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Evaluating the Spatial Trends and Statistical Determinants of Residential Solar Uptake in Washington State

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EVALUATING THE SPATIAL TRENDS AND STATISTICAL DETERMINANTS OF RESIDENTIAL SOLAR UPTAKE IN WASHINGTON STATE

A Thesis

Presented to

The Graduate Faculty

Central Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Cultural and Environmental

Resource Management

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by

Caleb Michael Valko

August 2021

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

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ABSTRACT

EVALUATING THE SPATIAL TRENDS AND STATISTICAL DETERMINANTS OF RESIDENTIAL SOLAR UPTAKE IN WASHINGTON STATE

By

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Washington State's Clean Energy Transformation Act and other state and federal policies encouraging solar power make Washington a ripe candidate to examine growth, trends, and potential determinants or barriers to residential solar uptake. In this thesis, residential solar is cumulatively and annually mapped by county (2000-2019) and Census tract (2017-2019) across the state to identify trends over time and space. Each variable (income, age, households, race, education, solar insolation, cost of solar per watt) was isolated individually to analyze the relationship (if any) to the dependent variable (i.e., residential solar installations). The covariates are then combined into a multiple regression model to examine their explanatory power. Finally, an annual fixed effect multiple regression model is used to identify policy events or economic conditions not being accounted for in the dataset. Collectively these variables help describe the overall drivers and growth of solar installations (2011-2019). Though more data is necessary to develop a more holistic understanding, it is certain that uptake is drastically impacted when subsidy policies are in limbo. Many consumers are delaying the investment until the policy frameworks are concrete, with legislation existing to support the consumer.

ACKNOWLEDGMENTS

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A special thank you goes out to the Washington State University (WSU) Energy Program, which provided the data regarding all solar installations performed between 2000-2019. Without it, this project would not have been possible.

Now on to the Solar!

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CHAPTER I

INTRODUCTION

Problem

Despite knowing the pitfalls of relying on fossil fuels to power energy needs, the world remains largely hooked on them. The theory of path dependence suggests that societies are inherently subject to an enduring cycle of dependence on particular energy sources due to technological, infrastructural, institutional, and behavioral lock-ins (Fouquet, 2016). While this has certainly been an extended reality in the making, governments worldwide have begun to acknowledge the existential threats of climate change, with many establishing programs for individuals and businesses to transition to a clean energy source such as solar power. In the U.S., the federal government created the Investment Tax Credit (ITC) in 2006, and since then has offered monetary incentives toward those purchasing eligible systems such as solar photovoltaics (PV). Additionally, state governments have taken further steps to support clean energy by implementing programs such as the Renewable Energy Cost Recovery Program (RECRP) in Washington State. Since 2010, domestic solar markets have grown 10,000 percent, yet as of 2021, total contributions from solar power are still marginal, only providing 2.3% of overall U.S. electricity in 2020 (SEIA, 2020).

Problem

The scientific community agrees that the continued release of greenhouse gases (GHG) will exponentially accelerate the warming of the climate and cause an ecological catastrophe (IPCC, 2018). Dirty fuels such as coal, gasoline, natural gas, and gas derivatives contribute to GHG warming effects and climate feedback loops. One promising avenue to pursue in the reduction of dirty fuel usage is residential solar power. To address this, Washington State's Governor, Jay Inslee, passed a bill seeking to transition Washington's energy economy to 100% fossil-free sources by 2035 and 100% renewable energy sourced by 2045 (CETA, 2020).

As solar installation continues to rise, costs are predicted to continue their decline (Figure 1). Swanson's law observes that PV module prices have declined 20% for every doubling of shipped volume since 1973 (Carr, 2012). The trends and determinants of residential PV must be further evaluated to best facilitate the uptake of solar power at the residential scale.

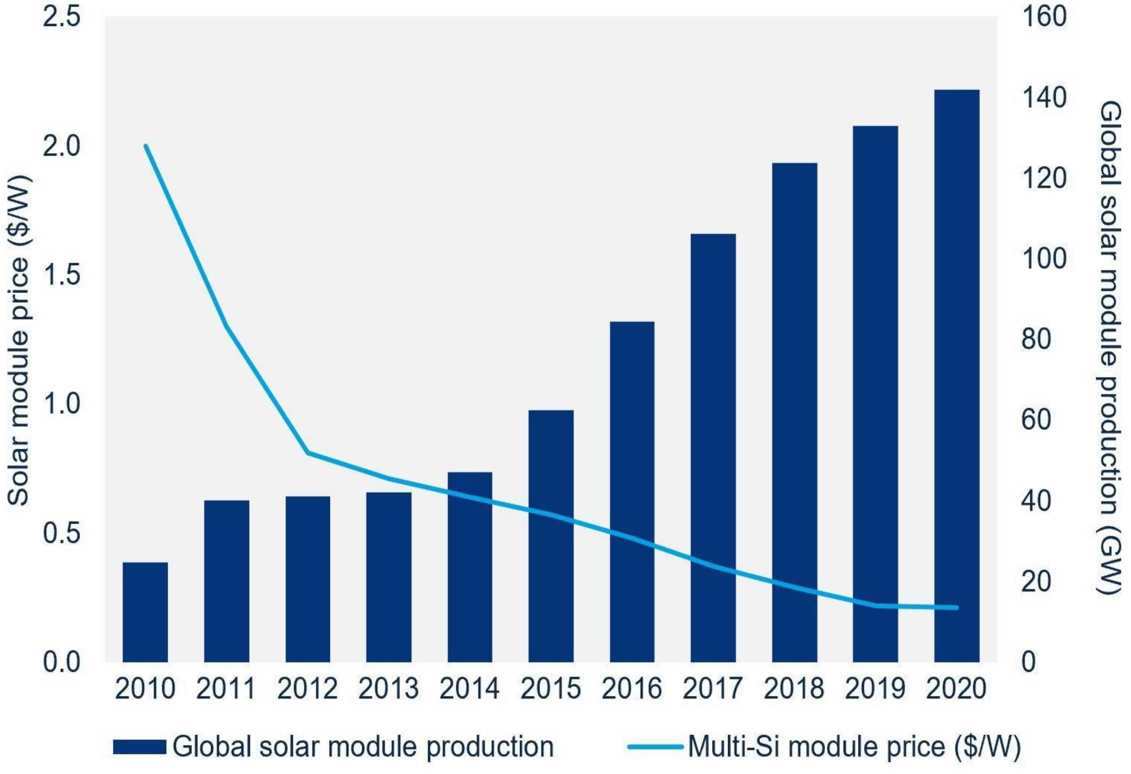


Figure 1

PV Module Production and Price Decline (Wood Mackenzie, 2020)

Purpose

This thesis evaluates the trends and determinants of residential solar uptake at both the county and Census tract scales in Washington State (2000-2019). Spatial and quantitative methods were employed to map the adoption trends and statistically determine what variables are conducive to uptake. This will provide local insight into the reasons for higher uptake.

Significance

By generating a better understanding of what drives solar uptake across time and space, more homes can be provided opportunities to go solar, in turn helping alleviate the climate problem. Washington State is a particularly suitable candidate for study for a couple of reasons. First, Washington is 28th out of all states for a total installed solar capacity, leaving room for improvement (SEIA, 2019). Second, the state government has had policies incentivizing solar power adoption since as early as 2006. Third, although the body of literature surrounding solar uptake does not lack by any means, there is little published on Washington State's residential solar markets. This study seeks to provide a baseline analysis of the trends of adoption. And lastly, by improving the understanding of what drives residential solar uptake in Washington, we can speed up the transition from dirty fuel sources to cleaner and more sustainable alternatives.

CHAPTER II

LITERATURE REVIEW

Climate Change and Pathways of Mitigation

For the past three decades, the Intergovernmental Panel on Climate Change (IPCC) has provided scientific analysis, cumulative reports, and policy guidance for politicians. The 2018 Summary for Policy Makers states that demand side measures, including reducing fossil fuel usage and replacing clean energy capacity, are key elements in preventing atmospheric warming above 1.5 degrees Celsius from pre-industrial levels (IPCC, 2018). The IPCC has stressed the importance of international cooperation to combat the global consequences associated with a warming climate since the early 1990s. Yet, still today, the globe struggles with dependence on fossil fuels. As of 2020, about 80% of the world's primary energy supply is directly tied to fossil fuels (IEA, 2020). The evidence has been overwhelming for decades; today's issue of climate change is largely a result of anthropogenic pollution.

The theory of path dependence suggests that agencies, institutions, or technologies tend to become committed to a 'certain kind of development.' The mantra here is that history is relevant to understanding the current technological lock-ins, resistance to change, etc. An International Monetary Fund report (2017) states that in 2017 that 4.7T USD was spent on fossil fuel subsidies globally, with the largest contributor being China (1.4T in 2017) and then the United States (649B in 2017). The usage of these funds ranges from subsidization of activities and business and the actual extraction, production, transportation, and storage associated with bringing the products to market. While the persistence of fossil fuels among industry, society, and government is certainly strong, it can be addressed by shifting subsidies from the fossil-fuel industry to clean energy.

In fact, if significant action is not taken, local and regional geographies are expected to continue to experience record levels of drought, precipitation, floods, hurricanes, average surface temperatures, and wildfires - with increasingly unpredictable variability, frequency, and intensity (IPCC, 2020). Coastal communities are disproportionately affected by the changing climate, sea-level rise, coastal erosion, and flooding (IPCC, 2018). In 2013, the International Organization for Migrations released a report to consider the impacts of climate change if global habits remain unchanged: "By 2050, over 200 million climate migrants will have been displaced or forced to resettle outside of their birth places due to climate change-related displacement." (IOM, 2013). Suppose we do not address the energy aspect of the climate change situation. In that case, this amounts to one in every thirty-five people across the entire planet's population, not accounting for the increase in population since this was forecast in 2013.

There are essentially four pathways available to mitigate climate change with current technologies: to change the way we generate power and electricity by de-carbonizing a bulk of global energy supply; to conserve, both in terms of energy and the environment; replenishing the earth's lungs by planting trees, protecting oceans, increasing photosynthesis; and to use technology to pull carbon out of the atmosphere (NRDC, 2017; IPCC, 2020).

Lately, much of the focus in the United States has shifted towards developing climate-resilient policies and preparing future generations for a sustainable future (CETA, 2020; Biden, 2021). This effort has seen progress, although not at the scale needed to significantly reduce annual GHG emissions. To change the way power is generated, an incentive structure or a market without too high entry barriers for consumers is needed. This can largely be accomplished by allocating more federal or state monies toward the clean energy markets, which the Biden Administration has pledged to do in their Climate Plan. President Biden addresses climate change head-on by stating that his administration will start onto the path to achieving 100% clean energy with net-zero emissions by 2050 (Biden, 2021). This is a multi-faceted problem that will need approaching via legislation. Caps on emissions, creating federal sponsorship of technologies such as solar PV, proposing fuel standards (or electric vehicles), and an aggressive approach to a sustainable future continue to echo through the hall. In respect to reducing residential and commercial building energy usage from dirty fuel, this objective is well suited to be reached going forward by the deployment of technology such as wind, solar, and anaerobic digesters (IPCC, 2014).

De-carbonization of energy sources is no easy task considering fossil fuels' path dependency on the global economy. However, in 2012 the U.S. Department of Energy (DoE) conducted a forecast analysis that predicted all U.S. energy needs would be met if 0.6% of U.S. land was used to capture solar energy (DoE, 2012). Solar panels are more efficient nine years later, and arguably less space would be needed in 2021. Nuclear energy is not considered a renewable or clean source of fuel, though it does offer carbon-neutrality and is delineated as an acceptable energy source by the CETA legislation.

As for conservation, extensive efforts are under way to ensure reforestation and planting, as well as designing better technology designed to conserve energy in households and industry (Department of Energy, 2020; IPCC, 2018). Wetlands, forests, oceans, grasslands, etc., provide ecosystem services that benefit the ecosystem they reside in and humans and animals. Increasingly, conservation has found footing in quantifying these values associated with the ecosystem and environmental services to humans, flora, and fauna (Hasan, Zhen, Miah, 2020; Costanza, 2020). Among these services produced are habitat, the recycling of carbon dioxide, and areas for recreation. The NRDC outlines four major steps in their 2017 report for conserving high carbon-landscapes revolving around retrofitting outdated buildings and infrastructure for energy efficiency, transitioning to newer and more efficient household and commercial appliances, considering a life-cycle approach to waste and commodities. The outlines also aim to preserve carbon sink landscapes like the Amazon Rainforest (Conservation International, 2020).

While pulling carbon directly out of the atmosphere seems like a simple solution, these technologies do not yet pose a viable method to address climate change, as research and development are still being carried out (Department of Energy, 2021). However, oil companies such as Shell, Total, and British Petroleum (BP)are making fast progress on these fronts, and a product for the market is expected by 2035 (Blommart, 2021).

United States National Solar Policies

The United States federalist system allows for federal law to serve as a baseline for all states. It then allows individual states to push the ball further with various incentives or legislation if they choose to do so. At the federal level, the U.S. Federal Investment Tax Credit (ITC) is a multi-pronged bill that was intended to sponsor the growth of the solar industry and allow a financial incentive for consumers. Enacted in 1992 and established by the Energy Policy Act, the production tax credit was the first federal policy to provide an incentive via a tax break that equals a percentage of the total system cost for solar, wind, and biomass power generation. In 2005, this mechanism was expanded with the Energy Policy Act of 2005 and renamed the “Investment Tax Credit.” This policy mechanism effectively provided consumers an avenue to alleviate costs through tax rebates when installing clean energy and resulted in the uptake of distributed generation capacity for electricity (Energy Sage, 2021). The declining block-rate structure, which can be understood as a rate paid to producers that declines X amount every set period, has been extended multiple times due to heavy interest, most recently in early 2021 (Table 1).

Table 1

Federal Investment Tax Credit Rebate Structure

Year	Original ITC Rates %	Updated ITC Rates % (2021)
2020	26	26
2021	22	26
2022	0	26
2023	0	22
2024	0	0

Across the nation, various policy mechanisms present themselves as the different methods for supporting the clean energy industry via policy legislation. Three main mechanisms are utilizing net energy metering (NEM), feed-in tariffs (FIT’s), and the value of distributed energy resources (VDER).

For NEM, the power produced by clean energy systems accrues credits on your utility bill that offset costs (DoE, 2019). Payments or credits are generally made monthly, with credits rolling over from period to period but renewing annually. These policies are prevalent in the western states such as Washington and California.

FIT's are similar to net metering because both mechanisms provide consumers a payment toward their electricity bill. However, the difference is that for FIT's, the value of the payment is not tied to the overall excess generation. Rather, the state determines the value and is intended to be competitive with retail electricity costs.

VDER, on the other hand, is a lump sum payment for the total value of the distributed resource system, which is determined by a mix of variables dependent on locality (Consolidated Edison, 2018). The payment amount is directly related to the geography and time of application, with programs changing as goals are met and remade. This method was more prevalent in states on the east coast of the United States. All three of these methods are effective ways of attaching a quantifiable value to desirable outcomes, in this case, the adoption of clean energy systems.

Additionally, various geographies have begun to make residential solar mandatory on newly constructed homes due to its economical versatility and sustainability (Shemkus, 2019). California is the first state mandating PV solar to be placed on all newly constructed homes (Penn, 2018). Colorado, Maryland, Massachusetts, Michigan, Minnesota, Nevada, New Mexico, North Carolina, Pennsylvania, and Texas have begun peddling similar bills through the legislature, seeking to have them introduced as law as early as mid-2022 (Environment America, 2020; Shemkus, 2019). For larger community-based PV systems, states such as New York offer front of meter (FTM) programs allowing similar benefits as net metering, except at wholesale contracted rates (Consolidated Edison, 2019). Certain states like WA, CA, and TX allow solar manufacturers' tax abatements and grants for schools and businesses or sales tax exemptions for eligible systems (DSIRE, 2020). Some PUDs and energy companies offer equipment loans and energy assistance (in grant form) for low-income residents to install rooftop PV (DSIRE, 2020). In the same vein, some PUDs are more likely to be willing to support solar policies and solar uptake than others. For example, PUDs in Arizona are known to lobby for high grid-connection costs for PV consumers, which is thought to be a way to protect their business model as electricity becomes more decentralized (Castaneda et al., 2017).

Going forward, the U.S. is poised to make strides in clean energy policy, as President Biden has voiced strong support for a green economic future in his proposed “America Rescue Plan” and “American Jobs Plan” (https://www.whitehouse.gov/ build-back-better) (Biden, 2021). Biden’s economic plan for the U.S. is led by shifts in infrastructure such as the electrification of transportation, directing more federal funds toward the green energy future of the country, and building a sustainable future.

WA Solar and Policies

Traditionally, legislation supporting the growth and adoption of photovoltaic markets has been used to incentivize the production of clean energy by offering reductions in costs through subsidies, tax breaks, or mandating renewable energy portfolio standards upon energy producers. In Washington State, two policies have had an impact on the adoption of solar PV and the fostering of the residential and commercial markets: The

Renewable Energy Cost Recovery Incentive Program (RECRIP) (2005-2017) and the Renewable Energy System Incentive Program (RESIP) (2017-2019).

The RECRIP was enacted in 2005, and it established a net metering system to generate income streams for those going solar and generating excess power. Higher payments were given to those sourcing WA-made panels. Essentially, a running tally is kept on whether the system owner is producing more electricity than he or she is using. At the end of the month, credits are awarded to the accountholder. Credits roll over month to month but reset annually at the end of June. From July 2006 to June 2012, the Department of Revenue (DOR) issued about 2500 solar certifications under the program, with participation skyrocketing the years following. By 2015, the DOR had issued roughly 9,000 systems. In 2017, the management of solar permits, data collection, and oversight of the cost recovery incentive program was turned over to the Washington State Energy program.

RESIP extended incentives introduced by RECRIP in 2017 for net metering payments for individuals, businesses, and non-utility government entities producing energy from a revised list of designated sources (anaerobic digesters, solar PV, and wind) (Washington State Legislature, RCW 82.16.130). Funding was allocated across utilities by either 2% of revenue (1994 revenue) or $100,000, whichever was greater (WSU, 2019). This method of allocation was inherently biased toward providing more funding to utilities with larger consumer bases, which ironically put more money for wind and solar projects on the maritime climate half of the state.

RESIP uses a declining block-rate structure similar to the one introduced by RECRIP (Table 2) to provide an outlook on the future support of solar and clean energy markets for consumers. Even though this program was well funded, all funds were exhausted by participating PUDs between February and June of 2019. Since then, all new applications have been halted, providing consumers with only the federal ITC currently for addressing high costs associated with installing solar. In July 2019, the Senate voted to remove the sales tax associated with the overall system and connection costs when investing in solar power (Northwest Solar, 2021). In 2020 and 2021, the Washington State Senate considered replenishing funds with an additional round. However, it was decided that these funds are in demand elsewhere in the coronavirus pandemic (Solar Washington, 2021). RESIP is also constricted in its scope of availability to customers as it is bound to only the PUDs and utility companies who voluntarily choose to participate in the net energy metering process (WSU Energy Program, 2019).

Table 2

WA RESIP Net Metering Rate Structure (WSU Energy Program, 2021)

Fiscal Year	Per kWh net metering rate (in $)	Additional bonus per kWh for modules made in WA (in $)
2018	.16	.05
2019	.14	.04
2020	.12	.03
2021	.10	.02

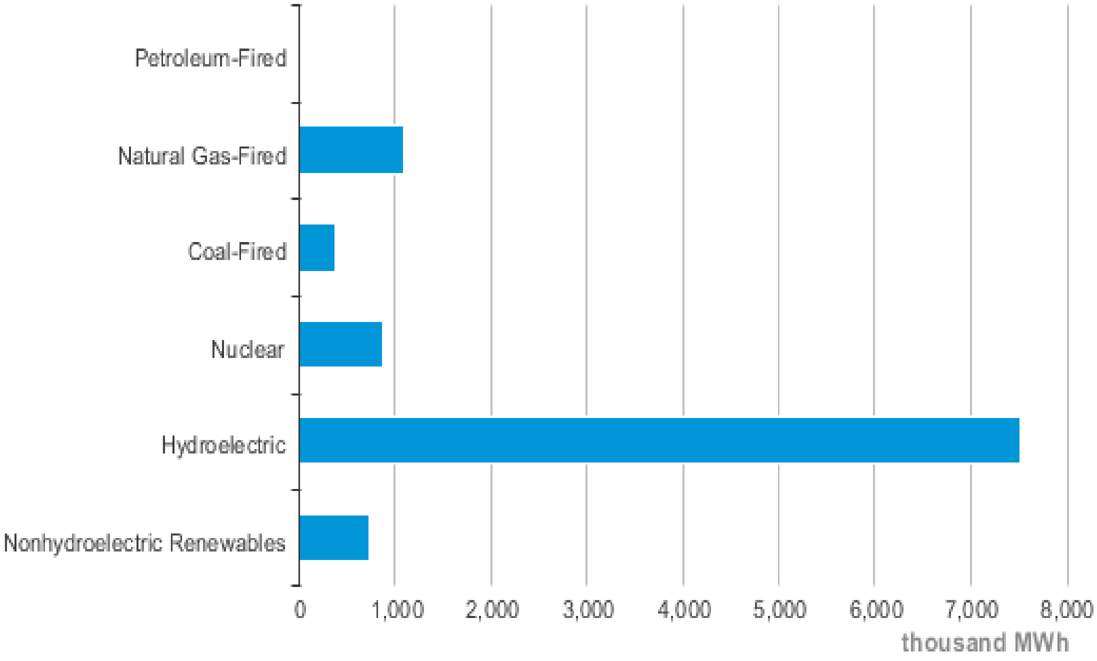
Paramount to both policies is the newly enacted Clean Energy Transformation Act (CETA). Washington State's clean energy legislation commits to sourcing 100% of its electricity from a carbon-free source by 2045 (CETA, 2020). CETA is an ambitious plan providing a three-stage timeline for when electricity providers must phase out all carbon emissions for electricity use: coal generation phased out by 2026, GHG-neutral by 2030, and produced entirely free of fossil fuels by 2045. It establishes two and ten-year follow ups by regulatory bodies to ensure active planning and actions are being made to ensure timely compliance. Non-compliance will be met with a monetary penalty of $150 per mWh of electricity sold to consumers that do not meet standards (SB 5116, 2019). It outlines the regulating, researching, and rulemaking agencies while acknowledging that this is a preliminary law, with more legislation to come once research has been conducted and interpreted. All in all, CETA addresses anthropogenic pollution by mandating electricity producers stop producing electricity from conventional sources and taking the social costs of carbon into account during the production process. While no direct solar incentives or subsidies have derived from this legislation, this law sets the tone for how the state government will hold a posture towards climate change, traditional fuels, and clean energy technologies going forward.

Cities and utility districts may offer additional policies that can further reduce barriers to entry by providing financial alleviation to overall costs. From the examination of the Ellensburg and Seattle City Light Utility Advisory Committee meeting minutes in 2017, these local incentives tend to be tied to funding received from agencies such as the Department of Energy, Bonneville Power Administration, etc. (Ellensburg Utility Advisory Committee, 2017). These programs are useful to boost the overall monetary discount applied for consumers on the cost of their system and are unique to geographies emphasizing clean energy in their greater growth management goals about integrated resource planning (IRP's). For example, the City of Ellensburg established a goal in 2017 to generate 25% of the city's 2015 electric fuel mix from solar by 2025, resulting in a campaign to generate interest in solar projects as well as awarding successful solar applicants with $1,000 per kW installed (Joint Meeting of the Utility Advisory Committee, 2017). To name a few more, Seattle City Light offers a low-cost way to support the clean energy transition by connecting power producers to residential consumers who wish to support clean energy projects at a reduced rate (often cheaper than Seattle electricity costs) (Northwest Solar, 2021). This program is called Green Up, and it is voluntary for ratepayers, acting as an avenue for those interested to support local solar projects. Chelan PUD offers a version of this in their Sustainable Natural Alternative Power (SNAP) program, allowing consumers to pay a fee generated per kWh of power consumed (Chelan County PUD, 2021). These programs effectively boost overall awareness of the opportunities in place supporting the solar power markets at the household level, with the Green Up and SNAP programs offering residences a way to obtain solar power without directly producing it on-site.

Washington State's Energy Profile

Washington State geographically benefits from renewable resources such as the Columbia River system, which has enabled the state to produce a bulk of its power via hydroelectric electricity (Figure 2). Noticeably, of the state's overall energy composition, natural gas, nuclear, renewables, and coal cumulatively still amount to less than the energy produced via hydropower (EIA, 2021). The hydroelectric capacity comes from 81 hydroelectric dams (Dept. of Ecology, 2019).

Keeping in mind that renewable energy is susceptible to intermittence (Gowisankaran et al., 2011). It takes a considerable amount of space to offset capacity from dirty to clean, a question arises regarding whether hydropower will be able to continue its role in heavy production. The state's journey to removing all dirty capacity will continue to rely heavily on hydropower (Figure 2).



eia Source: Energy Information Administration, Electric Power Monthly

Figure 2

WA Net Generation Capacity by Source (EIA, 2021)

Of the 81 hydroelectric dams in the state, more than 49 have exceeded the recommended 60-year lifespan (Figure 3). The costs of repairing these dams are high and often come with local opposition due to dams' adverse effects on streams and river ecosystems. Dams such as the Wanapum Dam, located in Grant County, Washington, are of these aging concrete infrastructures. The Wanapum Dam was built in 1963, making it fifty-eight years old. In July of 2014, divers found a 65-foot-long crack that ran underwater into one spillway, caused by eroding materials and infrastructure (Jones, 2014). Costs for repairing the cracked underwater spillway exceeded the initial project budget two-fold, and other dam problems are likely to be as costly to address (Geranios, 2016).

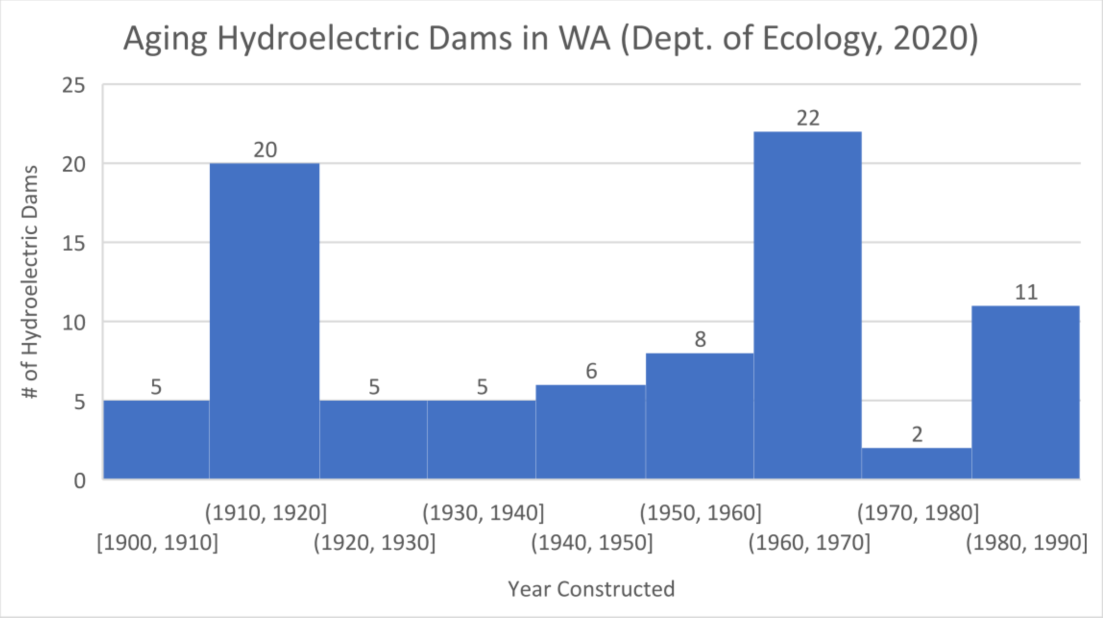


Figure 3

Aging Hydroelectric Dam Infrastructure in WA (Department of Ecology, 2020)

Because of the age and high cost of repairing Washington's power infrastructure. The State must replace this infrastructure with clean energy options.

Solar Economics

The decision to transition a home from traditional power to solar is an economic one, though it also includes environmental factors. Economic factors include socioeconomic status, ownership of a home, and income (Lan, Gou, & Lu, 2021; Mueller & Trutnevyte, 2020). Environmental factors regarding solar irradiance include an additional consideration of the roof shading.

The payback period of clean energy investment is wholly affected by the number of applicable incentives available to the consumer coupled with variables such as solar insolation, electricity costs, and size of the system (Fathoni, Utama, Kristianto, 2014).

The overall costs of a PV system typically range from $8,000 – $30,000, depending on size and other variables such as roof size and integrity (Solar City, 2018).

The willingness to pay (WTP) for an item is represented in economics as the total overall value that an individual is willing to spend to obtain a good, service, or amenity. The willingness to accept (WTA), on the contrary, is the minimum monetary amount that a person is willing to take for selling a good or service, or to bear a negative externality. WTA is usually much higher than WTP, specifically for non-market goods such as pollution (Horowitz and McConnel, 2002).

In 2020, 43% of all new capacity was derived from PV (SEIA, 2019) (Figure 4). Coal capacity saw its last rise in 2014. Meanwhile, the cost of electricity from PV solar has steadily fallen since 2010.

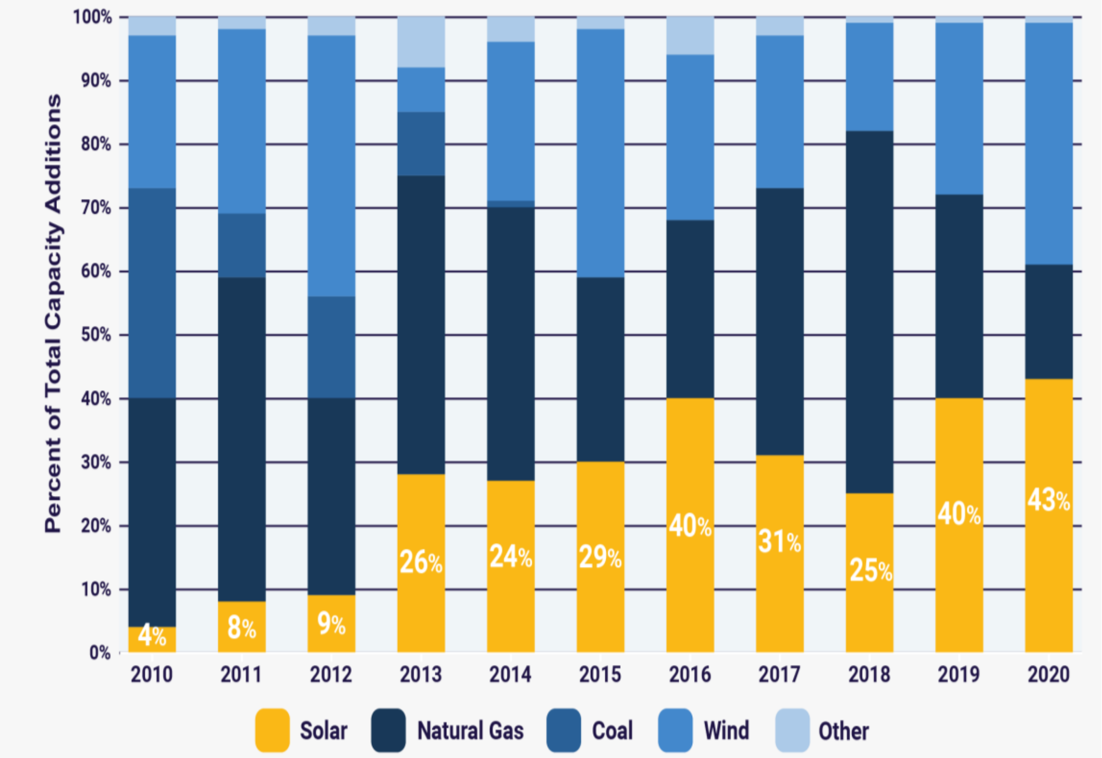


Figure 4

Annual Global Electric Capacity Additions (SEIA, 2020)

The International Energy Association (2020) forecasts global photovoltaic capacity to double by 2024 (using 2019 as a base reference year). This will replace outdated and dirty polluting fuels such as coal-generated power and eventually petroleum-based products. For electric capacity added in the United States, PV production had increased steadily since 2010, when only 4% of all new electric additions were solar PV. Meanwhile, in 2020, over 80% of all additional capacity installed was derived from solar and wind. Regardless, today solar makes up 2.3% nationally of the U.S. electricity use. The forecasted growth of PV is expected to continue through at least 2030 (Figure 5).

Figure 5

U.S. Solar PV Forecast

For solar power, the proven barrier to entry for consumers is the high initial outlay required to purchase the hardware and connect to the grid (Shai et al., 2013, Zhai and Williams, 2012). As time passes and the costs associated with PV systems decrease, namely the costs associated with the hardware itself, installations of PV have increased

(Shai et al., 2013). Some areas report a local peer effect (Kotchen & Moore, 2007, Diaz-Rainey & Ashton, 2011) that shows once solar begins to penetrate a local market, neighbors are more likely to adopt (Zhai and Williams, 2013). Other studies support a phenomenon by which an individual's environmental concerns are magnifying the willingness to accept the costs associated with "going green" for its benefits to the environment (Diaz-Rainey & Ashton, 2011).

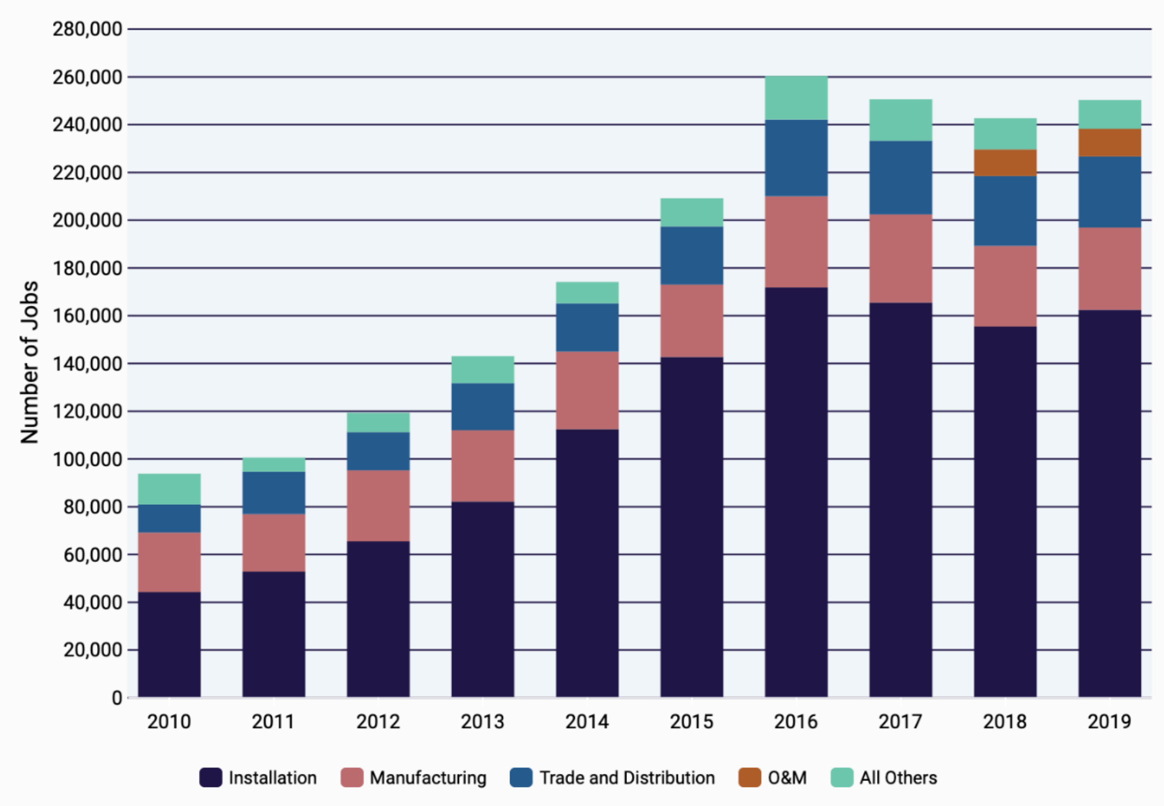


Figure 6

Solar Industry Jobs by Sector (Wood Mackenzie, 2020)

With installations forecasted to continue increasing, so will jobs in the solar industry (Figure 6). The cost of solar in terms of dollars per watt has been steadily dropping, and as a result, more economic agents, or individuals, are able to enter the market (Figure 1).

As of 2019, a quarter of a million Americans works in the solar industry, a figure that has doubled from 8 years ago and is represented visually in Figure 7 (SEIA, 2020).

Table 3 illustrates the observed levelized cost of electricity (LCOE), a standardized measurement meant for observing differences with all else held the same.

Table 3

Cost of one kWh per Energy Source (Department of Energy, 2019)

Energy Source	Levelized Cost of Electricity ($/kWh)
Coal	0.12-0.13
Natural Gas	0.04
Nuclear	0.09
Wind onshore	0.04
Wind offshore	0.11
Solar PV	0.04
Solar Thermal	0.17
Geothermal	0.04
Biomass	0.09
Hydro	0.04

Solar power finds itself competing for the top spot of cheap electricity, tied with geothermal hydro and onshore wind (Department of Energy, 2019). The federal, state, and local policies have sponsored the adoption, along with price declines and a demand for clean energy.

Further growth of PV markets will be achieved, to some extent, through further financial and economic incentives and legislation providing support to the consumers or utilities footing the bills for renewable energy production systems. However, clean energy technologies have now gained economies of scale and continue to become more cost-competitive. The relationship between the declining cost of energy per kilowatt derived from solar energy and the increasing number of installations can be seen in figure 7. This data is utilizing NREL's cost per wat of U.S. Solar power alongside the solar dataset received from the WSU Energy Program, which contains all WA installations under 50kWh ranging 2000-2019.

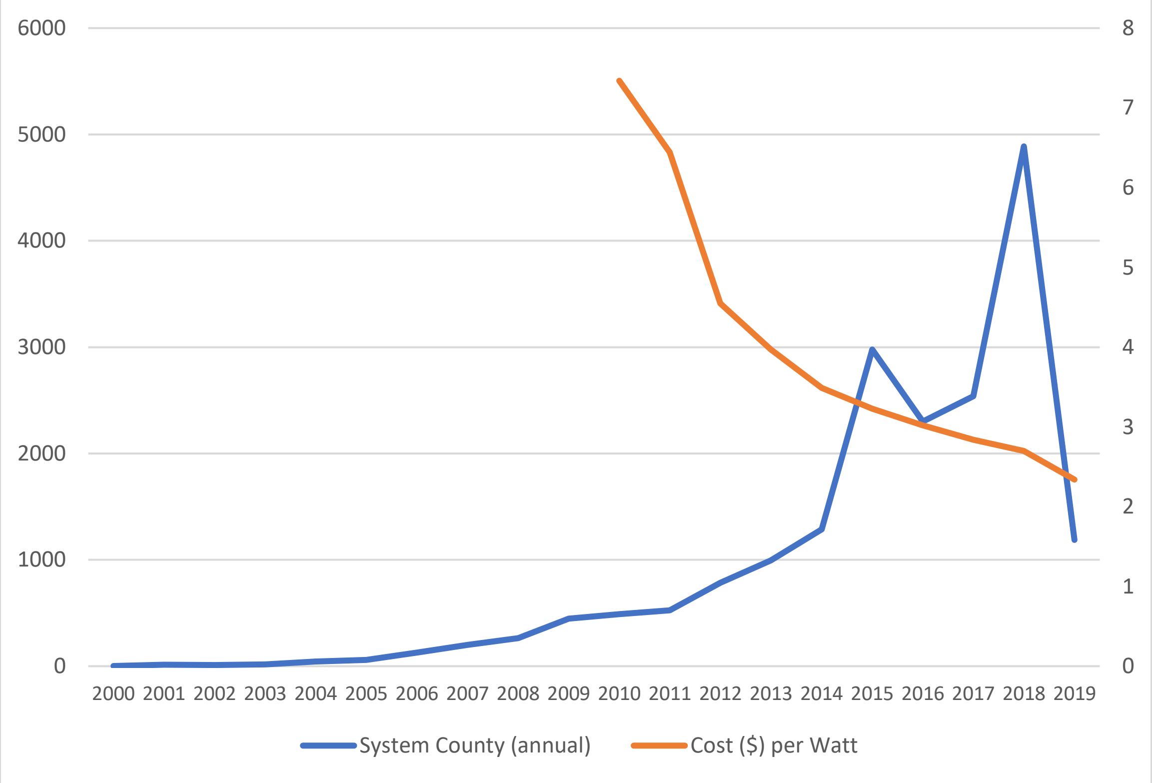


Figure 7

Cumulative Solar Installations and Cost per Watt in WA

According to the most recent International Renewable Energy Agency (IRENA) in 2020, solar and onshore wind are the cheapest forms of energy on a per kWh cost basis. The report states:

> "Renewable power generation continues to grow in 2020, despite the COVID-19 pandemic. The steadily increasing competitiveness of renewables, along with their modularity, rapid scalability and job creation potential, also make them highly attractive as countries and communities evaluate economic stimulus options. Renewables can align short-term recovery measures with medium- and long-term energy and climate sustainability. Solar PV and onshore wind offer easy, rapid roll-out possibilities, while offshore wind, hydropower, bioenergy and geothermal technologies provide complementary and cost-effective medium-term investment

> options. Costs for solar and wind power have continued to fall significantly. Electricity costs from utility-scale solar PV fell 13% year-on-year in 2019, reaching USD0.068 Kilowatt-hour (kWh)" (IRENA, 2020).

Determinants of Solar Uptake

A survey of the literature reveals that determinants of solar uptake can be boiled down to a few metrics: youth, subsidies and finance, environment, education, and local visibility (peer-effect). The economics of household consumption and the willingness to pay more for clean energy are well documented to influence who is willing to adopt PV (Kotchen & Moor, 2007; Ozaki, 2009; Diaz-Rainey & Ashton, 2011; Guangle and Girma, 2019; Mundaca, 2019).

Studies reveal a duality in which younger adults generally are more willing to accept longer payback periods for several reasons that come down to a perception of the environment in which they live as well as the amount of time it takes to pay off the investment. For these reasons, older populations tend to be more hesitant and less likely to accept a longer-term investment. Lange et al. (2015) posit that for this reason, younger adults are more willing to take on the payback period associated with a clean energy investment compared to their older counterparts. On the contrary, Shai (2013) offers that while younger people are more eager to adopt clean energy alternatives, they are willing to pay less monetarily for the benefits that come along with them. Other studies find that an individual's willingness to pay for clean electricity is a question of household size and energy demand compared to the costs of alternatives (Faires & Neame, 2006, Welsh, 2009, Bollinger & Gillingham, 2012, Zhai & Williams, 2013). Additionally, the price of available substitutes affects the demand for PV as well, namely because of impacts on the payback period (Fokaides & Kylili, 2019). The current and available subsidies empirically impact uptake and interest from consumers due to the direct effect a subsidy has on the overall price (Fathoni, Utama, & Kristianto, 2014).

Government subsidy and sponsorship, especially early in the solar industry's beginning, was largely successful in increasing PV adoption through its critical policy mechanisms such as feed-in tariff's (FIT's), net metering, and so on (Haas, 2011, Solangi et al., 2013, Jenner et al., 2013). After introducing U.S. and U.K. markets, FIT's increased adoption of targeted systems and immediately increases uptake across a range of geographies (Cherington et al., 2013). Additional subsidies in system rebates for desirable technologies to defer hardware and connection costs are effective (Hsu, 2012; DSIRE, 2019). A study in Massachusetts finds that tax credits and additional rebates are much more likely to generate a preferred response from consumers considering making a clean energy investment such as solar (Brauner & Crago, 2015).

Beyond subsidies are the financial variables that make one consumer more inclined than the next. Given that solar is a costly investment, income has been used to explain uptake statistically on the logic that those who make more can afford to spend more. Best, Nepal, and Saba (2021) test this hypothesis, stating that wealth variables – measures of ownership as opposed to income; were much more effective in statistically quantifying uptake. Through U.S. Census data and other open-source mediums, there are currently no available wealth metrics such as pensions, non-financial, and financial asset value, which the government of Australia provided in this case.

Beyond these financial motives, there are environmental and ethical motives that have been considered to drive uptake. Similar to the peer effect, there is general altruism when a conscious decision is made to stop sourcing energy that is a part of a climate problem and to change your household energy consumption over to a sustainable and clean source (Andreoni, 1990). Kotchen & Moore (2007) insist that this altruism is enough to drive some households to switch over because in doing so, the entire society benefits from their costs paid. Diaz-Rainey and Ashton (2011) find that in the Organization for Economic Cooperation and Development (OECD) nations, this altruistic approach will certainly affect an individual or society's willingness to pay for clean energy. Pfieffer (2017) finds that solar uptake is highly correlated to the installed base of solar, though this study does not normalize for population density.Education is commonly used as a proxy for environmental awareness and to gauge a general understanding of existing incentives and is a strong determinant of PV adoption (Shi et al., 2013).

Generally, the higher the level of education, the more likely the individual has a better and more accurate formed perception regarding the economics and overall general information regarding solar (Brauer & Crago, 2015). Furthermore, statistical models show that higher education levels result in higher uptake of solar (Best, Nepal, & Saba, 2021; Pfieffer, 2017). This coincides with findings from an Australian study that utilized machine learning to understand how socioeconomic variables affect uptake, resulting in an understanding that the level of awareness and education in an area is a predictor of uptake (Lan et al., 2021). In California, areas with higher educational attainment were more likely to be influenced by peer effects and social campaigns (Bollinger & Gillingham, 2013). Information campaigns seem to be the best way to directly address knowledge inadequacies and uncertainty of the payback period (Palm & Tengvard, 2011, Rhia & Beck, 2015, Brauer & Crago, 2015).

Literature suggests that suppressing factors of PV adoption are related to consumer economics and misperceptions of the systems themselves. Given the relatively high up-front costs associated with PV systems, policies that reduce costs for the consumer are immediately beneficial. Cost-reduction is a policy avenue that has successfully fostered the renewable energy markets globally (wind, solar, and biomass) and continues to advance adoption rates (Guangul et al., 2019; MacGillivray et al., 2014; Chaurey & Kandpal, 2009).

For many, perceptions exist that solar PV is too expensive to afford for the average person (Bazilian et al., 2013). When costs come down, installation rates go up (Kwan, 2012). Initial outlay costs (Edward & Kang, 2009), high renter to homeowner ratio (Welsh & Kuhling, 2009), local ordinances and rules permitting and regulating solar (Kittitas County, 2018), and even poor aesthetics (Duke et al., 2005) are all attributing factors to what may be preventing denser adoption and penetration rates of PV solar. Information campaigns regarding PV Solar in Sweden have positively affected the uptake (Palm & Lantz, 2020).

Law (2017) finds another phenomenon at play in areas with high costs of electricity that attribute to low PV adoption, known as the Utility Death Spiral. This process involves a feedback loop where customers seek alternatives to traditional power, only to find distributed generation (away from claws of the utility) via solar photovoltaics. When customers leave the utility company, the utility provider is left with pre-existing debts and declining numbers of customers. Of course, utility companies are willing to go to-bat for their business models, lobbying with millions of dollars in states like Arizona, Minnesota, Texas, and Virginia to “institute fees or restrictions that the solar industry says make projects less viable” (Kowlaski, 2020).

CHAPTER III

METHODS

Introduction

Data was processed in Excel, ArcGIS Pro, and R Studio to arrive at the product of this research. Time-series maps were created for both annual and cumulative residential solar installations and residential solar installations per household. This illuminates the rate and distribution of residential PV growth as well as the overall growth. To focus on the variables that might impact solar uptake, I then examine the relationships between residential solar installations and the covariates (independents). Installations and installations per household are evaluated for their relationship to sociodemographic variables, costs of solar per kilowatt, and residential costs of electricity per kW, and incoming solar irradiance. A multiple regression model is then run to understand whether solar power can be predicted with current explanatory variables. Then, a time fixed effects model is run for the years 2010-2019, using the natural log of installations per county per year, with annual dummy variables for each year to tease out phenomena that may have occurred statewide that were not picked up in the earlier analyses. In all, these methods help understand what is driving the residential solar uptake in Washington State.

Data

Data for this thesis was collected from four sources:

1. WSU Energy Program (http://energy.wsu.edu/)
2. U.S. Census Data Portal (https://www.census.gov/data.html)
3. Northwest Renewable Energy Laboratory (https://www.nrel.gov/gis/solar.html)

4. Electricity Local (https://www.electricitylocal.com/)

The main dataset contains all solar installations, locations of installations, date installed, and size of the system in Washington State between the years 2000 and 2019. This dataset included both residential and non-residential units. Managed by the WSU Energy Program, WSU has been the program administrator for the State's RESIP solar program since taking the reins from the State Department of Revenue (DoR) in 2017. To focus on residential systems, the data distribution of solar installs was viewed in a histogram and split at a natural break at 50kW (Figure 8).

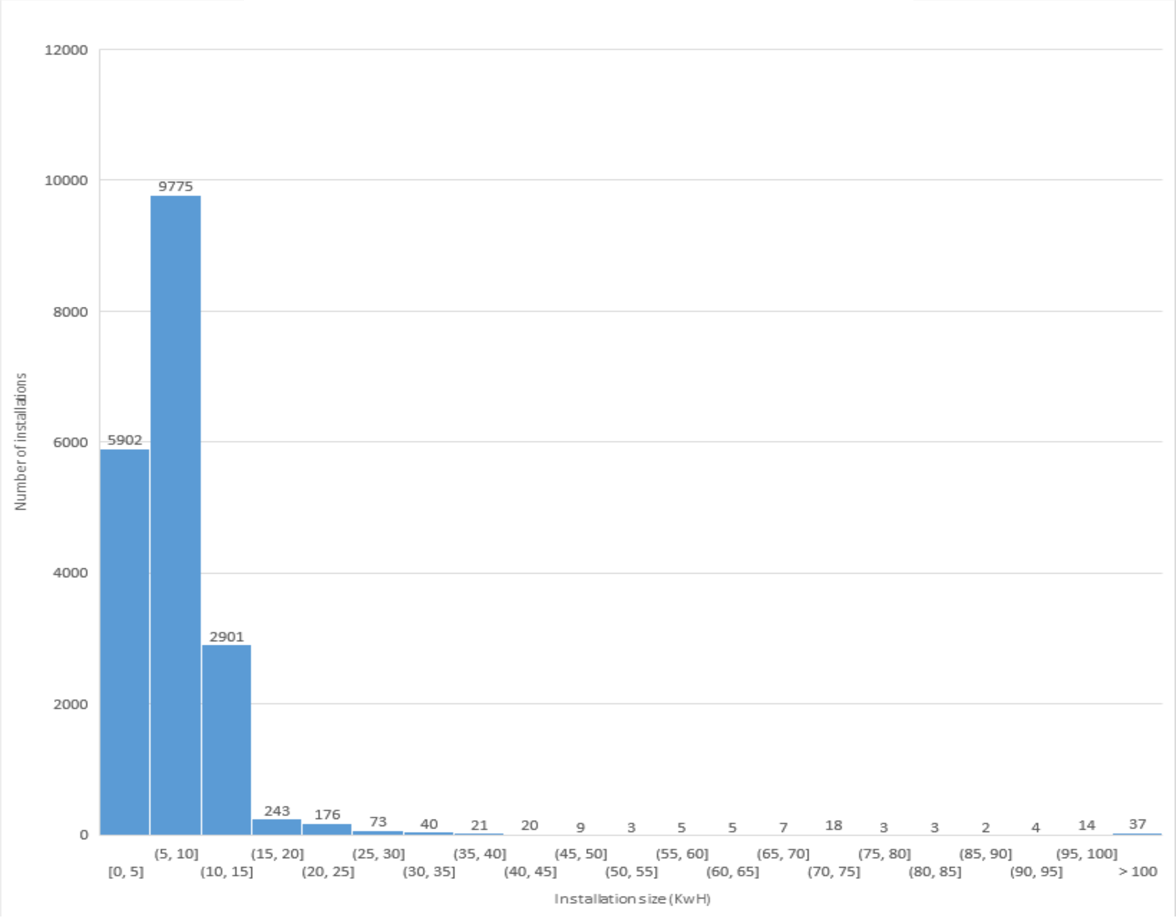


Figure 8

Frequency of Different PV Installation Sizes in WA (WSU Energy Program, 2019)

For the sake of definition, systems with a generating capacity <50kW were deemed residential; systems >50kW systems were considered non-residential and not used in this study. The summary statistics of the residential solar dataset are shown in Table 4. The growth and adoption of solar from the 2000-2010 split compared to the 2011-2019 split is largely one of the phenomena sought to be explained in this work.

Table 4

Summary Statistics of Residential Solar Installs (2000-2019)

2000 to 2010	PV System Size (kW)	2011 to 2019	PV System Size (kW)
Min	1.1	Min	0.6
Max	49.7	Max	49.6
Mean	7.5	Mean	8.9
Count	1,676	Count	17,484

Residential solar installs have grown almost annually in terms of installations per year, with local highs in 2015 and 2018 (Figure 9).

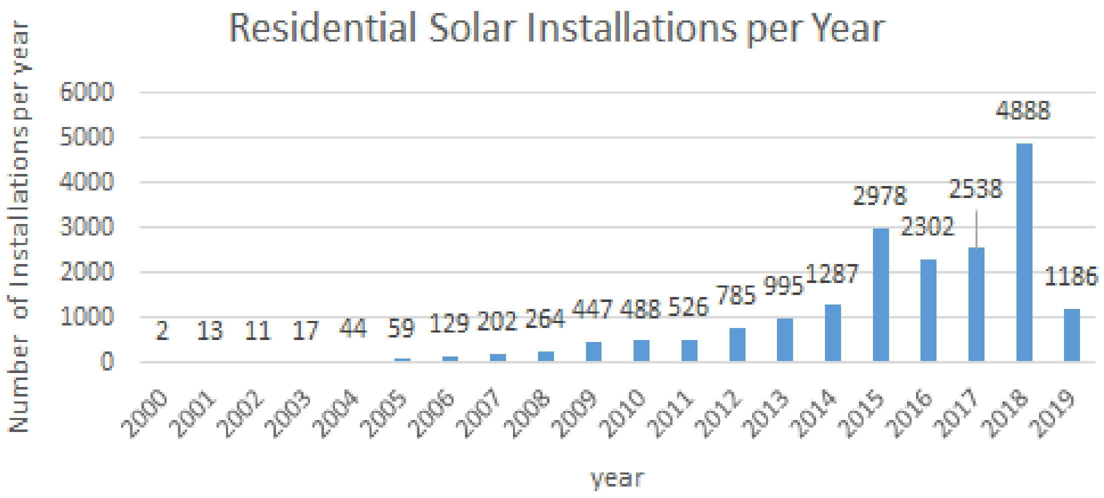


Figure 9

Residential Solar Installations per Year in WA (WSU Energy Program, 2019)

Average system sizes increased from one grouping to the next, as did the system count by a factor of about 11. Outliers are present in terms of small installations, with several small residential scale installations included, albeit they might not provide the entire power load a residence might need. Additionally, roughly 75% of the pre-2017 data was missing detailed locational information. The post-2017 data, however, included street addresses in virtually all the recorded observations. Due to these limitations, the solar data was analyzed for mapping at two different scales across two different periods: city joined to county (2000-2019) and address joined to the Census tract (2017-2019).

The household's variable has a minimum county household count of 952, a maximum count of 831995, and an average of 69143. Furthermore, Washington State's population is found mainly around the I-5 corridor, meaning that population variance over space is not random. In other words, the population distribution among Washington State is heteroskedastic. This is reflected in the mapping of households in Washington (Figure 10).

Using natural breaks in the data, you can see that the overall population in Washington state resides overwhelmingly on the western side of the Cascade Mountains, in the west half of the state, with King, Pierce, and Snohomish counties being the predominant population bases. On the eastern side of the state, Spokane County is the only heavily populated area.

The United States Census Data Portal was utilized to collect demographic data at the county and tract scale for the mapping in Arc GIS. The socioeconomic data was downloaded for the year 2017 for the statistical regressions. Households data was also downloaded for each year, ranging from 2000 to 2019, to ensure accuracy when normalizing residential solar growth by population.

For mapping solar installation uptake, considering households per geography, annual data (2000-2019) was downloaded and later used alongside corresponding annual installations to create a new dependent variable. All other data downloaded was included in the yearly fixed-effects model and required annual data for the years 2010 through 2019 for each variable.

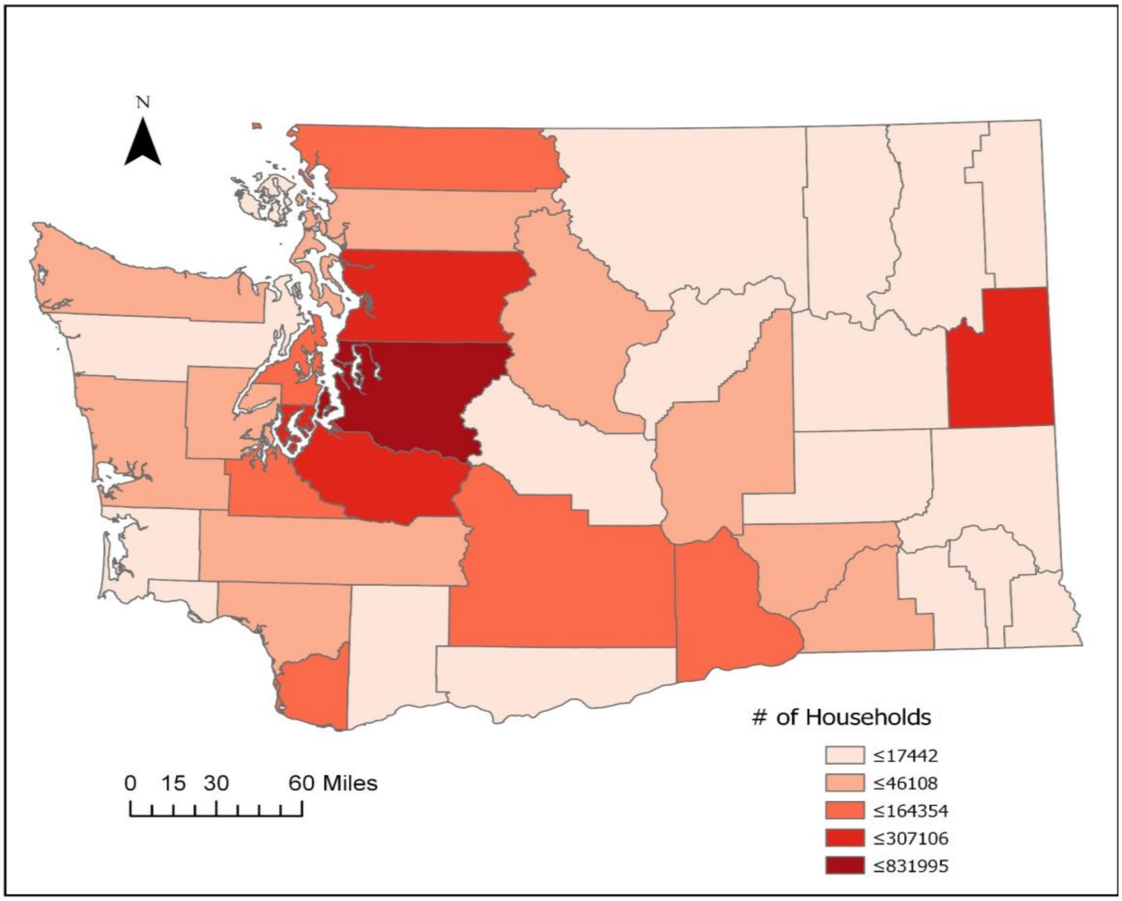


Figure 10

Number of Households per County (U.S. Census Data Portal, 2019)

The ACS annual data that was collected from the U.S. Census was reduced and reclassified to the following:

- Education by Attainment: No college, Some college, BA or higher obtained

- Race: Percent White, Percent Hispanic, Percent Asian, All others aggregated to Percent Other
- Age by group: Percent 20 to 55 and Percent 56 and above
- Mean household income (Adjusted to 2019 dollars for inflation)
- Households

A view of the summary statistics for each variable in this dataset is shown in Table 5. The educational attainment, race, and age data ere originally classified by age brackets of four years and each variable (for example, percent 20-24 with No HS Diploma, percent 25-28 with No HS Diploma, etc.…). The data was reconfigured in Excel to represent the overall percentage of the population with no high school education, some college, and a bachelor's or higher attained. Percent no college education shows a minimum value of 21% and a maximum value of 63% considering all counties. The average county finds 39% of its 18 and older population with no college experience. In terms of percent, some colleges obtained but no BA degree held, the lowest county contains 25% of the population while the highest boasts 48%, and the average county was falling closer to the high side of the spread with 40% of the 18 and older population. Overall, education varies across counties – with King, San Juan, and Jefferson counties leading the way in terms of an educated base population (percent BA or higher obtained).

Race variables were reclassified by the percent race of the overall population. Even though there is diversity in this state, all counties in Washington are predominantly white, with the minimum county percent total representing 72.4% and the max being 98.8%. King, Adams, Franklin, Grant, and Douglas counties each have the highest overall % total white population, respectively. Viewing the counties with the highest Asian populations, most of the demographic reside alongside the I-5 corridor spanning King, Snohomish, Whitman, Pierce, and Thurston Counties.

Table 5

Summary Statistics of Independent Variables

Variable	Min	Max	Mean
Percent Number of People No College	20.7	63.2	39.7
Percent Number of People Some College	24.5	47.5	37.1
Percent Number of People BA or higher	11.8	47.2	23.2
Percent of White to total	72.4	98.8	88.3
Percent of Hispanic or Latino to total	3	61.9	13.7
Percent of Asian to total	1.2	19.6	3.9
Percent of other to total	0	24.5	6.0
Annual Solar Irradiance (kW/m^2)	3.14	4.20	3.64
Median Age	33.60	55.60	44.25
rCoE cents per kWh ($/kWh)	0.04	0.104	0.079
Number of Households	952	831995	69144
Mean Income per Household	49,749	106,772	66,109
Cost per Watt ($/kWh) PV solar	2.71	7.53	3.6

Ferry and Okanagan County are the highest represented areas for native Americans. Meanwhile, Pierce and Thurston County are the densest population clusters for African American residents.

Arguably one of the most important variables playing into the economic attraction of solar is the local incoming average solar irradiance – whether there is enough sunshine in the first place to make a recovery on investment.

Washington finds itself in an interesting spot, with a western side of the state benefiting from the maritime climate and the cloud cover that comes with evapotranspiration. In contrast, the eastern side of the state experiences a leeward climate ripe for solar.

Figure 11 is a map of the solar irradiance across the state. The National Renewable Energy Laboratory maintains a vast dataset of renewable power source information, including national and global solar irradiance data. The 2019 Average Annual Solar Irradiance (kW/m^2) values were downloaded for Washington State in raster format from the data portal on NREL’s website. ArcGIS Pro’s Raster to Polygon tool converted these raster values into county and tract feature classes. Raster values calculated by summarizing the average raster value represent the average annual solar irradiance per unit of geography. Solar irradiance is an important factor in determining the efficiency and payback period of solar power systems.

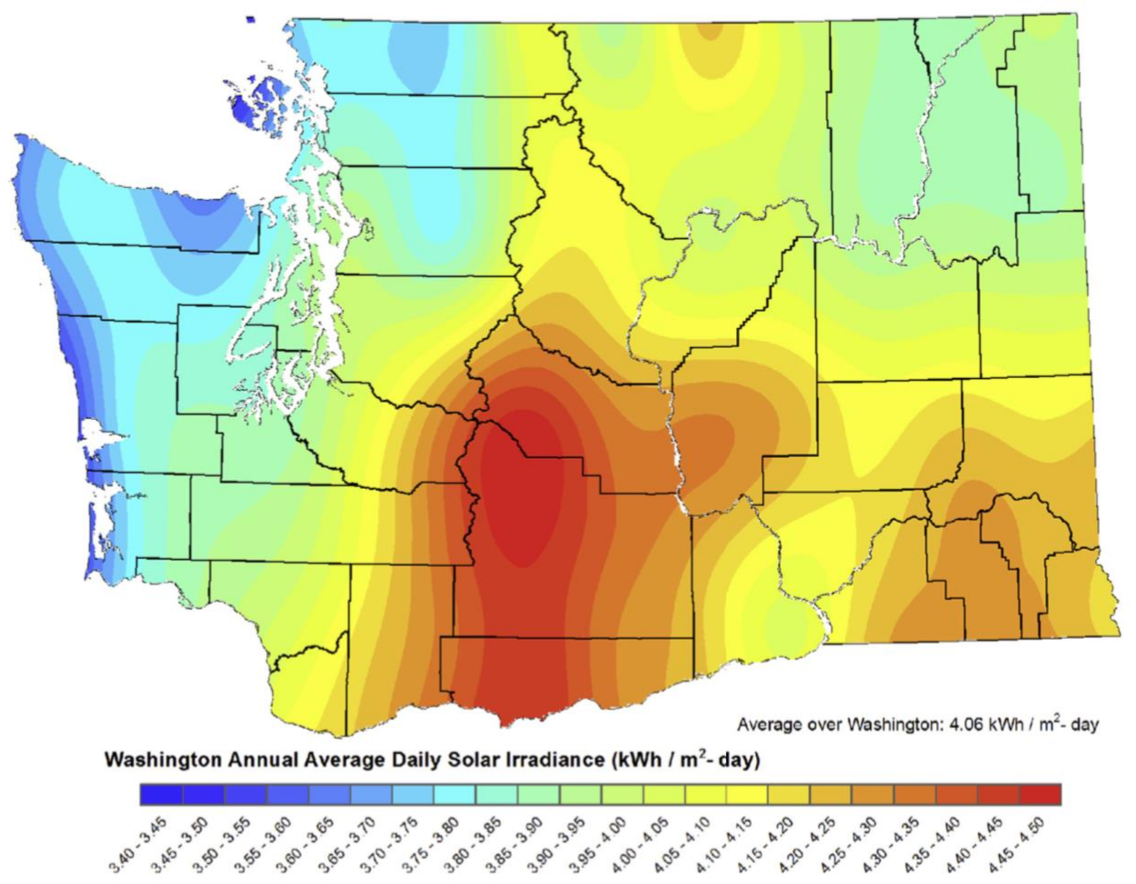


Figure 11

Washington Annual Daily Solar Irradiance (Jacobson et al., 2019)

To normalize for Washington State's skewed population distribution (see figure 10 on page 31), units installed, and capacity added (kW) have been divided by the corresponding number of households in each polygon to create an additional set of dependent variables. Households were used for normalization in place of population because residential solar applications are limited to the household itself. The dependent variables are the Residential units installed, and residential units installed per household.

Age groups were combined with one another for age classes of 20 years and older, placing a break at age 56. Age 20 to 55 and age 56 and older were then classified as younger and older cohorts by percent total.

Data on electricity rates at the county, tract, or even PUD scale is not readily and easily available for GIS analysis. However, Electricity Local maintains a record of residential, utility, and commercial electricity rates across the United States. To generate a general idea of the electricity cost variance across the state, each county was searched to determine the top cities within their boundaries (Figure 12). An average residential electricity price was taken from the top two cities in each county to determine a general cost of the alternative substitute to solar PV. Due to the lack of precision in electricity costs, this data was not used in the tract analysis.

GIS Methods

To show the growth and spread of residential solar photovoltaics, the solar dataset was mapped with units per household using time-series maps for 2000-2019. The corresponding geographies curated data was joined for households, units installed, and units per household inside of Excel and imported as a table into Esri's ArcGIS Pro. After solar installations and household dataset had been joined in Excel, it was geocoded at both county and tract scales in ArcGIS Pro. The “Summarize Within” tool was then run using the geocoded points and corresponding geographic boundary datasets for county and Census tract as their inputs, resulting in shapefiles at the county and tract scales containing solar installations and the Census data per year. Non-cumulative and cumulative datasets were then created for the residential dataset. For each map produced, data were classified by the same breaks.

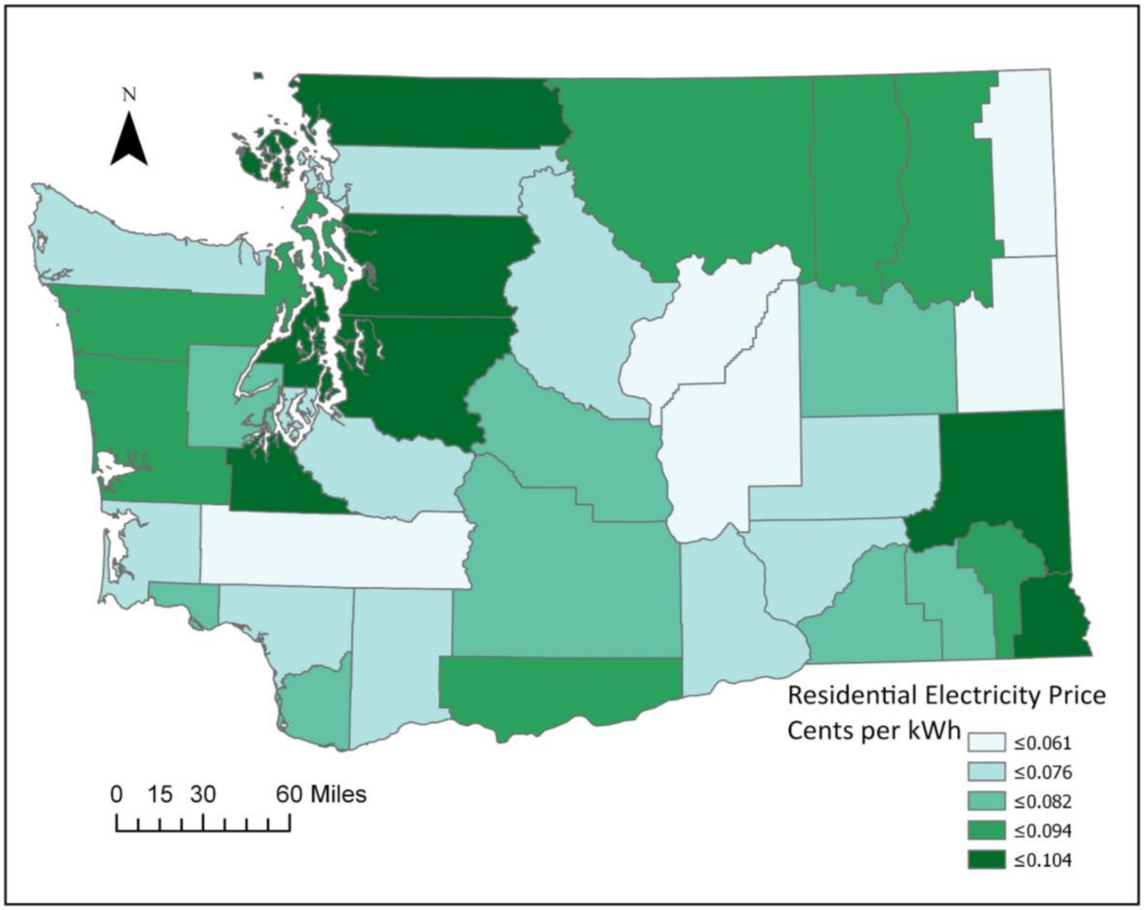


Figure 12

Residential Electricity Price per County (Electricity Local, 2021)

Since this thesis focuses on understanding the trends and determinants driving residential solar uptake and not overall capacity distribution at the residential scale, only units installed were examined from here on out. Time-series maps were used in tandem with a timeline of federal, state, and local policy to infer potential catalysts supporting the growth of residential solar across time.

To understand the spatial trends of uptake for residential solar in Washington state, time-series mapping was undertaken in ArcGIS Pro for the following variables:

- Cumulative Residential Solar Installations Added Per Year (County)
- Non-cumulative Residential Solar Installations Added Per Year (County)
- Cumulative Residential Solar Installations Per Household Per Year (County)
- Non-cumulative Residential Solar Installations Per Household Per Year (County)
- Cumulative Residential Solar Installations Per Household Per Year (Tract)
- Non-cumulative Residential Solar Installations Per Household Per Year (Tract)

Statistical Methods

Ordinary least squares regression is a method well suited for modeling the effect and change that one variable has on another when all factors are held constant. Solar installations are evaluated in isolation through univariate inquiry and presented in a correlation matrix to identify variables that might correlate to higher residential uptake. Solar installations per county between the years 2010 and 2019 are then modeled in this thesis using both a standard multiple regression model and a fixed-effects regression model inside of R. The multiple regression allows for inquiry into the covariates collective explanatory power after evaluating them each Individually. Then, using a yearly fixed-effect variable to isolate annual change while holding all variables constant, solar installs are modeled per county per year to tease out years that are statistically significant. These results are evaluated in tandem with the spatial analysis to understand the drivers and patterns of residential solar power across Washington State. In other words, the fixed effect model allows for all else to be held constant when examining solar uptake on an annual basis across counties, which may then be corroborated with policy changes and economic events to determine drivers.

To avoid multicollinearity in the regression models, some variables where the group adds up to represent 100% of the population needed to be removed. For example, percent no college was left out, and percent some college and bachelor's degree or higher were included. The three most predominant racial variables, as it pertains to state-wide representation, were included. These were percent White, Asian, and Hispanic. As far as the other independent variables in this model, median age, solar irradiance (annual average), number of households, mean income, and an average cost of electricity were also included.

Regarding the Gauss-Markov ordinary least squares assumptions for regression analysis, this dataset finds itself most problematic in relation to its heteroscedasticity. Heteroskedasticity refers specifically to the uneven and unequal variance in residuals across space. This can be perceived in the contexts of Washington State's geography at the county scale when considering the differences in population, economy, and crime in King County versus Chelan County. Standard robust errors will be used to correct the heteroskedastic qualities in this dataset.

Univariate Regression

Cumulative tallies were aggregated for the county (2010-2019) and tract scale (2017-2019) for units installed and units installed per household. Each of these dependent variables was then plotted against the list of independent variables in Table 5 to determine the statistical relationships (if any). Relationship strength was based on the adjusted *R*-squared value. Linear relationships were chosen as the method of evaluation, although some tract relationships among variables suggest relationships that are not linear. The independent variables themselves were then plotted against households to evaluate the dataset for multi-collinearity and autocorrelation.

Multivariate Regression

Once an understanding had been built of each covariates relationship with the dependent, the top three variables by state-wide representation were tossed into a multiple linear regression using R. The model was run twice, once without standard robust errors and once with them applied to account for the heteroskedasticity in the dataset.

Fixed Effect Regression

The fixed effect model is appropriate to tease out macroeconomic events at the policy level when evaluating yearly growth across counties in Washington. For each year ranging from 2010 to 2019, the natural log of the number of installations was calculated and used as the dependent variable to approximate the percentage change in the installations throughout the state. A binary annual year variable was included, classifying counties seeing an installation that year as a “1” and those without as a “0”. This model effectively measures the average growth or decline in variance of solar installs per county per year, somewhat putting a statistical value on the spatial results depicted in the maps. The coefficients of these annual fixed effect variables give insight into how many solar installations were present on average per county per year and yield the years of drastic change, insinuating a policy or economic event. The discrepancies from year-to-year time-series dummy variables will be an interesting result of this model.

Due to issues with heteroskedasticity in this dataset, robust standard errors are produced for the fixed effects model. A complete list of independent variables in this study are:

- No college experience
- Some college experience
- Bachelor’s degree or higher
- Number of households
- Percent White
- Percent Asian
- Percent Other
- Percent Hispanic
- Percent Age 20-55
- Percent Age 56 and up
- Household mean income (2019)
- Residential cost of electricity ($/kWh)
- Annual Avg. Solar Irradiance
- Cost per Watt ($/kWh) PV solar

The coefficients of the yearly fixed effect model will be examined to corroborate which years stand out from the rest. These coefficients are evaluated annually to determine the years appearing as outliers in uptake. For example, the yearly fixed effect variable may show a coefficient of -51, meaning counties on average saw -51 installations compared to solar in all other years. An annual uptick or downtick can signal some change has occurred, whether it be an economic event, incentive policy, or so on. These outliers can then be compared to the time-series maps and the literature review of the national and state solar legislation to build an understanding of solar uptake. If something unusual happens during one of these years, it should show up in the model's yearly fixed effect variable coefficients. A general understanding of all other independent variables included in this model and their strength to the residential units installed are constructed from the significance levels and overall *adjusted R*-Squared values.

CHAPTER IV

RESULTS

Introduction

The spatial patterns over are discussed in the context of regional and local scales. Next, the univariate relationships are examined among dependent-predictor variables and among the predictor variables themselves. Afterward, the multivariate regression results are evaluated for units installed per household at the county level. Then, to account for phenomena such as policy trends or economic events, a fixed effect model was run in which binary variables were created for the years 2010-2019, to be included in the regression. In total, these three methods provide insight into what does and does not explain residential solar uptake.

Map Results

Figures 13 and 14 illustrate the annual non-cumulative and cumulative metrics of residential PV uptake across Washington State from the year 2000 through 2019. Installed solar capacity is generally highest in counties with high populations. There is noticeably low adoption at the county level state-wide up until the year 2006, which is the first year of Washington State's RECRIP incentive and the beginning of the Federal ITC program. Through the next couple of years, there is an uptick in installations around the state. However, adoption remained relatively low except in King County, the highest population and population-dense county. Low adoption is noticeably prevalent in counties where the average residential cost of electricity is less than 6.5 cents per kilowatt hour, including Chelan, Douglas, Grant, Lewis, Pend Oreille, and Spokane Counties. This low cost of electricity is competitive to solar. It is reflected in the low solar uptake of all counties residential demonstrating very low solar uptake, Spokane County being the exception (Figure 13). Regardless of the view, both show that prior to the decreasing costs associated with PV in 2010, adoption remained low both annually and cumulatively across the state. It is also noted that the subsidization of solar economics via feed-in tariffs and net metering structures acted as a catalyst in the early 2000s after the ITC and RECRIP programs were introduced in 2006. Afterward, an uptick in installations is seen across the state.

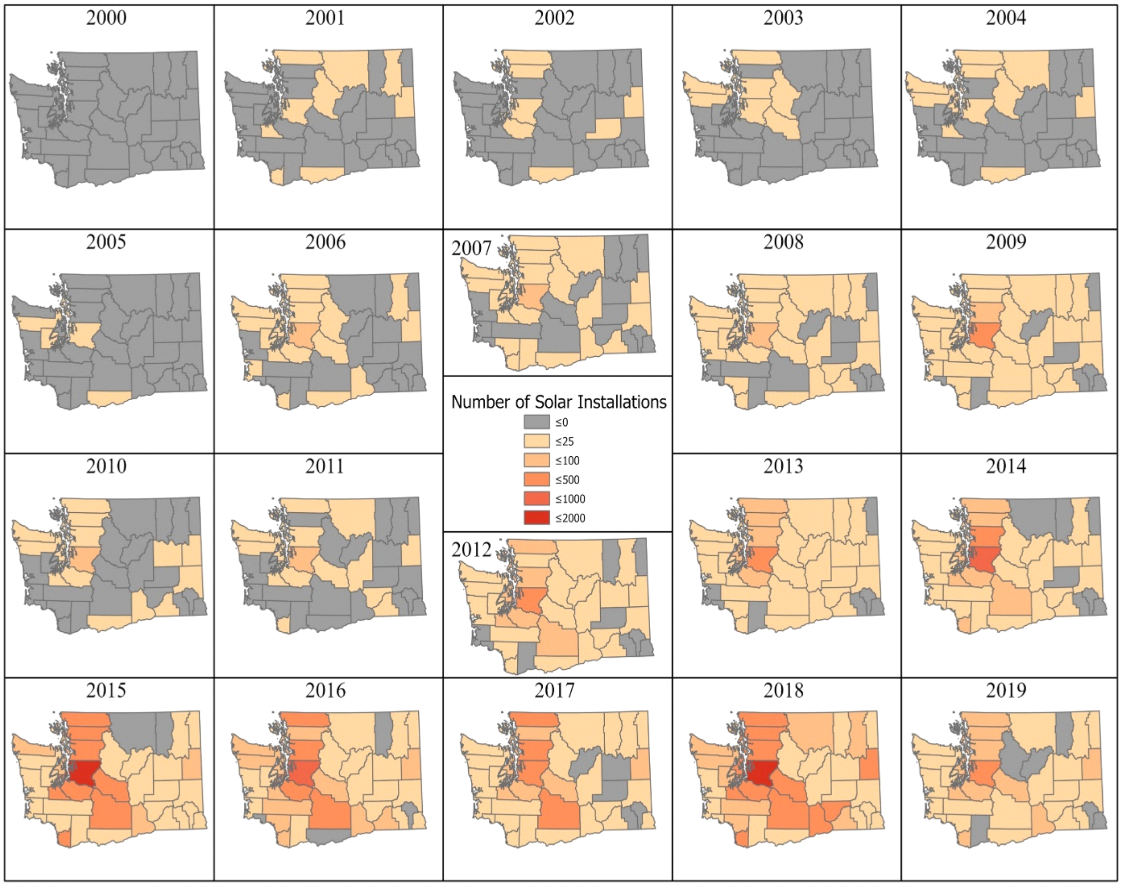


Figure 13

Time Series Map of Residential Solar Installations (non-cumulative)

As the costs of PV hardware and the associated soft costs decrease from the year 2010 onward, installations pick up around the state. The best year for residential solar came in 2018, with over 4500 installations during the year after RESIP was signed into law. 2019 exhibits the effects of RESIP running completely out of funding by July. The trends of solar installations over time and space indicate similar trends as the capacity installed shown in Figure 14. The uptake resides in, for the most part, around heavily populated cities and counties. This is to be expected since the choice to invest in a solar power system is inherently an economic decision, and economic activity follows the human activity. Areas of low uptake are observed in the low population counties making up northeastern and southeastern WA and Douglas County. Figure 13 illustrates the effect of Washington States RESIP incentive program running out of funding for new applicants in low adoption state-wide compared to prior years.

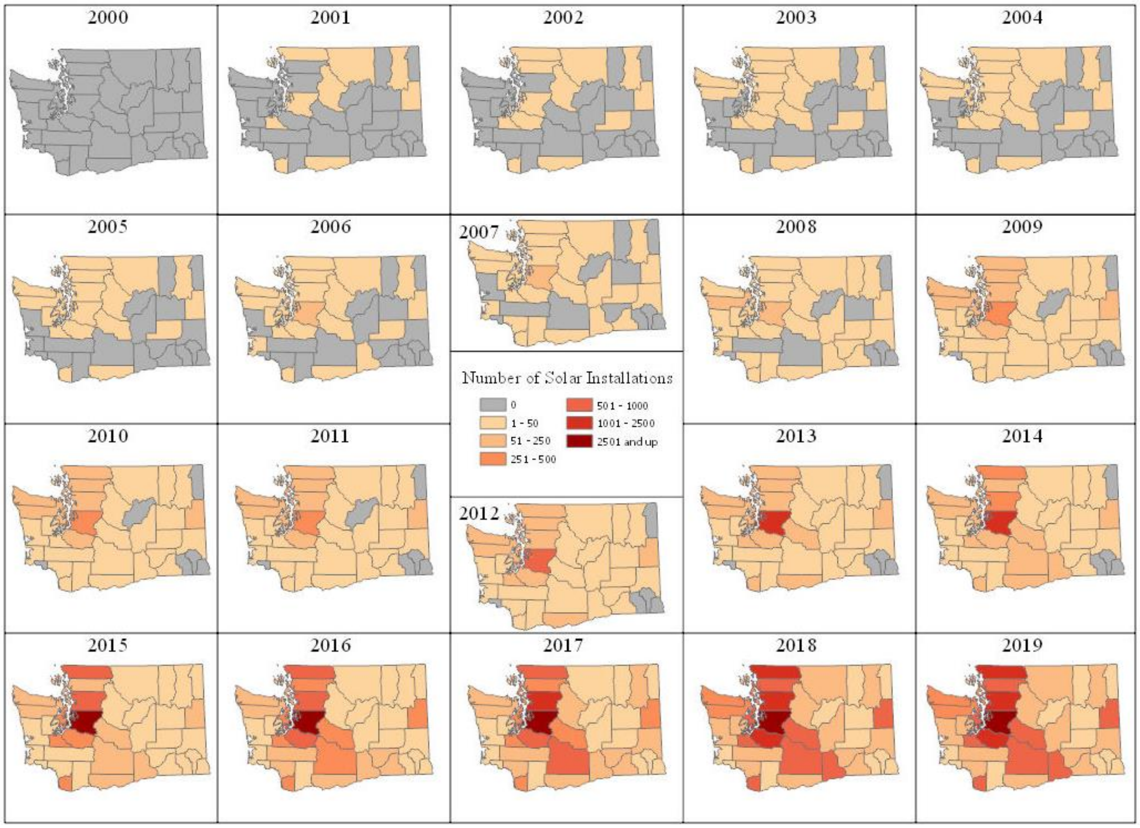


Figure 14

Time Series Map of Cumulative Residential Solar Installations

Similar is the net increase change of 2015 (Federal Tax Credit Extension) and 2018 (Washington State RESIP extension). As far as cumulative trends, installations are not uniform across the state's geography. Rather they are occurring in higher frequency in counties with higher populations and higher electricity prices. Heavily populated counties bordering the Western side of the Cascades (Whatcom County down south through Pierce County) demonstrated higher rates of installations earlier on. Meanwhile, counties such as Kittitas, Yakima, and Clark exhibit higher installation counts as the costs of solar were driven down in the years following 2015.

Normalized Map Results

When normalizing residential installs by the number of households, rates across the state are relatively consistent regarding solar uptake (Figure 15). Areas of high and low performance can then, in theory, be evaluated for their characteristics, population aside.

Kittitas County and Douglas County, located in central Washington, are the high and low outliers regarding residential solar market penetration, respectively. When accounting for population, Whatcom County leads the West side of the state in residential market penetration of PV. At the tract level, in 2017, normalized uptake of residential solar remained relatively uniform across the state, aside from areas around Vancouver, Bellingham, and Ellensburg, and Richland (Figure 16 and 17).

The tract map results resemble the trends seen in the county scale installs per household, with Douglas County as an outlier with low uptake, along with many rural and lowly populated Census tracts in the Okanagan. For residential solar, the outstanding body of literature states in many cases that peer effect, visibility of PV

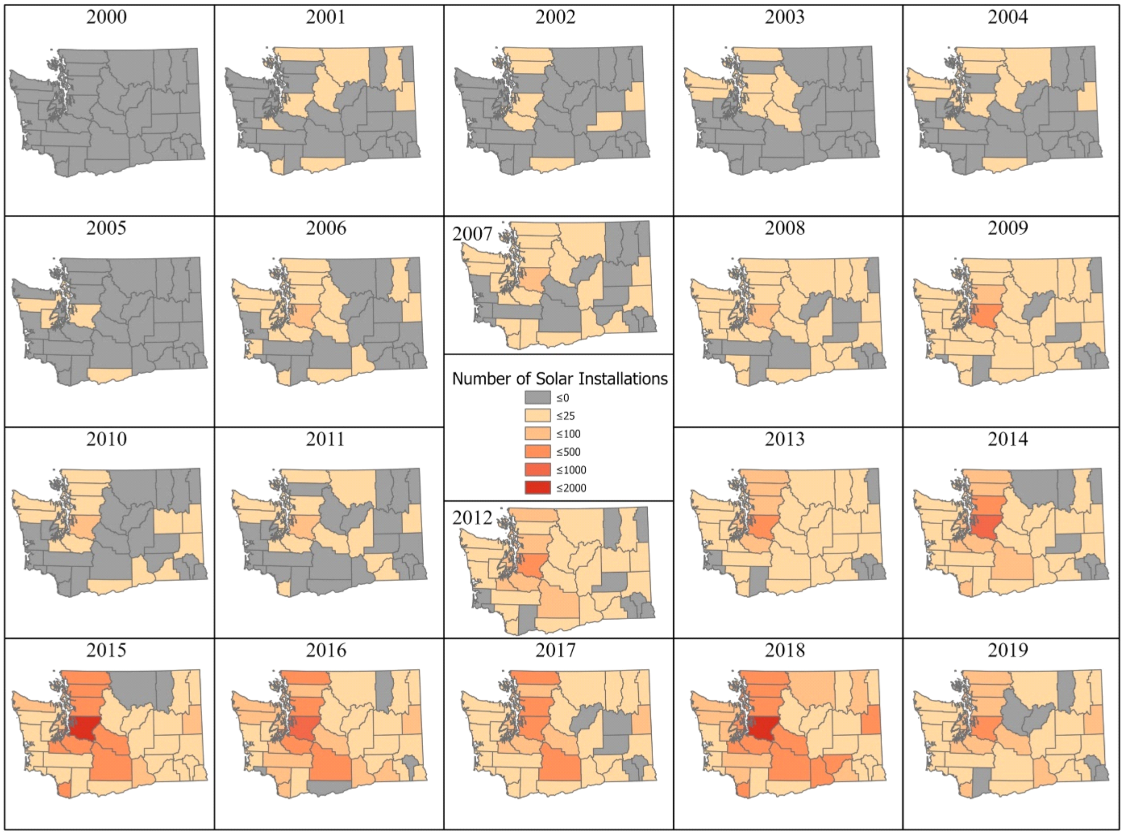


Figure 15

Time Series Map of Cumulative Residential Solar Installations

systems within the community, and ease of finding and obtaining solar services are all positively related to solar uptake (Sources from lit review). These phenomena are best measured through surveys and conducting visibility analysis, which this study is does not contain. However, the tract scale maps give insight into what localities are pulling the bulk of the weight for each county. These may then serve as an interesting study area to determine if local factors such as the presence of solar services or PV visibility within the community. Generally, Census tracts contain 2,500 to 8,500 residents, and when constructed, boundaries are designed to encompass homogenous characteristics of populations, economic status, and living conditions.

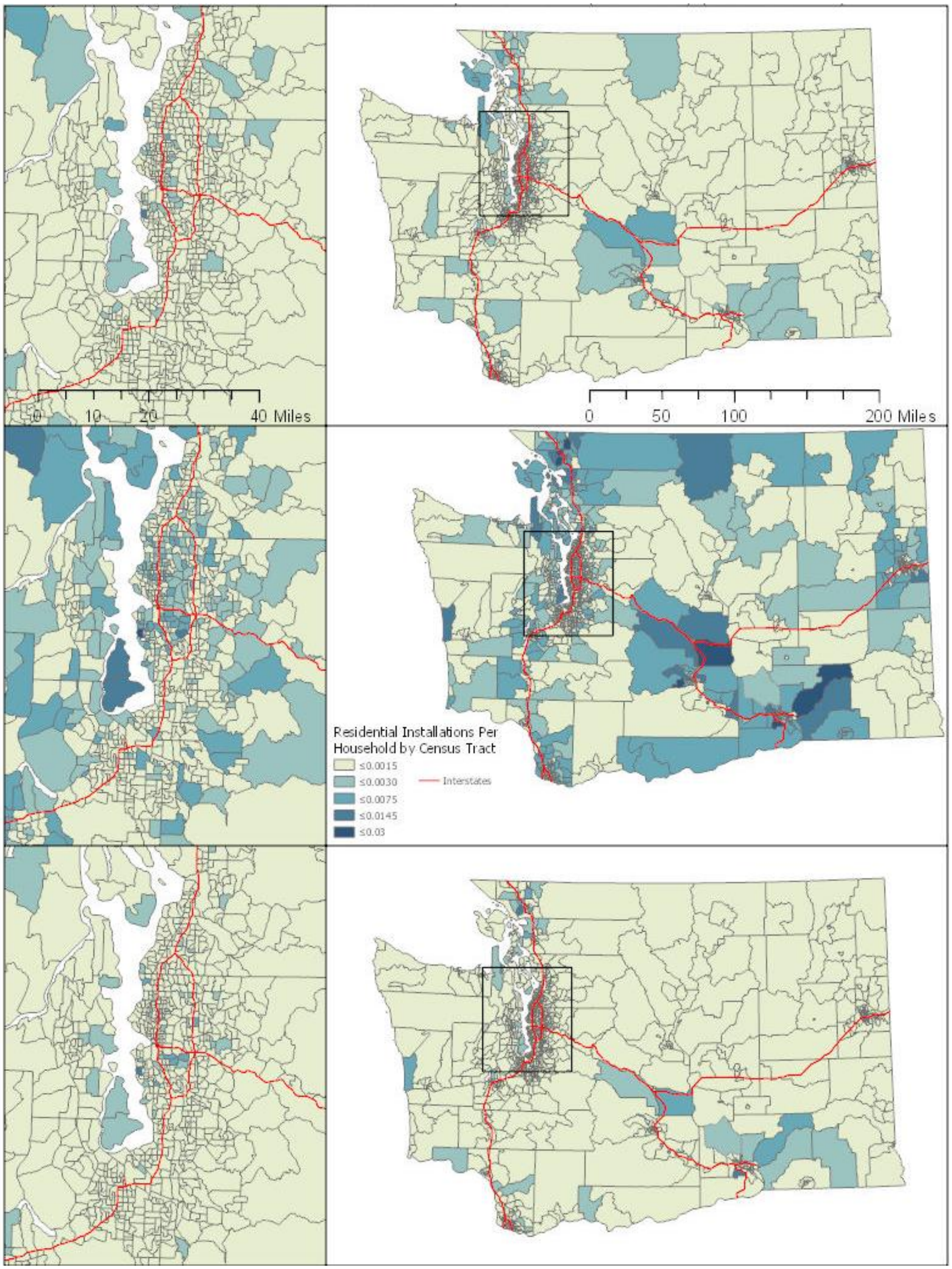


Figure 16

Annual Residential Units Installed per Household by Census Tract (Non-Cumulative)

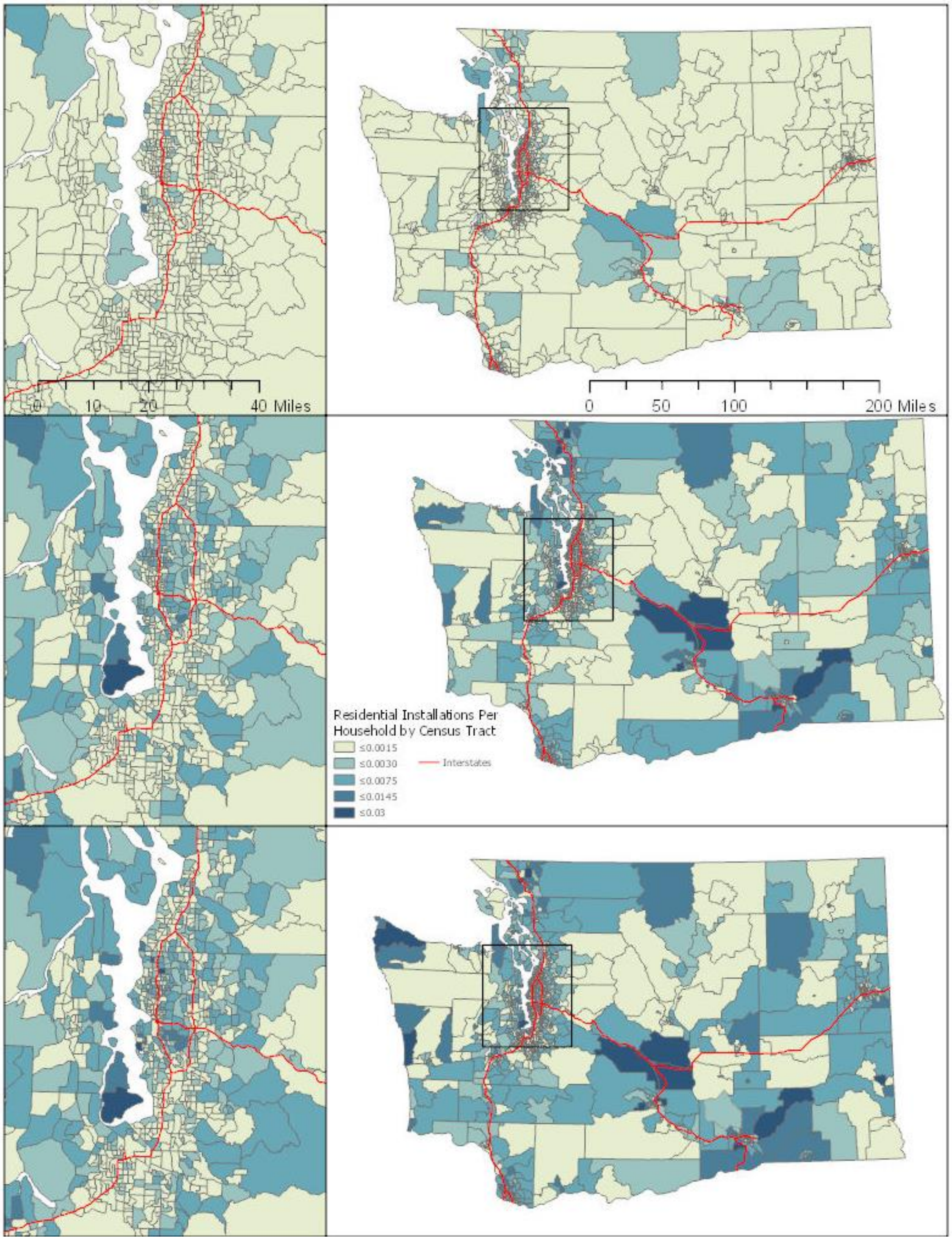


Figure 17

Cumulative Residential Solar Units Per Household by Census Tract

Univariate Regression Results

The relationships among dependent and covariates were ranked according to the classification in Table 6, a standard strength of relationship metric used in determining the relation between dependent and independent. The type of univariate relationships between predictor variables and dependent variables at the county scale are shown in Table 7. The adjusted r^2 and line of best fit were used to determine if any relationship exists between dependent and independent and any independent variables that are highly correlated with the dependent dataset.

Table 6

Coefficient Relationship Classification

Adjusted R Squared	Type of Relationship
0.8-1.0	Very strong association
0.6-0.8	Strong association
0.4-0.6	Moderate association
0.2-0.4	Weak association
0.0-0.2	Very weak

The non-normalized univariate results find meaningful statistical relationships between residential uptake and finance, population density, race, and educational attainment. The mean income per household elicits a significant result, while the cost of electricity shows little effect on uptake.

Most correlated is the number of households within each county (92%) (Table 7), which confirms the population trends depicted in the non-normalized residential uptake in Figures 9 and 10. Education elicits a positive relationship, with its strongest draw coming from "% BA or Higher." Solar irradiance has a weak negative relationship to residential solar uptake across the state, reflective of the dominant population and economies of the counties surrounding the Puget Sound Area. For age, older cohorts are taking on the long-term investment of solar less often in most counties when compared to their younger cohort counterparts.

Table 7

County Univariate Analysis Results

Variable	Residential Units Installed	R^2	Residential Units Installed by HH	R^2
Percent No College	Very weak negative	0.14	Weak negative	0.21
Percent Some College	Very weak negative	0.14	Very weak negative	0.03
Percent BA or higher	Weak positive	0.32	Weak positive	0.37
Mean Income per Household	Moderate positive	0.58	Weak positive	0.24
Number of households	Very strong positive	0.92	NA	NA
Average Solar Irradiance	Very weak negative	0.05	Very weak negative	0.03
Cost of Residential Electricity	Very weak positive	0.10	Very weak positive	0.15
Percent Age 20 to 55	Weak positive	0.39	Very weak positive	0.12
Percent Age 56 and up	Very weak negative	0.13	Very weak negative	0.02
Percent American Native	Very weak negative	0.03	Very weak negative	0.02
Percent White	Very weak positive	0.16	Very weak negative	0.01
Percent African American	Moderate positive	0.46	Very weak positive	0.06
Percent Hispanic or Latino	None	0.00	Very weak positive	0.10
Percent Asian	Very strong positive	0.70	Very weak positive	0.14
Percent Other	None	0.00	None	0.00

Race is seemingly relevant here, with % Asian and % African American eliciting a moderate positive and weak positive response across non-normalized uptake. However, because many of these are directly related to population, there are autocorrelation issues.

Going forward, residential solar uptake will be evaluated only when normalizing for households, to explain uptake determinants with population held the same.

When the solar dataset is normalized by household, none of the variables tested against uptake exhibit a moderate or strong positive or negative relationship. The strongest response elicited from the educational attainment variables was percent BA or higher, indicating that the more educated a population, the more likely that some of that population will adopt residential solar. Conversely, % No college elicits a very weak/weak negative relationship. The cost of substitute electricity elicits and the average household income make their mark in the normalized univariate results and represent weak positive relationships.

In summary, four variables stick out when examining the batch that was used in the model to explain residential solar uptake in Washington State. Percent of population with bachelor's degree or higher, mean income per household, cost of local residential electricity, and the age cohort ranging 20-55 (younger cohort) collectively help us understand what factors take place when consumers go solar, but there is still more that is not being picked up in the model that is going on. Similar to the non-normalized univariate relationships, an educational indicator variable consistently draws moderate positive linear relationships to the normalized units and capacity univariate regressions at the county scale. Since these were the only variables in this study that elicited some relationship, they were included in the multivariate regression for further testing.

Univariate regression results yielded no meaningful value at the tract scale. This is likely since the variables explaining the residential adoption and uptake of residential solar are not occurring at this scale. Rather, the functionality of the PUD and whether they are voluntarily participating in the state solar program seems to be a more suitable scale of analysis than the Census tract. Additionally, the cost of electricity is a function of PUD district, not neighborhood location, which is the focal point in the tract analysis. As a result, there will be no multivariate analysis conducted at the tract scale.

Multiple Regression Results

The results of the multivariate regression analysis on the cumulative solar installations per household ranging between the years 2010 and 2019 produced a model on residential units added per household (adjusted r^2 of 40%) (Table 8).

Table 8

Multivariate Regression (Residential Added Capacity per Household per County)

(Intercept)	Estimate	Standard Error	T Value	P Score
1) Percent BA or Higher Obtained	-0.02	0.02	-0.69	0.497
2) Mean Household Income	0.29	0.14	3.09	0.003 **
3) % Age 20 to 55	0,00	0.00	-0.58	0.0734.
4) Cost of electricity	0.24	0.18	1.30	0.200
Adjusted *R*-squared: 0.4052	0.27	0.48	0.58	0.570

Sig: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

F-statistic: 2.82 on 4 and 34 d.f, *p*-value: .003997

Multivariate regression results reinforce the statistical determinants proposed in the univariate analysis at the county level. An educational component, a cost component (cost of substitute or traditional power), median income, and an age variable (a higher ratio of the adult population aged under 55) prove significant determinants of residential solar power in Washington State. The cost, age, and education factors collectively explain 41% of the data distribution at the county level.

In conclusion, non-normalized maps reveal that population and solar uptake distributions seem to follow one another very closely. Further evaluation of the univariate relationship among households and the independent variables of race, education, income, substitute electricity costs, and solar insolation show that population alone explains 92% of the variance in the residential PV dataset. Due to this, solar uptake trends should be viewed solely when normalized for the population.

Fixed-Effect Model Results

Results from the fixed effect models are shown in a table view with a summary included below (Table 9). It is noted that ideally, this model would have interacted cost per watt with the yearly fixed effect variables. However, that data was not available for the cost of solar per specific geography per year. In interpreting the results, the focus will be on the yearly fixed effect independent variables. However, a general sense of the relationship between dependent and independent is also produced in the regression via the *p*-value and confidence interval for significance.

Since the dependent variable in this model is the natural log of solar installations per county per year, coefficients show results in the form of percent change annually. First off are the annual fixed effect variables, which show some interesting variance in the years modeled. 2011, 2012, 2015, 2017, and 2018 appearing as significant, though to differing degrees. In 2011, solar installs were, on average, 2.19% lower in all households compared to 2010, ceteris paribus.

In 2013, we see a 1.68% increase, following the decline from 2012 to 2013. Conveniently, this timeline aligns with the year the Federal Government extended the Solar Tax Credit, providing certainty to potential solar investors of a cost recouping mechanism. In 2012 installations rose, continuing annually for the most part as the costs of power generated by solar fell drastically from 2010 onward. In 2013 installations continued to benefit from falling costs and concrete subsidies supporting solar. Then, in 2015, Congress struck another deal extending solar tax credits through 2019. The model does not show any particular benefits to residential solar installations in the year of 2016, however 2017 and 2018 seem to strongly benefit from the policy change in Washington State, with the extension of RESIP.

Table 9

Time Fixed Effect Regression

Intercept	Estimate	Standard Error	*t* Value	*p* Value
Number of households	-15.76	95.85	1.73	0.08
Median income	0	0	2.49	0.01*
Inter. Mean income	0	0	5.06	0.00***
Percent White	0	0	-4.04	0.00***
Percent Asian	0.01	0.7	0.86	0.38
Percent Hispanic	15.43	4.97	3.04	0.00**
Annual_GHI	0.12	0.54	2.97	0.003**
Median age	-1.16	7.06	-2.61	0.009**
Some college	1.47	1.27	-2.63	0.009**
Bachelor degree or higher	-3.55	2.11	2.60	0.009**
Avg. cost per Watt	-0.83	0.84	4.30	0.00***
Interaction Avg. cost per Watt	31.07	18.92	-1.65	0.1
YR11	-3.58	1.87	1.54	0.06.
YR12	-2.19	1.69	1.15	0.02*
YR13	1.87	1.31	0.86	0.00**
YR14	1.68	2.07	0.81	0.02*
YR15	.30	1.28	0.22	0.82
YR16	.47	.86	0.54	0.09.
YR17	-.91	.54	-1.55	0.11
YR18	1.91	.73	-2.61	0.009**
Adjusted *R*-Squared: .653	2.09	21.3	-1.96	0.04*
Significance Codes	0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05‘.’ 0.1‘ ’ 1			

As installations increased in 2011-2014, the coefficient of each annual fixed effect variable decreased and the following year experienced a sharp uptick in 2012. Specifically, in 2011 you see a sharp downturn in the average number per household of solar installations and an uptick in 2012 after the announced policy news. Over the next five or so years, it appears that nothing special occurs statistically as none of the yearly variables return significant as their coefficients remain relatively small with a small range overall among values. However, 2015 draws weak significance but is still significant nonetheless and may explain the Federal Governments agreement to extend the 30% solar tax credit through 2019 from its 2015 expiration. Then in 2018, compared to 2017, counties saw on average an increase of .2%, following up a strong year of residential uptake in 2017. This is occurring in the same year that the States solar program is extended in 2018.

As far as the sociodemographic independent variables, the percent Asian and Hispanic of the overall population were significant, appearing at a 95% significance interval (SI) (Table 9). Median income, the number of households, annual irradiance, median age, and education level also came back as significant, albeit to varying degrees. However, insight given from the univariate analysis highlights that this is likely a pseudo response for households and population demographics. At the 5% confidence interval are the number of households and the interaction of median income per county with solar installations. Finally, at the 10% SI are percent some college.

Given the circumstances in not having ideal scale data on the price of solar per county annually, the model still outputs an adjusted *R*-squared value of 0.653, meaning that roughly 65% of the variation in installations per county is explained.

Table 9 reflects standard robust errors applied to the model's coefficients to correct for the heteroskedasticity in Washington's population. Beginning with the yearly fixed effect variables, 2015 draws minor significance at a 10% SI, the years 2011 and 2013 draw significance from the 5% SI. 2012 is significant at 5% SI, 2013 at 5%, 2017 at 5%, and 2018 is significant with a 10% SI. In evaluating the coefficients, we see that in 2011 and 2012, the average number of solar installations per county compared to the rest of the years included in the model is -2.2% to 1.87% increase for installs on average per county per year. During the next four years, installations across the counties each year saw an increase until 2016 when solar installations dropped by -.91% on average in each county.

Finally, in 2018, following the extension of RESIP state policy which carved certainty in a path forward through 2022 for consumers, counties across Washington State saw on average a rise of 2.09% installations more per county per year. All else held constant. Percent Asian of the total population and the cost per Watt interaction draws significance at the 99% CI, while some college receives weak significance at the 90% CI. All of these variables are together account for 62% in explaining the data variance. More interesting, though, are the results output regarding the annual dummy fixed effect variables, which highlight 2011-13, 2015, 2017, and 2018 as significant years for residential solar installations per county.

CHAPTER V

DISCUSSION

Spatial Trends

Residential solar installations in Washington State generally follow the population. This is demonstrated in Figures 13 and 15 as well as in the univariate regression results. Population, or households, correlates with installs almost perfectly, at 92% (Table 7). Economic activity follows human activity.

When accounting for the population with normalization by household, residential solar uptake is relatively uniform across Washington after State and Federal solar policy enactment in 2005. Additionally, PUDs themselves have a high impact on the availability and access to the state RESIP program, being granted voluntary participation after July 31, 2017. Further examination of residential solar trends should be conducted at the PUD scale.

Statistical Trends

The county univariate regressions indicate that residential solar uptake is roughly 41% explained with the metrics included in this study. Since population alone is a dominant determinant of residential solar, uptake should be normalized by the household to identify the areas of low and high adoption within the overall population. Literature published during the timeframe of this study suggests that wealth is a more suitable variable in measuring solar uptake (Best et al., 2021). Accessibility, the cost of alternative electricity, and the overall age and education of the population seem to be dominant factors of residential solar uptake throughout Washington State.

The tract regression results were inconclusive, likely because the determinants of residential solar are not acting at the tract scale. There are many tracts with no residential infrastructure, and electricity costs do not operate at this scale.

In the multivariate analysis, we learned that although individually these variables express some sort of meaningful relationship, when run collectively, they only explain 41% of the variance in residential installs, and only the education indicator variable “percent bachelor's or higher” shows as significant. This is likely due to the hidden variables present when measuring one variable against another. However, the model suggests the batch of variables. It is also most certain that of all variables measured, it is most confident with percent of the population holding a bachelor’s degree or higher (*t*-value of 4.34).

The fixed effect multivariate results helped explain some of the variances not picked up in the univariate and multivariate regressions. However, roughly 35% of data variance is still left unexplained, and this model does not account for households or population dispersion. Even then, this model suggests when there is indecision in the future of a subsidy or policy supporting a consumer incentive, the consumer will likely hold off on making a purchase as opposed to making the investment in good faith that the subsidy will be extended. This is shown in the years 2012, 2015, and 2018, in which installations saw drastic increases as the current solar subsidy was on its way out (without guaranteed support from the legislature).

The fixed effect model also picks up the uptick in solar installations demonstrated in the figure 13 time-series map of non-cumulative solar installations per county via 2011, 2012, 2013 relationships. In these years, Washington was well into solar subsidization via

RECRIP, although prices did not begin to see drastic declines in solar until around 2010-11, continuing annually. The other interesting point is picked up in the 2018-year dummy variable, again potentially explaining the State Governments decision to extend RESIP solar subsidy benefits through 2021. Consumers like certainty. In all, the sociodemographic variables explained about 62% of the overall variance in the dataset, which is not that bad, granted the availability of data regarding cost per watt over space, which is a key metric in determining benefits gained from going solar.

Ties to Literature

Washington State has begun on the pathway to carving out an entirely clean energy economy and has the support of the State Government, with Jay Inslee spearheading the Clean Energy Transformation Act in 2020. As solar becomes increasingly cheaper as the technology and energy service companies gain economies of scale, state and county governments begin to realize that the easier it is, the likelier it is to happen on end of the consumer, the faster solar power will be grow statewide.

As far as determinants of solar power go, the academic body of research has many claims. In Washington State, the number one determinant of residential solar uptake is population (92%). In all, the four variables included in the statistical measures that helped to explain some of what is causing installations, aside from population, were covered above. I would like to elaborate for any further studies to consider using the rate of homeownership per scale of geography as well as a variable to measure tangible wealth. These variables still need to be stress tested and were not included in this study. Wealth variables seem to be especially promising, granted it could proxy measure for home ownership, tangible wealth, and financial ingenuity all in one variable.

High and Low Outliers: Kittitas and Douglas County

Kittitas and Douglas County are neighboring counties in the central area of Washington State. The summary statistics for each county can be seen in Table 10. While Kittitas elicits some of the highest residential solar uptake in the state, Douglas shows minimal solar penetration. Why is this? According to the WSU Energy Program (2020), all three of these PUDs are still participating voluntarily in the RESIP program, meaning that they still offer net metering (although funding was exhausted for new applicants in 2019).

To better understand the factors driving uptake in the county, the webpages of the City of Ellensburg, Kittitas County PUD, and the Douglas County PUD were investigated. The terms "solar," "solar program," and "solar incentive" were searched after viewing the available webpages to see whether customers of the utility had the visibility and accessibility to RESIP benefits.

Table 10

Douglas & Kittitas County Characteristics

Geography	Kittitas	Douglas
Residential Units Installed	522	11
Residential Units Installed per Household	0.024646	0.000605
Percent Number of People BA or higher (18 & Up)	28.5%	16.4%
mean income per HH (adj for 2019 dollars)	59,933	64,801
Age 20-55	51.2%	44.7%
Electricity cost (cents per kWh)	0.079	0.032
Number of households	17164	14348

In searching the Douglas County PUD webpage (https://douglaspud.org/) all three searches returned results for 2020 amendments made to Douglas County's Integrated Resource Plan (IRP) and exhibited zero results regarding available solar incentives or

RESIP. The IRP stresses the maintenance of multiple hydroelectric dam projects that are already built and working closely with Avista to site and generate more wind power going forward (Douglas County PUD, 2019). This is expected due to new applicants being disqualified until the state approves new funds. However, both the City of Ellensburg and the Kittitas County PUD had information regarding solar incentives concerning the Federal Tax Credit, not shown on Douglas County PUDs webpage. Furthermore, an internet search reveals that all providers are from out-of-county when viewing solar services within Douglas County, residing in King, Kittitas, Chelan, and Yakima Counties. While this study did not concern itself over the visibility and accessibility of residential solar, this seems to be a factor for residential solar uptake in Douglas County.

The City of Ellensburg's PUD website browse (https://ci.ellensburg.wa.us/) returned many results ranging from the opportunity to get involved with community solar via a renewable energy park, Ellensburg Solar's permit exemptions and streamlining, as well as various rebates and benefits to adopting solar-powered appliances in the home (City of Ellensburg, 2021). Additionally, the same search applied to the Kittitas County PUD webpage (http://www.kittitaspud.com) returned a similar number of results regarding the net metering programs, information on how to become a distributed generator of power via solar power, as well as outlets for applying or request about going solar. The Ellensburg PUD, which resides as an enclave within the Kittitas PUD, has also demonstrated extreme commitment to meeting these goals by giving out thousands of dollars to residential solar power applicants each year.

Ellensburg Solar (Figure 18), a local solar company, handles everything for the consumer: permitting, loans (through credit union), install, and maintenance. This makes it as easy as possible for the consumers who are in the market for solar.

Figure 18

Ellensburg Solar "I've gone solar!" Sign

We know that information campaigns and visibility of solar services have positive effects on solar uptake (Lan et al., 2021, Palm and Lantz, 2020). Being that I am writing this thesis from Kittitas County, I can confirm that the abundance of solar policy and information on the PUD websites serving as means of visibility and accessibility is reflected on the ground. In 2012, the city of Ellensburg championed the streamlining of solar permits and applications alongside the WA State Department of Commerce, City of

Seattle, City of Bellevue, and the City of Edmonds (Spark Northwest, 2012). Ellensburg Solar, a local solar company with a geographical scope of all Central WA, has been at the forefront of this effort. Their signs can be found throughout the county in neighborhoods with residences that have gone solar.

In summary, Douglas County has no solar services available physically and locally; they are all online. Additionally, visibility and accessibility about the information regarding solar incentives for consumers remain low even though the PUD participates in the RESIP program. Alternatively, Kittitas County experiences the other side of this phenomenon, with high residential uptake, high visibility and accessibility, and a known history for being committed to making this process easy on the consumer.

Policy Trends and Fixed Effects Model

Consumers hold on to their wallets, statistically speaking as shown in the results from Table 9, when considering to invest in solar power while a current subsidy is up in the air or in question of being extended. For this reason, it would be wise for governments and the alike to develop and make known a contingency plan in the event of funding to run out (which it does). This might allow consumers the clarity needed to decide rather than abstain from it until a law has been passed to allow more funding or to find it has been left on the hill to die. This could be a particularly useful tool for clean energy goals, which I would imagine the Federal and State governments will want to meet.

Further Studies

Additional metrics are needed for measuring and predicting solar uptake at the Census tract scale. Research should be focused on forming a qualitative and quantitative understanding of the ease of obtaining solar services across space, that is, the ease of securing loans, permitting, the availability of services, and whether or not local PUDs are willing to provide a pro-solar framework in their business model. There is much to be learned about how these processes compare over time and space regarding accessibility, visibility, and time to go through the process from beginning to end.

Collecting demographic data, wealth data, and ownership data of residences could complement an analysis at the utility district scale. Given that PUD participation or non-participation is a major barrier to the solar market, an analysis should be performed at this scale. Alternatively, a binary variable could be included at the county level, indicating whether a PUD district within the county is participating in solar incentive programs.

The Census Tract is seemingly too small and coarse a scale to provide meaningful results in the statistical results, though this can potentially be addressed. This study did not reclassify or subset any of the Census tracts – and there are many which exist without any residential buildings at all. Sub-selection of certain exhibiting local incentives and not could be used to observe and quantify the fixed effects between geographies with local incentives piled atop state and federal.

Past studies regarding residential solar in Washington have concerned themselves with environmental education among the school districts in the state and how it relates to uptake. This study examined a swath of economic, social, and environmental factors in tandem with mapping the trends of uptake across the past twenty years. It seems appropriate then for additional studies to take place regarding the specifics of what makes the consumer decide to go solar. This data is widely available, as it is already collected when solar companies follow up with their customer in the form of an in-person visit.

Alternatively, this could be done in part by calling the list of people who have gone solar and are registered with the state.

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