Household cost-effectiveness of Tesla's Powerwall and Solar Roof across America's zip code tabulation areas

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ABSTRACT

In this paper, we develop a cost-benefit model to study cost-effectiveness by zip code of purchasing one particular model of a rooftop solar installation, the Tesla solar roof and Powerwall. The Tesla solar roof and Powerwall is a solar roofing installation paired with a housing-unit scale power storage device. Tesla's model was selected due to high brand profile, the mixture of solar rooftop generation with battery storage, and the economies of scale granted by Tesla's battery production capacities. Our model compares an eight-year forecast of electricity usage for control households against a eight-year forecast of generation revenue and capital expenditures for households which purchase Tesla's Solar Roof/Powerwall. We model four different scenarios: direct purchase with no subsidies, direct purchase with federal subsidies, direct purchase with federal and hypothetical California-style subsidies, and under Tesla's leasing agreement. We find that zip codes in the arid, sunny Southwest have the highest cost-effectiveness, while Appalachia and western Washington have the lowest cost-effectiveness, due to low prices and low solar irradiance, respectively. We discuss the impact of different subsidy models on cost-effectiveness, and briefly describe policy interventions that can be taken to increase adoption in areas with carbon intensity.

Keywords: solar energy, household energy storage, cost benefit analysis, tesla, powerwall, solar roof

1. Introduction

Over the past decade, the United States has seen a consistent yearly decline in the pre-subsidy price of solar panels alongside a concurrent rise in the rate of rooftop solar unit installations, with installation rates peaking in 2016, when solar represented 40% of all new electric capacity added countrywide [1]. For many homeowners, a rooftop solar panel installation is starting to appear financially within reach.

However, there are manifold considerations that need to be taken into account when evaluating the cost-effectiveness of buying a rooftop solar installation. Households must take into account average rates of sun exposure, what subsidies are available, electricity prices, and more; as far as purchasing choices go, rooftop solar is a thoroughly complex one.

In this paper, we constructed an intuitive model to study the cost-effectiveness by zip code tabulation area (ZCTA) of purchasing one particular model of a rooftop solar installation, the Tesla Solar Roof and Powerwall. We selected the Tesla model due to its high brand profile, its mixture of battery storage technology with rooftop solar, and due to the economies of scale obtained for these models from the newly operative Tesla battery Gigafactories.

Our model compares an eight-year forecast of electricity usage for control households against an eight-year forecast of generation revenue and capital expenditures for households which purchase the powerwall and solar roofing combination. We analyze cost-benefit of adopter households compared to control households across zip codes, and produce a cost-benefit estimation of purchasing for a given household in any given ZCTA. We provide CBA estimations for four different scenarios: **1)** direct purchase of Solar Roof and Powerwall with no incentives, **2)** direct purchase with the current federal solar investment tax credit, **3)** direct purchase with current federal incentives and with Californian-style incentives (specifically those offered by the Los Angeles Department of Power and Water), and **4)** leasing of the solar roof from Tesla.

We apply the model to an aggregate dataset we constructed that contains data for each zip code tabulation area enumerated by the U.S. Census. This dataset includes data from four disparate sources.

Firstly, it includes data from Google's Project Sunroof, which uses machine learning for roof segmentation on Google Maps' extensive satellite imagery to compute average roof surface area by ZCTA.

Secondly, we included Direct Normal Irradiance data from the National Renewable Energy Laboratory (NREL). Though the data was provided as a raster (pixelated) image and therefore not associated to each ZCTA, we computed this association using zonal statistics.

Thirdly, we obtained the population and number of housing units in each ZCTA—used to calculate housing density—from the U.S. Census.

Finally, we computed electricity prices by ZCTA using two datasets compiled by NREL that described the utility companies operating in each ZCTA and the average prices of their plans. We assumed, through basic competition theory, that the electricity price of each ZCTA was the mean of the average prices offered by the utility companies operating in that zip code.

We find a number of general geographical trends from our analysis. Generally speaking, the sunny, arid Southwest has the highest benefit-to-cost ratio, with high average irradiance and thus high return on solar roofing. Places like Hawa'ii with steep electricity pricing also experiences a high benefit-to-cost ratio. We found that Appalachia and Virginia, with low electricity prices and average to below-average irradiance compared to the nation as a whole, tends to have the lowest cost-to-benefit ratio. Western Washington, with low weather-adjusted irradiance, also has a very low cost-benefit ratio. Further, we find that while federal incentives generally improve cost effectiveness, the same areas that are cost-ineffective in the no incentive scenario tend to remain cost-ineffective. Finally, our model found that Tesla's leasing option makes installation the least cost-effective over the eight year period for the average household, compared to a non-installer and compared to direct purchase, in virtually every county, excepting only a small handful of outliers.

Our paper draws on and contributes to a growing literature discussing the economics of solar rooftop paneling adoption. A number of papers contribute to our understanding of adoption rates. Delmas, Khan, and Locke describe how unrelated benefits like vehicle safety in Teslas increases not just adoption of electric cars, but seemingly unrelated green technology like rooftop solar [2]. Curtius, et. al. find that rooftop solar adoption often occurs through a snowball effect, with large-scale adoption occurring after a critical mass of adoption is attained in a smaller, central part of a region [3]. Our actor analysis of adopters is also influenced by Zhang, et. al., who use advanced statistical analysis to model agent behavior as it relates to solar roofing adoption [4]. Sunter, et. al. also illustrates why the possibility that political affiliation serves as a discount rate may be discounted in our analysis, as they found little evidence in the revealed preferences of voters of partisanship impacting their preference for adoption [5]. Our usage of satellite data on irradiance to determine roof yield is influenced by Gangnon, et. al. [6], who found that while the vast majority of single-family housing units are suitable for solar roof adoption, only 26% of roofing space is usable. Finally, our paper contributes to the growing body of literature that analyzes cost-benefit on a regional level, alongside a paper using Hillshade analysis of Seoul by Hong, et. al. [7], and a regional analysis of adoption around Mumbai by Singh and Banerjee [8].

The paper is structured into five sections. Section 2 will describe the context and considerations of our model. Section 3 will discuss our cost-benefit analysis model in depth. Section 4 will describe limitations to our model. Section 5 will explain our conclusions.

2. Background

2.1. Tesla Powerwall

In 2015, Tesla announced two rechargeable stationary energy storage products: Powerpack and Powerwall. Both are lithium-ion batteries, but the former is designed for use as components of the electric grid, while the latter is intended for home energy storage.

The rectangular wall or floor-mounted first-generation Powerwall, called Powerwall 1, was intended to have two variants with different total capacities; one rated at 7 kWh, the other at 10 kWh. By the next year, however, Tesla phased out the 10 kWh option.

The 7kWh Powerwall was priced at 3,000 USD, and was highly received by the market, with many users praising the compactness of the product [9]. Orders for the first-generation Powerwall exceeded production capacity by several months, and in the first quarter of 2016, over 2,500 powerwalls were delivered.

In October 2016, Tesla introduced its second generation Powerwall [10]. Powerwall 2, as it is called, is slightly smaller than its predecessor at 1150 mm x 755 mm x 155 mm dimensions, but has double the capacity with 14 kWh of total energy storage or 13.5 kWh of usable storage. Like its predecessor, Powerwall 2 uses lithium nickel manganese cobalt oxide cathodes.

Its price has fluctuated since the announcement and as of December 1, 2018 costs 6,700 USD [11, 12]. The cost does not include the 1,000 to 3,000 USD installation cost along with 1,100 USD in supporting hardware. The cost for the supporting hardware covers the Backup Gateway, which allows the Powerwall to serve as a source for partial or full backup power [13].

Powerwall 2 is designed to store energy from home generated solar energy, and can serve as a backup power source with or without solar power. Like other Tesla products including the Model S, the Powerwall can be controlled remotely through the Tesla app and periodically receives updates from the company through a recommended internet connection. Though Tesla has not released how many cycles the Powerwall can be charged, the product has an ten-year warranty [12].

2.2. Tesla Solar Roof

Tesla announced a solar roof product in October 2016. The roof is composed of 8.65×14 inch tough glass tiles that can generate energy while still looking like their normal counterparts, due to random perturbations purposefully introduced in the manufacturing process.

Tesla says that the solar roof costs \$21.85 per square foot, but this estimate could vary depending on location and installation costs [14].

3. Cost Benefit Analysis

3.1. Overview

The goal of this paper is to determine if a full Solar Roof/Two Powerwall installation has a positive net value for a household over an eight year period. Our cost-benefit analysis will compare two scenarios for a household United States: a house solely reliant on the grid for electricity (without situation) and a house with a full Solar Roof/two Powerwalls (with situation). This particular configuration was chosen because it corresponds to Tesla's default configuration for households. Future analysis should optimize each building or zone's Solar Roof/Powerwall configuration to match expected electricity consumption patterns. As presented, this analysis assumes that no building generates electricity in excess of their long term average consumption rate–that is, no buildings are required to feed electricity back into the grid via a net metering pattern. Under this assumption, a Solar Roof/Powerwall configuration generates value for a household by reducing electricity consumption from the grid.

The costs and benefits of a Solar Roof/Powerwall configuration will be considered over a eight-year period starting from the present day (late 2018). This period was chosen because it corresponds to the median length of time Americans live in the same house [15]. As will be discussed below, the Powerwall/Solar Roof will generate costs and revenues during this eight year period. These cash flows will be discounted using the yield on the 1-Year Treasury Bill to determine their present net value in our cost-benefit calculations.

In this analysis, benefits and costs are considered solely at the household level. Considerations of national energy security, national materials security, and environmental impact (among other factors) are disincluded from the model. Instead, these broader costs and benefits are considered in the model analysis, limitations, and policy discussion section.

Households, aggregated within a given zip code, are considered throughout the United States to demonstrate the wide range of net values that the Solar Roof/Powerwall might present at the household level. Data related to the Powerwall/Solar Roof products themselves was taken from Tesla's technical product specifications page where possible. Geographic data was taken from multiple datasets, including Google's Project Sunroof and the National Renewable Energy Laboratory's Geographic Information System [16]. Economic data, including interest rates and inflation, were taken from the St. Louis Federal Reserve Economic Data (FRED) collection.

When possible, confidence intervals were taken from technical product specifications. Where this was not possible, confidence intervals for discrete variables with outliers (e.g. roof size) were determined using interquartile range (IQR) assessments. For continuous variables (e.g. interest rates), confidence intervals were determined with historical minimums/maximums.

The analysis that follows has two principle sources of uncertainty: (1) estimation uncertainty for the model inputs and (2) uncertainty about future events in the design of the model itself. In the former case, confidence intervals were chosen to represent the great majority (in excess of 90%) of historical observations. In the latter case, the underlying uncertainty of future events in this model is difficult to root out because of the lack of long-term performance data available for Tesla's products. As such, estimates of efficiency and performance over time are especially rough.

The following two sections of this cost benefit analysis will discuss the forms of the models used. The principle variables discussed will be summarized in a table along with their estimated confidence intervals. Last, the final forms of the models will be summarized at the end of the cost benefit analysis.

3.2. Cost Benefit Model for Households Dependent on the Grid

For homes without the Solar Roof/Powerwall, all electricity consumption is drawn from the grid. In this case, the net cost to the household will be the product of the price per kilowatt-hour of electricity P_t and the total number of kilowatt-hours of electricity consumed C_t in a given year. Electricity prices by zip code are aggregated from data gathered by NREL [17]. This stream of costs is discounted over the eight year period of the analysis using forecasted 1-Year Treasury interest rates from data given by the FRED collection.

$$Net\ Cost = \Sigma_{i=1}^{T} \frac{CP_t}{(1+R)^t} \tag{0}$$

3.3. Cost Benefit Model for Households with Solar Roof/Powerwall

Households with the Solar Roof/Powerwall are able to generate their own electricity and store it for future use, up to the capacity of the battery. Although installation and operation of the necessary equipment present new costs to the household, electricity consumption from the municipal grid by these households will be reduced by the amount of electricity they are able to generate and consume at a later point. This analysis assumes that households cover their entire roof with solar cells and purchase two Powerwall units (as recommended by Tesla) that are not equipped for net metering. As such, this model assumes that households consume electricity in average of what they generate over long periods of time. The model further assumes that roofs are unobstructed by objects (e.g. chimneys or trees) that may reduce direct solar irradiance.

Energy generation from the solar roof is dependent on several variables, expressed in equation (1). The total incident solar energy on a roof is given as the product of roof surface area

A and the average solar irradiance I in a given county. Median roof surface area data by zip code is aggregated using Google Project Sunroof data. It should be noted that solar irradiance varies significantly with geography and weather [16]. The National Renewable Energy Laboratory (NREL) dataset used in this analysis provides expected daily solar irradiance for four square kilometer surface cells calculated using weather models and satellite/ground data collected from 1998-2009[18]. The cost-benefit analysis present here relies on NREL's model for finding the weather-adjusted expected value for solar irradiance at a given location.

The Solar Roof and Powerwall have efficiencies lower than 100%, even under ideal conditions. The conversion efficiency factor ESR of the Solar Roof is stated by Panasonic to be 19.7% for the N330 HIT cells used in the Solar Roof tiles [19]. For simplicity, we assume that all energy generated by the Solar Roof is first cycled through the Powerwall before being drawn for use. As a result, the Solar Roof/Powerwall combination have an additional round-trip efficiency factor EPW, stated to be 90% on Tesla's Powerwall specifications data [12].

Finally, we estimate the market price P_t of the generated electricity using the same grid prices from NREL aggregated by zip code used in the grid-dependent household model [17]. This rate is assumed to increase over the eight year period being considered at the average annualized rate of national electricity price changes between 2007 and 2017. The market values for this stream of generated electricity are discounted back to the present using the same FRED forecasted 1-Year Treasury interest rates used in the grid-dependent household model.

$$Generated\ Energy\ Value = \Sigma_{i=1}^{T} \frac{365 P_t F A I E_{sr} E_{pw}}{(1+R)^t} \tag{1}$$

Two methods of acquiring the Solar Roof/Powerwall are considered: purchasing the system outright, shown in equation (2), and participating in Tesla's leasing program, shown in equation (3). The upfront/leasing costs depend on several variables, expressed in equations (2) and (3) below.

For upfront purchasers, the unit cost of the Powerwall CPW is listed as $14,500, and the unit cost of the Solar Roof CSR is $21.85 per square foot. Both costs include initial installation fees. Tesla also states that there are no expected maintenance costs for the consumer during the eight year period being considered [12]; Tesla will cover expenses incurred by premature equipment failure. Finally, households that purchase the Solar Roof and Powerwall qualify for the Federal Investment Tax Credit (ITC) that will reduce upfront costs by 30% for households with tax liabilities in excess of 30% of the purchase cost of the Solar Roof/Powerwall. This tax credit is represented as ITC. Finally, to capture any state or local incentives, an addition quantity ISL is appended to the end of equation (2). For households in California, this incentive is $0.25/W of installed solar capacity.

Variables and Confidence Intervals

Variable	Value	Confidence Interval
C_{sr}	$\$21.85/sq.ft$	Constant, Tesla's website [21]
C_{pw}	$\$14500$	Constant, Tesla's website [12]
ITC	30%	Constant (federal policy)
I_{sl}	$0.25\$/watt$	Constant (Los Angeles policy) [22]
L_t	$\$2730$	$[\$1230, \$4263]$
i	1.45%	$[0\%, 2.9\%]$ [13]
R	2.69%	$[0\%, 6\%]$
A	location-dependent	–
I	location-dependent	–
P_t	location-dependent	–
E_{sr}	0.197	Constant, Panasonic Cell [23]
E_{pw}	0.89	$[0.6, 2.9]$ [24]
F	1	$[1, 1]$
$Inflation$	2.16%	$[0.05\%, 4.26\%]$ [25]
$\frac{P_{t+1}-P_t}{P_t} - 1$	2.16%	$[0.05\%, 4.26\%]$

$$Outright\ Purchase\ Cost = (C_{pw} + C_{sr} F A)(1 - ITC) - I_{sl} \tag{2}$$

The second method of payment is a lease on the Solar Roof equipment (Tesla still requires the Powerwall to be purchased upfront). This payment method allows the household to make monthly payments instead of an upfront payment. Households that choose this option are ineligible for solar tax incentives. Each year, leasing households pay L_t per square meter of leased solar. L_t is 12.5% of the upfront cost of a Solar Roof installation and is projected by Tesla to increase every year by i, 1.45% [20]. As before, these future payments are discounted using the present 1-Year Treasury interest rate.

$$Cost\ For\ Lease = C_{pw} + \Sigma_{i=1}^{T}\left(\frac{L_t(1+i)^t}{(1+R)^t} F A\right) \tag{3}$$

3.4. Discussion of Confidence Intervals and Uncertainty

The quantities present in the aforementioned three sections are estimates that carry uncertainty. Below, we summarize all of input quantities to the models, their estimated value, and their estimated confidence interval. The final cost-benefit expression will use these confidence intervals to generate a confidence interval on the final net value presented for each household.

3.5. Final Cost-Benefit Expression

The final cost-benefit expression for households in the without situation is identical to equation (0) presented above. There are two cost-benefit expressions for households in the with situation, depending on how they choose to pay for the Solar Roof/Powerwall. For households that choose to purchase the equipment outright, the net cost-benefit expression is the difference between equation (1) and equation (2). For households that choose to lease their equipment instead, the net cost-benefit expression is the difference between equation (1) and equation (3).

$$Net\ Outright\ CB = (1) - (2) \tag{4}$$

$$Net\ Lease\ CB = (1) - (3) \tag{5}$$

4. Limitations

Several factors were not included in the above cost-benefit analysis and place limitations in how the current analysis can be interpreted. These limitations fall into five categories: (1) basic simplifying assumptions, (2) time dependence of household-level costs and benefits, (3) continued development of household-level power generation and storage market, (4) safety/cybersecurity risks, and (5) environmental externalities during product manufacturing and disposal.

4.1. Basic Modeling Assumptions

Our model establishes cost-benefit through a comparative to a control household with no Powerwall/solar roofing. One main assumption of this model is that electricity price increases will remain constant, once adjusted for inflation. While the past decade has been characterized by this pattern, it is possible that electric prices could generally shift for any number of reasons [26]. For example, if a carbon tax was enacted, it would likely cause increased electricity costs due to its impact on America's main baseload power source, natural gas generation. Conversely, wide-scale adoption of solar roofing and other distributed generation sources could actively drive down prices overall, if utilities are forced to effectively compete with the consumer to generate with the consumer's electricity. However, for our purposes, we assume the pattern of electricity prices observed in the past decade will continue into the next.

Our model also takes an eight-year time period for our cost-benefit analysis, primarily to avoid engaging with the impact of installation on home resale value. The average American homeowner resides in their household for 8.7 years, so a longer period of analysis would necessarily need to incorporate resale in cost-benefit equations, which is outside the scope of this paper's analysis.

One final assumption we make in order to simplify our analysis is that all electricity will be cycled through the powerwall, even if used directly. This assumption could lead to an overestimation of electricity loss, as electricity would likely be used directly from solar generation during peak hours. Nonetheless, doing otherwise would greatly complicate our analysis, as this assumption of the storage intermediary is key to our use of averages for seasonal weather changes and other variables; it is much simpler to view each unit of electricity as equal to any other unit of electricity generated by a household, in terms of cost-benefit return.

4.2. Changes to Projected Costs and Benefits During the Product Lifetime

During the expected ten and thirty year respective lifetimes of the Powerwall and Solar Roof, usable battery capacity and realized cell efficiency are expected to change. Additionally, exogenous shocks to either the portfolio of energy sources to the US grid or to the infrastructure of the US grid itself may substantially change the expected household level costs and benefits.

4.3. Projected Development of the Household Energy Generation and Storage Market

Although Tesla was not the first company to develop household-level energy generation and storage products, its high-profile entry into the market has increased mainstream consumer awareness. After Tesla's products began to increase mainstream consumer interest in electric vehicles, a wide range of companies–from Audi to GM to Faraday Future–announced plans to enter the market with competitive alternatives. The same might be expected to happen in the household-level energy generation and storage market if Tesla can demonstrate that they can gain traction with mainstream consumers.

4.4. New Physical Safety and Cybersecurity Risks

Households installing the Tesla Powerwall and Solar Roof accept new physical safety and cybersecurity risks. The Powerwall–like all lithium-ion batteries–can pose a combustion risk due to manufacturing error or improper user management. These risks are especially pertinent to consider with the Tesla Powerwall because of its large capacity for a consumer-managed battery and wide range of expected installation environments. For safe functioning, users must consider how these combustion risks may change with expected variations in temperature, ambient humidity, charge/discharge rate, and physical damage. Fires that do break out may be more difficult to control than typical residential electrical or chemical fires that local fire departments are accustomed to seeing, which we do not incorporate into our cost structure for lack of data.

The design of the Tesla Powerwall requires an internet connection to allow for user control and for periodic software updates from Tesla. Traditional household electrical grid connections are rarely internet connected, making centralized attacks on multiple household energy connections difficult. However, increased Powerwall and Solar Roof adoption increases the value of cyberattacks on household installations via their requires internet connection. These attacks may take on a variety of forms, from disabling parts of the assembly to prevent energy generation and storage to disabling security controls that reduce the risk of unsafe operation.

4.5. *Environmental Externalities*

The Tesla Powerwall and Solar Roof allow households to shift the energy source portfolio of the electricity they consume towards a renewable energy source. However, the manufacturing and disposal of Tesla's Powerwall and Solar Roof incur significant environmental costs outside of the window of user operation.

Like the other batteries used in Tesla products, the Powerwall uses an array of lithium-ion cells. In order to make these cells, the raw materials that Tesla must source include lithium and cobalt. These metals often come from mines in which their purity in raw ore is low and requires extensive processing for extraction, refining, and transportation. In the communities that host these mines, the extraction and processing of lithium and cobalt consumes local land, water, and energy while also increasing the risk of environmental contamination.

According to an analysis by Wired, mines in South America's mines in the Lithium Triangle, which holds much of the world's lithium supply, consume 500,000 gallons of water per ton of lithium produced [27]. In one region of Chile, these mining activities consume 65% of the local water supply. Local communities and mining companies clashed over discarded waste, contaminated surface water, and unusable tracts of land left behind by mining activities.

One of the primary sources of cobalt, another critical material input in the Tesla Powerwall, is artisanal mines in the Democratic Republic of Congo [28]. The quantity and accessibility of cobalt in the DRC are unusually high, as cobalt prices have increased, so have the incentives to mine the valuable metal irrespective of the environmental or health consequences for workers and residents near the mines.

Over time, degradation of the lithium-cells within the Powerwall will require the unit to be replaced [29]. However, current disposal and recycling techniques for the Powerwall are crude and can sometimes lead to additional environment contamination. At present, most recovered battery cells are shredded and burned. While this disposal technique allows for the flexible processing of a wide range of battery designs, it is inefficient at recovering valuable materials (including lithium and cobalt) that can be reused and produces hazardous waste products, including fine particulate matter and toxic oxides.

Similar environmental concerns exist regarding the manufacturing and disposal of photovoltaic systems, including the Solar Roof [30]. Many assemblies contain toxic compounds, including gallium arsenide, copper-indium-diselenide, and cadmium-telluride, that are difficult to extract and recycle at the end of a product's useful lifespan.

Although these environmental costs are often neither borne by the household consumer nor the manufacturer, a full lifecycle analysis of the costs the Tesla Powerwall and Solar Roof should include these factors to determine the net impact of deploying household energy generation and storage. In a different regulatory environment, these externalities might be captured and passed on to one or both parties.

5. Policy recommendations

Our findings suggest that rooftop solar installations are potentially cost-effective for a large set of—but not all—consumers. Insofar as it is socially beneficial to increase adoption rates [31], via modifications to the cost-benefit analysis or otherwise, we have a number of policy recommendations to improve solar roof adoption, particularly in areas with grids with high carbon intensity.

First, substantial research shows that (contra our assumptions) consumers do not appear to behave perfectly rationally and responsively to cost-effectiveness; social factors and familiarity appear to play a substantial role [3]. Curtius, et. al. found a substantial snowball effect, such that when installations reach a certain density in a given area, installation rates increase in neighboring areas. If solar roof installation adoption lags behind cost-effectiveness (as is generally the case nationally), local governments can subsidize a small group of initial adopters in order to initiate a snowball effect in the larger area. This would be a relatively low cost intervention that could nonetheless create sizable knock-on effects.

Further, green technology adoption seems to beget green technology adoption in ostensibly unrelated fields [2]; if governments wish to increase green technology adoption more generally, and potentially more green consumer preferences, they should subsidize adoption of solar roofs in particular. Further, Delmas, Khan, and Locke found that unrelated quality advantages (such as high safety ratings in Tesla vehicles) had a disproportionate impact on adoption of green technology [2]. As such, governments could offer research grants for companies specifically for improvements in safety, durability, and even aesthetics in order to improve adoption rates for both solar roofing and green technology more generally.

States can also adopt net metering standards, in order to substantially increase the benefits for adopters of solar roofs. When solar panels generate electricity in excess of household usage (and, in the Powerwall's case, household storage), they displace the excess electricity back on to the electric grid. Net metering is the practice of crediting the cost of electricity generation to the consumer who generated solar electricity, such that they gain revenue when they effectively sell their solar energy back on the grid [1]. Many, but not all, states have adopted these standards; doing so would make solar roof installations substantially more economically affordable and attractive. Further, states can invest in grid infrastructure that is capable of handling peak-generation-hours electricity surges from distributed generation

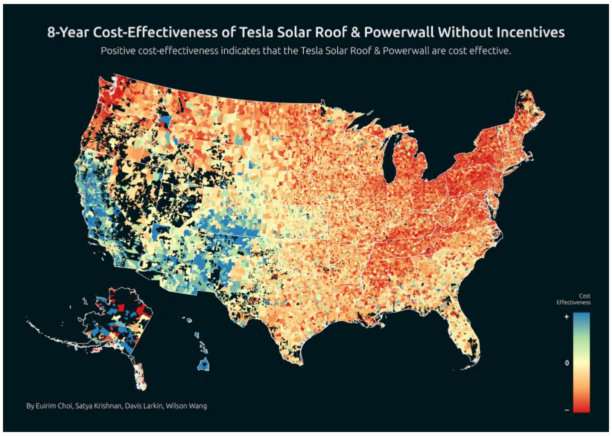

Fig. 1.

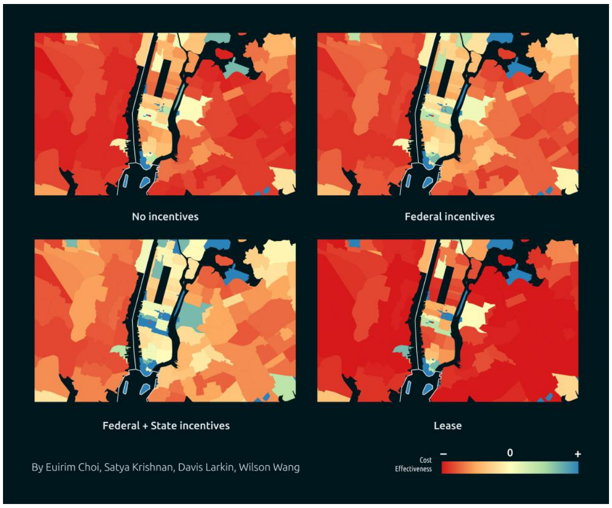

Fig. 2. Cost Effectiveness of Solar Roof/Powerwall in Urban Area (New York City)

by consumers [19]. Investing in grid-scale electricity storage technology for grid utility suppliers can substantially ease the integration of solar roofing into the broader electric grid.

Finally, as found in our third scenario, broad adoption of California-style electric roofing incentives can substantially increase cost effectiveness for consumers in virtually all areas of all states. By introducing this slate of incentives, both initial adoption costs and long-term costs are substantially reduced for consumers. With implementation in the areas with the least cost-effectiveness and a large share of carbon-intense electricity generation, such as Appalachia and Virginia, these state incentives could have a drastic impact on the amount of electricity that is generated in carbon-intensive manners nationwide.

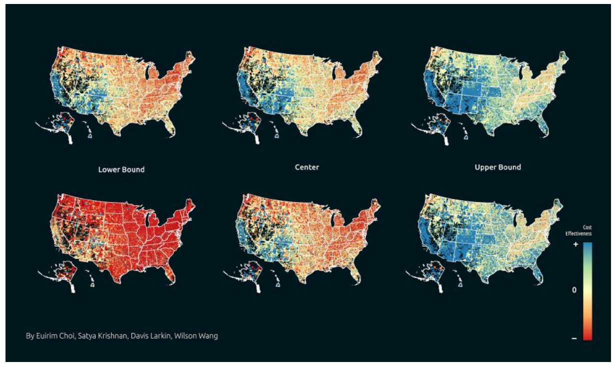

Fig. 3. Confidence Intervals of Incentivized Purchase vs. Lease

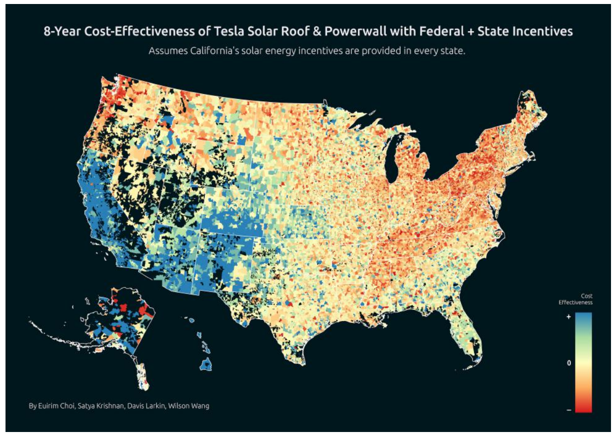

Fig. 4.

6. Conclusions

For the fixed-cost no incentive case, we see that our mean (center) value map is mostly cost-effective in the southwest region, and not cost-effective anywhere else (Fig. 1). This conclusion holds for both the lower bound and the upper bound maps, meaning that we predict that the southwest region is cost-effective for the Solar Roof/Powerwall combination. Once federal tax incentives are added, the map stays mostly the same, indicating that federal tax incentives alone are ineffective in promoting use of solar. Once state-level incentives are added on top of the federal tax incentives, we begin to see areas of solar cost-effectiveness in other parts of the country. For example, Kansas and Florida have areas of blue (cost-effectiveness) interspersed among the red (cost-ineffectiveness) (Fig. 4). Finally, the variation in the lower bound leasing map and the upper bound leasing map indicates that cost-effectiveness in the leasing case is sensitive to variable changes (Fig. 3). Thus, even though the mean leasing map looks roughly similar to the mean no-incentive map, we cannot conclude very much in the leasing case.

The granularity of the maps is also interesting (Fig. 1). In

Table 2: Results In No Incentive Case

Strictly Cost-Effective	Unclear	Strictly Not Cost-Effective
AK, HI	AZ, AR, CA, CO, FL, LA, NM, TX, UT	All other states

Table 3: Results In Federal Incentive Case

Strictly Cost-Effective	Unclear	Strictly Not Cost-Effective
AK, HI	AB, AZ, AR, CA, CO, CT, FL, GA, ID, KS, LA, MS, NV, NM, OK, SC, SD, TX, UT	All other states

the mainly 'red' states in the Eastern US, counties that border one another sometimes have significantly different cost-effectiveness, represented by different color. One would expect neighboring counties to have similar grid prices and for the colors to smoothly change. Thus, our map suggests that grid prices may not be stable across county lines, something to check in future research.

It is interesting to note that even with aggresizve federal and state incentives, Tesla Solar Roofs/Powerwalls are not cost-effective in urban areas with a high population density (e.g. New York, Fig. 2). This traces to the high electricity consumption relative to generation potential. Because urban high rises tend to have small roofs relative to their internal volume, Solar Roof installations generate relatively little electricity relative to building consumption. Furthermore, direct solar irradiance as measured by ground stations is reduced throughout the day by the number of tall buildings spread in each direction.

We can also test these conclusions quantitatively. For each state, we will average the cost-effectiveness and construct a confidence interval for the average cost-effectiveness. Afterwards, we will take note of which states have confidence intervals that are strictly cost-effective or strictly cost-ineffective. The results are found in tables 2-5.

We see generally the same pattern that we saw in our qualitative analysis: for the fixed-cost case, the more incentives added,

Table 4: Results In Federal and State Incentive Case

Strictly Cost-Effective	Unclear	Strictly Not Cost-Effective
AK, AZ, CA, HI, NM	All other states	DE, DC, ME, MD, MI, NH, NJ, OH, PA, VA

Table 5: Results In Lease Case

Strictly Cost-Effective	Unclear	Strictly Not Cost-Effective
None	All other states	DE, DC, ME, MD, MA, MI, NH, NJ, NY, OH, RI, SC, VA

the more cost-effective the southwest region tends to be (Tables 2-4). It is worth noting that Alaska and Hawaii are consistently cost-effective in the fixed-cost case - probably because they are not connected to the main grid and rely on their own, more expensive, electricity generation (Tables 2-4). Also, even though a state might look blue or red on the map, the quantitative analysis shows (especially in the federal and state incentive case) that the confidence interval may contain 0, meaning our conclusion may not be robust. To reiterate, the states that are robustly cost-effective in the federal and state incentive case are Alaska, Arizona, California, Hawaii, and New Mexico (Table 4). Leasing appears to be the least cost-effective option; no states are strictly cost-effective under leasing, not even Alaska or Hawaii (Table 5).

Our research provides multiple directions for future researchers to investigate. More research needs to be done on determining what factors other than cost-effectiveness influence adoption rates. As mentioned above, there are substantial environmental externalities induced by the mining and refinement of the materials used in batteries and solar panels; further analyses should examine how to best incorporate this externality into pricing or subsidies, and how to mitigate it. We also assume electricity price changes will progress in roughly the same way as they have in the past. Researchers should look into how other environmental policies such as a carbon tax may affect price in the long term; further, more research is needed to establish how widespread adoption of solar roofing will affect both regional electricity prices and the grids in which they are integrated. Our model also did not seek to examine the impacts of net metering. As such policies would have a large impact on consumer electricity expenditures, they should be further researched.

Note: We hope to submit this to *Econometrica*, per one of the TA's recommendation.

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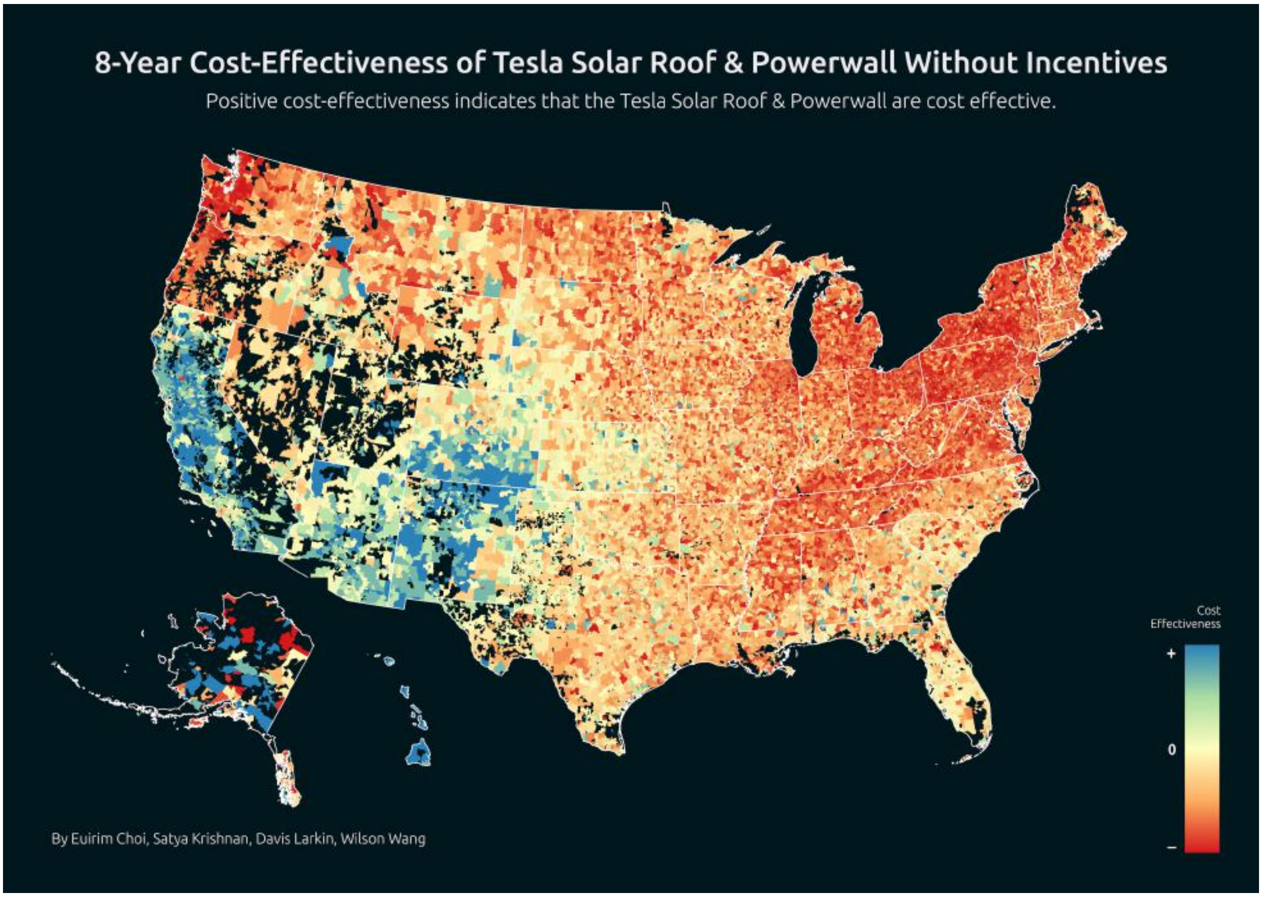
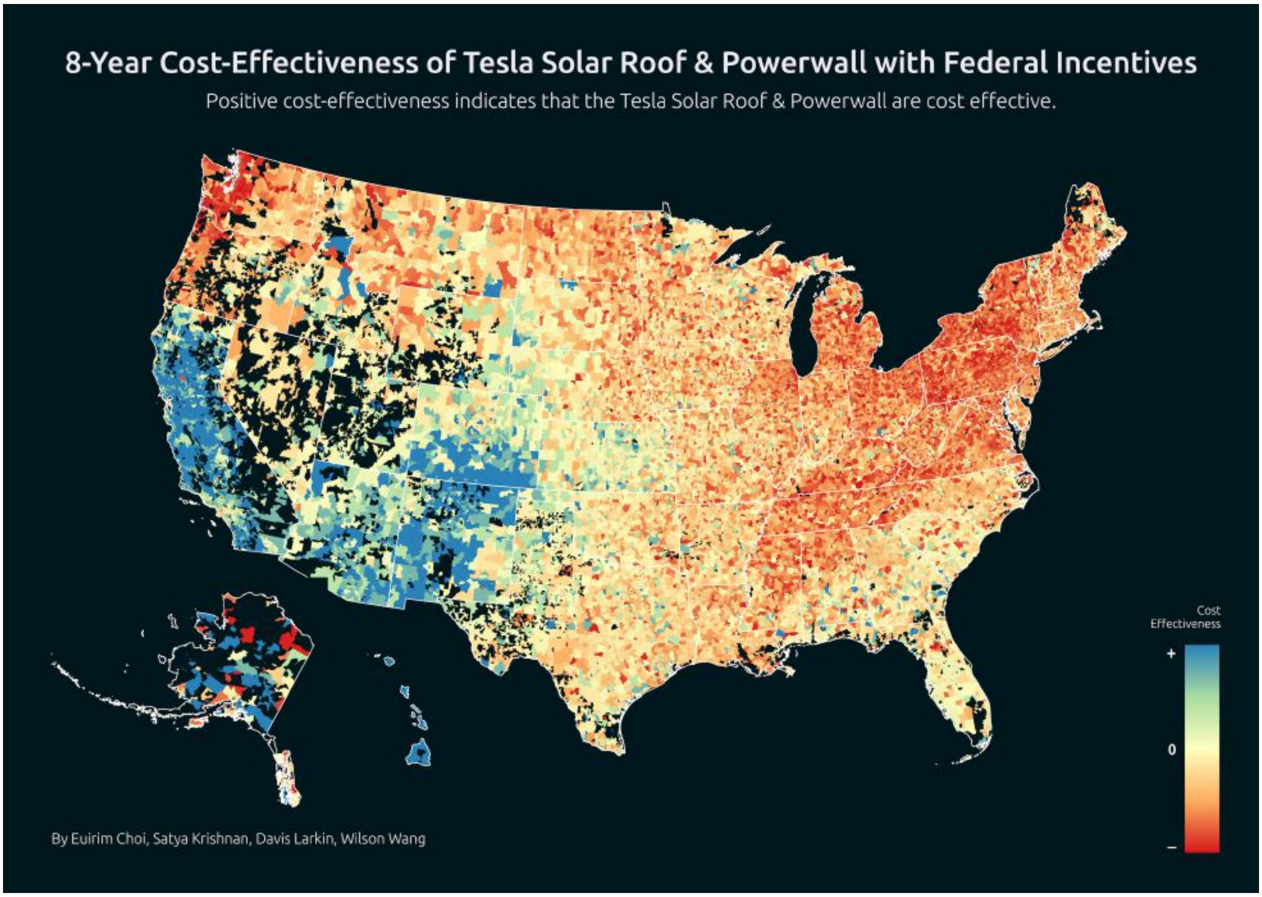
Appendix

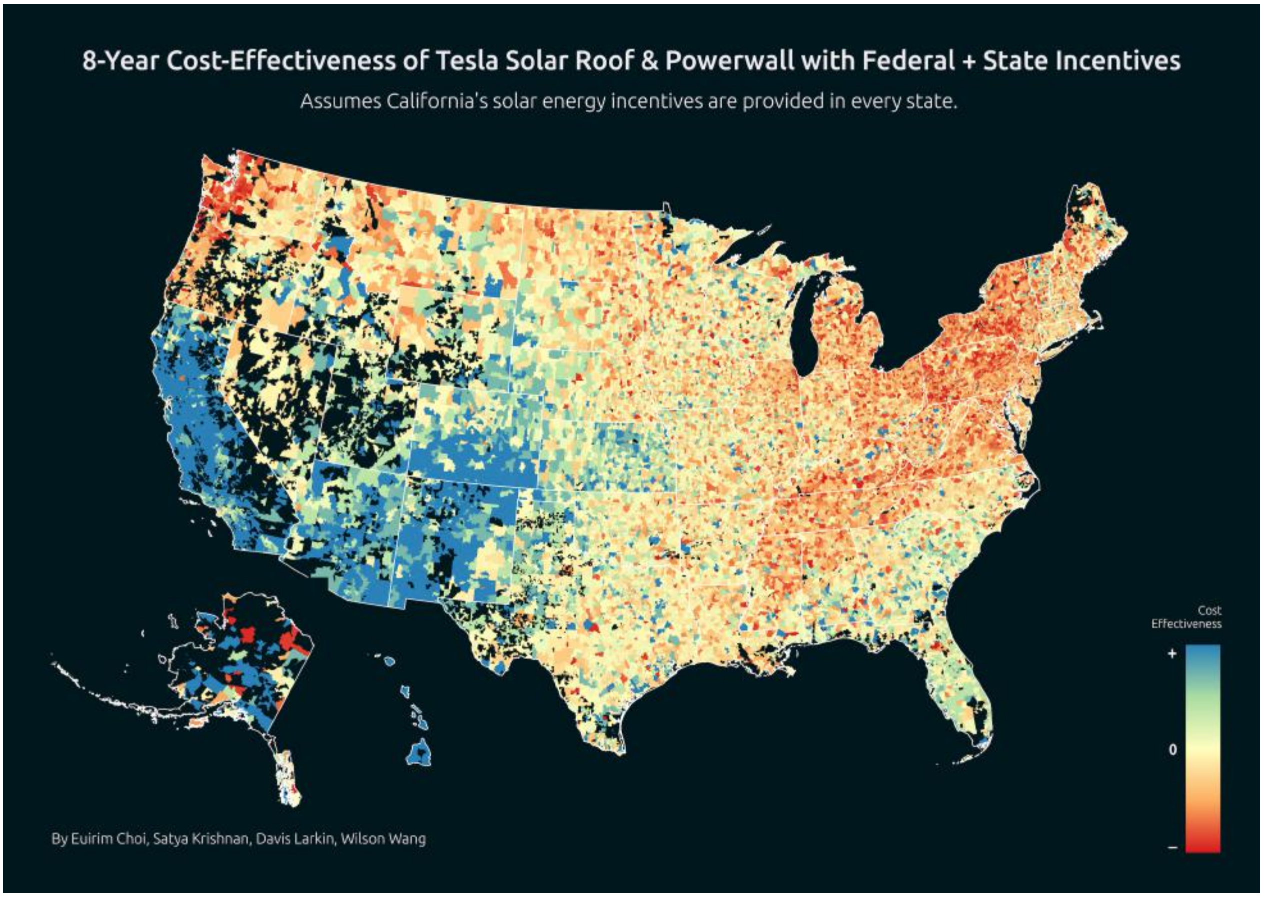
6.1. Map of 8-year cost effectiveness with no incentives



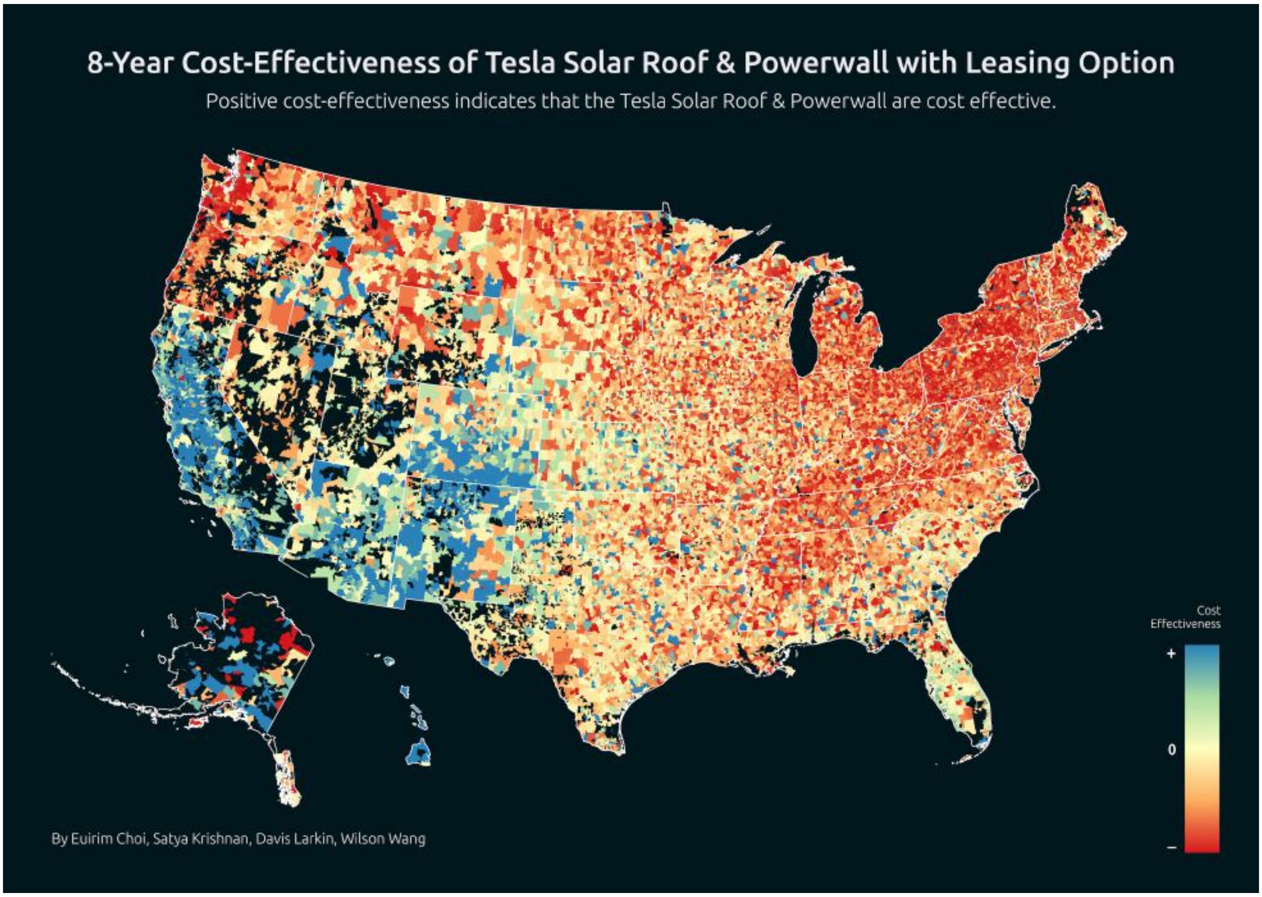
6.2. Map of 8-year cost effectiveness with federal incentives



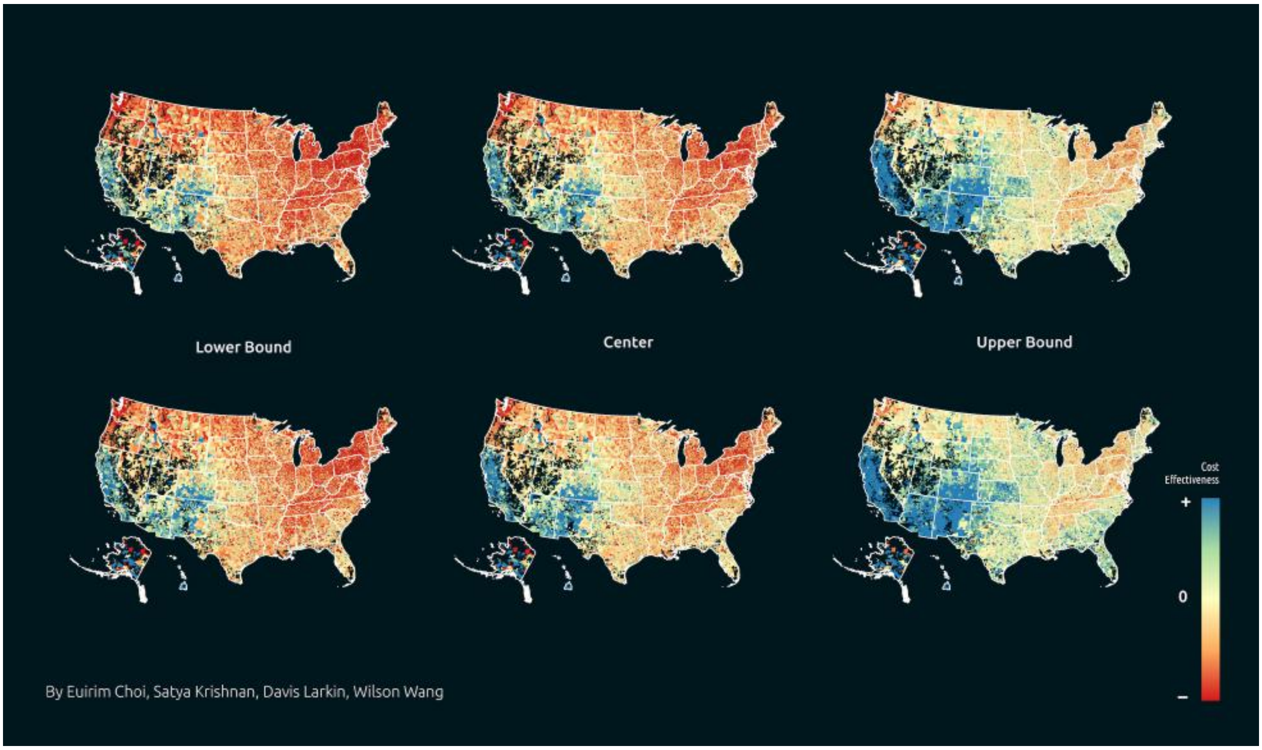
6.3. Map of 8-year cost effectiveness with federal and state incentives



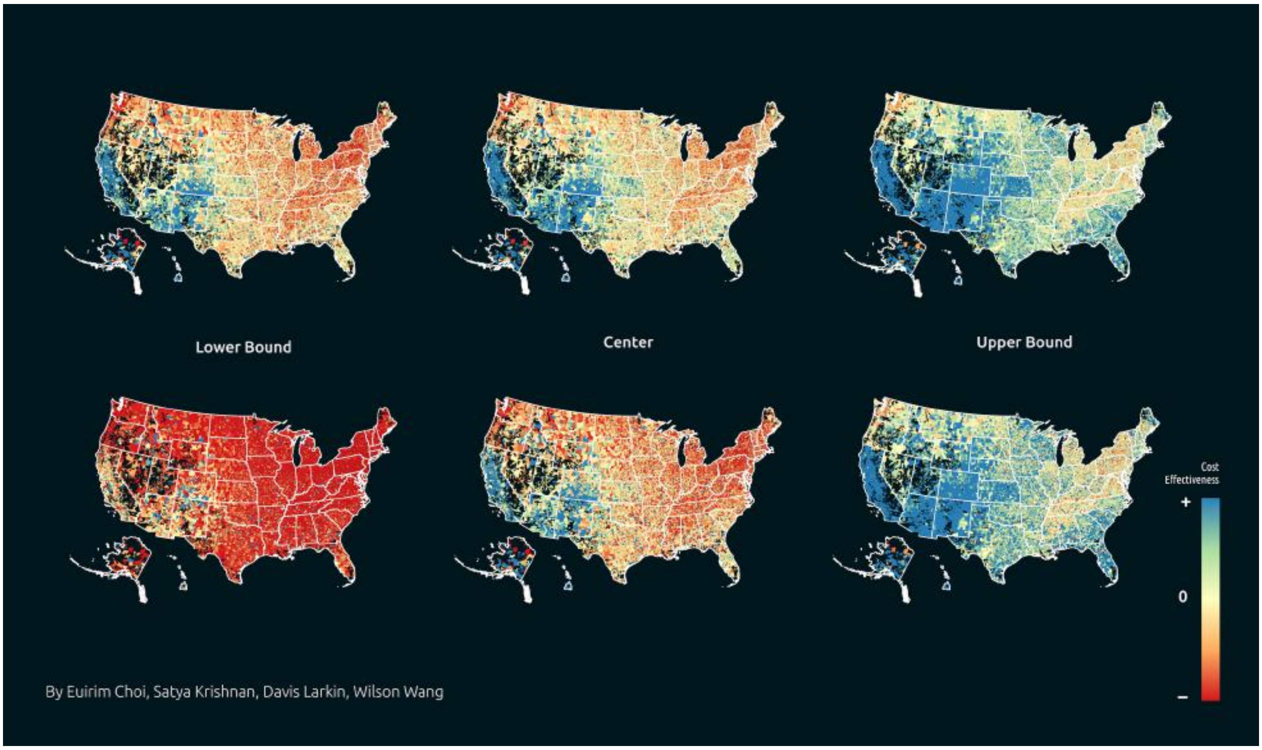
6.4. Map of 8-year cost effectiveness with leasing option



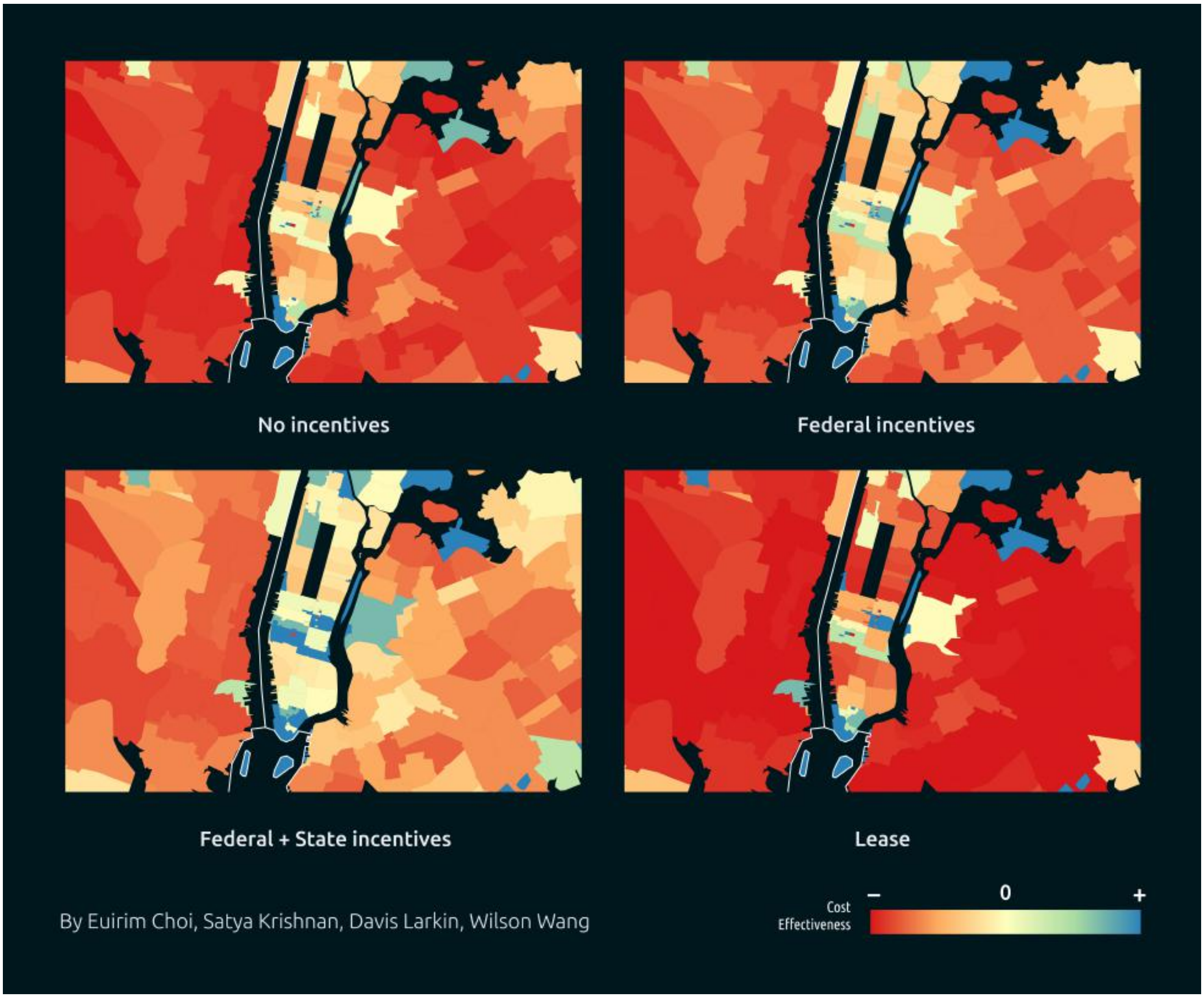
6.5. Visual representation of confidence intervals of 8-year cost effectiveness of the no incentive case and federal incentive case



6.6. Visual representation of confidence intervals of 8-year cost effectiveness of the federal and state incentive case and the leasing case



6.7. Map of 8-year cost effectiveness in the greater New York City area under various scenarios



6.8. Project code

To see this project's respository, visit `https://github.com/euirim/tesla-energy-cba`.

6.9. *High-resolution map imagery*

To see very high-resolution images of the maps presented in this article, visit `https://drive.google.com/drive/folders/11QODKt0YMsaXII_Aw6OVms_PGVzkY29a?usp=sharing`. Opening the files with a high performance machine is recommended.