Testing and Comparing the Viability of Different Hypothetical PV Systems on School Campuses

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Background

Residential energy reportedly accounts for around 38% of the total energy consumption in the United States. (Aksanli & Rosing, 2013) One article found that households are responsible for 72% of global greenhouse gas emissions. (Dubois, Ghislain, et al., 2019) By focusing on and shifting to renewable energy production and storage for residential areas, we would be able to effectively reduce emissions from one of the largest contributors of harmful emissions around the globe. For example, in 2012 harmful emissions from fossil fuels reported by the European Commission were about 18% less than their 1990 level, while the use of renewable energy sources was around 14.1% more than their 2005 report. (Pisacane, Ornella, et al., 2019) This suggests a direct correlation between the decrease in use of fossil fuels with the implementation of renewable energy systems. While also being a clean alternative to fossil fuels, renewable energy has shown to be an equally viable option for a reliable grid. A report from 2021 shows that 29 percent of current coal generation can retire and be replaced with lower-cost wind and solar, without the need for additional resources. (Engel et al., 2021) Not only are renewable energy systems beneficial for the grid in helping to supply a percentage of power being consumed throughout the day, but they also are becoming increasingly cheaper.

Since 2010, the cost of solar power equipment has dropped by 70%, allowing more than 10 million homes across America to be powered by solar photovoltaic panels on homes, businesses and from large-scale solar projects. (Greentumble, 2022) These systems also help mitigate disruptions in the power grid caused by inconsistent technology or natural disasters. On average, Americans experienced eight hours without power in 2020 (an all-time high and more than double what it was in 2013) primarily due to extreme weather. (Freeman & Michael, 2022) 21 national grid experts, including the former CEO of the largest U.S. regional grid, PJM, said that “both experience and research show” that the U.S. power system can maintain “full reliability” while achieving 80 percent carbon-free electricity. (Freeman & Michael, 2022) Research into 100 percent renewable energy systems from another source has shown that these systems are “not only feasible but also cost effective”, with wind and solar power being the areas of most effective growth. (Christian et al., 2022) The reduction in harmful emissions prevents the severe fluctuations in temperatures often linked to global warming, in turn preventing extreme weather patterns from appearing so frequently. (National Academies, 2019) The resulting lower frequency of these weather events would result in power outages occurring less often. So why isn’t every viable household installing these renewable energy systems?

The challenge with installing storage for specific homes or buildings is mainly unpredictability. Many renewable energy systems, especially residential ones, are not heavily automated, which makes these systems vulnerable to inefficiency. (Aksanli & Rosing, 2013) Cloudy days and other times with no light such as night make photovoltaic systems unreliable. By implementing a storage system, though, we would be able to increase the reliability of these systems by preventing fluctuations in energy output.

Schools especially would benefit from the implementation of these storage systems. About 1 in every 10 schools nationwide are now using solar systems on campus. A report found that from 2015, the number of solar panels installed at K-12 schools in the US has tripled, and the number of schools that use solar has doubled. (The Hill, 2022) A study found that a school district on average uses about 30% of its energy inefficiently or unnecessarily. (Energy Star) This inefficiency results from extensive usage of lights and inefficient heating and cooling programs set by schools. By figuring out a way to fully utilize the capability of these schools' solar panels, we would be able to mitigate the impact of all of the misused energy on the grid. It is difficult to know what implementing a system on a school campus could cost, as school energy demands can vary dramatically. For example, a larger school would in turn require a larger system. The size of a school, the size of its student body, the type of lights used, and much more causes variations in a school's energy usage.

Simulation Setup, Reasoning, and Input Data

John Burroughs School

John Burroughs is a private college preparatory school in St. Louis, Missouri. The newest buildings on campus are LEED certified. From Google Maps, the campus is approximately 1.5 million square feet (about 146,500 square meters). There are solar panels installed on the STAR building and field house. There is geothermal heating and cooling in the IT wing. (John Burroughs School) Groundskeeping vehicles are powered with biodiesel fuel, and all food and waste material is composted. The school also owns 40 acres of land in the Ozarks. While the school does have the aforementioned solar panels, most of our power comes from the grid to power the school on a day to day basis. From a rough calculation, when powering one building on campus with solar, there would still be approximately 674,054 watts needed to adequately power the building for one day (about 88 percent of power needed will have to come from the grid). In this research project, we are proposing to implement a system that would satisfy a notably higher percentage of the energy needs of the school, which would result in less demand on the grid, cost reduction, and a net-zero production for the school.

Figure 1: Picture of the John Burroughs School campus

Case Studies

For research and background I will be using case studies. Case studies, as one source puts it, "are narratives that present real-life scenarios/problems and allow students to experience how professionals address problems encountered in the field." (Davis & Yadav) They help in anchoring knowledge and providing reasoning behind learning it and require the integration of multiple sources in an authentic context. (Davis & Yadav). I gathered data from these case studies with the goal of determining optimal values for a cost-efficient and high-production system created specifically for the Burroughs campus. During this process I simulated the current PV systems on campus with an additional battery bank in order to compare the results to the hypothetical ideal PV system. I then extended this goal to include testing a system that would provide my campus with 100% renewable energy for all electricity needs.

Values

Category	Input	Reasoning
Location and Resource	Custom input for St. Louis area	As this project was conducted from my school (located in the St. Louis Metro area), I needed accurate solar data from the region, meaning I needed to input custom solar library data.
Self and External Shading	None/minimal	I left these categories at their minimal values, as the buildings at my school are unobstructed from the sky, with the current solar array at my school being a fixed roof mount. A new system would likely be installed similarly.
Module Aspect Ratio	1.7	This is close to the average ratios that I found online (most came out at 1.6667).
Irradiance Losses	5%	I was aiming to create an optimal scenario, while leaving minimal losses. The annual soiling losses account for this 5%.
DC Losses	2.5% accumulative	Similar reasoning to irradiance losses. 2% loss

		from DC wiring and 0.5% loss from diodes and connections. Other DC losses remained optimized for scenarios.
AC Losses	1% AC output	Similar to other loss categories, I aimed for the most optimal outcome.
Transmission and Transformer Losses	0%	Left out for finding maximum hypothetical results.
Battery Current and Capacity	50 Vdc desired bank voltage 3.6 Vdc cell nominal voltage 3.2 Ah cell capacity	Left at default values computed by simulator sizing calculation.
Battery Bank Replacement	Replace at 10% capacity	Intended to reduce battery system replacement costs, while also in parameters allowed by simulation.
Charge Limits and Priority	30% minimum state of charge 85% maximum state of charge 50% initial charge state	I aimed to increase the longevity of the batteries by slightly altering the default battery limits.
Annual Degradation Rate	0.5% per year	Optimal situation for maximum result values.
Financial Parameters	50% debt fraction 25 years at 4% loan term 2.5% inflation rate 6.4% discount rate 15% /year federal income tax 5.3% /year state income tax 5% sales tax (direct cost) 0.85% property tax (percentage of installed cost) $104.86 fixed monthly charge for electricity	These values I left as either default or average values set into place in my state. I left other values untouched for the sake of the simulation optimization that I was aiming for.
Electrical Load	Average consumption for private secondary school (~3.5 million kWh)	Since I was conducting these simulations on my school, I needed the monthly average kWh consumption for similar institutions.

If someone is looking to replicate my experiment, here are the values that I used for trials one and two. I used the REC Solar REC405AA Pure-P module and the Enphase IQ7-60-2-US [240v] inverter for the PV part of the system. For the array size I used 28.5 kWdc with 1.2 desired AC/DC ratio. I later switched the inverter and module to the Fronius Primo 15.0-1 [240v] and the Hanwha Q CELLS Q Prime L-G5.2.G 345 respectively. The tilt degree and azimuth were set to the default values for a fixed solar system. For the losses section I input a 0.5% DC loss due to wiring connections and a 2% DC wiring loss. AC wiring accounted for 1% loss. The battery bank system was the area I changed the most for the first few trials, and you can find those values in the hypotheses section. For current and capacity I used a desired bank voltage of 50 Vdc, a cell nominal voltage of 3.6 Vdc, and a cell capacity of 3.2 Ah. The battery type I used was lithium-ion NMC/Graphite. I planned for a battery replacement at a specified 10% capacity. I set the minimum state and maximum state of charge at 30% and 85% respectively, with an initial state of charge at 50%. I decided to not factor in both grid limits and grid outage in these simulations. For the financial section, the operating costs were set at $31 per kWdc a year and $10 per kWdc a year for the PV and battery systems. I had the debt fraction set at 50% with a loan term of 25% with a loan rate of 4% per year. I then adjusted the sales tax, insurance tax, and income tax to those set in the US and in my state (Missouri). I, similar to before, factored out both the incentives and electricity rates section for my simulations. I then uploaded the average monthly load summary of a medium to large secondary school in the US for the electric load section.

Software

SAM	Used to simulate and provide in-depth results and costs based on module, inverter, and other inputs. Also used to plot and analyze graphs based on the data provided by the system.
REopt	Used to size battery bank capacity and voltage for various simulations and provided payback and production data for year 25.

The software I utilized for modeling this project include SAM and REopt. SAM or the System Advisor Model is a free techno-economic software that was developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). It was created to assist in the decision making process of people working in the renewable energy industry by providing an accurate representation of a system's viability and performance in the real world using calculations and algorithms. SAM is an open source project, allowing software programmers to contribute their own models and improvements, and giving researchers an insight into modeling softwares similar to it. The software takes data inputted by the user and creates accurate estimations of the user's hypothetical system for the first year and beyond, providing information such as net savings and value, and annual energy production. The system may take a little experimentation to get used to, and can be a bit slow at times, but overall it provides an easy to access service that helps its users make decisions about hypothetical projects and systems by utilizing in depth financial models and simulations. The other program I used, REopt (Renewable Energy Integration and Optimization), is a techno-economic decision support platform used by many researchers working at NREL. This program, similar to SAM, creates optimized energy systems and recommendations for buildings, campuses, and more from specific data that the user inputs. The results are given to the user as an easy to download and access report that provides information from potential lifetime value to proper kW sizing for batteries. The only downside for REopt is that projects that require extremely custom features and development may need to be worked on with assistance from an NREL expert. Both of these softwares were extremely helpful in helping me to research the viability of PV systems and potential solutions and decisions that my school can make in the renewable energy field.

Simulations

First simulation

For my first hypothesis/simulation, I was looking to test the system and get a baseline/control for my future simulations. I aimed to leave most inputs at their recommended values for the system size I inputted. Since I at the time did not have the current brand of PV system on campus, I opted to use the Sunrise Solartech module combined with an Enphase Energy Inverter. By calculating the approximate area of the solar panels from google maps, I was able to create the array size in SAM by matching the calculated area from values I plugged into for the array size and usual AC to DC ratio. I assumed no shading problems and minimal losses due to the positioning of the solar system at the school. For the battery system I opted to use Lithium-ion (NMC/Graphite), with a specified replacement at 10% battery capacity. The bank power of the battery system was 5 kW and its bank capacity was 12.5 kWh, the default input that the system created. All the financial inputs were left to their default values, and I set the average electric load for a medium to large secondary school over the course of a year.

Second simulation

My second simulation, I hypothesized that a larger battery system more appropriate for the size of the PV system on campus would result in improved net value despite the increased cost. By utilizing REopt, and taking into account the average secondary school annual consumption in the US, the grid emission factor in the Upper Midwest region, and the electricity rates in the district of my school, I hoped to end up with a value more suitable for the school's system. It is also important to note that this system was sized specifically for economic performance and maximizing savings for the school. then took this value and used it as the input for the desired bank power and capacity of the hypothetical PV system from the first trial.

Third simulation

The third simulation, I looked to improve the overall value of the system by also factoring in the other solar panels currently on campus into the REopt calculation. To figure out this rough estimate I divided the rough area I found earlier by the area of the solar panel brand supplied to me by the Director of Plant Operations at my school. By getting an estimated number of solar panels, I multiplied that value by the average Wh production of that specific brand that I found online. By bringing this value back into the REopt simulation, I received a new hypothetical that I re-input back into the SAM simulation.

Fourth simulation

On the fourth simulation, I attempted to figure out the size of a hypothetical system that would allow my school to convert to 100% renewable energy. I first began by collecting kWh data from my school by looking at electricity bills from 2021-2023. I averaged this value to find a mean electricity consumption for my school. I then calculated a rough value for the array size by comparing the energy production of our current system to the energy consumption value I found. By then going back to REopt, I plugged in our value into the minimum array size and got the appropriate battery sizing and capacity. I hoped that with these new values, I would be able to simulate a system that would produce most if not all of the electricity needs at our school.

Simulation #	Changes
Simulation 1	Used system inputs equivalent to on-campus PV system, with additional sized battery bank
Simulation 2	Same setup as system 1, with optimized module and inverter brands, more specific inputs for system costs, and more accurate solar panel sizing in accordance to campus
Simulation 3	Much larger array size, improved module and solar brands (same brands as simulation 2), along with specific inputs for battery life and degradation
Simulation 4	Array size changed for around 100% consumption coverage, with battery banks sized accordingly. Used non optimized brands (same as simulation 1)
Simulation 5	Same setup and array size as simulation 4, but module and inverter brand inputs changed to optimized versions (same brands as simulations 2 and 3)

Results

First Simulation

My first simulation purely included the current solar system on the field house along with a typical PV battery system. The energy produced by the system annually for the first year came out to be 40,253 kWh, with an energy yield of 1,418 kWh/kW. This system accounted for a calculated 0.77% of my school's annual electrical consumption. The net savings with the system installed for year one came out to be $3,598, representing approximately 0.0112% of the school's total annual electric bill expenses. By year 10, the system was able to slightly appreciate in value, resulting in an annual saving of $4,220.25 for that year. The resulting net present value of having this system installed (which does not include the battery system currently active on campus) comes out at -$43,556 at the initial installation. Using this setup, and assuming that the system will appreciate by 1.005% each year, by around year 23 we will start to see the system beginning to create an income. The LCOEs for this trial came out to be 17.96 cents/kWh for the real LCOE, and 22.49 cents/kWh for the nominal LCOE. These LCOEs come in marginally higher than the average residential rooftop LCOE values measured in 2023 at 117$/kWh to 282$/kWh (11.70 cents/kWh to 28.20 cents/kWh). Considering that this simulation is almost identical to the current PV system installed at Burroughs, aside from the included “default” battery system, it is likely that the system on my campus can be further optimized for peak efficiency and savings.

Second Simulation

The system in the second stimulation generated 58,493 kWh in its first year, with the same energy yield as the first trial at 1,065 kWh/kW. While having an increased kWh output, this trial still only covered about 1.5% of the annual consumption at Burroughs (just 0.73% more than trial 1). With the simulated system installed, the net savings for the first year was $4,269. By year 10, the savings increased by about 17.3%, resulting in $5,006 saved annually. The installation cost for this system is $124,323, which, by using the previous pattern of net saving appreciation, would take around 24 years for the setup to pay for itself (23.7 years more precisely). The LCOEs for this simulation came out higher than those of simulation 1, with the real LCOE at 25.20 cents/kWh, and the nominal LCOE at 31.56 cents/kWh. Despite an increased output, the cost for this system outweighed its benefits compared to the first trial.

Third Simulation

The results for the third simulation were more promising. This system had an annual energy production of 1,561,168 kWh for the first year after installation, with an energy yield of 1500 kWh/kW. The production is able to cover 39.6% of the electricity consumption at Burroughs annually. The system had an annual net saving for year one of $108,475, with savings increasing by about 1.68% each following year. By year 10, this system would already be saving my school $126,781. While the net present value for this system comes in at $-1,799,047 (which is the actual value, as solar panels currently on campus would need to be replaced with optimized brands), this system pays for itself much quicker than the previous trials, paying for itself in just over 14 years of installation. Both the real and nominal LCOEs for this trial are notably lower than all scenarios tested, at 16.55 cents/kWh and 20.73 cents/kWh respectively.

100% Renewable Simulations

For the first non-optimized, 100% renewable system, the annual kWh production for the first year was 5,239,814 kWh, with the energy yield at 1410 kWh/kW. The net savings for the first year were $276,635, appreciating by 2.5% each year, resulting in an annual saving of $336,465 by year 10. The net present value for this system is $8,055,288, which, by using the system’s appreciation, would result in a full payback by the system in around 22 years. The LCOEs of this system were higher than those of other simulations, with the real LCOE at 18.44 cents/kWh and the nominal LCOE at 23.10 cents/kWh. Using an identical setup, but this time utilizing the most efficient modules and inverters currently, the system now outputs 5,547,894 kWh annually (for year 1), with a 1494 kWh/kW energy yield. Not only does this account for the electrical needs on campus, but it also produces 40.9% more energy than needed. The net present value is cheaper than the non-optimized trial, costing $8,045,548 upon installation. The net savings in year 1 came out at $277,001, growing to $336,782.20 by year 10. The system appreciated by 2.16% per year, meaning a full payback by the system (similar to the first trial) in 22-23 years after installation. The LCOEs for this simulation were second lowest, at 17.38 cents/kWh for the real LCOE, and 21.78 cents/kWh for the nominal, most likely due to the optimization of the module and inverters.

Simulation	Annual kWh Production (kWh)	Approximate Payback Period (Years)	Net Present Value (Dollars)	Real LCOE (cents/kWh)
Current + Batt	40,253	23	-58,395	17.96
Current + Batt (Opt)	58,493	24	-124,323	25.20
Fully Optimized	1,561,168	14	-1,799,047	16.55
100% Renewable	5,239,814	22	-8,148,343	18.44
100% Renewable (Opt)	5,547,894	22	-8,045,548	17.38

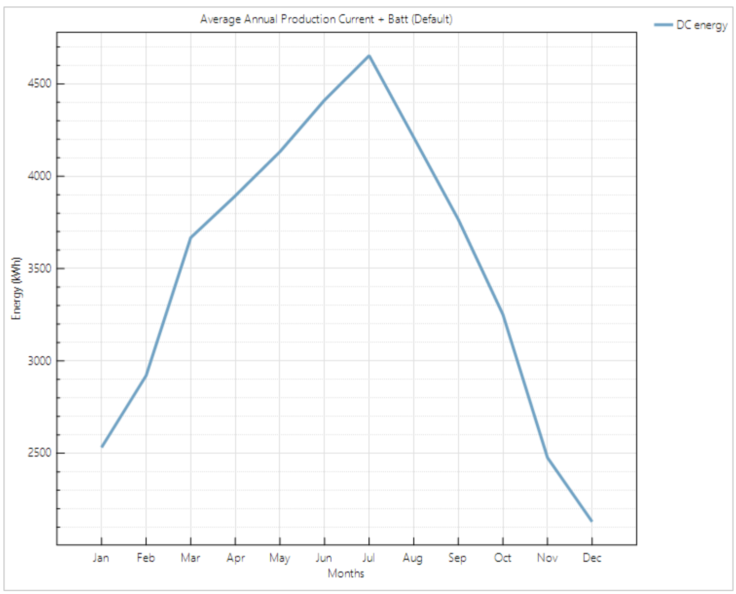
100% Renewable Requirements

What would these 100% renewable PV systems require to be installed on campus? From the simulations that I ran, for a system that accounts for 99.8% of my schools current yearly consumption, we would need to install a system that has a 3,715 kWdc array size combined with a 593 kW battery bank power and a 2,617 kWh battery capacity. This whole system would cover around 23,640 m^2 or about 4.5 football fields. The 4557 m^2 (taken from rough calculation) worth of open roof space on the common, STAR, and Brauer buildings could be utilized (Google Maps). About 12,000 modules would be needed, along with around 8,800 inverters as calculated from the simulation. Of course, the purchasing and installation of this system would not be cheap, coming in with a net capital cost of $17,989,296 (also calculated from the simulation). From calculating how much my school profits from student tuition, I was able to figure out an approximated time frame for how long this system would take to be completed. Taking the approximate total tuition profit of my school ($21,000,000 per year) and factoring in instruction, student support, financial aid, and other costs, we get a total of around $14,860,800 left in school income. If we would potentially aim to roll out this system over the course of five years, we would need about $3.6 million worth of the remaining income (about 24% each year) in order to sufficiently reach this goal. An additional option would be to use subsidies (ideally a direct subsidy) in order to pay for the bulk of this project. The viability of using subsidies for this project is entirely dependent on the simulation the school would choose, along with its corresponding opportunity cost (Scott, 2023).

Annual kWh Production Graphs

The annual productions for each of the simulations resulted in being practically identical with one another, aside from the scale of which their energy in kWh was measured (Y-axis). Those that utilized similar module brands and inverters had similar results in monthly performance (e.g. Sim 1 and Sim 3). Overall, the graphs maintained a similar pattern of peaking in the summer months, while having expected reduced productivity in winter.

Figure 2 (left): production in kWh for Simulation 1 (Current PV System w/ Battery Bank)
Figure 3 (right): production in kWh for Simulation 2 (Optimized current PV System w/ Battery Bank)



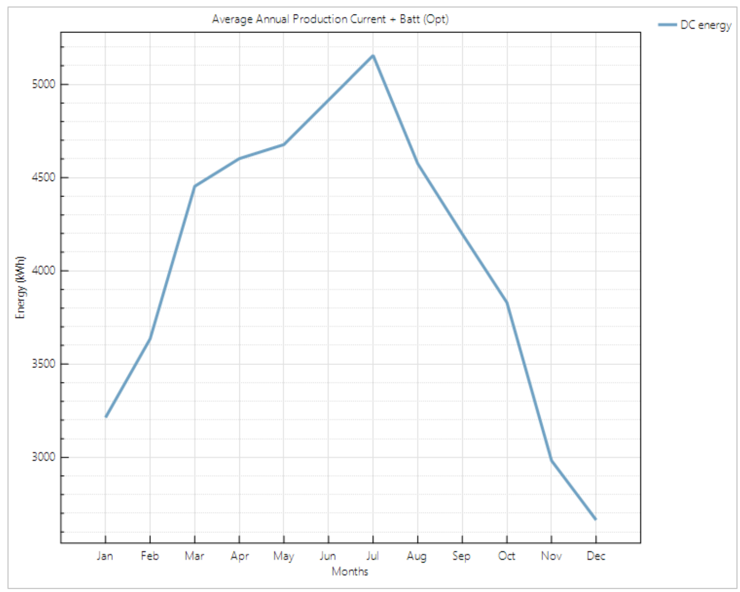
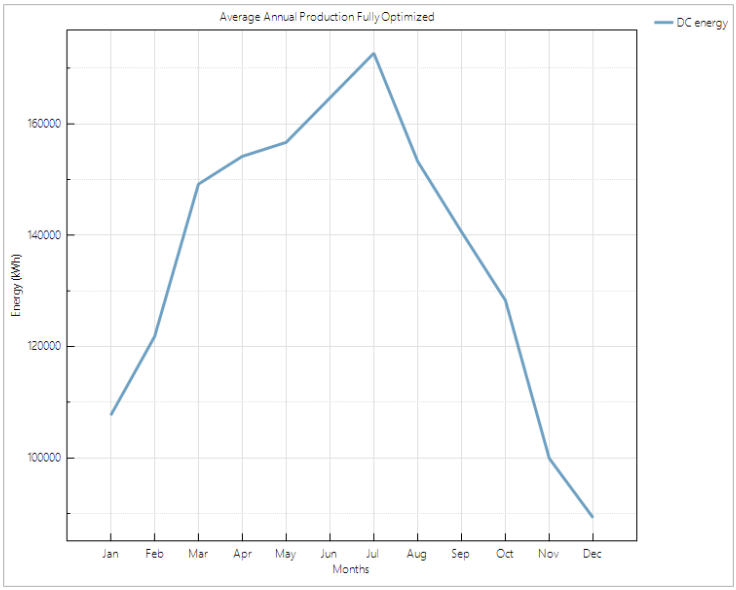


Figure 4 (top left): annual production for Simulation 3 (Ideal system setup sized for Burroughs)
Figure 5 (top right): the production for Simulation 4 (First 100% renewable viability test for Burroughs)



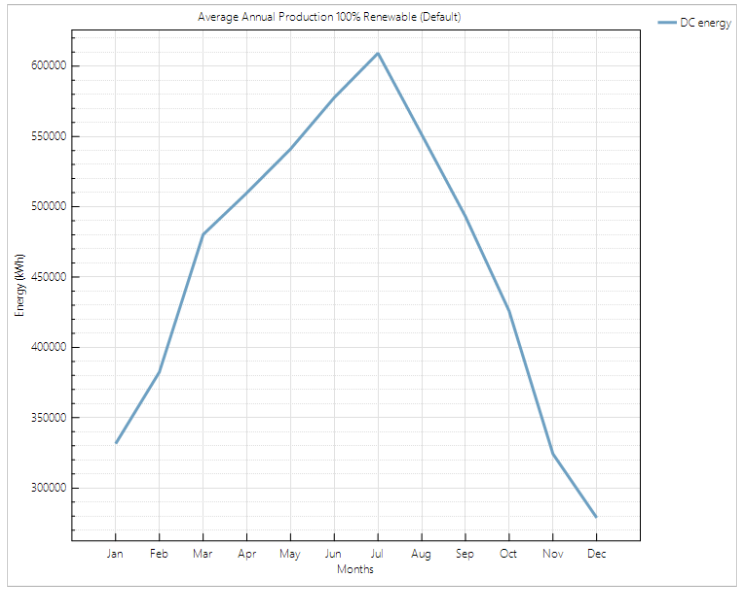
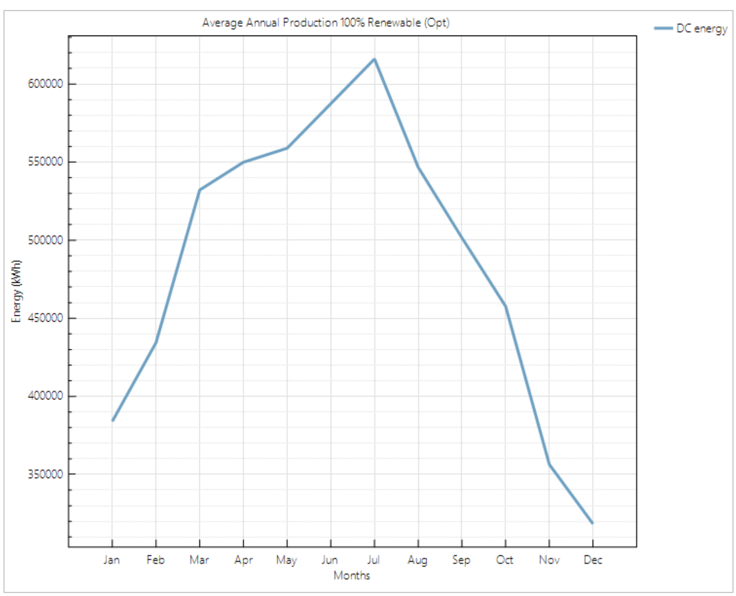


Figure 6 (middle): production in kWh for Simulation 5 (Optimized 100% renewable hypothetical for Burroughs)

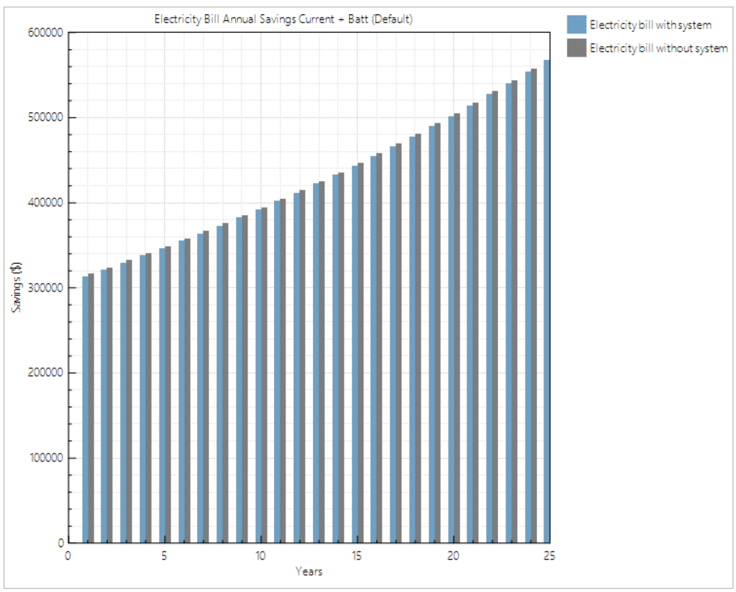


Electrical Bill Graphs

The differences between the systems is evident in the electric bill savings. One can see how much more effective the later simulations are compared to the current and current with battery systems. Additionally, you are able to see the optimized PV and battery modules reducing the eventual increase in hypothetical annual electricity spendings in the 100% renewable trials. Especially in years 15-25, the linear yearly growth seems to be almost completely reduced.

Figure 7 (left): the electricity bill savings for Simulation 1 (Non-optimized current system w/ battery bank)

Figure 8 (right): the electricity bill savings for Simulation 2 (Optimized current system w/ battery bank)



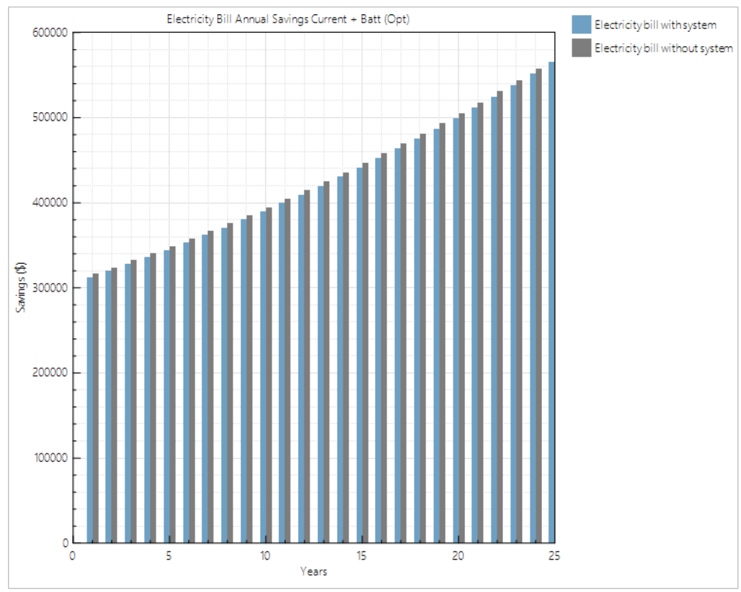
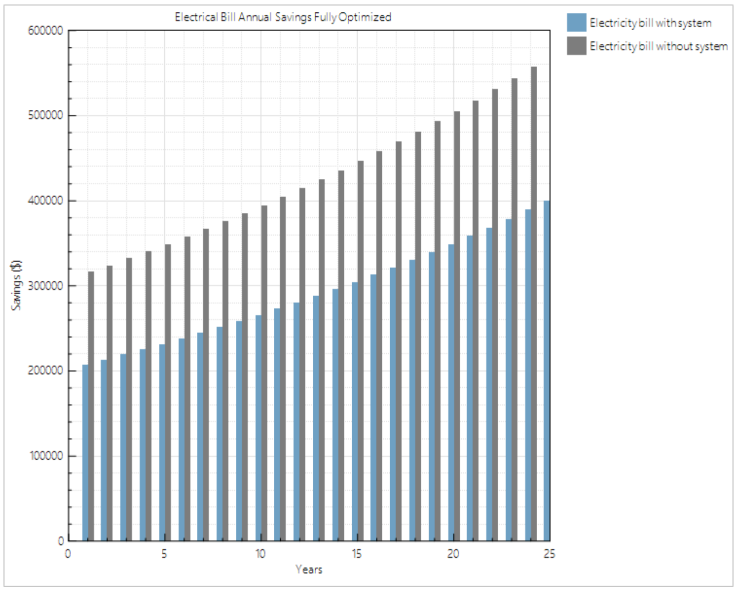


Figure 9 (top left): the electricity bill savings for Simulation 3 (Ideal sized system for Burroughs)
Figure 10 (top right): the electricity bill savings for Simulation 4 (First 100% renewable simulation)



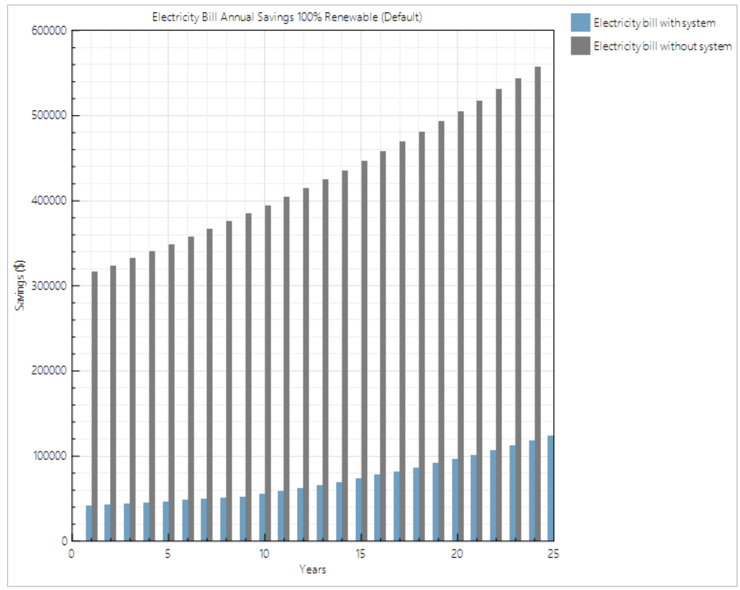
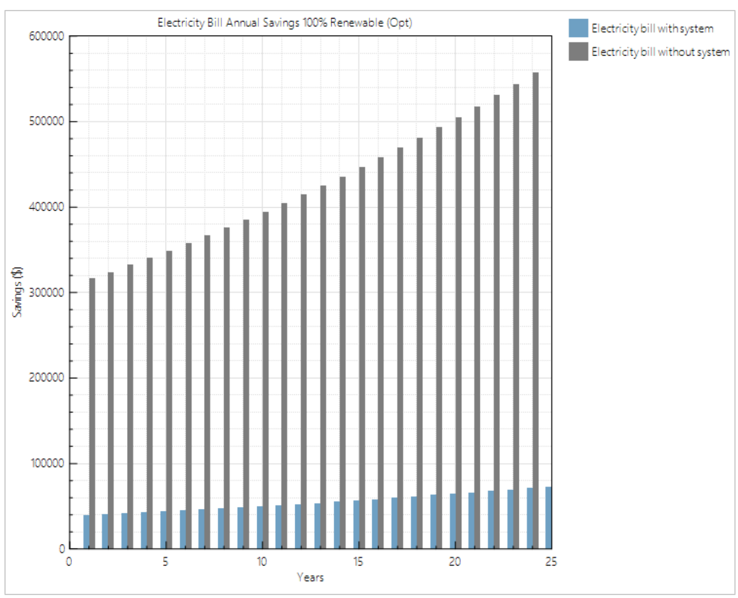


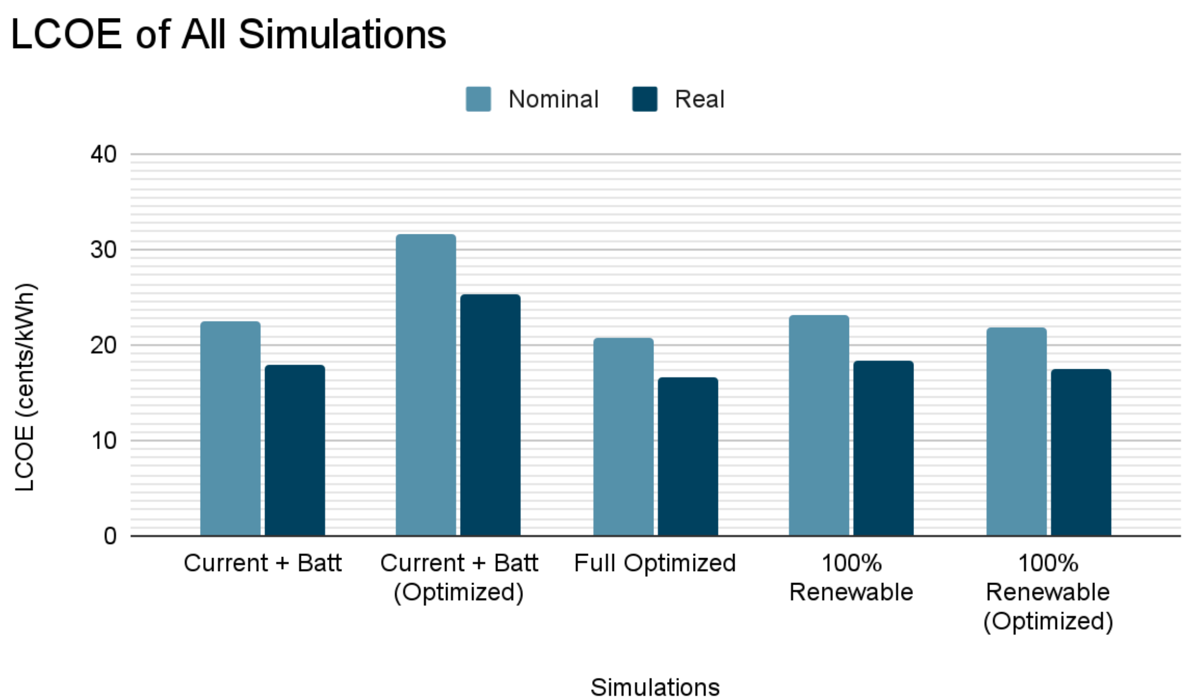
Figure 11 (middle): the electricity bill savings for Simulation 5 (Optimized 100% renewable setup)



LCOE Graph

In this graph you can see both the real and nominal LCOEs compared across the trials that I conducted. As stated before, the fully optimized system for Burroughs' campus size comes out to be the most plausible for both installation and generation of profit. Coming in close second is the optimized 100% renewable along with the current PV system on campus with the addition of a battery bank and the non-optimized 100% renewable simulation. The optimized current system with the battery add-on had the highest LCOE in both categories.

Figure 12: the nominal and real LCOE values calculated through the SAM system



Possible Incentives

The climate mitigation and adaptation goals of St. Louis offer insight into how to align incentives around this renewable project. St. Louis aims to build a city that is healthy, prosperous, and low carbon by aiming to reach around 80% renewable energy by 2050 ("Climate Action & Adaptation Plan - Sustainability", 2017). There are five categories of objectives in this section, each exploring different ways and strategies for the city to reach this goal. These objectives include: the creation of an energy efficient city, accelerating clean renewable energy production, creating equitable access to inter-modal transportation, supporting community well-being, and protecting natural resources and greenspaces.

The first objective involves measuring progress and equity for climate action and sustainability in addition to retrofitting and renovating existing buildings for energy savings. This would also include incentivising and normalizing green buildings as the standard in St. Louis and making clean energy and energy efficient measures more affordable. The second objective is to accelerate the production of clean renewable energy in the city. This would be achieved by providing an increased amount of those sources for people and increasing renewable energy options and utilization on the community scale. The next objective is to create equitable access to inter-modal transportation. This goal will encourage healthy, compact development through integrating improved land use and transportation methods, reducing congestion and vehicle emissions, and supporting alternative fuel vehicles and commutes. The fourth objective aims to support community well-being. The goals of this category are to empower the community to aim for a green economy and create neighborhoods that encourage and advance public health and safety. The final objective focuses on protecting natural resources and greenspaces. This would be achieved through restoring and regenerating natural systems that act as carbon sinks, improving water efficiency, and improving waste and consumption diversion tactics ("Climate Action & Adaptation Plan - Sustainability", 2017).

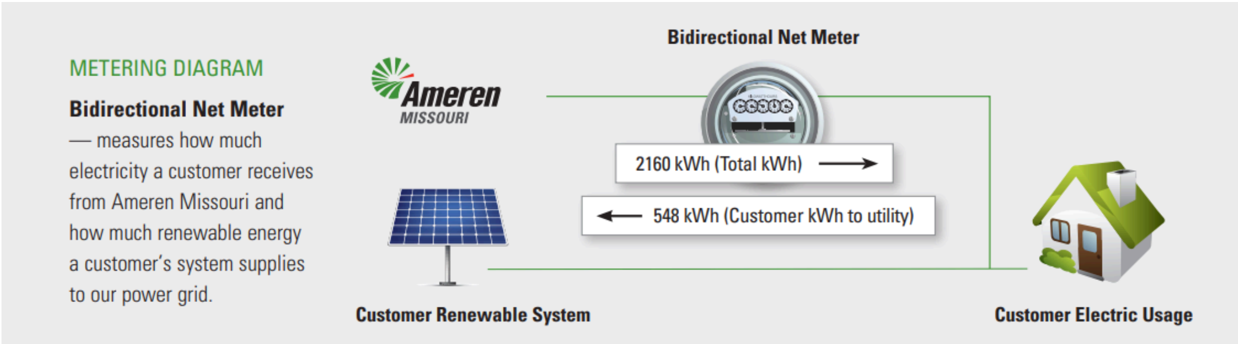
Figure 13: the climate mitigation goals stressed by the St. Louis Area

On the adaptation side, St. Louis aims to build resilience to climate climate hazards, preserve ecology and biodiversity, and mitigate the effects of climate change on susceptible populations ("Climate Action & Adaptation Plan - Sustainability", 2017). There are three primary objectives associated with adaptation: preserve and enhance the natural environment, protect human health and safety, and maximize preparedness efforts. For the first objective, St. Louis plans to improve and restore natural systems so that theta are fit for the changing climate by using vacant land as stormwater management and developing new urban forests. To accomplish the second objective, the city aims to protect people from temperature extremes, and create a healthy, cool, and flood resistant community environment. This will be done by increasing the mobility and capability of heating and cooling centers, and encouraging the restoration of wetland areas. For the third and final objective in the adaptation category, the city wants to focus on preparing the city for natural disasters that come with the changing climate. More storm shelters will be available around areas of high risk, and the EAS (Emergency Alert System) will be upgraded and monitored ("Climate Action & Adaptation Plan - Sustainability", 2017). The implementation of an improved PV system on the Burroughs campus would be a great method for the school to align more with the goals set by St. Louis, especially by taking part in forming a more energy efficient city.

Looking at incentives specifically for schools, data from Ameren suggests a recent increase in coal dependent electricity rates across multiple sectors. Ameren's dependence on coal resulted in 43% higher electricity rates between 2009 and 2014, meaning higher costs for building owners and rising prices for coal dependent buildings. Investing in building energy efficiency and sustainability can increase property values, lower maintenance costs and utility bills, reduce energy demand and the risk of rising energy prices, and provide a more comfortable and healthier indoor environment. A study published in the journal *Environmental Research Letters* found utilization of available spaces on campus could result in 75% of campus electrical needs being met, along with up to a 28% reduction in carbon emissions by the education sector in the US (Garthwaite). Another study conducted by Stanford looking at the potential of solar panels on school campuses found that nationwide, school buildings could potentially be valued at as much as $4 billion per year following an "all out push for solar installations." The study also concluded that more than 90 percent of schools across the country have spaces available for solar system installations.

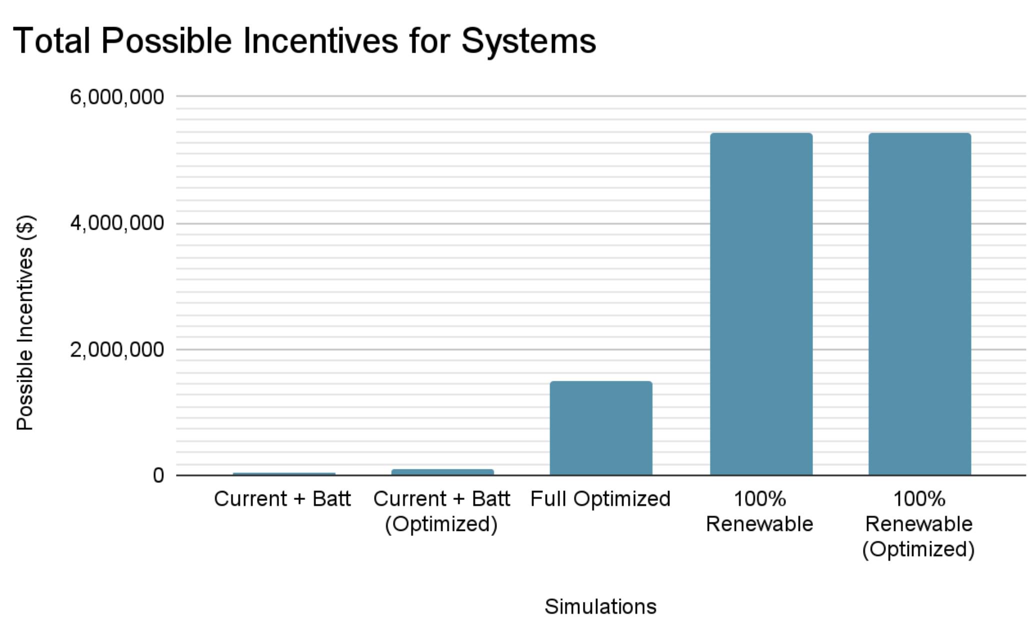
Looking at Burroughs as an example, we can see the potential for these incentives after installing a system, along with possible savings included for the installation itself. One of these pre-installation incentives in the St. Louis area is Renew STL, a new non-profit track within the Renew Missouri program. This program allows schools in the Metro area to install solar panels with no upfront cost by utilizing monthly payments from their solar array savings. This new program uses third-party owners to pay for the installation of solar energy systems by taking funds from the allotted tax credit. The school then pays the owners back from the aforementioned monthly savings until the system is fully paid for ("Renew STL Solar for Schools and Nonprofits"). Missouri schools will receive $300 million from the Congress-approved $200 billion in COVID relief funds, with the Clayton area receiving $829,048 in funds ("Renew Missouri"). Another tax credit, the Federal Solar Investment Tax Credit (ITC) and its extension, the Inflation Reduction Act (IRA), is applicable for all states (Coates). This program will supply a 30% tax credit for any purchased home-installed solar systems by the end of 2032 (Bopray). There are also programs that involve pre-installed systems. The Property Assessed Clean Energy (PACE) program offers a 100% upfront, long term, fixed-rate financing for renewable energy system improvements or upgrades (Bopray). The eligibility for this program covers a wide range of system improvements, such as solar, HVAC, and lighting setups. The continual emergence of these programs along with the current dropping prices of solar equipment will allow for much lower installation costs than before.

Figure 14: an example of Ameren's net metering program through its website



Once the system is installed, companies such as Ameren have started rebate programs for additional payback. In Missouri, Ameren's solar rebate program provides $0.25 per watt for a home solar system ("Solar Incentives in Missouri (2023 Guide)"). Ameren also participates in the net metering practice, that is, the company will supply homeowners with electricity credit for any excess kWh their systems generate and return to their grid ("Understanding your Net Metering Energy Statement"). The value that homeowners can get from Net Energy Metering (NEM) varies on how much energy your system is able to generate, which is calculated usually on a 12 month basis by the bill using the difference between excess electricity generation from the system and energy consumption from the building. The value also varies due to the Net Surplus Compensation rate (NSC–determines actual payout amount for net metering), which in turn relies on calculated estimated pre-hourly rate demands for future dates known as the Default Load Aggregation Point price (DLAP) (Southern California Edison).

Figure 15: values for the sum of all possible incentives for each simulation



I believe that the incentives listed are helpful and quite applicable when it comes to my school. If utilized correctly, the incentives could hypothetically pay for 46% to even 100% of the installation cost of the system, which depends on whether the school would replace or improve upon the current campus system. The incentives would allow the installation process to be cheaper and give the system a greater chance at turning profit efficiently. Using the Full Optimized system as example, after incentives are applied, the LCOE drops significantly to 11.15 cents/kWh. This provides compelling evidence for the viability of incentives offered prior to installation.

After installation, programs like ITC and the Ameren Rebate program only increase the motive to install even more. More programs like Renew STL and PACE should be implemented for lower income or public schools to allow them to similarly make the decision and benefit from installing either a new solar system or upgrading their current one. Rebate programs across the country could also make an effort to increase their reward for renewable energy production in order to increase motivation for more schools to participate in installations.

Discussion

Optimal Simulation

The results of these trials suggest purely installing an additional battery system to the current PV systems on campus, while helpful, would overall be a worse investment than that of optimized systems as explored in trials 3 and 4. A battery system installation and its potential potency are completely dependent on the investment put into the system (an expected linear relationship), not taking into account the power outage mitigation these systems supply. As seen from the electrical bill graphs, purely installing a battery system to the current setup on the Burroughs campus results in marginal changes in system efficiency. That is why simulation 3 is the optimal scenario for Burroughs to select. The simulation was unique because it was able to maximize efficiency and consumption coverage (with its 1.5 million annual kWh production) and, even more importantly, because of its cost. Out of all simulations, scenario 3 had one of the lowest payback periods (14 years), and proportionally one of the highest value to net capital cost ratios. While being about 6% lower than scenarios 1 and 2 at 63.14% (still quite a low differential), scenario 3 makes up the difference with its high kWh production ceiling, largely attributable to the system's increased overall system size. Cost-wise, the $4.8 million capital cost of the system is quite large, but the benefits appear to outweigh the losses. The payback period of 14 years is longer than the previous plan, but the huge cut to the electrical bill is not a factor to overlook. With a yearly budget of $30.1 million, Burroughs is capable of purchasing a system of this size, even if it would require a multiple year coverage. Looking at these values and the remaining results from the simulations, this system proves to be the most promising for the Burroughs campus.

LCOE Significance

It is imperative that we look at the LCOE and its significance with this project, as the LCOE helps to supply valuable insights into a system's economic viability over the course of its lifespan, enabling companies and interested parties to make informed decisions about sustainable energy system implementation. The LCOE, or levelized cost of energy, is a method many firms and companies utilize to decide whether they move forward with a project such as this one. The LCOE's primary function is determining whether a system is capable of breaking even and creating profit for the installer (Corporate Finance Institute). It is derived from dividing the lifetime cost of a system or plant by expected electrical generation. Profitability for a project is found by comparing this value to the electricity value that the system can achieve. If the LCOE should come out as valued lower than the electricity price, the system is capable of turning a profit (RatedPower).

This is my reasoning behind why simulation 3 would be the most viable and feasible course of action moving forward. Designed and optimized specifically for the Burroughs campus, it wasn't a huge surprise that simulation 3 had the lowest LCOE of all simulations (see figure 10). Simulation 3 was the only trial I ran which had an LCOE lower than the national average of 17 cents/kWh ("Electricity Cost in Missouri: 2023 Electric Rates").

My main fascination about the results, though, was the comparison of the two 100% renewable system trials compared to the trials involving the current campus system. While the LCOEs for the former two simulations remain consistent with my assumptions about optimization, the latter two seem to be outliers. While the LCOE of the current system on campus remains relatively consistent with the other trials, the optimized variation of the system had an abnormally high LCOE value (the highest value of all simulations). I believe this may be due to the possible incompatibility with the optimized solar brands in accordance with the system size, negatively affecting the maximum possible energy production for the system.

Limitations

Throughout my trials there existed limitations on the system and its calculations, which in turn affected the realistic accuracy of this experiment. I simulated all trials with the default losses, grid limits, and degradation values. Many of my results came from ideal scenarios with minimal losses and soiling along with optimal battery life and capacity. The simulations also used values specifically targeted at the St. Louis area, such as electricity rates and solar values. Many of my calculations weren't 100% exact and contained some estimation, as exact consumption values weren't available. The simulation software itself also had some abnormal outliers I found in the data. For example, using the non-optimized solar module and inverter brands caused an abnormally low DC/AC kWh output for the month of August. The limited pool of data that I used along with generalized inputs in certain categories made the results more specifically targeted towards schools of similar size and in a similar location to Burroughs.

Future research

The next step would be to ask my school about their plan for renewable energy projects, and seeing how a system renovation like this could fit into future goals for the campus. If this project would align with the school's aims, further consultation and research would most likely be the most strong option, as the system would need to be further refined to comply with building codes and regulations, along with the allotted school budget for the project. The school would also need to choose what simulation seems most realistic in accordance with costs and potential system generation. For my recommendations, there are two ways which seem the most optimal from my standpoint.

The first would be the properly sized battery bank installation for the two solar systems currently installed on campus. We not only see the performance of the solar panels doubled, producing an extra 25,869 kWh annually, but we also see the Levelized Cost of Energy for the current system get cut in half. Additionally, most of the system costs as stated in Simulation 2 have already been covered by the already existing solar systems. This leaves only the actual battery system to be installed, which only accounts for 14% of the total installation cost calculated (about $38,902 for system purchase). Ample space on campus is also available for its installation, with more than enough open roof space and other areas that can be utilized. While this PV battery system is not necessarily the most optimal choice, it is the most realistic in terms of costs and installation. Its relatively low cost compared to other trials and notable increase in kWh production is promising to invest into. The possible financial repercussions are also minimal, considering little need for a loan along with a relatively quick payback period compared to the average PV system.

The second option would be a complete optimization/reinstallation of the current PV systems installed on campus. While obviously the more costly option, the simulation results were proportionately the best out of all trials. Accounting for 40% of the energy needs on campus is a huge improvement to the current 0.01% coverage the system at Burroughs has. The LCOE in Simulation 3 was the lowest value of all system calculations run, and the system's performance ratio is consistently on par to values reported online of proposed solar plants (simulation pr 0.84, plant pr 0.86-0.87) (Navothna and Thotakura). The size of this system should be able to fit on campus, only needing about 7 of the 50+ acres on campus (although the system may have to be split up across the school due to spacing constraints).

Another equally viable option would be to add solar canopies to the Burroughs parking lots. Just focusing on one of the lots at the school, 10,088 square meters worth of open space becomes available for a solar system implementation. This lot alone could potentially account for 35.6% of the total space needed for the system, while also supplying shade and cover for parked cars in the process. A notable example of these systems in action can be seen at Michigan State University. MSU has utilized solar canopies over 5,000 of their parking spaces, supplying shade and protection from the weather, while saving the school an expected $10 million over 25 years (Samilton). Even though more expensive than usual installations (40% more compared to a ground mounted system), there are other reasons a school might consider the investment. Looking again at MSU, their carports have won them multiple national and state awards, giving the school an attractive reputation (Blok). These systems are also notably efficient, with a 2011 study at Rutgers University reporting that their parking lot solar array helps meet 63% of campus electrical needs (Spanne). Solar canopies also serve as a good incentive for the use of electric vehicles. One article reports that a solar canopy with 286 modules can produce 140 megawatts of electricity per year, allowing it to charge around 3000 vehicles per month (Delgado).

The next steps for this project are taking into account an actual suggested budget from Burroughs and determining the available spaces on campus that can sufficiently accommodate the new modules. I would also aim to conduct more research into the possibility of an off-campus solar generation site. The 40 acres of Ozark woodland that Burroughs currently owns has the potential for a substantially sized solar system. This system could connect to the power grid and supply a portion of clean energy in return for extra income for the school. The next best steps for Burroughs would be to go into more in-depth data collection from the physical PV systems on campus, and subsequently begin to test possible prototypes of the systems based on the simulations.

Outside of my school, more research would be needed into the extended effectiveness and viability of PV systems at schools different from Burroughs in size, location, and income. Ideally enough schools would be tested to create a possible database or benchmark for schools across the country to utilize when installing these types of systems. More research could also be done on the overall effectiveness of installing these systems at school, and whether incentivising more schools to develop renewable energy production would be worth the resources required. A more manual mathematical approach could also be a possibility, as most results from the simulations came from pre-programmed calculations in the system.

Uncertainties

One main uncertainty for these systems would be fluctuating material and replacement costs. The average cost of a PV system in 2023 is around $25,000, which is half of what it was back in 2013 ("Solar Industry Research Data | SEIA"). Another article shows an almost 97% decrease in price for PV Lithium-Ion batteries since 1991 ("Photovoltaic Energy Factsheet | Center for Sustainable Systems"). Although these costs are expected to continue declining for the foreseeable future, there is always a small uncertainty as to whether these prices will stay low. SEIA has reported recent tariffs have increased the price of solar panels by 43% to 57% ("The High Cost of Tariffs | SEIA"). The cost of polysilicon specifically has been increasing quarterly since 2021 (Bellini). Indirect capital costs such as grid interconnection and engineer and developer overhead were also not included during my trials.The fluctuating costs of materials and labor combined with unincluded indirect costs create some uncertainty in the final cost of installation, which may affect the decision-making process for hypothetical installation.

Another uncertainty comes from the optimal production for the system. The values the system gave me were near perfect performance results from the system under optimal conditions. While solar efficiency for panels can reach 41% to 50%, solar cells most commonly remain somewhere between 15% to 20% efficiency. A study conducted from a real time 425 kW applied PV (BAPV) system found that the annual performance ratio was 78.09% and the annual capacity factor value was 21.85% (Alazazmeh et al.). While these values are relatively consistent with the values reported by the simulations, it shows marginal error in the calculation of these hypothetical systems compared to actual PV installations.

Another uncertainty comes from whether a PV system improvement would be worth the resources to move forward with. Specifically, would installing an improved system such as these simulations be more efficient than the purchase of green energy through sources such as Ameren Community Solar? From Ameren's website, the estimated rate for a small program is $0.1479/kWh (Ameren Community Solar FAQ). At the moment, the company allows for up to 50% of a site's usage to be powered through their sustainable sources. If we take half of our average kWh usage annually (3,938,339 kWh), and multiply it by the estimated value, we would be charged yearly about $291,248.30 for being supplied with external sustainable energy. Comparing that to the simulations, those that I ran excluding the 100% sustainable trials have an upfront cost that is significantly lower than the yearly charge it would require for my school to take part in Ameren's program. Even by taking the largest net present value deficit from simulation 2, my school would still save an estimated $113,035.30 by installing an improved PV system. That is also not taking into account the costs negated by the current PV systems already installed on campus.

Self Sufficiency vs. Clean Grid

The ideal outcome to this situation would be a combination of both self-sufficient energy production and a larger, system-wide clean grid. Self sufficient school campuses across the US could massively reduce our carbon footprint. One study found that if all K-12 schools in America (roughly 130,000) were able to fully transition to solar, our carbon footprint would be reduced by 60 million metric tons (Buckley). Schools that are self-sufficient not only save themselves money that can be utilized for other important campus projects (an estimated $14 billion in energy costs saved) but also mitigate risk during natural disasters by supplying a reliable source of reserve electricity (Garthwaite) (Morrison). The impact on the grid is massive as well. By cutting back completely the 11% electrical consumption chalked up to the education sector in the US, the grid is less strained and has excess energy available for times of high consumption and traffic. The reduced strain in turn reduces the possibility of rolling blackouts and increases consistency.

An increased amount of self-sufficient schools also help towards many company goals of a clean grid. Multiple clean grid development companies have goals that coincide with renewable school self sufficiency. These goals being to reduce environmental footprints, design clean products, and develop clean solutions to develop a grid that is both reliable and sustainable (GE Grid Solutions). Many aim to work on early-stage renewable energy pipelines in the US, which can also include integrating self-sufficient green schools and allowing them to supply portions of clean energy needs through excess production (Clean Grid Development).

Conclusion

Renewable energy will play a growing role in the future due to the increasing global population and rising energy consumption. This trend is driven by the finite nature of fossil fuels and other non-renewable resources, which are depleting over time. In contrast, solar and wind energy sources are considered nearly inexhaustible due to their abundant availability. Moreover, the benefits of renewable energy far outweigh the continued reliance on non-sustainable power sources. As renewable energy continues to become more efficient and more accessible, the importance of this field only will become more prominent in society.

Renewable energy can be especially impactful when it comes to the education sector in the US, which accounts for a quite substantial chunk of the current annual energy consumption of the country. The implementation of renewable energy systems will allow for self-sufficient schools and steps towards cleaner, more sustainable grids, and it will allow schools to save funds and give students the opportunity to learn first hand the potential of renewable energy.

For my project I used SAM and REopt to test different variations of current and hypothetical PV systems for my school campus and used the results to measure their performances both individually and comparatively. From there I utilized these results to find the most viable option for a PV installation.

I have obtained results for hypothetical PV systems that can serve as reference points for potential future implementation, should my school decide to proceed with PV system enhancements. Through my simulations, I have identified the most cost-effective and promising options, utilizing my school as a practical example to showcase the potential efficacy of campus PV systems based on real-world data and values.

Among the trials I tested, Trial 3, depicting fully optimized system for Burroughs campus, resulted in the lowest LCOE at 16.55 cents/kWh, while Trial 2, representing the current system with a sized and optimized PV battery, resulted in the highest LCOE at 25.20 cents/kWh. Although I found the fully optimized PV system as the most viable among the simulations, it's worth noting that the 100% renewable systems display significant potential, further incentivising reason for increased investments in school PV systems.

This project will hopefully provide an additional baseline to incentivise other schools to look further into PV or other renewable system possibilities for their campuses, including John Burroughs.

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