Original article

Journal of High School Science

Costs, efficiencies, and carbon: analyzing solar photovoltaics and the smart grid as sustainable energy solutions

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Submitted: January 6, 2025, Revised: version 1, May 5, 2025
Accepted: June 4, 2025

Abstract

The electrical grid in the United States cannot continue to meet the ever-increasing economic, electrical, and environmental demands. Demand has far outgrown its carrying capacity. It is therefore in urgent need of expansion and/or modernization. Its inability to handle natural disasters, and even minor incidents, has impacted essential services and millions of families. Therefore, action must be taken to improve its resilience and reliability. This paper aims to find the most cost-effective, energy-efficient, and environmentally sustainable way to enhance a grid by examining three approaches: adopting a smart grid, implementing a solar photovoltaic with battery storage, or combining both approaches, using a natural gas combined cycle (NGCC) system as the baseline. Similar trends were found using Austin, Texas, and Sammamish, Washington, as case studies. Of the three scenarios evaluated, the smart grid performed the best overall; however, it was not the best performing choice in every category. For construction cost, an NGCC was the best option, and for operation and maintenance and yearly residential bills, the smart grid was the least expensive. The smart grid also proved to be the most energy-efficient solution. A solar photovoltaic with battery storage integrated within a smart grid was the most environmentally friendly option, with the lowest annual carbon footprint.

Keywords

Electrical grid, Economic costs, Energy efficiency, Sustainability, Carbon emissions, Natural Gas Combined Cycle, Smart grid, Solar photovoltaic, Battery storage

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https://doi.org/10.64336/001c.140616

Introduction

The United States' electrical grid was built in the 1960s to 1970s, and after 50 to 60 years of use, it is struggling to meet modern economic, electrical, and environmental demands (1). The outdated grid has significant consequences, such as a contributor in the chain of causation of the Northeast Blackout of 2003. In this historical event, a power line problem occurred and went unnoticed due to a software bug. This led to 50 million people losing their power for up to two days, causing an estimated 6 billion dollars of damage and marking the largest blackout in North American history (2). As major power outages like the Northeast Blackout of 2003 continue to occur, it is crucial to increase the grid's carrying capacity, build redundancy, and to provide automatic balancing and feed-back loops, grid stability and smart options to prevent future incidents.

This vulnerability extends to the grid's resilience during natural disasters, as seen in the 2021 Texas power crisis. In February of 2021, in Texas, a deep freeze across the state resulted in equipment failure at many coal and natural gas power plants. Power generation could not match the high consumption, forcing the state's grid operator to cut power to millions to ensure grid stability. By doing so, unbeknownst to the state operator, electricity stopped flowing to the still (barely) functioning natural gas power plant facilities as well, leading to a perpetual loop of an ever increasing demand-supply gap (3). The failure of the Texas electrical grid shows that although operationally independent from the U.S. grid, despite Texas's substantial use of renewable energy, accounting for 16% of the nation's total electricity generation from renewable sources, it still largely relies on coal and natural gas power plants (4). With the U.S. grid farther behind the Texan grid in terms of integrating renewable energy, it is clear that transitioning to a more sustainable grid is not – by itself – a solution without simultaneous expansion and modernization.

Throughout the years of its implementation, there have been many differing opinions on how to make the United States' electrical grid more reliable. In the early 2000s, a solution emerged to build natural gas combined cycle (NGCC) power plants as an alternative to constructing additional coal-fired power plants (5). This led to natural gas being the most used energy source for the United States' electricity generation at 43.1%, and coal dropping from 54.6% to 16.2% as of 2023 (5,6). Furthermore, on average, an NGCC emits 44% of the carbon dioxide (CO_2) emitted by coal power plants per unit of energy produced (7). Yet, even with its advantages over coal, it still is not an efficient and dependable source of electricity, which became apparent from the 2021 Texas power crisis. NGCC will be the focus of this paper, however it is important to note that not all power plants have switched to NGCC as some still use coal.

Upgrading the United States' electrical grid is not a trivial task, and a comprehensive understanding of its operation is essential to developing solutions. Numerous steps must be accounted for to understand how electricity travels from a power plant to a home. The generation of electricity originates from power plants. In 2024 USD (2024 U.S. Dollars), an NGCC power plant costs around $1,451 per kilowatt (kW) to construct, then another average of 35 dollars per kW per year (kW/yr) for maintenance, and as of June 2024, residents have had to pay 17.43 cents per kilowatt-hour (kWh) (8-10). In an NGCC power plant, around 45% of potential energy is lost due to combustion and another 5% in transmission and distribution (11,12). Additionally, the carbon footprint, or the lifecycle carbon emissions, of an NGCC power plant is 499 grams of CO_2 per kWh (13). As shown in Figure 1, subsequent to power generation, the electricity passes through a transformer to step up the voltage for transmission. The idea is to decrease current, so as to decrease power loss, thereby increasing efficiency (14). The transmission lines carry the electricity to places miles away, experiencing some energy loss as heat (15). After reaching the residential destination, neighborhood transformers step down the voltage to make it safer, distribution lines carry the power to the homes, and transformers on poles step down the electricity one last time before entering the home (16).

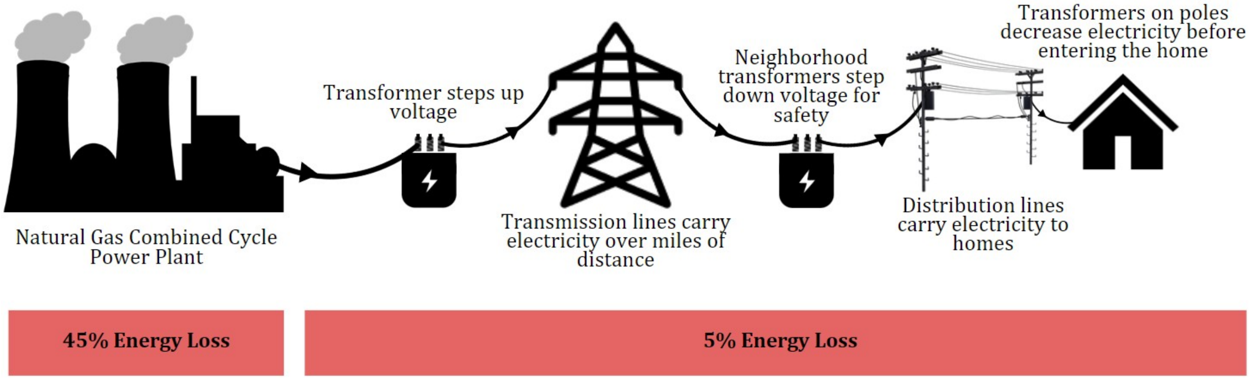


Figure 1. A model of today's electrical grid, including the areas where energy losses occur.

It is not only the energy loss in Figure 1 that is responsible for the demand-supply gap. The challenge is that the existing grid capacity is unable to meet spiraling demand; even if energy losses (such as those shown in Figure 1) were to be minimized. Ironically, there are solar farms and battery banks that have already been built; but are waiting to be connected, since the existing grid cannot handle the load. The situation is so dire that the private sector is investing and building NGCC/nuclear power plants near data centers or manufacturing hubs for captive power consumption, entirely separated from the US grid. Expansion of the grid capacity therefore is paramount. The U.S. electrical grid must hence be improved/expanded to meet the demands of modern electricity consumption. As an alternative to outright grid expansion, modernization by implementing a smart grid may enable the existing grid to handle larger capacity, at least to a certain extent. A smart grid would allow for real-time monitoring of energy distribution to enable capacity utilization of supply, ensure fewer energy losses and reduce unnecessary energy consumption by integrating technologies and creating an interconnected grid.

Research conducted by the Pacific Northwest National Laboratory and the U.S. Department of Energy has identified the essential mechanisms to transform a traditional grid into a smart grid. For the purpose of this paper, these mechanisms define a smart grid system. The *Conversation Effect of Consumer Information and Feedback Systems* is a mechanism that involves advanced metering infrastructure, or AMI, which collects data on a consumer's energy consumption. This system provides daily feedback to the consumer on their energy usage patterns and delivers advice on reducing energy consumption (17). The *Coordination Marketing of Energy Efficiency and Demand Response Program* is a program that provides education to consumers on how to save energy and money. It allows for easy access to all energy consumption information and encourages consumers to shift energy use to off-peak demand times or when the price of electricity is low (18). *Disaggregation of Total Loads into End Uses* is a technology that allows for the breakdown of the total energy consumption into different end uses such as heating, air conditioning, or lighting. It helps people understand where the most and least energy in a residence is used, allowing for more efficient measures (17). *Deploying Diagnostics in Residential Buildings* implements diagnostic tools in residences to identify inefficiencies that need improvement (17). *Evaluation, Measurement, and Verification* is a technology that assesses whether the smart grid mechanism has been generating the level of energy savings it claims to ensure its working (19). *Load Flexibility* is a mechanism where consumers can move their energy consumption to times during the day when electricity is cheaper. This helps them use less energy during peak load times, helping balance the grid (20). While this mechanism could allow utilities to remotely manage certain appliances during peak demand, they would target non-essential devices rather than crucial systems such as air conditioning, and would require voluntary participation from residents for control over essential devices (21). *Conservation Voltage Reduction and Advanced Voltage Control* uses systems along distribution lines to decrease the voltage during low peak times as certain end-use loads' energy usage decreases as the voltage decreases (17,22). It also reduces energy losses while electricity travels hundreds of miles in the intertwined grid. This balances energy consumption and reduces overall electricity demand while ensuring voltage levels stay within operating limits.

If a smart grid can handle more capacity, it is worthwhile to generate that capacity using environmentally sustainable, renewable power sources. A single-axis tracking utility-scale crystalline silicon solar photovoltaic (PV) absorbs direct sunlight and converts it into electrical energy. Its tracking technology allows it to follow the sun's movement, increasing the energy output (23). The effectiveness of solar PV systems depends on the location's average global horizontal irradiance (GHI), which measures the solar radiation that falls horizontally at the Earth's surface (24). Implementing solely solar photovoltaics can make a 'dumb' grid unstable as the sun's solar irradiance is not constant throughout the day, but a smart grid can help maintain stability. Energy storage options such as lithium-ion batteries can also be added to store any surplus energy generated during high solar irradiance periods (25). This stored energy can be used during times of low solar production or during high energy demand to ensure a reliable power supply. By integrating storage with solar photovoltaics, the grid can better balance energy production and consumption changes, without overloading.

The significance of addressing the capacity challenge of the U.S. electrical grid cannot be over emphasized. A combination of a smart grid and a tracking solar photovoltaic with storage would theoretically ensure that there would never be a repeat of the Northeast Blackout of 2003 as well as the 2021 Texas power crisis. This would ensue by enhancing real-time monitoring and response capabilities, preventing failures caused by undetected events, and adapting to demand by distributing energy more efficiently. Additionally, the risk of disrupting electricity flow to power plants would be eliminated as the advanced mechanisms of the smart grid would manage and channel power flows.

This paper aims to assess the most cost-effective, energy-efficient, and environmentally sustainable way to expand the carrying capacity of an energy grid by examining three solutions: adopting a smart grid, implementing a solar photovoltaic coupled with battery storage, or a combination of both approaches using an NGCC system as the control. The author hypothesizes that combining the smart grid and solar photovoltaic will be the optimal solution, but only in areas with high solar irradiance. To test this, the paper will analyze construction cost, yearly operation and maintenance cost, and yearly residential bills in 2024 USD to account for inflation. The paper will also look at energy efficiencies and the lifecycle CO_2 emissions (the carbon footprint) of the three systems and the control. Austin, TX, and Sammamish, WA, will be used as case studies as they represent varying solar irradiance levels and different geographic locations across the United States. The paper will compare the performance of solar photovoltaics, intended to power all city residents, with battery storage, both with and without a smart grid, in comparison to the actual residential demand in the city.

Methods

Data retrieval for irradiance and city energy consumption

Irradiance levels for solar photovoltaic analysis were retrieved by an input of the study locations –Austin, TX and Sammamish, WA – into the National Renewable Energy Laboratory application programming interface, or NREL API (National Renewable Energy Laboratory, Golden, CO, USA), which returned the average of each month's Global Horizontal Irradiance (GHI) from 1998 to 2009 for each location (26). If the total average monthly GHI was < 4.5 kWh/m^2/day, then the data was not used, because a utility-scale solar photovoltaic with or without a smart grid is not viable in areas with such low solar energy potential (27). Otherwise, the GHI data was used to create an analysis of the solar photovoltaics in the chosen city.

Data was retrieved via an API from Austin's Open Data Portal (City of Austin Open Data Portal, Austin, TX, USA) to find the city's residents' monthly kWh energy consumption from 2000 to 2018 (28). A dataset of this size was used to capture both older and newer energy trends to find a long-term average since energy consumption is expected to follow a gradual change, rather than using non-representative short-term trends. Then, the energy used by a household was averaged to find the overall usage for each month in a year and multiplied by the 458,505 households in Austin to find the total residential energy consumption for the city (29). To find Sammamish's residential energy consumption, an average family of four's home energy consumption from August 2023 to July 2024 was downloaded from Puget Sound Energy (Bellevue, WA, USA) from the account to an Excel spreadsheet (30). As Sammamish lacked available long-term data, only a single year was used since it was the only data available. The energy consumption data was adjusted by subtracting the energy used by the EV charging station in the home to determine the average household energy usage. In King County, where Sammamish is located, there are ~ 1,832,000 cars, with 3.74% being electric vehicles (31, 32). By removing the energy used for EV charging, the adjusted data provided a more accurate representation of the average household energy consumption in Sammamish. Subsequently, for each month, the total consumption was calculated by summing the minute-by-minute usage for each day and then multiplied by the 22,146 households in the city (33). This was done to compare the total energy consumption of residents in the city to the output of the utility-scale solar photovoltaic systems, both in their standard form, and when improved by the smart grid. Figure 2 is a representation of the Code flow chart that shows an overview of the process of how the program works.

Fixed data

Table 1 is a list of assumptions that were made to calculate the costs, efficiencies and carbon footprint of the four options used in this study.

Table 1. Costs, efficiencies, and carbon footprints of the four options.

Assumptions	
Crystalline silicon PV cells solar conversion efficiency (34)	20%
Single-axis tracking technology improvement in efficiency (35)	+31%
Transmission and distribution efficiency [t&d efficiency] (12)	95%
Performance ratio [PR] (36)	78.6%
Battery storage efficiency (37)	82%
NGCC power plant efficiency (11)	55%
NGCC power plant yearly carbon footprint (13)	499 grams of CO_2 per kWh
Solar PV construction cost (8)	$1,649.89 per kW
Battery storage construction cost (38)	$781.97 per kWh
Solar PV & battery storage operation and maintenance cost (9)	$65.49 per kW
Solar PV & battery storage yearly carbon footprint (39)	123.8 grams of CO_2 per kWh
U.S. smart grid construction cost (40)	$664,834,910,798
U.S. smart grid operation and maintenance cost per substation (40)	$69,835.60
U.S. smart grid # of substations (40)	66,450
U.S. smart grid + solar PV & battery storage # of substations (40)	67,150

Solar PV system size and energy delivery to residents

The size of the solar photovoltaic was calculated next. As previously mentioned, if the average monthly GHI for the city was ≥ 4.5 kWh/m^2/day, then a utility-scale solar photovoltaic was suggested to be implemented, as shown in Figure 2. Equation 1 shows the calculation to find the optimal size, in square meters, for the PV plant, where PV efficiency refers to that of the solar photovoltaic cell which is the percentage of sunlight the cell can convert into electricity. To find PV efficiency, the base efficiency of crystalline silicon PV cells was adjusted using the enhancement provided by single-axis tracking technology, which is found in Table 1. Equation 1 also includes transmission and distribution efficiency and performance ratio, to reflect real-world conditions, also from Table 1. The NREL's API was used to determine the daily average GHI for each month, and the total energy that residents in the city used was retrieved from Austin's Open Data Portal API and Sammamish's Puget Sound Energy Household Dataset. Equation 1 was calculated for each month noting that 2024 was a leap year, so February had 29 days.

$$PV\ Plant\ area\left(m^2\right)=\frac{energy\ city\ residents\ used\ that\ month\left(kWh\right)}{month's\ avg\ GHI\left(kWh/m^2/day\right)x\ days\ x\ PV\ efficiency\ x\ td\ efficiency\ x\ PR} \quad \text{(eq 1)}$$

Then, the average of the twelve monthly plant areas was calculated to find the best size for the photovoltaic plant to sufficiently meet the residential consumer's energy demands. The average was used since, with the battery storage paired with the solar PV, any energy shortfalls in solar production could theoretically be compensated for by the stored energy in winter. This allowed for the size of the solar PV not to be based solely on the worst case (e.g. winter months at less solar radiation), avoiding unwarranted oversizing. Equation 2 used this area of the solar photovoltaic from equation 1 to calculate the solar PV energy output each month.

$$Month\ PV\ output\left(kWh\right)=month's\ avg.GHI\left(kWh/m^2/day\right)x\ days\ x\ PV\ efficiency\ x\ td\ efficiency\ x\ PR\ x\ plant\ area\left(m^2\right) \quad \text{(eq 2)}$$

If the city's average monthly GHI was ≥ 4.5 kWh/m^2/day, then as shown in Figure 2, a line graph would have been output showing each month's energy generated from the solar PV (in kWh) from Equation 2 compared to how much energy the city's residents consumed, and would also return the size of the solar PV either in square meters (m^2) or square kilometers (km^2). A bar graph would also show the shortfall and excess in the amount of energy the solar PV in low and high GHI months respectively. Any surplus energy would then be channeled to the battery storage. The efficiency of the utility-scale battery storage, found in Table 1, was also applied to the amount of excess power that the solar PV generated. If there was a surplus of energy created by the solar PV, then the city could use that excess for other uses.

Solar PV with smart grid energy delivery to residents and system size

Calculating the monthly solar photovoltaic energy with a smart grid was conceptually similar to calculations using only the solar PV. Smart grid mechanisms reduce a household's energy consumption by ~ 7.5% and reduce energy losses by 10% (41,42). To account for the 7.5% reduction, each city's monthly energy usage was multiplied by 92.5%. Then, to account for the reduction of energy losses by 10%, the efficiency of the solar PV, the transmission and distribution efficiency, and battery efficiency were updated as shown in equations 3-5 (43).

$$Solar\ PV\ New\ efficiency = 1 - [(1 - efficiency)\ x\ 0.9] \quad \text{(eq 3)}$$

$$T\ \&\ d\ New\ efficiency = 1 - [(1 - t\ \&\ d\ efficiency)\ x\ 0.9] \quad \text{(eq 4)}$$

$$Battery\ Storage\ New\ efficiency = 1 - [(1 - battery\ efficiency)\ x\ 0.9] \quad \text{(eq 5)}$$

If the city's average monthly GHI was ≥ 4.5 kWh/m^2/day, the best size for the solar PV system was calculated using Equations 1 and 2 with the recalculated variables derived from their improvements in equations 3-5. This returned a line graph comparing the energy produced by the solar PV (in kWh) to the total energy consumption of the residents in the chosen city. A bar graph was also output to compare the shortfall to the surplus of energy produced by the solar photovoltaic throughout the year, and the excess energy would be channeled to a battery storage.

Natural Gas Combined Cycle capacity, costs, efficiency, CO_2 data and calculations

The capacity of the NGCC power plant, in kW, was found by dividing the total amount of kWh used by residential consumers in the city by the efficiency of the power plant, transmission and distribution efficiency (found in Table 1), and the number of hours in 2024; 8,784 hours, as shown in Equation 6.

$$NGCC\ plant\ capacity\,(kW) = \frac{total\ energy\ used\ by\ city\ residents\,(kWh)}{plant\ efficiency\ x\ td\ efficiency\ x\ hours\ per\ year} \quad \text{(eq 6)}$$

Table 2. Table showing the natural Gas Combined Cycle base costs

NGCC Base Costs	
Construction Cost per kW (8)	$1,451.63
Operation and Maintenance Cost per kW (yearly) (9)	$35.43
Residential price per kWh (10)	17.43¢

To find the construction costs and yearly operation and maintenance costs for an NGCC, the two costs from Table 2 were multiplied by the power plant capacity. The cost of a resident's annual bill was calculated using the total energy consumption in the city, divided by the number of households, and then multiplied by the residential price per kWh from Table 2. The losses of the NGCC were shown in Figure 1, thus resulting in an efficiency of 55%. The efficiency of transmission and distribution was 95%. The two numbers were multiplied to find the total efficiency of the grid.

The yearly carbon footprint in an NGCC grid in the selected city would be the number of grams of CO_2 per kWh (refer to Table 1), hence that was multiplied by the energy the residents in the city used. The residents' usage was affected by the 95% transmission and distribution efficiency, hence Equation 7 was used to calculate the yearly carbon footprint.

$$Yearly\,Carbon\,footprint\,(g) = \frac{grams\,CO_2\,per\,kWh\,x\,total\,residential\,energy\,usage\,(kWh)}{td\,efficiency} \quad \text{(eq 7)}$$

Solar photovoltaic with battery storage: costs, efficiency, CO_2 data and calculations

The cost to construct a crystalline silicon tracking solar photovoltaic is $1,649.89 per kW (8). Since it is per kW, the total energy produced (in kWh), was divided by the 8,784 hours in a leap year to find the total amount the solar PV produced in kW, which was then multiplied by the $1,649.89. Then, the cost of constructing a battery storage, $781.97 per kWh, was multiplied by the total amount of excess energy stored in the battery. The assumption made in this calculation is that during the first year of implementing the solar PV and battery storage, *all* excess energy generated by the solar PV will be stored in the battery storage, which be utilized in the following year. It is important to note that solar PV may not be the sole source of power generation during the first year; further examined in the results section. The operation and maintenance cost per kW, found in Table 1, were multiplied by the total energy production in kW.

Table 3. Levelized cost of energy for a natural gas combined cycle plant and a solar photovoltaic with battery storage

Levelized Cost of Energy (LCOE)	
LCOE of NGCC (44)	7.65¢
LCOE of Solar PV with Battery Storage (9)	10.31¢

Calculating the bill per year for a household required more work since only the levelized cost of energy (LCOE) was known, which does not reflect what residents pay. The residential price per kWh from Table 2 and the LCOE of NGCC found in Table 3 were substituted into Equation 8. This returned the amount companies increase the LCOE for profit margins, which was found to be 9.78¢. This Markup was subsequently substituted into Equation 9, as was the LCOE for a solar PV with battery storage (from Table 3), to obtain 20.09¢ as the residential cost per kWh.

$$Markup = (residential\ cost\ per\ kWh\ for\ NGCC) - (LCOE\ for\ NGCC) \quad \text{(eq 8)}$$

$$Residential\ cost\ per\ kWh = (Markup) + (LCOE\ for\ solar\ PV\ with\ battery\ storage) \quad \text{(eq 9)}$$

$$Residential\ bill\,(Solar\ PV + Battery\ storage) = \frac{20.09\ cents\ per\ kWh\ x\ energy\ used\ by\ city\,(kWh)}{number\ of\ households} \quad \text{(eq 10)}$$

Equation 10 was then used to calculate the annual residential bill for a solar photovoltaic with battery storage. The total efficiency of a solar photovoltaic with battery storage would be the solar PV efficiency, with its increase in efficiency due to tracking technology, multiplied by the battery storage efficiency, performance ratio, and transmission and distribution efficiency. These were the same numbers that were used in Equation 1 with the added battery storage efficiency.

The yearly carbon footprint of a solar photovoltaic with battery storage is 123.8 grams of CO_2 per kWh (39). Equation 7 was then used; however, instead of using the energy consumption of the residents, the amount of energy the solar PV produced was used. This was because solar production may fluctuate and overproduce, hence it could be greater than what residents use. However, it still needed to be accounted for.

Smart Grid with Natural Gas Combined Cycle plant costs, efficiency, CO_2 data and calculations

The construction cost of building a smart grid, found in Table 1, was multiplied by the percentage of all U.S. households that live in the chosen city, to estimate the city's share of the cost (45). The cost of operation and maintenance per year includes $69,835.60 per substation with 66,450 substations, once again multiplied by the percent of U.S. households that lives in the city (40). These substations will serve as critical infrastructure to accommodate the increasing load growth. They will help alleviate any backlog of energy and aid in expanding the grid's capacity and enhance transmission. The 66,450 substations are derived from the Electric Power Research Institute's report, *Estimating the Costs and Benefits of the Smart Grid*, which identified the necessary infrastructure needed to support the integration of a smart grid in the United States. A residential bill per year in the city was once again 17.43 cents per kWh however, it was multiplied by the reduced total residential energy consumption due to the smart grid mechanisms and then divided by the number of households.

To calculate the new efficiency, Equations 3 and 4 were utilized, but instead, the NGCC efficiency data was used. The emitted grams of CO_2 per kWh in an NGCC (from Table 1) was substituted into Equation 7, but with the updated 7.5% reduced residential usage to find each year's carbon footprint.

Smart Grid with a solar photovoltaic plant with battery storage costs, efficiency, CO_2 data and calculations

To calculate the construction cost, the smart grid construction cost (the city's portion), the total energy the solar PV produced in kW, and the new amount of excess energy generated throughout the year were substituted into Equation 11. The output of equation 11 is the construction cost of the Smart Grid with solar PV and Battery storage; represented simply as 'construction cost' in the equation.

$$Construction\ cost = (Smart\ Grid\ construction\ cost) + (total\ energy\ produced\ (kW)\ x\ \$1649.89) + (surplus\ energy\ generated\ (kWh)\ x\ \$781.97) \quad \text{(eq 11)}$$

The operation and maintenance costs per year are the cost per substation (refer to Table 1), multiplied by an additional 700 substations. These 700 additional substations are to ensure that the United States' electrical grid will have adequate load carrying capacity for the nationwide integration of solar photovoltaics. Then, \$65.49 was multiplied by the total energy the solar PV produced in kW, multiplied by the percentage of U.S. households in the city, and added to the operation and maintenance for the solar PV and battery storage costs. The city's new and reduced residential energy consumption was substituted into Equation 10 to find the annual residential bill in a smart grid with a solar photovoltaic paired with battery storage. The efficiency of a smart grid with a solar photovoltaic with battery storage was the new efficiency of the solar photovoltaic, battery storage, and transmission and distribution, all multiplied. To find the yearly carbon footprint of a smart grid with a solar photovoltaic plant and battery storage, 123.8 grams of CO_2 per kWh was substituted into Equation 7 with the reduced solar PV energy production (due to the reduced energy usage in a smart grid).

Tables with analysis

The code generated and returned three tables, as shown in Figure 2.

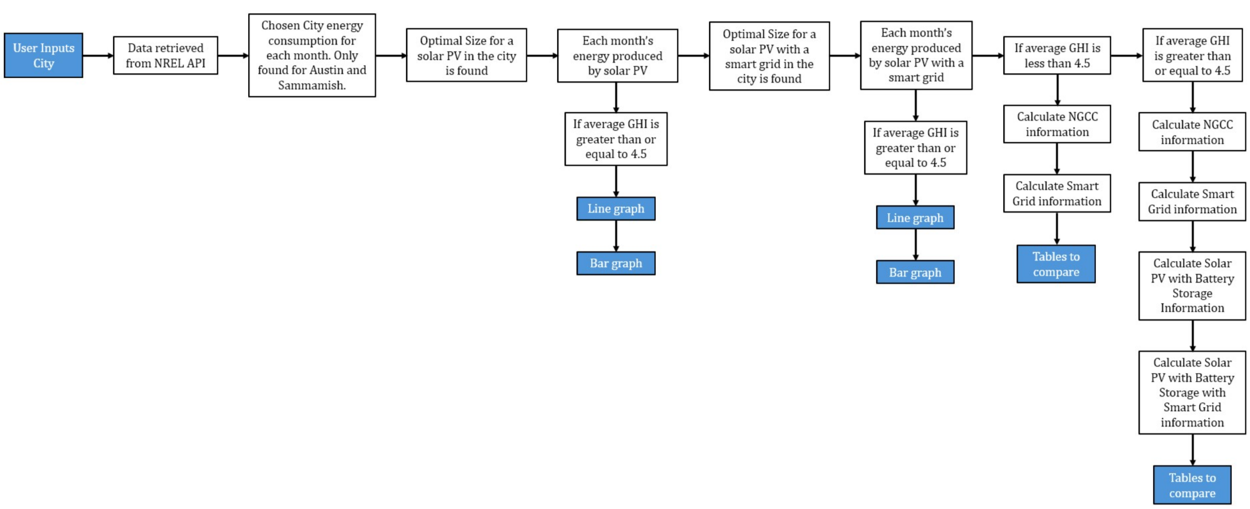
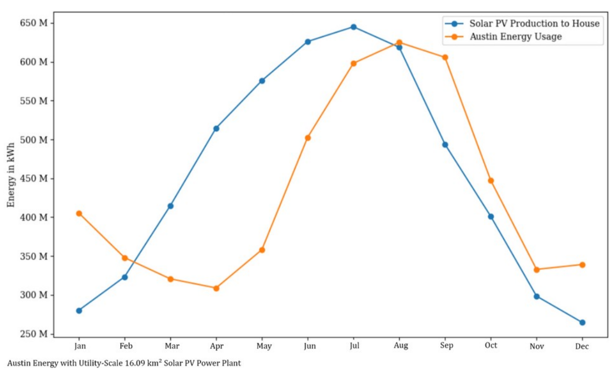


Figure 2. Methodology flowchart

The methodology flowchart in Figure 2 shows the calculated information of the costs, efficiencies, and CO_2 footprint with the four given scenarios: an NGCC, a solar PV with battery storage, implementation of the smart grid, and implementing the smart grid with a solar PV and battery storage. However, if the total average monthly GHI for the city was ≤ 4.5 kWh/m^2/day, only two scenarios were displayed: an NGCC and the implementation of the smart grid, since solar photovoltaics were not recommended in the area chosen.

Results

The results for Austin showed that its GHI level was ≥ 4.5 kWh/m^2/day. Therefore, for Austin, a line graph was output showing the implementation of a solar photovoltaic over the year 2024, providing the user with a visual representation of how the solar PV would have functioned.



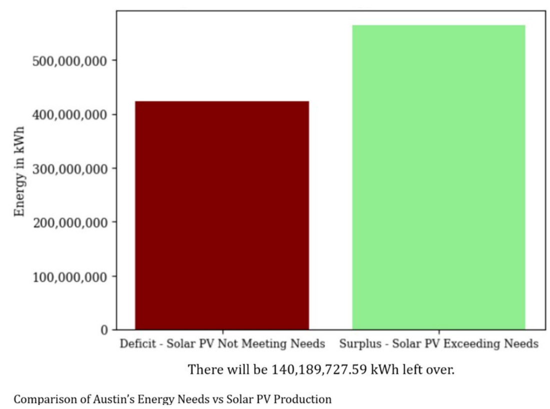
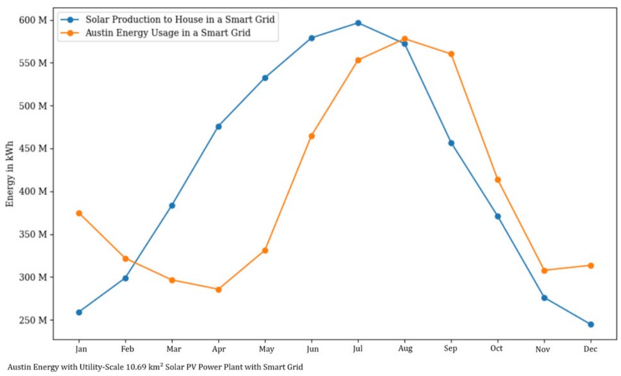


Figure 3. Left Panel, The line graph shows the solar photovoltaic output that reached residents throughout 2024 in blue versus the actual needs of the residents in orange. The graph shows the trends of the months the solar PV met and exceeded energy needs and the months the solar PV did not meet needs.

Figure 4. Right Panel, The bars show that the amount of energy the solar photovoltaic in Austin exceeded the needs of residents more than underperform. Under the graph, the number shown was the exact amount of energy that was left over.

An overview of the battery storage versus consumption in Austin was output (Figure 4). The bar on the left in Figure 4 shows the overall amount of energy that the solar PV did not meet, or the deficit, totaled from each month. The bar on the right showed the amount of excess energy that the solar PV produced over the year, and then below, it shows the amount of energy that was left over once the surplus energy helped meet the unmet needs for the coming year.

Since the GHI in Austin was above the required threshold, another line graph showing production and usage for a solar PV with a smart grid was output (Figure 5). Note the lesser energy demand, when compared to Figure 3, because of the Smart Grid incorporation. The graph showed a yearly overlook of how a solar photovoltaic with a smart grid would perform versus the actual energy demand needed in Austin.



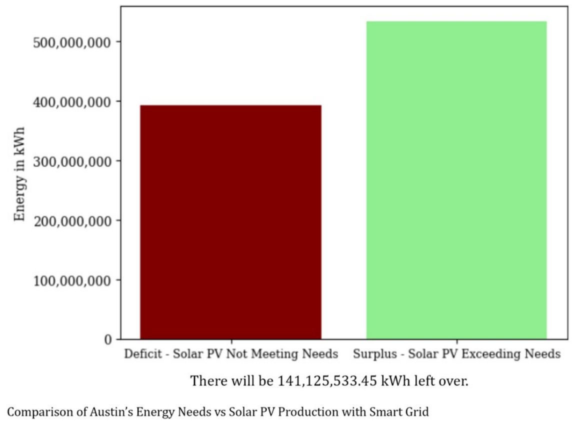


Figure 5. Left Panel, The graph shows the energy in solar photovoltaic with a smart grid that reached residents throughout the year in blue, versus the actual Austin residential consumer energy usage in a smart grid in orange throughout the year of 2024.

Figure 6. Right Panel, The bar graph shows the amount of energy that the solar photovoltaic in Austin combined with a smart grid did not meet (Red). The green bar on the right then shows the surplus of energy the system created.

Then, a bar graph was output (figure 6) which showed the total amount of energy that the solar photovoltaic failed to meet throughout the year on the left. On the right, the bar showed the total amount of energy the solar PV excessively created.

Table 4. Comparison between an NGCC power plant and the three options: a solar photovoltaic with battery storage, the smart grid, and the combination of the options in Austin.

Costs in 2024 USD for Austin				
	Natural Gas Combined Cycle Power Plant	Utility-Scale Solar PV with Battery Storage	Smart Grid	Smart Grid and Solar PV with Battery Storage
Construction Costs x 10^{-9}	\$1.56	\$538	\$2.32	\$500
Yearly Operation & Maintenance x 10^{-6}	\$38	\$40	\$16.2	\$54
Yearly Residential Bill	\$1,973.67	\$2,274.88	\$1,825.65	\$2,104.26

Energy Efficiencies for Austin			
Natural Gas Combined Cycle Power Plant	Utility-Scale Solar PV with Battery Storage	Smart Grid	Smart Grid and Austin Solar PV with Battery Storage
52.25%	16.04%	56.82%	22.84%

Yearly Carbon Footprint in Kilograms for Austin			
Natural Gas Combined Cycle Power Plant	Utility-Scale Solar PV with Battery Storage	Smart Grid	Smart Grid and Solar PV with Battery Storage
2,727,631,499.17	710,979,369.16	2,523,059,136.74	657,655,916.41

The table for the city of Austin (Table 4) shows all four options exploring their economic costs, energy efficiencies, and yearly carbon footprints. The following table (Table 5) displays two options: NGCC and the Smart Grid, as any solar options would not be optimal in Sammamish. The table shows their costs, efficiencies, and carbon footprints.

Table 5. The table shows the costs, energy efficiencies, and yearly carbon footprint of an NGCC compared to the United States' smart grid (with NGCC) in Sammamish, Washington.

<table>
<tr><th colspan="4">Costs in 2024 USD for Sammamish</th></tr>
<tr><td></td><td colspan="2">Natural Gas Combined Cycle Power Plant</td><td>Smart Grid</td></tr>
<tr><td>Construction Costs x 10^{-9}</td><td colspan="2">$0.09</td><td>$0.11</td></tr>
<tr><td>Yearly Operation & Maintenance x 10^{-6}</td><td colspan="2">$2.28</td><td>$0.78</td></tr>
<tr><td>Yearly Residential Bill</td><td colspan="2">$2,447.58</td><td>$2,264.01</td></tr>
<tr><th colspan="4">Energy Efficiencies for Sammamish</th></tr>
<tr><td colspan="2">Natural Gas Combined Cycle Power Plant</td><td colspan="2">Smart Grid</td></tr>
<tr><td colspan="2">52.25%</td><td colspan="2">56.82%</td></tr>
<tr><th colspan="4">Yearly Carbon Footprint in Kilograms for Sammamish</th></tr>
<tr><td colspan="2">Natural Gas Combined Cycle Power Plant</td><td colspan="2">Smart Grid</td></tr>
<tr><td colspan="2">163,379,828.20</td><td colspan="2">151,126,341.09</td></tr>
</table>

Discussion

Summary of code

When discovering the options for the city of Austin, Texas, the program executed all the options, including information on solar photovoltaics. This means that solar energy can be harnessed in Austin. However, since no information about solar photovoltaics in Sammamish, Washington, was printed, implementing them in Sammamish would not be optimal.

Size of the solar photovoltaic plants in a real-world scenario

The size of the utility-scale solar photovoltaic suggested for Austin was 16.09 km^2, as shown in Figure 3. The size of the solar PV combined with a smart grid in Austin, which was the most optimal, was 10.69 km^2, shown in Figure 5. For perspective, in 2024, the largest solar photovoltaic plant is the Xinjiang solar farm in China, with a size of about 809.37 km^2 (46). Given that Austin's total area of land is about 845.63 km^2, the size of the solar PV in Austin would be 1.9% of its area of land, and the size of the solar PV with the smart grid would be 1.26% (47).

Battery storage

The battery storage in Austin for both the standard NGCC system and the combined smart grid system shows how solar photovoltaics can be utilized in the city. The author suggests that in the first year of implementing the solar PV systems, NGCC plants can provide support. This way, all the excess energy created in the months of March, April, May, June, and July (which is the same for the solar PV with and without the smart grid seen in Figures 3 and 5), can be stored in the battery storage. By the following year, the battery storage will have enough energy to cover any deficit, as seen in Figures 4 and 6, allowing for NGCC plants to be phased out. Also, throughout this next year, energy will continue to be stored in high solar radiation months, keeping a steady and reliable supply. Additionally, as shown in Figures 4 and 6, at the bottom, Austin will still have leftover power that can be used for other purposes.

Limitations

A main data limitation that arose was that many cities, with the exception of Austin, TX, did not readily provide available data about their residents' average energy consumption for each month, which was why more cities were not studied. The data for Sammamish was obtained from a four-person household’s energy consumption from August 1st, 2023, to July 31st, 2024, which was not ideal as it was only for a year and did not capture overall trends throughout larger periods of time Additionally, the data was from one household rather than the average of multiple. The implications of using short-term trends is that the total estimated energy demand may not fully reflect long-term consumption patterns. This could influence the resulting calculations, such as the size of the solar PV systems, NGCC emissions, and other related factors long term. Hence, cities need to have their residents’ energy usage for each month to use this program.

Battery storage was assumed to be unlimited and fluid. It was assumed that power could be stored in batteries for an unlimited amount of time with no parasitic or natural discharge. No depth of discharge (DOD) was assumed. Consequently, power drainage from battery was assumed to be 100%.

Another limitation is that the 7.5% reduction in household energy consumption assumes full consumer participation in smart grid mechanisms and programs. However, if there is public resistance to some features, then this could reduce the actual amount of energy being saved.

Economic costs

The construction cost for a natural gas combined cycle power plant in Austin is estimated to be the cheapest option, as shown in Table 6. The smart grid was the second least expensive with the solar PV with the smart grid and battery storage, and the solar PV with battery storage following. The solar photovoltaic systems were not as cost efficient as they needed to account for the price of a solar photovoltaic and battery storage. In contrast, natural gas plants needed to only account for their cost. The construction cost for an NGCC in Sammamish is less than the construction cost of it paired with a smart grid in Sammamish, as seen in Table 6. It is important to note that the reasoning for the difference in costs between Austin and Sammamish is due to Austin having to accommodate power for 20.7 times more households than that for Sammamish.

Table 6. The table shows the construction costs in 2024 Dollars of all four options for Austin ranked from least to most expensive, and for the two options for Sammamish.

	Austin	Sammamish
NGCC	1.16×10^9	9.34×10^7
Smart Grid	2.32×10^9	1.12×10^8
Smart Grid with Solar PV and Battery Storage	5.01×10^{11}	NA
Solar PV with Battery Storage	5.39×10^{11}	NA

In Austin, the rankings of the operation of maintenance costs from inexpensive to expensive are as follows: the smart grid (with NGCC), natural gas combined cycle power plant system, the solar PV with battery storage, and the solar PV with battery storage with the smart grid, as shown in Table 7. In Sammamish, the NGCC combined with the smart grid operation and maintenance cost is estimated to be cheaper than the NGCC cost, as seen in Table 7.

Table 7. The table consists of the yearly operation and maintenance costs in 2024 Dollars of all four options for Austin, ranked from least to most expensive, and the costs for the two options for Sammamish.

	Austin	Sammamish
Smart Grid	1.62×10^7	7.81×10^5
NGCC	3.81×10^7	2.28×10^6
Solar PV with Battery Storage	4.07×10^7	NA
Smart Grid with Solar PV and Battery Storage	5.40×10^7	NA

Finally, the options for residential bills can be compared and analyzed. In Austin, the residential average yearly bill from least to most expensive is the smart grid, NGCC, the smart grid with a solar photovoltaic with battery storage, and the solar PV with battery storage, as shown in Table 8. The cost of a solar photovoltaic with battery storage is the highest as the price of energy going through battery storage is high (9). However, a solar PV with battery storage with the smart grid does not significantly increase a resident's bill, costing $131 more than the average NGCC. However, the *Coordination Marketing of Energy Efficiency and Demand Response Program* smart grid mechanism teaches and provides energy consumption information to consumers, and it can be argued that the program encompasses the $131. Additionally, in Sammamish, the smart grid reduced the NGCC price by $184, as seen in Table 8. The NGCC residential bill price for Sammamish versus that for Austin differs due to heating and other contributing factors, such as the fact that the environment and climate in Sammamish are much colder than that of Austin's.

Additionally, for the purpose of this paper, the price of constructing the smart grid is calculated under the construction cost category for this paper, but if it were decided that residents would pay for it, then residential energy bills would be higher for ~ the first ten to twenty years of implementation.

Table 8. The table shows the yearly residential bills in dollars of all four options for Austin, ranked from least to most expensive, and the costs for the two options for Sammamish.

	Austin	Sammamish
Smart Grid	1826	2264
NGCC	1974	2448
Smart Grid with Solar PV and Battery Storage	2104	NA
Solar PV and Battery Storage	2275	NA

To summarize, the cost of construction is the most affordable in a natural gas combined cycle system. For operation and maintenance and residential bills, the smart grid is the cheapest option, as shown in Tables 4 and 5.

Energy efficiencies

Energy efficiencies, whether in Austin or Sammamish, are equal as the technology being implemented in both cities is the same. For the NGCC, it is 52.25% efficient, 16.04% for the solar PV with storage, 56.82% for the smart grid, and 22.84% efficient for the solar PV with storage in a smart grid, as shown in Table 4. The solar PV options have such low-efficiency rates because solar photovoltaic cells have an efficiency of 20%, compared to a natural gas combined cycle plant with an efficiency rate of 55%. So, the smart grid options make the original plants more efficient, and the most efficient one is just the smart grid (meaning the one with NGCC).

Carbon footprints

Table 9 shows the carbon footprints of the four options for the two cities.

Table 9. Yearly carbon footprint in kilograms of all four options for Austin ranked from least to most emissions, as well as for the two options for Sammamish.

	Austin	Sammamish
Smart Grid with Solar PV and Battery Storage	6.58×10^8	NA
Solar PV and Battery Storage	7.11×10^8	NA
Smart grid	2.52×10^9	1.51×10^8
NGCC	2.73×10^9	1.63×10^8

The yearly carbon footprint for NGCC has the highest emissions out of all the four options, while the smart grid comes in second in Austin. Finally, on the lower side of the scale are the solar PV with battery storage, and the solar PV and battery storage combined with the smart grid, as shown in Table 9. The results seem reasonable as solar energy is more environmentally sustainable than natural gas, and a smart grid will reduce the needed power, thereby reducing the amount of CO_2 emitted in a year. This trend repeats in Sammamish, with its NGCC emitting more CO_2 yearly than the smart grid, as seen in Table 9. This difference is not as significant, since the energy needs of Sammamish are smaller than those of Austin's.

Reviewing the hypothesis

The author hypothesized at the experiment's beginning that the smart grid and solar photovoltaic would be the most sustainable energy solution in places with high solar irradiance. The hypothesis was confirmed after evaluating Austin, Texas, and Sammamish, Washington, as case studies. In Sammamish, a solar PV with or without a smart grid was not suggested, indicating that solar photovoltaics cannot be implemented to reasonable scale and cost in low solar irradiance places such as Sammamish. However, the results concluded that the best overall option was implementing the smart grid. The best cost options were NGCC for construction, and the smart grid for operation and maintenance and yearly residential bills. The smart grid was also the most energy efficient, and the solar PV with battery storage in a smart grid was the most environmentally friendly option. A single option did not perform the best across all categories (cost-effective, energy-efficient, and environmentally sustainable) but the smart grid excelled in most of these areas. The United States government can still use this program to see how cities will be affected after implementing the options and could choose which would best suit a particular city. However, future work could lead to a more definitive answer. For example, if a more efficient solar photovoltaic cell were to be developed, or the price of energy in a battery storage system decreased, this could influence the results and lead the country into a more greener future as the solar PV with the smart grid option could then become the preferable option.

Conclusion

This paper uses a natural gas combined cycle (NGCC) power plant as a baseline to compare the economic costs, energy efficiencies, and environmental sustainability of three options: adopting a smart grid, implementing a solar photovoltaic with battery storage, or combining both approaches. Austin, Texas, and Sammamish, Washington, were used as case studies. However, in Sammamish, implementing solar photovoltaics was not feasible due to the significantly low solar irradiance levels.

When evaluating construction costs, the NGCC was the cheapest. The smart grid was the most affordable for yearly operation and maintenance, and, once again, the smart grid was the most inexpensive for annual residential bills. The high cost of the solar photovoltaic options was due to the expensive battery storage. The smart grid was the most energy-efficient out of all four options. The solar photovoltaic with battery storage in a smart grid was the most environmentally sustainable option with the least yearly carbon footprint. No one solution excelled in every area, however, the smart grid performed the best in most categories.

Future studies could provide more conclusive results by exploring technological advancements that may change the findings. Research aimed at increasing the efficiency of solar photovoltaic cells and studies on decreasing the cost of energy in battery storage are crucial areas to further investigate. These efforts could sway the results in favor of a more environmentally-friendly and cheaper energy future and help transform the United States' electrical grid into a sustainable energy system.

Acknowledgments
I would like to thank my mentor, Claire Butler, for her invaluable guidance in developing this paper.

Data Access and supplementary file
The code for Sammamish and Austin is deposited in Github at
https://github.com/kavyasharma08/Analyzing-Solar-Photovoltaics-and-Smart-Grids-as-Sustainable-Energy-Solutions-Code/tree/main
The Excel spreadsheet containing energy consumption data for the Sammamish home is presented in the supplementary file.

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