Optimization of Solar and Storage at Behind-the-Meter Residential and Commercial Sites in Three Michigan Utility Service Territories

Rina Davila Severiano and Constance Crozier

Introduction

With technological advancements, evolving energy markets, and rising electricity prices, integrating behind-the-meter renewable energy sources such as solar power has become increasingly economically advantageous. Understanding which building types, residential or commercial, can benefit from behind-the-meter solar and energy storage (e.g., batteries) is crucial. In Michigan, different utilities have varying rate structures, which influence both whether solar and storage are economically beneficial and the amount of capacity that is incentivized. Using a mixed-integer linear programming (MILP) model, we determine which building types and utilities benefit the most from implementing solar and storage, providing actionable recommendations for policymakers and stakeholders.

In the sections below, we describe the specifics of the model, including the assumptions, framework, and parameters. We then present results from analyses conducted on numerous residential and commercial properties, including both small and large commercial buildings with varying energy demands and characteristics under three selected electric investor owned utilities in Michigan.

Methods

A mixed linear integer program was formulated to minimize the total system costs, defined as the sum of the electric bill and system capital costs, which included both the behind-the-meter solar and energy storage system (installation costs only). The model was designed to endogenously determine whether it was cost-effective to install solar and storage, as well as the optical sizing of each in kW and kWh, respectively, under the incentivized condition

Modeling Assumptions

Several assumptions were used in the model to reflect Michigan's policy structure for behind-the-meter installations at residential and commercial sites. First, the installed solar capacity could not exceed 110% of the total annual energy demand. Additionally, the installed solar capacity was capped at 550 kW and constrained by the available rooftop square footage, as only rooftop solar installations were considered. The model further assumed that no financing mechanisms were in place or specified which party incurred the capital costs or acquired the associated benefits. No discount rate was applied, and inflation in utility electricity rates was not considered; in other words, electricity rates were assumed to remain constant over the lifetimes of the solar and storage installations. In reality, the effects of discounting and utility rate increases may partially offset each other. Current Federal Reserve rates are around 4.25%, while DTE Electric's average residential rates increased by 0.78%, 6.38%, and 4.65% in 2022, 2023, and 2025, respectively. Consumers Energy residential rates increased by 1.61% and 2.79% in 2024 and 2025, respectively. Over the lifetime of the projects, these moderate annual increases in electricity rates could roughly counterbalance the effect of discounting, suggesting that the assumption of constant rates likely provides a reasonable approximation.

Modeling Framework and Parameters

For this model, we examine how different residential and commercial building energy demand impacts the economics for installing behind-the-meter solar and energy storage. We consider three categories: Residential, Small Commercial, and Large Commercial. Residential buildings include single-family homes, multifamily housing, and mobile homes. Small commercial buildings consist of warehouses, small offices, stand-alone retail (mercantile), restaurants, small hotels, and small to medium-sized office buildings. Large commercial buildings comprise large hotels, large office buildings, hospitals, and outpatient facilities.

The data for these building types is sourced from the U.S. Department of Energy's building energy modeling datasets, developed by the National Renewable Energy Laboratory (NREL) referred to as Restock (residential) and Comstock (commercial). Note that the data is modeled, not actual building data. These datasets provide a detailed breakdown of properties across varying types, sizes, and characteristics, such as location (by county), climate zone, heating fuel type, and cooling system type. For each property, the database includes annual energy demand profiles at 15-minute intervals. Properties with different characteristics were selected from the database and incorporated into the model for analysis.

To assess the impacts of the model across different utility rates, three distinct service territories were examined: DTE Electric, Consumers Energy (CE), and Upper Peninsula Power Company (UPPCO). The time-of-use (TOU) rate strcutures for each territory were analyzed and organized. Data for the utility rates were sourced from the Michigan Public Service Commission (MPSC) "Electric Rates 12 2024" spreadsheet, utility rate books, and in consultation with MPSC staff. A detailed breakdown of the rates for DTE, CE, and UPPCO can be seen in Table 1. Each property pulled from the Restock and Comstock dataset was assigned to one of the three utilities based on its location. Note that Summer is defined as the period from June 1 to September 30, while Non-Summer refers to October through May. For DTE, during the summer, electricity is charged at the On-Peak rate from 3–7 p.m. on weekdays, with Off-Peak rates applying from 7 p.m.–3 a.m. on weekdays and all day on Saturdays and Sundays. During Non-Summer months, On-Peak rates apply from 3–7 p.m. on weekdays, and Off-Peak rates apply from 7 p.m.–3 a.m. on weekdays and all day on weekends. Meanwhile, for CE and UPPCO, during both Summer and Non-Summer periods, the On-Peak rate applies from 2–7 p.m. on weekdays, and the Off-Peak rate applies from 7 p.m.–2 p.m. on weekdays as well as all day on weekends.

Table 1: Utility Rate Breakdown by Building Type and Utility

	DTE			CE			UPPCO		
Rate	Residential	Small Commercial	Large Commercial	Residential	Small Commercial	Large Commercial	Residential	Small Commercial	Large Commercial
On-Peak Summer ($/kWh)	0.2337	0.1401	0.0757	0.2357	0.1735	0.0784	0.2339	0.2393	0.1189
Off-Peak Summer ($/kWh)	0.1771	0.1401	0.0757	0.1867	0.1735	0.0784	0.2339	0.2393	0.1189
On-Peak Non-Summer ($/kWh)	0.1907	0.1401	0.0757	0.1820	0.1598	0.0762	0.2339	0.2393	0.1189
Off-Peak Non-Summer ($/kWh)	0.1771	0.1401	0.0757	0.1820	0.1598	0.0762	0.2339	0.2393	0.1189
PS Demand Summer ($/kW)	0	0	0	0	0	0	0	0	0
PS Demand Non-Summer ($/kW)	0	0	0	0	0	0	0	0	0
Distribution Demand ($/kW)	0	0	16.59	0	0	27.60	0	0	12.98
Demand FIC Summer ($/kW)	0	0	16.59	0	0	16.55	0	0	12.98
Demand FIC Non-Summer ($/kW)	0	0	21.80	0	0	1.00	0	0	0
On-Peak Summer FIC ($/kWh)	0	0	16.59	0	0	27.60	0	0	12.98
Off-Peak Summer FIC ($/kWh)	0	0	16.59	0	0	16.55	0	0	12.98
On-Peak Non-Summer FIC ($/kWh)	0.1451	0.0836	0.0361	0.1503	0.1099	0.0292	0.2339	0.2393	0.1189
Off-Peak Non-Summer FIC ($/kWh)	0.0885	0.0836	0.0361	0.1013	0.1099	0.0292	0.2339	0.2393	0.1189

Detailed Notes: PS Demand refers to the Power Supply Demand Charge, and FIC refers to the Feed-in Credit for solar generation, which represents the billing mechanism for inflows of excess solar energy back to the grid."

In addition to the building and utility data, we incorporated 2019 historical solar capacity factor data, which represent the fraction of energy actually generated relative to the system's maximum possible output. For each utility service territory, a representative location was selected, and annual hourly solar generation data was obtained from Renewables Ninja. These data are derived from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) global atmospheric reanalysis dataset, which incorporates satellite observations to provide historical climate information (Renewables Ninja). To provide a snapshot of the solar capacity dataset, the average solar capacity factors were 0.158419 for DTE, 0.153247 for UPPCO, and 0.154555 for CE. In other words, these systems generate approximately 15 to 16% of the electricity they would produce if operating at full capacity.

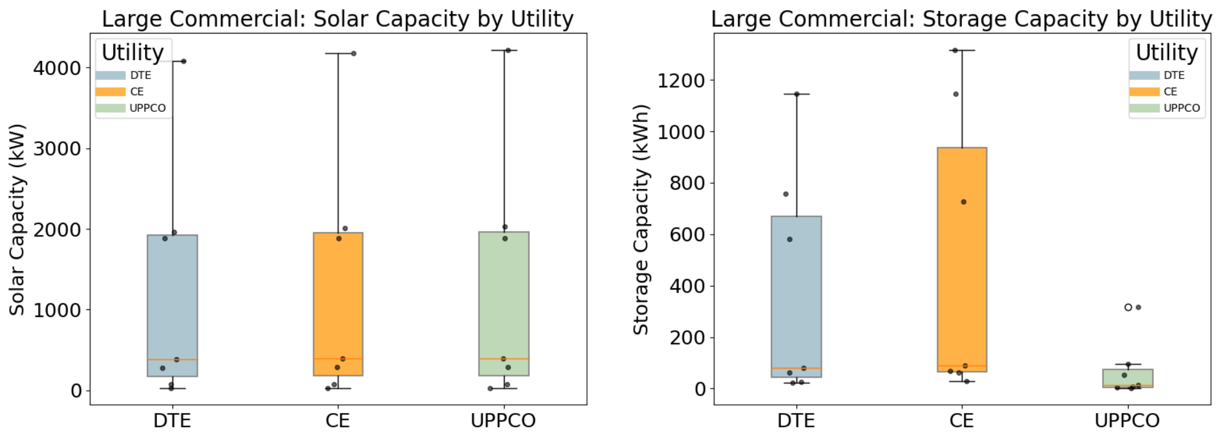
For the system, we also needed to know several key parameters, including the energy storage efficiency, the lifetimes of the solar panel and storage systems, and the installation costs of behind-the-meter solar and energy storage. We assumed a lifetime of 25 years for the behind-the-meter solar system, with an installation cost of $3,130 per kW (EnergySage, 2025), and a lifetime of 10 years for the storage system, with an installation cost of $400 per kWh (PNNL 1 and PNNL 2). The energy storage efficiency was assumed to be 0.9, commonly seen in lithium-ion batteries (Science Direct, 2022).

Results

The results for the different scenarios evaluated with the model can be divided into four main parts. For commercial buildings (Small and Large Commercial), we ran both unconstrained and constrained cases. In the unconstrained case, the system was allowed to install as much solar capacity as it deemed optimal, provided that the number of panels did not exceed the total available roof area. In the constrained case, solar capacity was limited to a maximum of 550 kW while still respecting the total available roof area. Similarly, for residential buildings, we ran both constrained and unconstrained cases. In the unconstrained case, the system could install any amount of solar capacity, while in the constrained case, installations were limited to discrete sizes of 0, 3, 5, or 7 kW.

Results for Commercial in the Unconstrained Case

In this section, we present the results for commercial properties under the unconstrained case. We begin with box plots illustrating the incentivized solar and storage capacities for large commercial customers across each utility. The box plots display the middle 50% of solar and storage capacities, with the horizontal line indicating the median. The vertical lines represent the highest and lowest non-outlier values, while points outside these ranges denote outliers. From the box plots in Figure 1, we observe that large commercial properties install approximately the same amount of solar capacity for all utilities, ranging from 0 to 4000 kW. For average values installed of solar and storage for large commercial look at Table [?]. In contrast, storage adoption varies: CE installs the most storage (0 to 1400 kWh), followed by DTE (0 to 1110 kW), with UPPCO installing the least (0 to 350 kWh). This variation is likely attributable to differences in demand charges, which are highest for CE, followed by DTE, and lowest for UPPCO. As a result, the system incentivizes more storage where demand charges are greater, since shifting load and reducing peak demand yield higher economic benefits. Meanwhile, in Figure 2, we present box plots of the solar and storage capacities installed by small commercial properties across all utilities. For a look at the averages installed of solar and storage look for small commercial look at Table 3. From these plots, we observe that CE and UPPCO install similar amounts of solar capacity, while DTE installs slightly less. Furthermore, none of the small commercial properties across any utility invest in storage. This outcome arises because small commercial utility rates do not include a demand charge, eliminating the incentive to shift load across time periods and making storage economically unattractive.

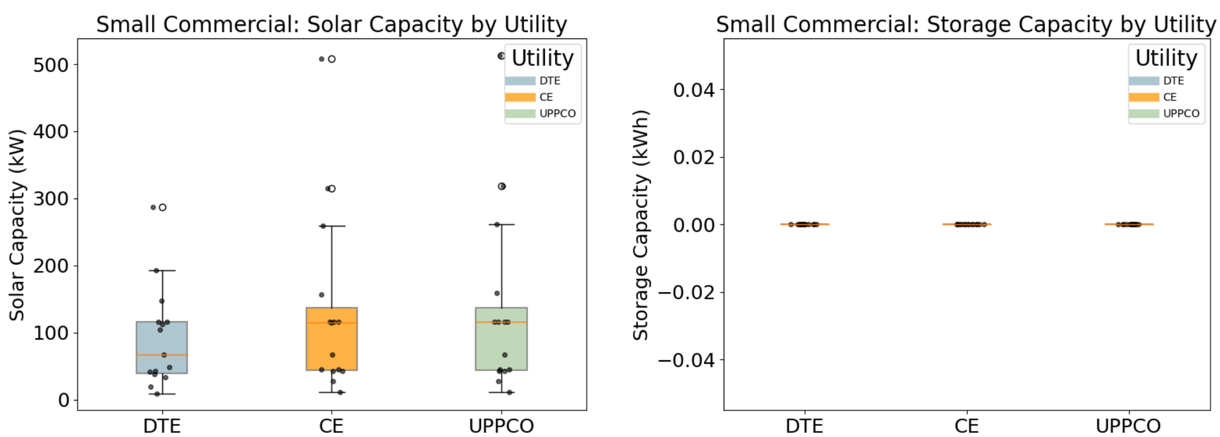


(a) Large Commercial Solar Capacity by Utility (b) Large Commercial Storage Capacity by Utility

Figure 1: Large commercial property box plots for installed solar capacity and energy storage for all utilities (unconstrained).

Utility	Avg. Solar Capacity (kW)	Avg. Storage Capacity (kWh)
CE	1266.332598	490.7715588
DTE	1242.022054	382.3184664
UP	1274.833555	70.83158813

Table 2: Unconstrained Case – Large Commercial: Average Solar and Storage Capacity Across Utilities



(a) Small Commercial Solar Capacity by Utility (b) Small Commercial Storage Capacity by Utility

Figure 2: Small commercial property box plots for installed solar capacity and energy storage for all utilities (unconstrained).

Utility	Avg. Solar Capacity (kW)	Avg. Storage Capacity (kWh)
CE	131.9096723	0
DTE	91.42726937	0
UP	132.7567069	0

Table 3: Unconstrained Case – Small Commercial: Average Solar and Storage Capacity Across Utilities

Now we explore the economic impacts of installing solar and storage capacities for large and small commercial properties. Table 4 shows the average electricity bill for small and large commercial properties, with and without solar, while Table 5 presents the corresponding reductions in electricity bill and peak demand between the solar and no-solar scenarios. From these tables, it is evident that commercial properties under the unconstrained case experience significant savings, particularly large commercial properties, which incentivize the installation of substantial solar capacity and result in considerable amounts of solar being fed into the system, sometimes producing negative electricity bills.

Both small and large commercial properties exhibit smaller savings under the constrained scenario, with the reduction being more moderate for small commercial properties. For commercial properties under the unconstrained case, large commercial customers see the largest electricity bill reductions for UPPCO, followed by CE and then DTE, a pattern that is similar for small commercial customers. All building types and utilities show reductions in peak demand (kW/Year). Specifically, UPPCO exhibits the largest savings across all three utilities, likely due to its higher utility rates, followed by CE and DTE, with UPPCO also demonstrating the largest peak demand reduction.

Table 4: Commercial (Annual Results) (Unconstrained)

Utility	Building Type	Solar Status	Avg. Electricity Bill ($/Year)	Avg. Peak Demand (kW)
CE	Small	Solar	8,609.49	58.15
		No Solar	31,207.33	60.40
	Large	Solar	(160,494.70)	275.35
		No Solar	207,998.66	443.02
DTE	Small	Solar	12,180.00	57.87
		No Solar	26,531.09	60.40
	Large	Solar	(122,728.97)	287.69
		No Solar	196,743.96	443.02
UPPCO	Small	Solar	2,657.41	58.11
		No Solar	45,305.21	60.40
	Large	Solar	(132,081.10)	366.52
		No Solar	241,826.40	443.02

Note: Large Commercial has both solar and storage installed, while Small Commercial only has solar. Values in parentheses correspond to negative values.

Table 5: Commercial: Annual Reductions and Lifetime Comparison (Unconstrained)

Utility	Building Type	Avg. Electricity Bill Reduction ($/Year)	Avg. Peak Reduction (kW/Year)	Avg.Total System Cost ($)	Avg.Total 25-Year Bill Savings ($)
CE	Small	22,597.84	2.25	412,877.27	564,946.00
	Large	368,493.36	167.67	4,159,929.65	9,212,334.75
DTE	Small	14,351.09	2.53	286,167.35	358,777.25
	Large	319,472.93	155.33	4,040,456.41	7,986,823.25
UPPCO	Small	42,647.80	2.29	415,528.49	1,066,195.00
	Large	373,907.50	76.50	4,018,561.66	9,347,687.50

For a more detailed breakdown of the electricity bill for small and large commercial properties, we present Figure 4, which decomposes the electricity bill for each utility and commercial building type into four components: energy charge, demand charge, feed-in credit or outflow credit (the monetary credit customers receive for excess solar energy exported to the grid), and feed-in demand (credit a customer receives on their peak electricity demand corresponding to solar generation exported to the grid during peak periods). Feed-in demand is intended to compensate customers for the capacity contribution of their solar generation to the utility system. These components are further broken down by time-of-use: the energy and feed-in charges are shown for on-peak/off-peak periods and for summer/non-summer periods, while the energy demand and feed-in demand are shown for summer and non-summer periods. Key takeaways from the figure include an overall reduction in energy costs for all utilities and building types when solar is installed. Most notably, large commercial properties gain substantial revenue from feed-in credits, driven primarily by the demand credit for feed-in.

For unconstrained solar and storage at commercial properties, up to 50% of generated solar energy is exported to the grid. Solar arbitrage, which involves charging storage when electricity prices are low and discharging or selling back to the grid when prices are high, is minimal, under 2% of total demand. This shows that the economic benefits of these systems come primarily from on-site consumption and avoided peak charges, rather than active trading with the grid.

A more detailed analysis of the impact by individual building type focuses on properties under DTE electricity rates. We find that among large commercial properties, hotels experience the largest bill reductions, offices see moderate reductions, and outpatient/hospitals have the smallest reductions, as seen in Table 6. For small commercial properties, retail establishments achieve the greatest bill reductions, offices and warehouses experience moderate reductions, and restaurants show a mixed impact, with fast-service restaurants having high reductions and full-service restaurants seeing lower reductions. These differences are largely driven by the demand profiles of each building type; for example, hospitals have significant late-evening or overnight energy demand compared to office buildings as seen in Table 7.

Table 6: Large Commercial Properties (Unconstrained): Electricity Bills, Solar, Storage Costs, and Percentage Reduction under DTE utility

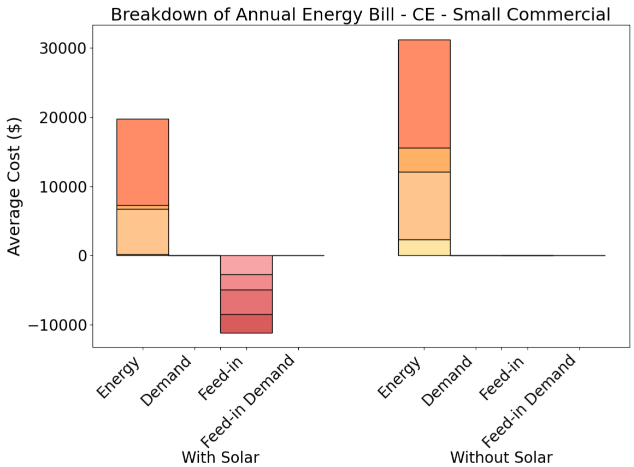
Property	Property Type	Electricity Bill (No Solar) ($/yr)	Electricity Bill (Solar) ($/yr)	Reduction in Bill ($/yr)	Solar Cost ($)	Storage Cost ($)	% of Annual Bill Reduction (%)
7481	LargeHotel	287,836.90	-208,778.43	496,615.33	245,312.13	23,266.93	172.7
25942	LargeHotel	40,259.91	-28,637.35	68,897.26	34,593.72	2,471.64	171.2
17638	LargeOffice	57,476.35	-38,312.06	95,788.41	48,281.18	3,192.90	166.7
46826	LargeOffice	618,422.39	-385,623.72	1,004,046.11	510,403.82	30,293.97	162.4
28398	Outpatient	5,270.71	-3,076.17	8,346.88	3,764.38	922.90	158.3
128348	Hospital	355,018.94	-189,570.19	544,589.13	236,229.81	45,749.15	153.4
27287	Outpatient	12,922.51	-5,104.86	18,027.37	9,178.03	1,078.40	139.5

Table 7: Residential and Commercial Properties: Electricity Bills, Solar, Solar Costs, and Percentage Reduction

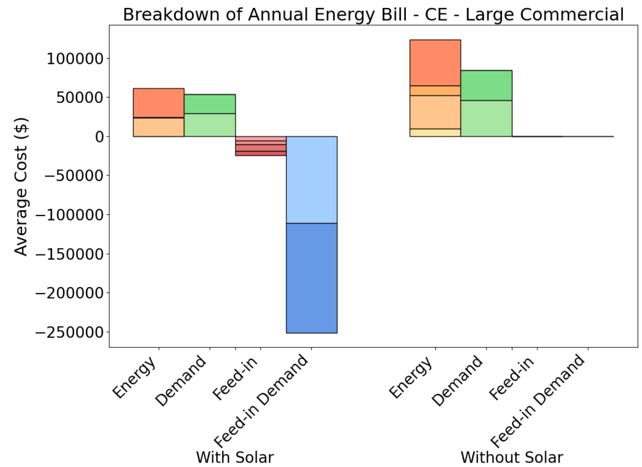
Property	Property Type	Electricity Bill (No Solar) ($/yr)	Electricity Bill (Solar) ($/yr)	Reduction in Bill ($/yr)	Solar Cost ($)	% of Annual Bill Reduction (%)
1664	RetailStandalone	7,646.32	1,167.94	6,478.38	5,138.73	84.7
590	QuickServiceRestaurant	23,081.82	5,889.78	17,192.04	14,023.66	74.5
34	RetailStandalone	1,912.63	553.75	1,358.88	1,149.08	71.0
7386	QuickServiceRestaurant	8,800.14	2,970.22	5,829.92	4,751.22	66.3
26	SmallOffice	11,501.06	3,979.17	7,521.89	6,018.45	65.4
1521	Warehouse	7,728.19	2,712.20	5,015.98	4,188.17	64.9
1553	SmallOffice	4,636.14	1,628.73	3,007.41	2,443.58	64.9
53	FullServiceRestaurant	28,220.49	9,209.98	19,010.50	14,436.27	67.4
6308	SmallHotel	54,389.31	24,703.46	29,685.84	24,116.23	54.6
15	Warehouse	27,102.52	11,703.45	15,399.07	13,068.98	56.8
27897	MediumOffice	44,653.26	22,076.93	22,576.33	18,382.77	50.6
16996	SmallHotel	19,819.57	9,832.29	9,987.29	8,307.62	50.4
6987	MediumOffice	87,712.04	44,123.99	43,588.04	35,872.33	49.7
1744	FullServiceRestaurant	48,070.13	27,435.66	20,634.47	14,436.27	43.0
45	FullServiceRestaurant	22,692.76	14,712.45	7,980.31	5,249.55	35.2

Use the legend below for Figure 4, 7, 9 and 11.

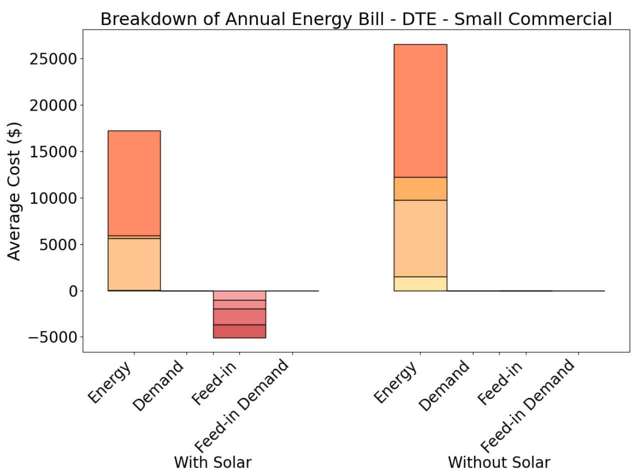
Figure 3: Legend to be used for Figure 4, 7, 9,and 11.



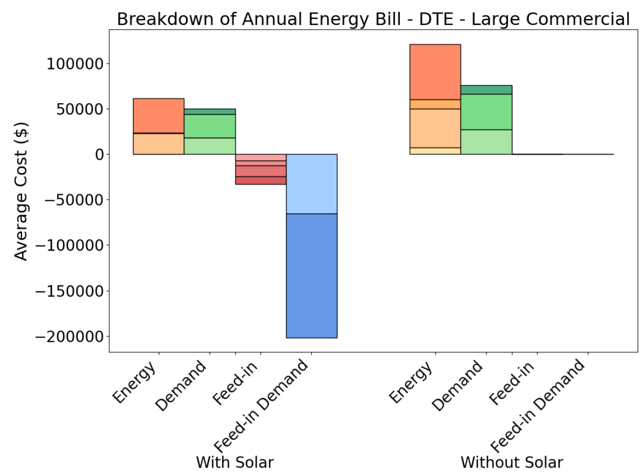
(a) CE Small Commercial



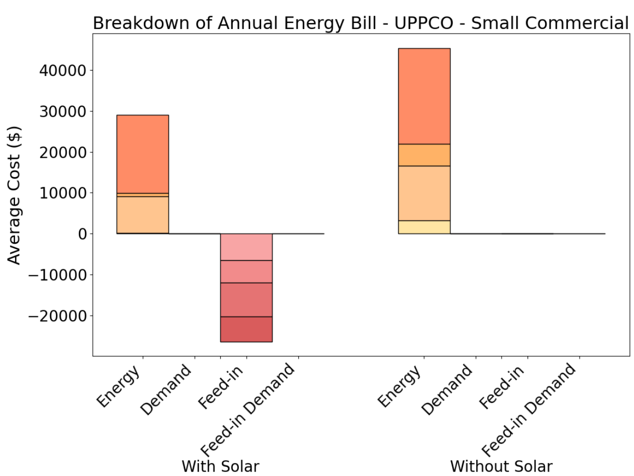
(b) CE Large Commercial



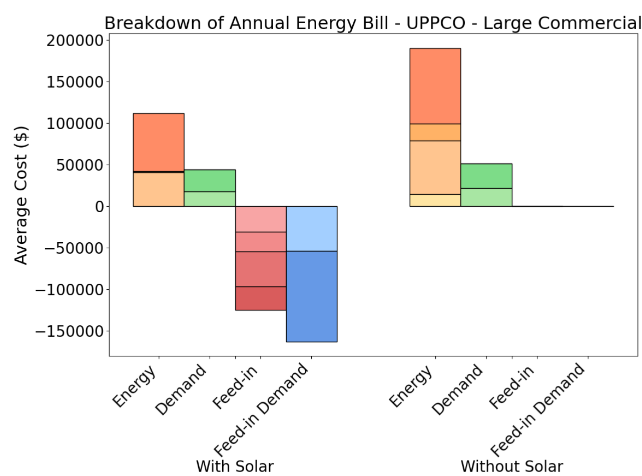
(c) DTE Small Commercial



(d) DTE Large Commercial



(e) UPPCO Small Commercial

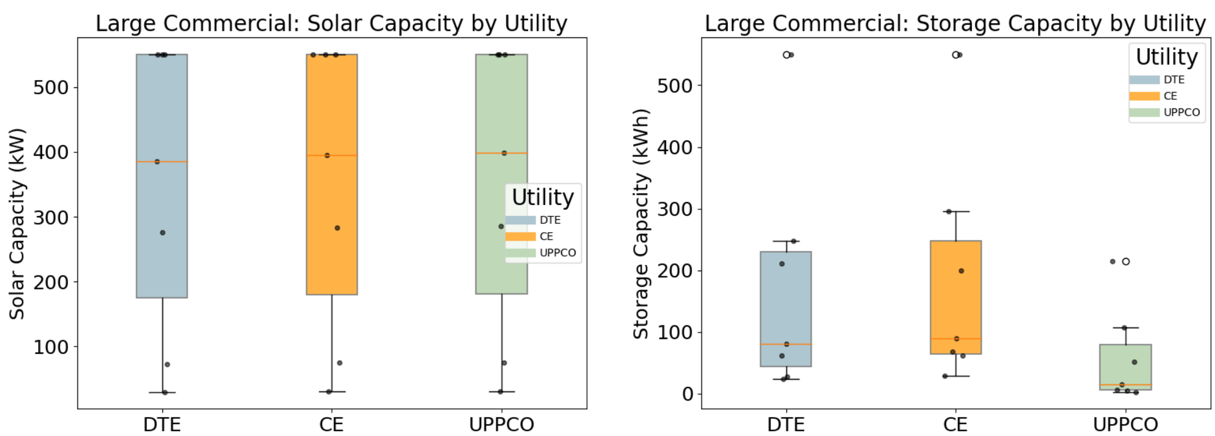


(f) UPPCO Large Commercial

Figure 4: Breakdown of energy usage and cost results for Small and Large Commercial buildings under CE, DTE, and UPPCO utilities with unconstrained solar capacity.

Results for Commercial in the Constrained Case

The subsequent results focus on commercial properties under the constrained case. Similar to the unconstrained case, we begin with box plots illustrating the installed solar and storage capacities for both large and small commercial buildings. As shown in Figure 5, large commercial properties again install comparable amounts of solar capacity across all utilities. For further details on the average solar and storage installed for large commercial look at Table 8. However, storage adoption follows the same pattern observed previously: CE exhibits the highest levels of storage installation, followed closely by DTE, with UPPCO installing the least. This outcome can be attributed to differences in demand charges, which are highest for CE, moderate for DTE, and lowest for UPPCO. Accordingly, greater storage capacity is incentivized where higher demand charges make it economically advantageous to shift load and reduce peak demand.



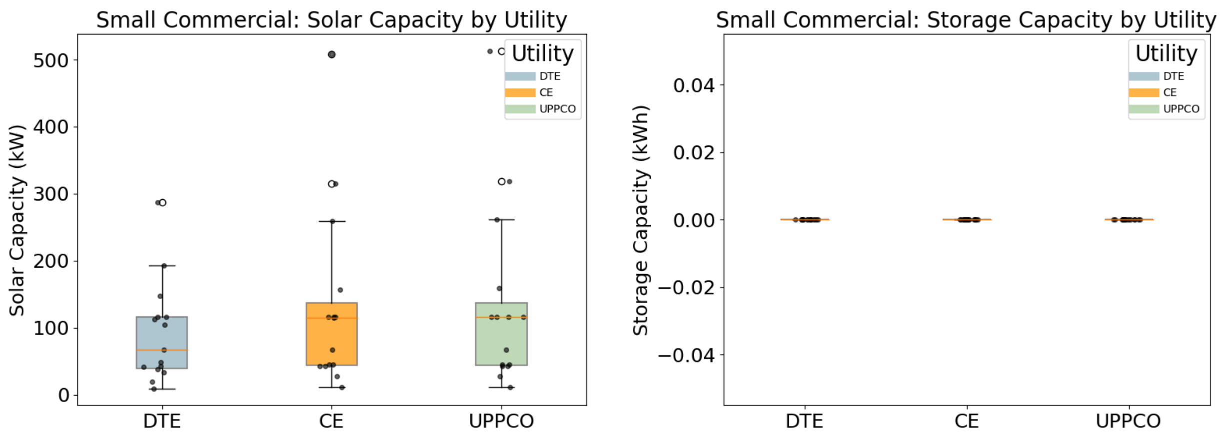
(a) Large Commercial Solar Capacity by Utility (b) Large Commercial Storage Capacity by Utility

Figure 5: Large commercial property box plots for installed solar capacity and energy storage for all utilities (constrained).

Utility	Avg. Solar Capacity (kW)	Avg. Storage Capacity (kWh)
CE	347.8552529	184.7622111
DTE	345.1197506	171.5220155
UP	348.8118085	57.38601765

Table 8: Constrained Case – Large Commercial: Average Solar and Storage Capacity Across Utilities

Looking at Figure 6, we see box plots of solar and storage capacities for small commercial properties under the constrained case. The details for small commercial for averages of solar and storage installed can be seen in Table 9. The results closely mirror those of the unconstrained scenario, since the capacities required by small commercial properties do not exceed the 550 kW limit. As before, no property installs storage, and CE and UPPCO install similar amounts of solar capacity, both a tiny bit higher than DTE.



(a) Small Commercial Solar Capacity by Utility (b) Small Commercial Storage Capacity by Utility

Figure 6: Small Commercial property box plots for installed solar capacity and energy storage for all utilities (constrained).

Utility	Avg. Solar Capacity (kW)	Avg. Storage Capacity (kWh)
CE	131.9096723	0
DTE	91.42726937	0
UP	132.7567069	0

Table 9: Constrained Case – Small Commercial: Average Solar and Storage Capacity Across Utilities

Table 10 presents the breakdown of the annual average bill ($) and average peak demand (kW) for all utilities and for small and large commercial buildings under the capacity-constrained scenarios, comparing cases where behind-the-meter solar is installed versus not installed. Table 11 shows the reductions between the two scenarios, illustrating that when solar is constrained, the average bill remains lower for examined commercial building types in all three utility service territories. For small commercial properties, UPPCO achieves the greatest annual savings while DTE sees the least, consistent with the unconstrained case. For large commercial properties, CE exhibits the largest annual savings at $116,703.80, followed by UPPCO, with DTE again having the smallest savings. Notably, the electricity bill is no longer negative for large commercial, as observed in the commercial properties under the unconstrained case, because less solar can be fed back into the system under the 550 kW capacity limit. All utilities and building types show a decrease in peak demand, with reductions ranging from 2.25 to 2.53 kW for small commercial properties and from 64.42 to 96.32 kW for large commercial properties. The much larger reductions observed for large commercial customers are due to their higher energy consumption and the presence of demand charges, which incentivize load shifting across time to minimize peak demand. Consequently, large commercial customers experience greater cost savings and larger peak demand reductions compared to small commercial customers, reflecting their higher electricity usage and their incentive to shift demand due to demand charges.

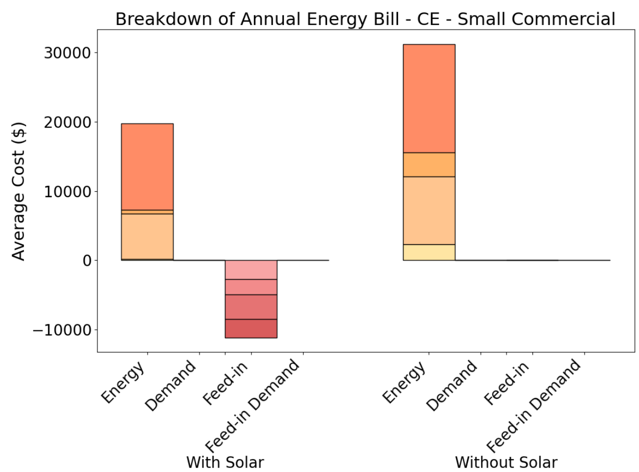
Table 10: Annual Commercial Results (Constrained)

Utility	Building Type	Solar Status	Avg. Electricity Bill ($)	Avg. Peak Demand (kW)
CE	Small	Solar	8,609.49	58.15
		No Solar	31,207.33	60.40
CE	Large	Solar	91,294.88	346.71
		No Solar	207,998.66	443.02
DTE	Small	Solar	12,180.00	57.87
		No Solar	26,531.09	60.40
DTE	Large	Solar	93,760.13	347.33
		No Solar	196,743.96	443.02
UPPCO	Small	Solar	2,657.41	58.11
		No Solar	45,305.21	60.40
UPPCO	Large	Solar	135,611.24	378.60
		No Solar	241,826.40	443.02

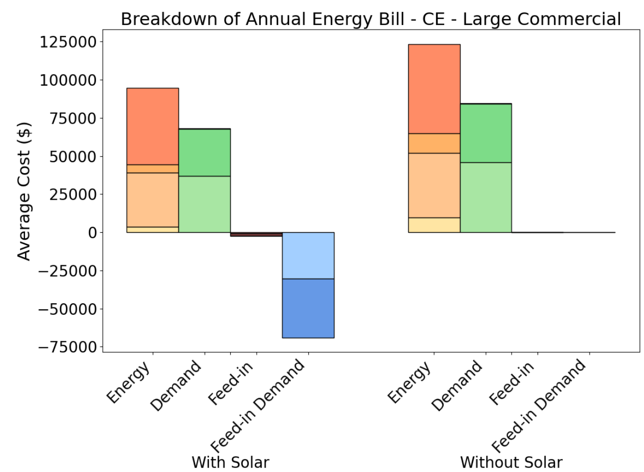
Table 11: Commercial: Annual Reductions and Lifetime Comparison (Constrained)

Utility	Building Type	Avg. Electricity Bill Reduction ($/Year)	Avg. Peak Demand Reduction (kW/Year)	Avg. Total System Cost ($)	Avg.Total 25-Year Bill Savings ($)
CE	Small	22,597.84	2.25	412,877.27	564,946.00
	Large	116,703.78	96.32	1,162,691.83	2,917,595.00
DTE	Small	14,351.09	2.53	286,167.35	358,777.25
	Large	102,983.83	95.69	1,148,833.66	2,574,595.00
UPPCO	Small	42,647.80	2.29	415,528.49	1,066,195.00
	Large	106,215.16	64.42	1,114,735.37	2,655,375.00

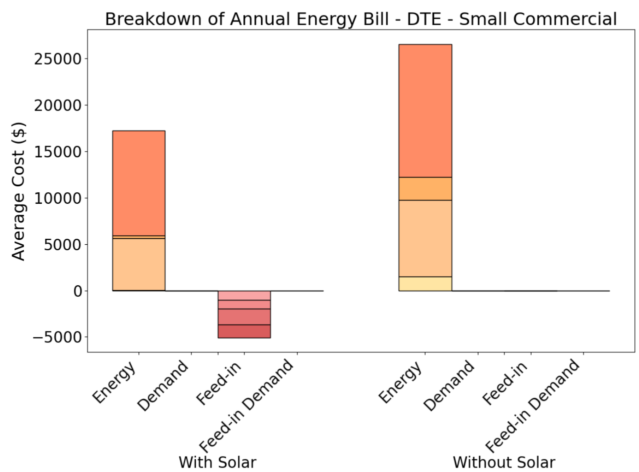
Similar to the commercial under the unconstrained case, Figure 4 provides a detailed view of the electricity bill, breaking it down into energy charge, demand charge, feed-in credit (outflow credit), and feed-in demand for the two scenarios (with and without solar) and across the different time-of-use periods. Under the constrained commercial case, we again observe lower feed-in credits due to the 550 kW solar capacity limit. However, there is still an overall decrease in the energy charge and feed-in credit when properties install solar. For large commercial customers, we also see a reduction in demand charges with solar installation compared to no solar, along with feed-in demand benefits, which further reduce the overall electricity bill.



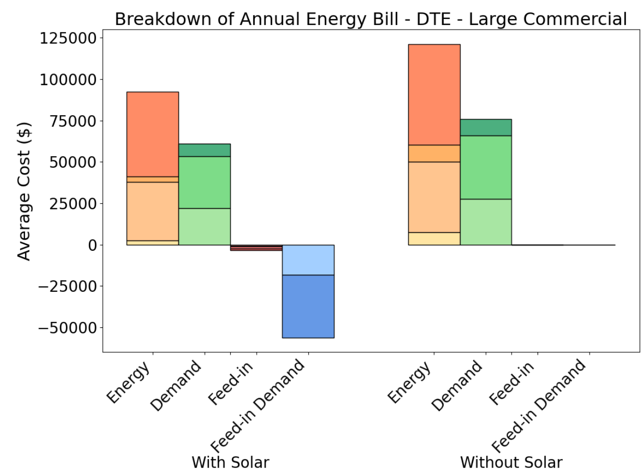
(a) CE Small Commercial



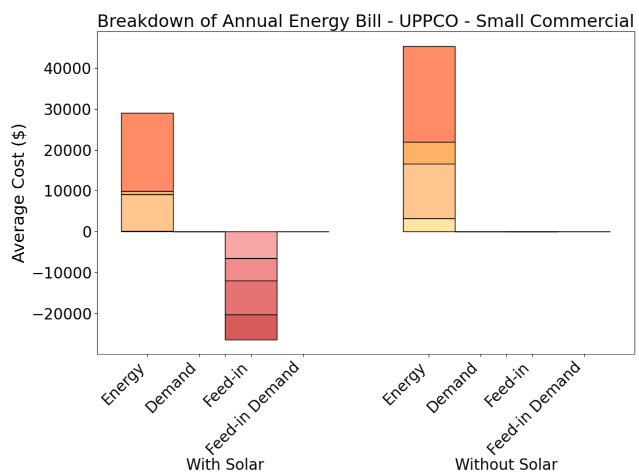
(b) CE Large Commercial



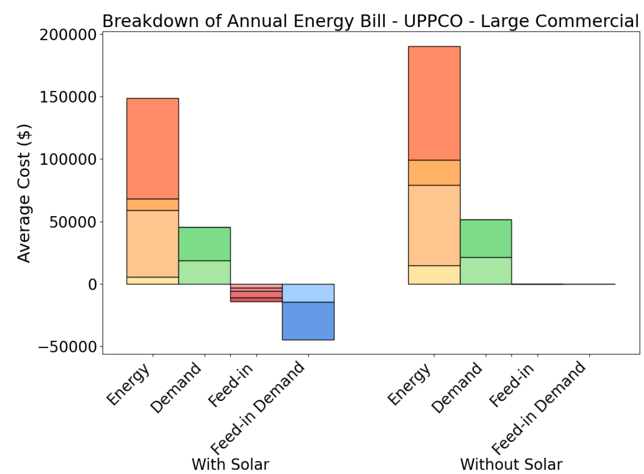
(c) DTE Small Commercial



(d) DTE Large Commercial



(e) UPPCO Small Commercial



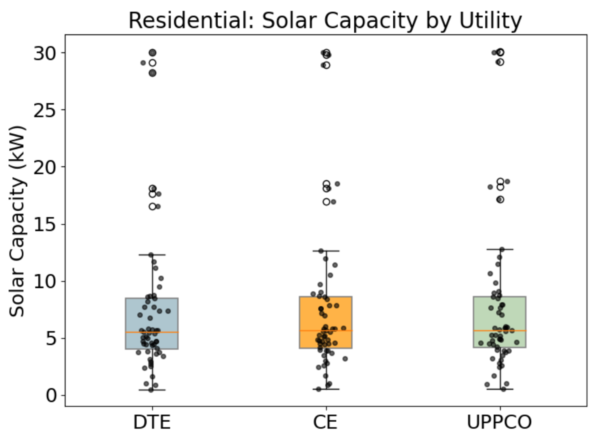
(f) UPPCO Large Commercial

Figure 7: Breakdown of energy usage and cost results for Small and Large Commercial buildings under CE, DTE, and UPPCO utilities with constrained solar capacity. (Constrained)

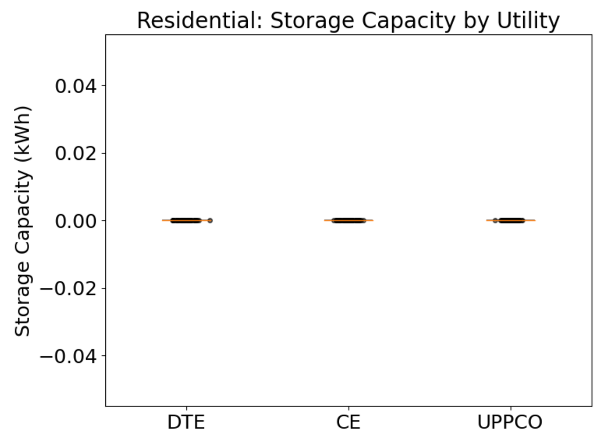
Results for Residential in the Unconstrained Case

In the section below, we present the residential results for the unconstrained case, where residential properties are not limited in the amount of solar they can install. Instead, properties can install as much solar capacity as they want, as long as it fits within the available rooftop square footage.

To begin, we show box plots for the installed solar and energy storage capacities for each property under each utility. From Figure 8a, we see that most properties install a median solar capacity of slightly above 5 kW, although some properties install up to 30 kW. All utilities install relatively similar amounts of solar for their properties, and from Figure 8b none of the residential properties under any utility are economically incentivized to install storage. It is important to note that this analysis only considers economic incentives. Other factors, such as environmental and energy resilience benefits, are not considered.



(a) Residential Solar Capacity by Utility



(b) Residential Storage Capacity by Utility

Figure 8: Box plots for installed solar capacity and energy storage for residential properties for all utilities (unconstrained).

The effect of installing behind-the-meter solar on the electricity bill and peak demand is shown in Table 12, while the reductions in electricity bill and peak demand between the solar and no-solar scenarios are presented in Table 13. We observe that UPPCO exhibits a negative average electricity bill when solar is installed. All utilities experience a decrease in the average annual electricity bill with solar installation, with UPPCO achieving the largest reduction—approximately $800 more annually than CE and DTE, which show similar reductions. UPPCO customers realize the greatest electricity bill savings because their retail electricity rates are higher than those of DTE and CE, meaning each kilowatt of solar installed offsets more cost, and the feed-in compensation is more favorable. Additionally, all three utilities exhibit a slight decrease in annual peak demand, ranging from 0.26 to 0.29 kW.

Table 12: Annual Residential Results (Unconstrained)

Utility	Solar Status	Avg. Electricity Bill ($/Year)	Avg. Peak Demand (kW)
CE	Solar	366.35	6.79
	No Solar	1,819.27	7.07
DTE	Solar	366.75	6.78
	No Solar	1,774.80	7.07
UPPCO	Solar	(131.02)	6.81
	No Solar	2,283.23	7.07

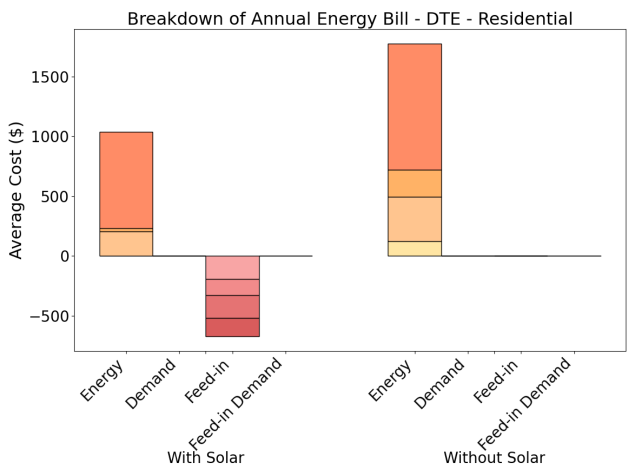
Note: Values in parentheses correspond to negative values.

Table 13: Residential: Annual Reductions and Lifetime Comparison (Unconstrained)

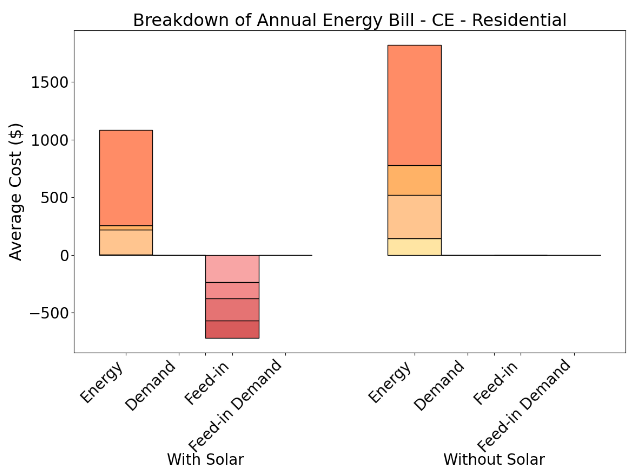
Utility	Avg. Bill Reduction ($/Year)	Avg. Peak Demand Reduction (kW/Year)	Avg. Total System Cost ($)	Avg. Total 25-Year Bill Savings ($)
CE	1,452.92	0.28	23,886.70	36,332.00
DTE	1,408.05	0.29	23,362.69	35,201.25
UPPCO	2,414.25	0.26	24,069.93	60,356.50

In Figure 9, we observe the effects of installing solar on the specific components of the electricity bill, particularly the energy charge and the feed-in credit (outflow credit), since residential customers do not have a demand charge for either electricity or feed-in (outflow). The figure shows that, for all utilities, installing solar reduces the energy charge and provides additional benefits from the feed-in credit. These components are further broken down by time-of-use (TOU), distinguishing between on-peak and off-peak periods as well as summer and non-summer months. In particular, we observe a substantial decrease in both the on-peak summer and on-peak non-summer energy charges, although decreases occur across all periods.

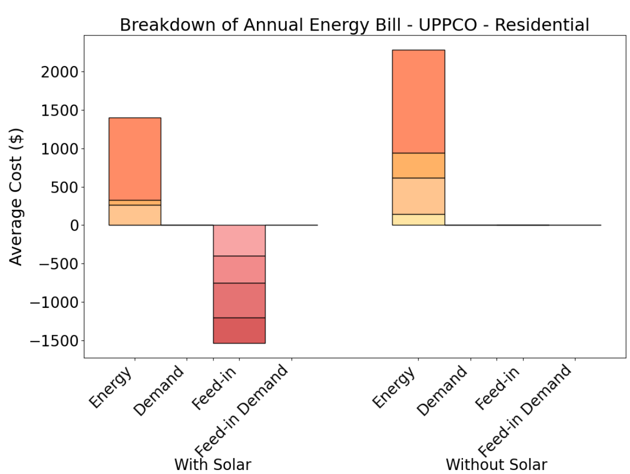
For residential buildings with unconstrained solar capacity, approximately 50 to 60% of the solar energy generated is fed back into the grid. When examining results by individual residential building types, we observe very small differences in electricity bill savings across the different types, especially compared to the variations seen among commercial buildings. There are no clear trends between single-family and multi-family buildings. Even within multi-family buildings, some of the highest and lowest energy savings occur for the same building type. See the Appendix for detailed information on individual residential buildings. A more significant factor for residential buildings is electric heating, as properties with electric heating tend to experience smaller electricity bill reductions.



(a) DTE utility



(b) CE utility

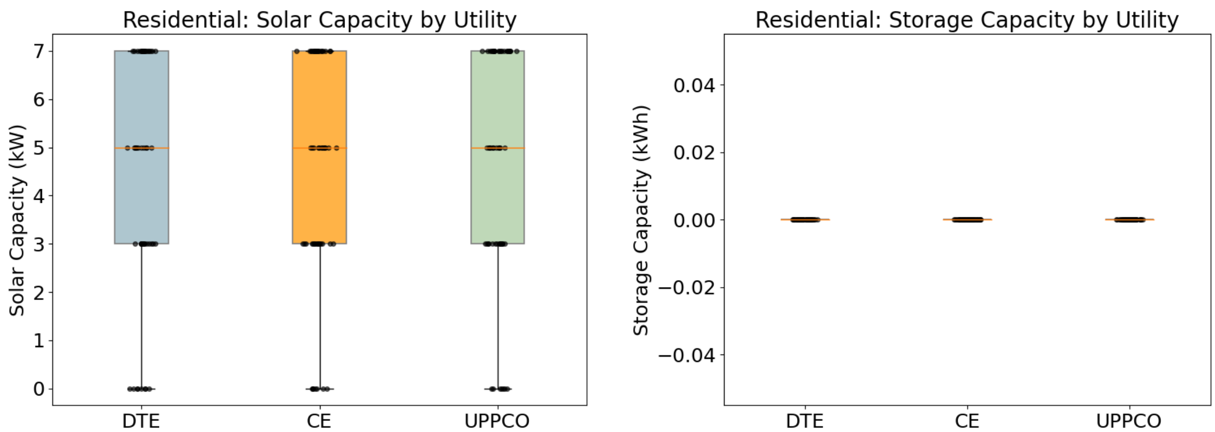


(c) UPPCO utility

Figure 9: Breakdown of energy usage and cost results for utilities (DTE, CE, UPPCO) with and without solar under unconstrained solar (Unconstrained).

Results for Residential in the Constrained Case

This final results section presents the findings for constrained residential properties, where the solar capacity for each property is limited to deterministic values of {0, 3, 5, 7} kW. From Figure 10a, we see a box plot showing the solar capacities installed for each property across the three utilities. The box plot indicates that similar amounts of solar are installed across all utilities, with different properties installing the four deterministic capacity levels. Meanwhile, Figure 10b shows that no storage is installed by residential properties, as they do not incur a demand charge.



(a) Residential Solar Capacity by Utility (b) Residential Storage Capacity by Utility

Figure 10: Box plots for installed solar capacity and energy storage for residential properties for all utilities (constrained).

Next, we examine the impacts of installing solar on residential properties across the different utilities by comparing the average annual electricity bill and peak demand with and without solar. From Table 14, the average electricity bill after solar installation is relatively similar across all three utilities, ranging from \$842.46 to \$882.70. The average peak demand with solar is nearly identical for CE and DTE at 6.81 kW, and slightly higher for UPPCO at 6.82 kW.

Table 15 shows that all utilities experience decreases in both average electricity bill and peak demand, with UPPCO achieving the largest savings, similar to the unconstrained case, likely due to its higher electricity rates for all times.

Table 14: Annual Residential Results (Constrained)

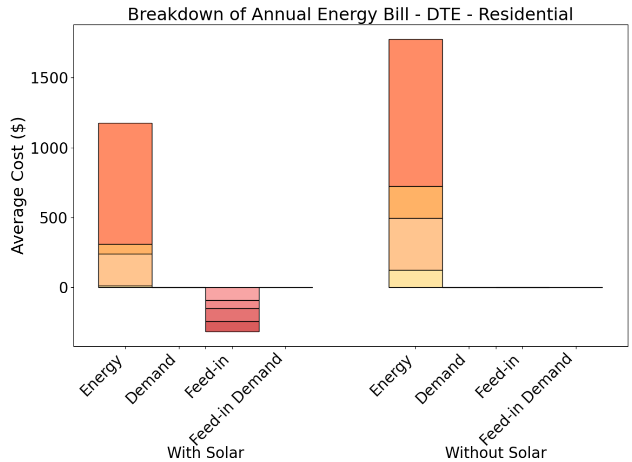
Utility	Solar Status	Avg. Electricity Bill ($/Year)	Avg. Peak Demand (kW)
CE	Solar	881.70	6.81
	No Solar	1,819.27	7.07
DTE	Solar	859.51	6.81
	No Solar	1,774.80	7.07
UPPCO	Solar	842.46	6.82
	No Solar	2,283.24	7.07

Table 15: Residential: Annual Reductions and Lifetime Comparison (Constrained)

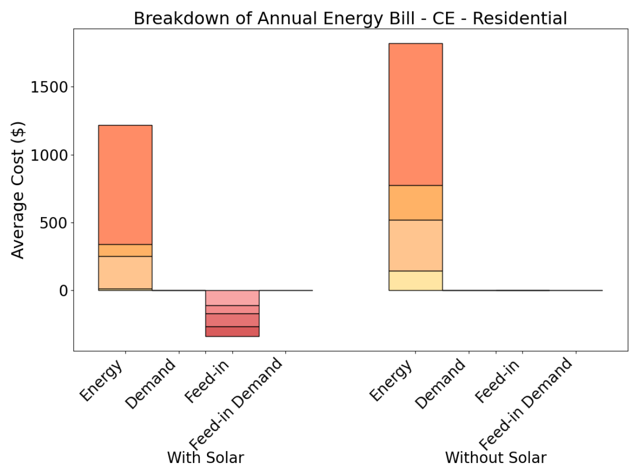
Utility	Avg. Electricity Bill Reduction ($/Year)	Avg. Peak Demand Reduction (kW/Year)	Avg. Total System Cost ($)	Avg. Total 25-Year Bill Savings ($)
CE	937.57	0.25	14,252.68	23,439.50
DTE	915.29	0.26	13,973.21	22,882.25
UPPCO	1,440.78	0.24	14,364.46	36,019.50

To examine the specific composition of the electricity bill with and without solar for residential properties with constrained solar capacity, see Figure 11. The figure shows the breakdown of the electricity bill into energy charges and feed-in credits, with quantities shown for on-peak/off-peak periods and summer/non-summer months, consistent with the other results. From the figure, we observe that for all utilities, installing solar reduces the energy charge, particularly for on-peak summer and non-summer periods. Additionally, solar is fed back into the grid for all utilities when solar is installed, with UPPCO exhibiting the largest feed-in quantities.

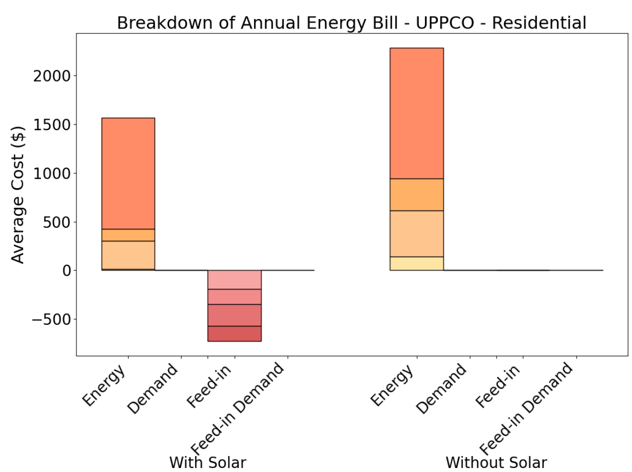
From a broader perspective, for residential properties with solar capacity capped at deterministic values, only 35 to 55% of the generated solar is fed into the grid, which is lower than in the unconstrained case.



(a) DTE utility



(b) CE utility



(c) UPPCO utility

Figure 11: Breakdown of energy usage and cost results for utilities (DTE, CE, UPPCO) with and without solar under constrained solar (constrained).

Conclusion

To summarize the results, all building types, residential, small commercial, and large commercial, experience substantial savings with solar installation in Michigan for the three examined utilities. The largest savings are observed in large commercial buildings due to their high energy consumption and the ability to reduce peak demand, which decreases costs because they are the only building type examined subject to demand charges. Among the utilities, the greatest energy savings for both commercial and residential buildings occur under UPPCO, except for constrained large commercial buildings, where CE achieves the highest savings. Large commercial buildings are the only type that consistently incentivize the installation of storage; specifically, CE's large commercial buildings install the most storage capacity, while UPPCO installs the least. Overall, both commercial and residential buildings achieve a high percentage of solar energy fed back into the grid, particularly under unconstrained scenarios.

Appendix

Table 16: Annual Results for Individual Residential Properties

Property	Building Type	Avg. Electricity Bill (Solar) ($/Year)	Avg. Electricity Bill (No Solar) ($/Year)	Avg. Bill Reduction ($/Year)
21	Single-Family Detached	340.09	1025.37	685.28
28	Single-Family Detached	219.30	625.06	405.77
46	Single-Family Detached	176.35	498.81	322.46
119	Multi-Family (20 to 49 Units)	117.62	312.79	195.17
232	Single-Family Detached	643.79	1927.68	1283.89
292	Single-Family Detached	189.18	549.24	360.07
415	Single-Family Detached	131.68	539.50	407.82
522	Multi-Family (20 to 49 Units)	140.86	408.93	268.07
579	Single-Family Detached	182.18	565.33	383.15
597	Single-Family Detached	232.16	554.53	322.37
644	Multi-Family (20 to 49 Units)	712.21	523.90	-188.31
784	Multi-Family (10 to 19 Units)	134.43	552.59	418.15
965	Single-Family Attached	236.88	605.30	368.42
1043	Single-Family Detached	62.56	249.89	187.33
1113	Single-Family Detached	286.73	796.17	509.44
1118	Multi-Family (10 to 19 Units)	682.26	513.06	-169.20
1204	Single-Family Detached	99.13	314.06	214.93
1207	Single-Family Detached	267.05	1060.27	793.22
1703	Single-Family Detached	138.18	508.82	370.64
1777	Single-Family Attached	172.50	720.56	548.06
1916	Single-Family Detached	206.64	434.74	228.11
1923	Mobile Home	189.16	656.20	467.04
2067	Multi-Family (3 or 4 Units)	794.26	775.42	-18.84
2305	Mobile Home	164.73	356.87	192.14
2350	Multi-Family (5 to 9 Units)	391.55	558.29	166.74
2648	Single-Family Detached	3653.05	2590.66	-1062.39
2671	Single-Family Detached	370.41	1132.72	762.31
2850	Single-Family Detached	1484.19	1316.89	-167.30
3123	Single-Family Detached	271.78	820.31	548.53
3233	Single-Family Detached	287.01	775.72	488.71
3366	Single-Family Detached	86.00	305.70	219.70
3863	Single-Family Detached	659.05	1927.21	1268.16
5545	Single-Family Detached	265.30	1063.71	798.41
6069	Single-Family Detached	162.99	517.91	354.92
6699	Single-Family Detached	312.79	1097.56	784.76
6756	Single-Family Detached	591.57	635.37	43.80
6791	Single-Family Detached	1408.87	1573.04	164.17
7774	Single-Family Detached	741.57	1319.45	577.88
8922	Single-Family Detached	312.80	1079.27	766.47
20943	Multi-Family (5 to 9 Units)	156.45	394.89	238.44
67771	Single-Family Detached	216.55	579.86	363.31
68198	Single-Family Detached	417.96	1414.69	996.73
79010	Single-Family Detached	37.97	141.61	103.63
120014	Multi-Family (10 to 19 Units)	116.06	337.53	221.48
135718	Multi-Family (50 or More Units)	161.47	438.24	276.77
179915	Multi-Family (50 or More Units)	88.82	343.05	254.23
1390	Mobile Home	175.37	689.72	514.35
2585	Multi-Family (5+ Units)	337.69	869.99	532.31
3386	Mobile Home	166.99	598.93	431.94
3439	Multi-Family (5+ Units)	17.89	65.83	47.94
5359	Mobile Home	182.80	637.44	454.65
6464	Multi-Family (5+ Units)	37.60	107.12	69.53
6610	Multi-Family (5+ Units)	292.53	528.36	235.82
6643	Mobile Home	180.03	462.76	282.73
9580	Multi-Family (5+ Units)	249.56	471.28	221.72
18135	Mobile Home	183.21	663.72	480.51