3	75.07	After 2050

4.2 Solid Waste

Solid waste forms are a key benefit of solar, wind, and nuclear technology since society can decide how and where the waste will be stored or recycled. Solid waste is advantageous when compared to liquid or gaseous effluents (e.g. NO_x, SO_x, CO_2, and air particulates) which are more challenging to manage. Figure 6 shows the total waste that must be handled by 2050.

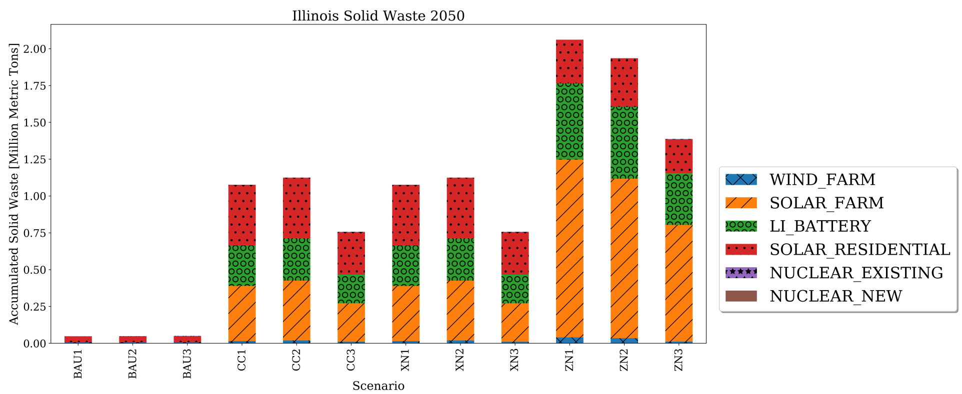

Figure 6: The total solid waste accumulated from each clean technology by 2050.

The solid waste generated in scenarios BAU1, BAU2, and BAU3 are lower than all other scenarios because most of the electricity generation in those scenarios comes from fossil fuels. Which, of course, produces gaseous waste. Implicit to handling solid waste are unmodeled energy and transportation requirements. In every carbon-constrained scenario, keeping the existing nuclear plants open through 2050 avoids the most solid waste production. Table 5 shows the total accumulated waste. Once again, the scenario that generates the least solid waste is CC3/XN3, where the existing nuclear fleet is kept open, renewable energy is built aggressively, and advanced nuclear technology is pursued. In Table 5, the scenario with the lowest accumulated waste is in bold.

Table 5: Solid Waste Accumulated by 2050

Scenario	Solid Waste [Million Tons]	Existing Nuclear Closures
BAU1	0.0481	Premature
BAU2	0.0485	Scheduled
BAU3	0.0500	After 2050
CC1/XN1	1.0765	Premature
CC2/XN2	1.1254	Scheduled
CC3/XN3	**0.7569**	**After 2050**
ZN1	2.0623	Premature
ZN2	1.9363	Scheduled
ZN3	1.3873	After 2050

4.3 Land Use Change

Land use is another important consideration for sustainable development. Figure 7 shows the required land use in each scenario. Conventional electricity generation requires very little land to operate due to the high power density of those generators.

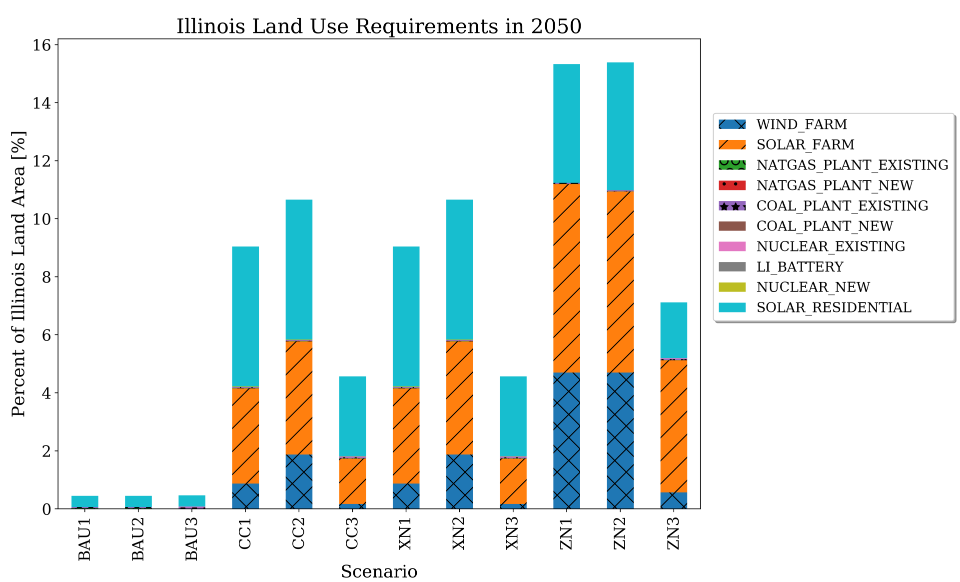

Figure 7: The percentage of land use required for each scenario.

Table 6 shows the breakdown of land use change for each renewable energy source as a percentage of Illinois' land area. In each of the carbon-constrained cases, keeping the nuclear plants open through 2050 reduces the land use change by half.

Table 6: Land Use Requirements as a Percentage of Illinois' Area

Scenario	Wind Farms [%]	Solar Farms [%]	Rooftop Solar [%]	Existing Nuclear Closures
BAU1	0.0000	0.0000	0.3891	Premature
BAU2	0.0000	0.0000	0.3891	Scheduled
BAU3	0.0000	0.0000	0.3891	After 2050
CC1/XN1	0.8687	3.2818	4.8227	Premature
CC2/XN2	1.8731	3.8973	4.8227	Scheduled
CC3/XN3	0.1676	1.5625	2.7486	After 2050
ZN1	4.6948	6.4962	4.0922	Premature
ZN2	4.6948	6.2401	4.4083	Scheduled
ZN3	0.5685	4.5510	1.9208	After 2050

5 Discussion

This work constructed a techno-economic model of the Illinois electric grid using the Temoa framework [7]. With this framework, we simulated twelve (12) potential economic and policy futures for this energy system spanning the 2020-2050 timeframe. The linear programming model identified energy mixtures that minimized total system costs in the context of those potential technology, economic, and policy constraints.

This work accordingly adds to the growing body of research demonstrating how decommissioning existing, emissions-free nuclear power plants endangers the feasibility of near-term zero-emissions targets. Our conclusions are consistent with and confirmatory of such literature, in particular, the February 2021 National Academy of Sciences, Engineering, and Medicine consensus report, "Accelerating Decarbonization of the U.S. Energy System," which determined unequivocally that U.S. decarbonization will require keeping existing nuclear plants open [2].

Specifically, our simulations indicate that decarbonization in Illinois will require not only maintenance but expansion of nuclear energy capacity. When the 2020-2050 cost of the Illinois electric system is minimized, comparison of these twelve (12) scenarios showed that :

- Nuclear energy is necessary to reach Illinois' carbon reduction goals.
- Without existing nuclear power, reaching zero carbon would require solar deployments to displace $10,000 km^2$ of critical Illinois farmland.
- Deploying new advanced nuclear generation is the least expensive way to allow Illinois farmland to remain farmland while reaching zero-carbon by 2030.
- Keeping Illinois' existing nuclear plants open through 2050 avoids 25 million metric tons of life-cycle CO_2 emissions and 600,000 metric tons of e-waste.
- Even if advanced nuclear deployments experienced 200% capital cost overruns, total system cost impacts would be negligible.
- Deploying advanced nuclear avoids approximately 900,000 metric tons of e-waste.
- Extraordinary, possibly infeasible, grid-scale battery storage capacity is required to meet any zero-carbon target with significant renewable penetration.

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A Technology Models

The technology models in Temoa representing energy source are configured with data regarding fundamental techno-economic parameters such as their capacity, capacity factors, seasonal generation profiles, auxiliary products, waste generation metrics, and costs (fixed, capital, variable, and otherwise). The following subsections describe the key assumptions about electricity generation and storage technologies in the Illinois model built for this report.

A.0.1 Solar Energy Model

Existing solar power capacities and cost data were averaged over the state and based on the the National Renewable Energy Laboratory (NREL) Annual Technology Baseline for 2020 [29]. However, power generation profiles loaded into Temoa representing the variability of solar power, such as the seasonal variation in Figure 9, were derived from a reference solar farm, the University of Illinois at Urbana-Champaign (UIUC) Solar Farm 1.0, located in Champaign, IL. The data was provided by the University of Illinois Facilities and Services Department.

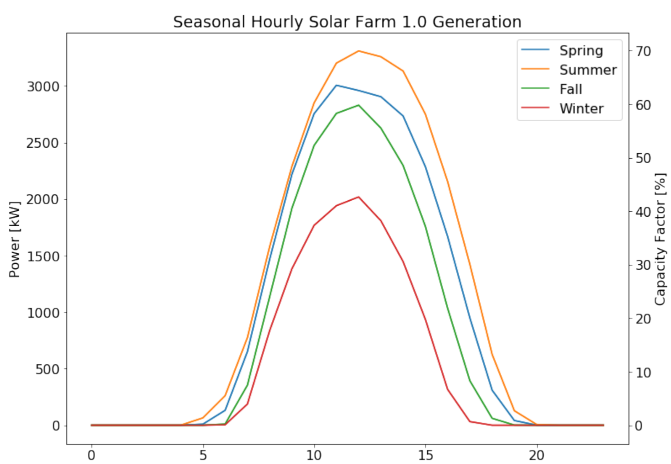

Figure 8:

Figure 9: The seasonal variation in hourly generation from Solar Farm 1.0 at UIUC, used as a scaled reference in the Temoa model of the Illinois grid.

A.0.2 Wind Energy Model

Existing wind power capacities, capacity factors, and cost data were averaged over the state and based on the NREL Annual Technology Baseline for 2020 [29]. However, power generation profiles loaded into Temoa representing the variability of wind generation, such as the seasonal variation in Figure 10, were derived from a reference wind farm, Railsplitter Wind Farm, located in Lincoln, IL. The data was provided by the University of Illinois Facilities and Services Department. F&S Department. UIUC has a power purchase agreement with Railsplitter Wind Farm.

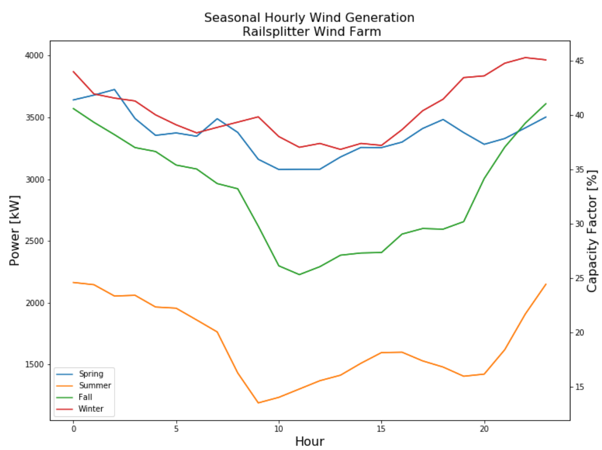

Figure 10: The seasonal variation in hourly generation from the Railsplitter Wind Farm, used as a scaled reference in the Temoa model of the Illinois grid.

A.0.3 Nuclear Energy Model

Existing nuclear plants in Illinois were specified in the model in accordance with their power levels, licensed lifetimes, capacity factors, and costs. Advanced nuclear power plants, when available to the model, used pricing from the NREL Annual Technology Baseline as well as the the Nuclear Energy Institute (NEI) Nuclear Costs in Context report series [33, 32, 29].

A.0.4 Battery Technology

Grid operators must plan for resource adequacy, and these simulations adopted the standard North American Electric Reliability Corporation (NERC) recommendation for planning reserve margin, defined as:

$$PRM = \frac{C_{\text{firm}} - D_{\text{peak}}}{D_{\text{peak}}} \tag{2}$$

where

$$\begin{aligned} C_{\text{firm}} &= \text{The firm capacity [GW]} \\ D_{\text{peak}} &= \text{The peak demand [GW].} \end{aligned}$$

Firm capacity is sometimes considered the amount of power guaranteed to be available for the duration of a commitment. We consider firm capacity to be the amount of power that is available "on-demand." Thus, renewable energy sources do not contribute to firm capacity. In simulations requiring carbon free electricity by 2030 in, the only technologies available to contribute to firm capacity are nuclear power and battery storage.

A.0.5 Coal Energy Model

Coal emissions (NO_x, SO_x, and CO_2) data were retrieved from the 2020 Sargent and Lundy report, "Capital Costs and Performance Characteristics for Utility Scale Power Generating Technologies" [37].

A.0.6 Natural Gas Energy Model

Natural gas emissions (NO_x, SO_x, and CO_2) data were retrieved from the 2020 Sargent and Lundy report on Capital Costs and Performance Characteristics for Utility Scale Power Generating Technologies [37].

A.1 Cost Modeling

Where available price and cost data could only be found for previous years, we accounted for the time value of money by adjusting for inflation using the consumer price index from the Bureau of Labor Statistics [48]. The adjusted price becomes:

$$
\begin{aligned}
P_{2020} &= \text{adjusted price in 2020 dollars [\$]} \quad (3) \\
&= \frac{P_n \cdot CPI_{2020}}{CPI_n} \quad (4)
\end{aligned}
$$

where

$$
\begin{aligned}
P_n &= \text{price in year previous year, n [\$]} \quad (5) \\
CPI_{2020} &= \text{consumer price index for 2020 } [-] \quad (6) \\
CPI_n &= \text{consumer price index for year n } [-]. \quad (7)
\end{aligned}
$$