No Place Like Home
Fighting climate change (and saving money) by electrifying America's households.

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Abstract

We demonstrate a pathway to total decarbonization of U.S. households on a timeline only limited by our political will and the changeover of household infrastructure. We use historical energy use and pricing data to build a model of the total electrification of the household. We use this model to investigate combinations of finance, regulatory policy, and incremental technology scaling that would save households and the entire economy money. With small and predictable improvements in technology costs over the next five years, and with aggressive interest rates, we could save every household $1000-$2500 per year. Collectively, the nation would save $130-320bN per year. This offers the opportunity for a new dialogue about solving climate change that is optimistic and based in real possibility. This analysis also leads to many conclusions and recommendations about policy mixes that can accomplish decarbonization at the fastest possible rate of infrastructure changeover.

1 Where is the moon?

To succeed at a moonshot, you need to know where the moon is. To win a war, you need a strategy. If we are to succeed at keeping our climate to 1.5–2° C of warming, moonshot and wartime mobilization analogies are apt. But we haven't yet had a clear answer to the question of "where is the moon?" or a basic strategy to win a war.

In this paper we answer the question of where is the moon and show a pathway to get there. We explore whether there is a strategy by which we can win the war by combining existing technologies with innovations in policy and finance. The moonshot is to fully decarbonize American households with the key constraint of not costing money, but of saving money — for all of our households.

When most people use the term "moonshot" they refer to high–risk technology, but in this case we don't have time for science projects, and we've already got all the technology we need. The moonshot lies in marrying technology, policy, and finance to allow all households to decarbonize their daily living.

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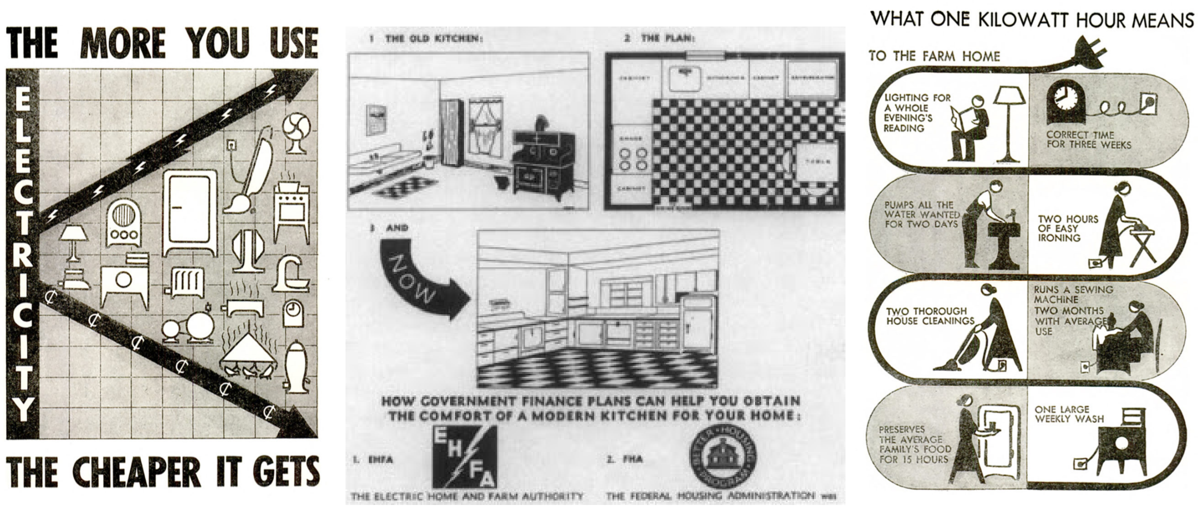

Figure 1: *Advertisements for the Electric Home and Farm Agency under a Great Depression stimulus package, pushing early electrification of America (and not–so–subtle gender roles).*

1.1 Methodological Constraints

We constrain this study to using technologies that (1) we know can work; (2) already exist at significant scale; (3) are cost–effective somewhere in the world; and (4) can be scaled up to the level required for residential decarbonization. As the final lever to see whether this is possible, we investigate the interest rates and financing methods to make it work economically.[1]

We focus on America's households. We do this because it makes climate policy and possibility *personal*, and because the energy (and carbon) expenditures of the household are close to half of all U.S. energy emissions.

Decarbonizing households is more critical than is implied by the traditional analysis of the U.S. energy economy by sectors, which is typically divided into Residential (21%), Commercial (17%), Industrial (31%), Transportation (28%), and Electricity (38%)[1][2]. Critically, the decarbonizing of the household includes not only the residential sector energy and emissions, but close to half of our transportation (because the majority of vehicle miles are in the personal vehicles owned or leased by the households) as well as significant portions of emissions due to fossil combustion in the electricity sector. Additional benefits accrue because close to 10% of the U.S. energy economy, and its emissions, come from finding, mining and refining fossil fuels. For this reason, decarbonizing U.S. households plays a much larger part in the solution for climate change than typically acknowledged — somewhere between 40 and 50%[3].

[1] This is in the tradition of 1974's *Project Independence*, a collaboration between a nascent DOE and the Federal Reserve to explore whether America could afford to solve the energy crises of that era.

[2] These don't add to 100% because it does not include the government sector, and the electricity sector is actually an input into the other four sectors

[3] If we applied this methodology to the commercial sector, which we will in a future study, this would represent up to ∼65% of U.S. emissions

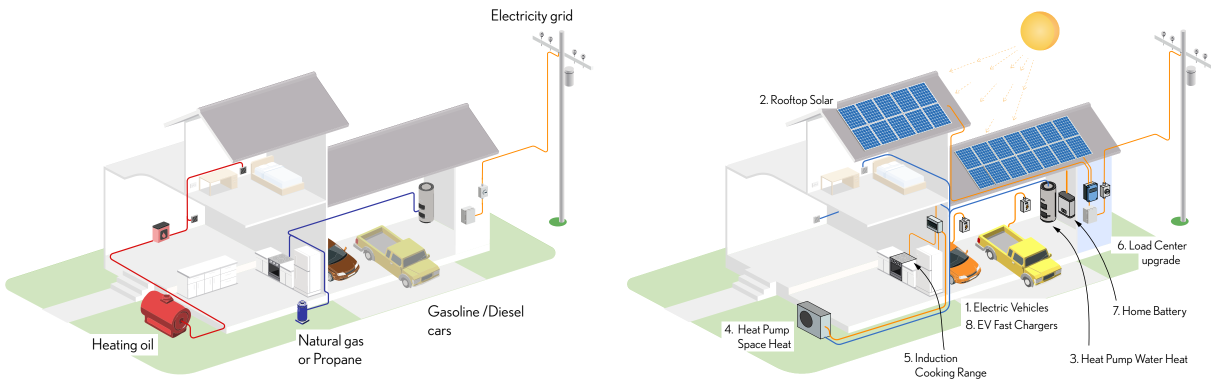

Figure 2: *a) Average household today, running on fossil fuels, b) Electrified house*

1.2 The big question

Will decarbonization hurt or help the typical American household? This question is even more important after the financial disruptions of COVID-19 and 2020, and we will try to address it here. Specifically: *What is the combination of technological solutions, appliance and vehicle costs, regulatory conditions, and, critically, the cost of financing, that can make this a win–win for the American public?*

During the Great Depression, when households were in similarly dire straits, one of FDR's programs was the Federal Housing Authority (1934) that invented the modern home mortgage and created Fannie Mae (1936). In one perspective of this, the U.S. made a policy decision deciding that homes were critical national infrastructure deserving of the best possible financing rates. This created the largest capital market ever to exist in the world, before or since. This program was so successful it unexpectedly turned a profit for the U.S. government.

Also under the New Deal, another program offered low–cost federal financing support — for electrification. The Electric Home and Farm Agency (EHFA), originally an offshoot of the Tennessee Valley Authority (TVA), helped provide financing for the purchases of electric appliances — refrigerators, ranges, and hot water heaters. Advertisements from the program are shown in Figure 1. The focus was rural America (especially the Tennessee Valley), and it was part of an effort to expand the domestic market for electricity consumption. Manufacturers that wanted to participate had to produce standard–issue, low–price appliances subject to EHFA approval. Consumers would then select an EHFA–approved appliance and purchase it on an installment credit contract from the dealer, backed by the U.S. Treasury. The terms were 5–10% down (much lower than any other installment credit offered at the time) and 36–48 month terms at 5% interest. The offer was available only to consumers who got their electricity from companies that charged rates that were acceptable to EHFA. The program ultimately financed some 4.2 million appliances, at a time when there were around 30 million households nationally.[2]

These were two audacious plans that helped the U.S. economy at a critical juncture. Another was when President Franklin D. Roosevelt led the nation into WWII. He didn't ask, "What is the least we can do?" but set goal posts and production goals, and developed policies and programs that enabled industry to achieve those production goals. The critical war materials were defined (liberty ships, tanks, airplanes, guns, munitions), and industry encouraged to deliver them while reducing time and costs.

With that style of leadership in mind, we imagine a scenario for decarbonizing America's households with a similar critical list of items, this time electric vehicles, rooftop solar, heat pump hot water heaters, heat pump HVAC including furnaces, electric cooking systems, and batteries. We also imagine financing their purchases as part of a national infrastructure, and therefore with access to low–cost financing. A schematic of this infrastructure upgrade is shown in Figure 2.

1.3 Why now?

Two insights enable making this analysis today. The first are proof points of extremely low cost solar installations in other countries with similar labor rates. While the average unsubsidized cost of solar in the U.S. is around \$3/Watt installed, in Australia it is closer to \$1.20 and trending further downward. The DOE's Sunshot program is on track to systematically bring costs down to less than \$1.00/W. This is not a technology win as much as it is a regulatory and training success story. Australia figured out how to optimize regulations and a workforce to get very low cost solar on rooftops. There is no barrier to a similar revolution in the U.S. apart from regulations and inertia.

The second insight is the continued and relentless cost reduction that is occurring in the critical components of household decarbonization. In the solar world this is known as Swanson's Law, analogous to Moore's law, that demonstrates the continued falling price of solar as a function of the scale of production. To meet our climate goals, the scale of production needs to increase around ten–fold, justifying confidence that the price will continue to fall. We show this phenomenon in Figure 3. A similar effect has been observed in the other critical component, batteries, which have fallen in price from \$1000/kWh to around \$130/kWh in a decade.[4]

This gives us confidence that there are three sources of cost reductions available — there are significant winds at the back of more rapid decarbonization than people think. The first is that regulatory reforms that achieve the lowest cost of products to the consumer, such as we have seen in the Australian rooftop solar market, are possible for not only the rooftop solar component, but home batteries, home heating systems, vehicle charging infrastructure and more. The second is that the scale of the project alone is sufficient to sustain even further price reductions for the critical components. The third is that technology will continue to improve. The range and lifetime of batteries increases year after year. The efficiency of solar cells continues to climb. The cost of EVs is coming down. The performance of heat pumps continues to improve.

2 Summary of methodology and model

Because people think about issues from their kitchen table out we will use the household as our atomic unit of analysis. There are about 130 million households in the U.S. with an

[4] Data from BloombergNEF (1, 2) and Kittner, et al.

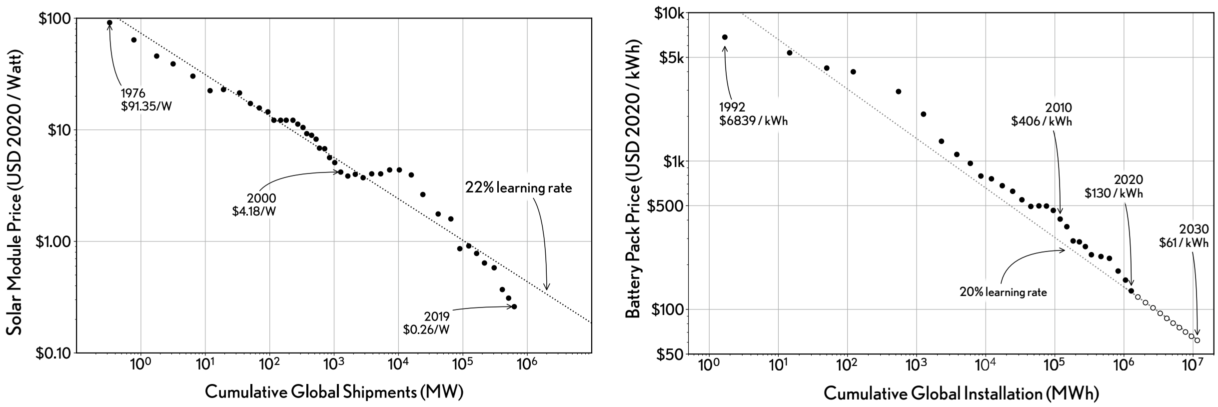

Figure 3: *a) Learning rates of photovoltaic modules, data from [3, 4, 5], b) Learning rates of lithium-ion batteries, data derived from [6, 7, 8]*

average of 2.52 people in them[5], and 1.9 vehicles in the driveway[6].

To calculate the costs of converting our current households to a future of carbon–free, electrified households, we divided it into four components: (1) the historic fuel or baseline costs which we establish in Appendix A; (2) the future fuel costs which we establish in Appendix B; (3) the capital costs which we establish in Appendix D; and (4) the financing costs which we establish in Appendix E.

By understanding the interaction of these costs we can have models for the design of federal, state, and local policies that support the most rapid decarbonization of the home possible in ways that positively, rather than negatively, impact the economics of the household.

It is worth highlighting the three dominant uses of energy in the home: transportation, heat, and everything else. Transportation is dominated by gasoline and diesel, with tiny fractions of electricity due to the small penetration of electric vehicles to date. Heat — for water, air, washing, and cooking — is dominated by natural gas, with some electricity, and small amounts of propane, fuel oil and tiny amounts of biofuels (firewood)[7]. Everything else (besides transportation and heat) is almost exclusively electricity, powering our TVs, computers, X–boxes, lights, kitchen appliances, and power tools.

In bullet point form our methodology is as follows:

- Establish the current baseline energy costs per household, broken down by state and by our three main categories: transportation; heat (both water and space heating); and everything else. This is covered in detail in Appendix A.
- Specify the infrastructure required to convert these household energy uses to electric sources and the cost of that infrastructure. This includes the (1) vehicle batteries, (2) A home battery, (3) A heat pump for HVAC, (4) a heat pump for water heating, (5) electric cook top, (6) a new load center, (7) vehicle charging units, and (8) rooftop solar.

[5] See Census Bureau households data

[6] See FHWA's National Household Transit Survey

[7] We ignore the small amount of firewood in this analysis as at least in concept it can be carbon neutral.

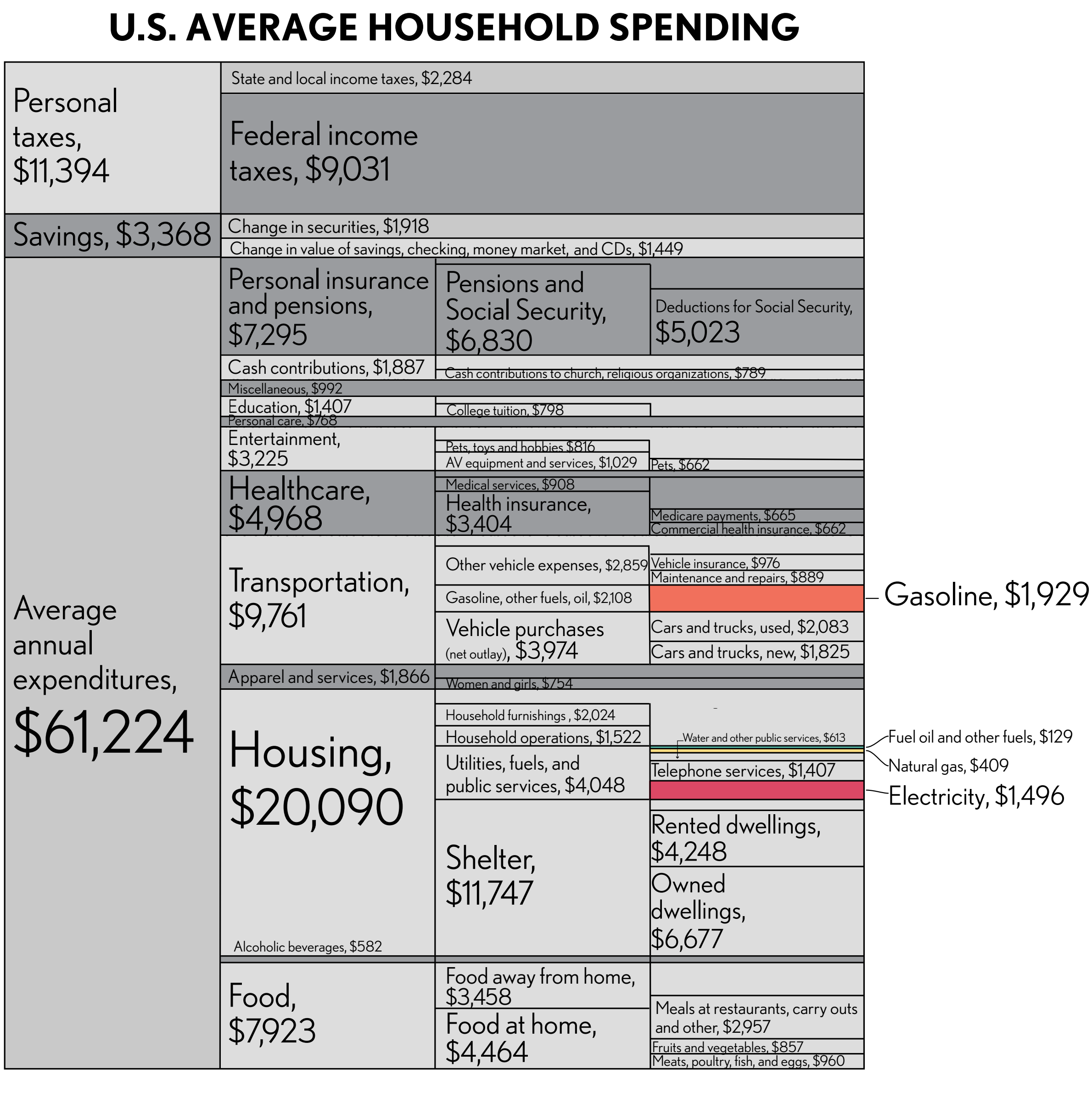

Figure 4: *Average U.S. Household spending breakdown, using data from [9]*

- Build an "Electrification Exchange Rate" (EER) that converts each unit of useful energy services in the current world to an equivalent unit in the future electrified world. For instance, the fraction of a gallon of gasoline used to travel a mile today can be exchanged for a fraction of a kWh for the same mile travelled in an electric vehicle tomorrow. Similarly the BTUs of a combustible fuel required to heat a gallon of water will be replaced with the kWh to do so with an electric heat pump. This is covered in detail in Appendix B.
- Calculate a future cost of electricity by blending our financed cost of rooftop solar (compensating for the solar insolation per state) with the current cost of electricity in the same state. This is covered in detail in Appendix C.
- Calculate the annual savings in costs of fuels from this electrical transformation using the future total household electrical load, and an average cost of future electricity, and purchased cost of grid electricity at the 10 year average price.
- Calculate the capital costs required for this transformation. This is covered in detail in Appendix D.
- Estimate the annual financing payments for the capital expenditures assuming various interest rates and various amortization periods determined by product lifetimes. This is covered in detail in Appendix E.
- We subtract the finance payments for capital from the annual fuel savings to calculate the real savings possible for households in each state for "BAU," "Good," and "Great" scenarios. This is covered in detail in Appendix F .
- Finally, we perform break-even analysis of interest rates and utility electricity prices to explore how this transformation can fit inside the existing energy economy.

2.1 The starting point: today's household energy costs, by state

The average U.S. household expenditures are shown in Figure 4, using data from the Bureau of Labor Statistics' Consumer Expenditure Survey [9]. The average house spends $61,224 after taxes and savings. Our direct uses of energy and fossil fuels – gasoline, electricity, natural gas, propane, and heating oil – are shown in the context of our other expenditures. We spend more on electricity ($1,496) than we do on education ($1,407). We spend more on natural gas ($409) than dental services ($315). And we spend more on gasoline ($1,929) than we do on meat, poultry, fish, eggs, fruit and vegetables combined ($1,817).

We can make a better estimate of current household energy expenditures, broken down by state and by fuel, as summarized in Figure 5. The consumption estimates take state level consumption data from the EIA's State Energy Data System (SEDS) [10]. The fuel cost estimates are taken from averaging the 5 or 10 year time series of residential fuel costs also available through SEDS as summarized in Figure 25.

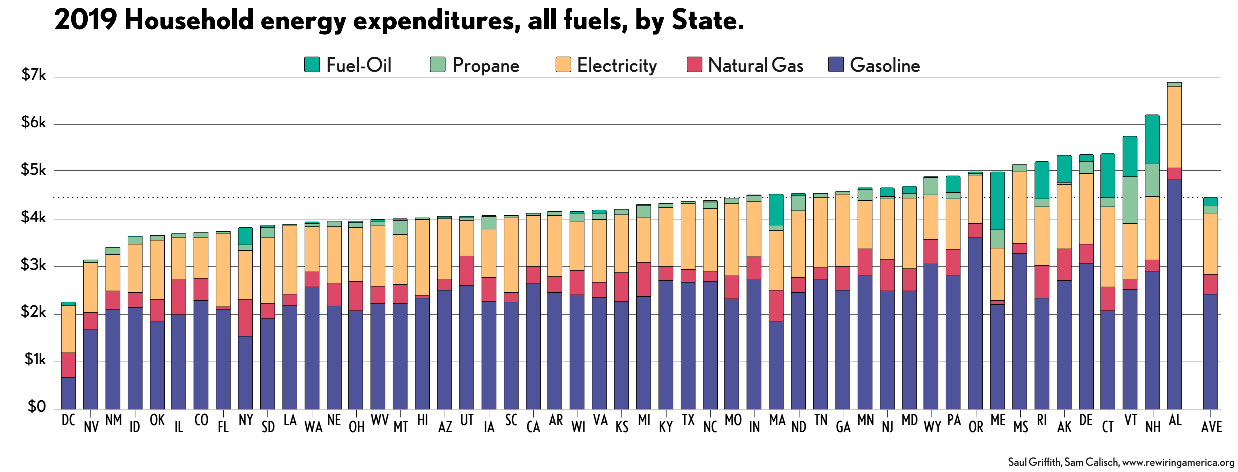

Figure 5: *Existing household energy costs by state, census region, stacked by fuel type.*

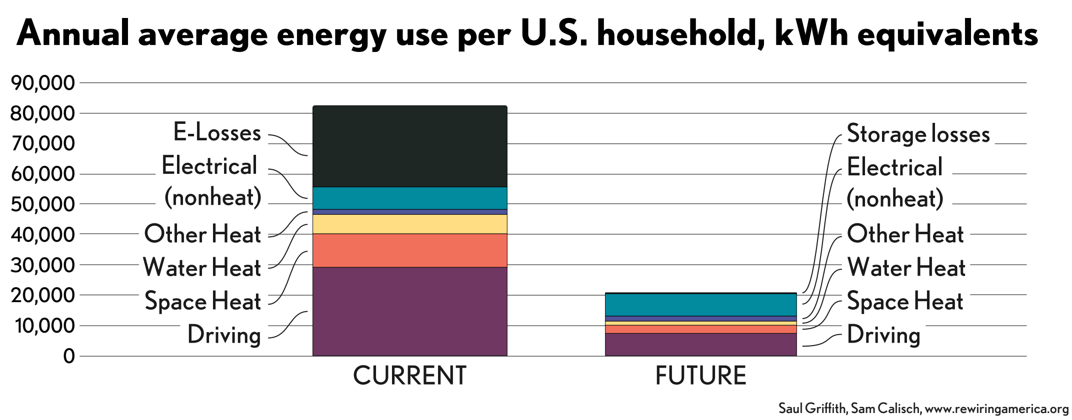

Figure 6: *Average US household energy consumption comparing contemporary households with their fully electrified future equivalents.*

2.2 Energy savings through electrification

The average energy consumption by household in the U.S., before and after electrification, is summarized in Figure 6 and the analagous state-wise analysis in Figure 7.

If we save so much energy, why can't we save money? Clean, electrified technologies have high up-front costs, but very low fuel costs in the future. Fossil fuel machines are cheaper at point of sale, but require constant refilling with expensive fuels.

Because of this, electrification requires us to spend more money on changing the infrastructure of our lives. Most Americans don't have the cash on hand for this. But if this equipment were financed, would the savings be larger than the loan payments?

A large part of the challenge is figuring out how to minimize up–front costs, which is a regulatory question and a matter of industrial scale. Then we have to figure out how to minimize the cost of financing, as few households can afford to pay the capital costs of decarbonization up–front.

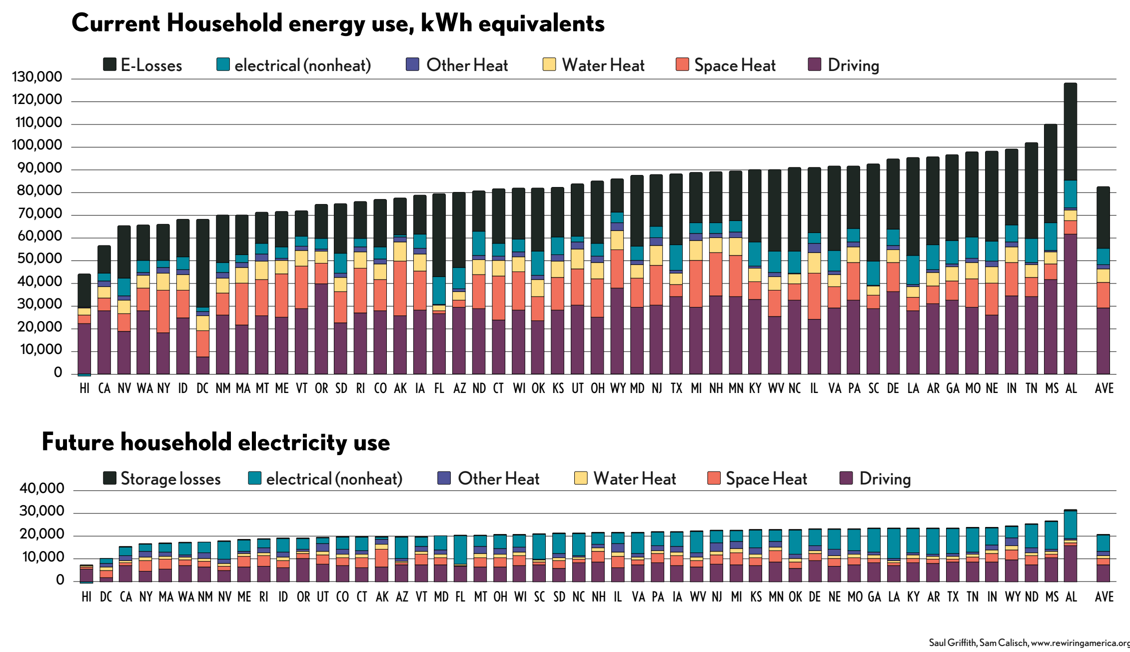

Figure 7: *State–by–state comparisons of current household energy consumption to future entire household electrification.*

Using price estimates[8] to find the difference between fossil-fueled and electric infrastructure, we find that today it would cost a household around $70,000 to completely decarbonize, something only the wealthiest households can afford. In Figure 8, we show the capital costs today by state, using the 8–step electrification plan described above.

We need to prioritize lowering these costs using regulatory reform and industrial scaling. We also need to prioritize financing to help American households afford these items.

3 Fully Electrified Household Savings

Once we have models of existing household energy costs, future electrical energy use, and future electricity prices, we can model the savings for the typical US home. We do this for a number of scenarios:

- **"Business as Usual"** - Does it work currently in the U.S.? We assume currently–available, unsubsidized costs and an interest rate of 5% for financing all items.
- **"Good"** - Does it work using global best practices? We include regulatory improvements and an interest rate of 2.9% for financing, comparable to current mortgage rates.
- **"Great"** - Does it work if we make it a national priority? We includes cost reductions through larger scale of production, regulatory optimization, technology improvements, and a 2% interest rate.

[8] Data from BloombergNEF, NREL, Homewyse, and Fixr

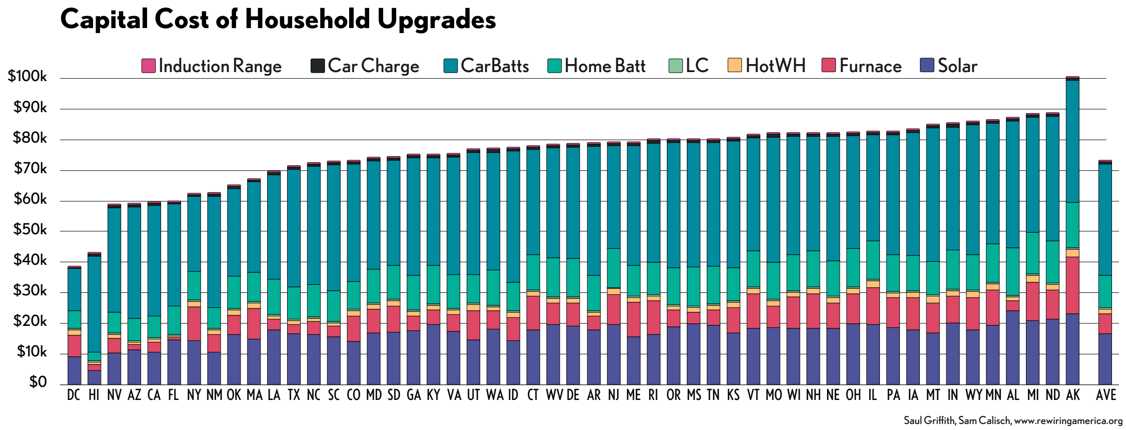

Figure 8: *State by state capital costs.*

The full list of variables, and their values is listed in Table 9. The model allows for flexible modelling of the full costs of household energy services. The variables include:

- Capital cost variables for all upgrades.
- A lifetime (used for financed lifetime) for each upgrade component.
- A percentage of solar produced on rooftops that we set to close to 70%, as that approximates the total technical potential of U.S. rooftops as determined by the NREL rooftop technical potential study.
- A percentage of the energy that is stored in chemical batteries (set to 15% for these scenarios).
- A COP model for all states based on TTMY3 climate data (NREL).
- A labor cost component for the installation of each item.
- Round trip efficiency for any energy stored in batteries (set to 90% in these studies).
- A model for future COP improvements expressed as multiples of current COP.
- A car charger efficiency value set to 95%.
- A residual battery value for vehicle and home batteries for end–of–life recycling.
- The model allows for subsidies or rebates for any or all of the capital items to enable future exploration of the most cost effective policy scnearios, but for the purposes of this study subsidies or rebates were set to 0.
- Interest rates (these could be varied for different items, but we chose to set all interest rates at the same value, though we vary the amortization period).

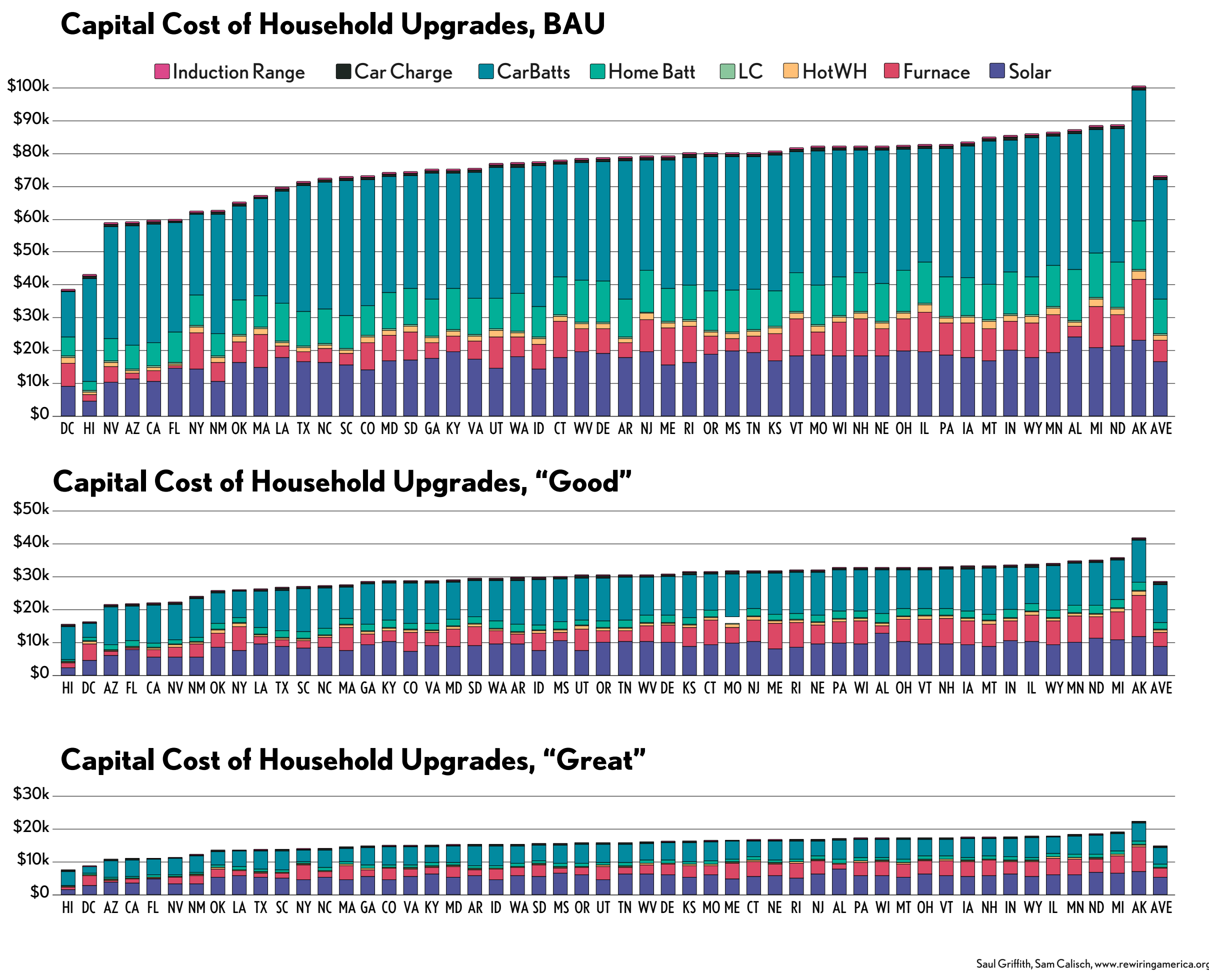

Figure 9: *Capital cost reductions due to industrial scale, soft costs reduction, and improving technology maturity.*

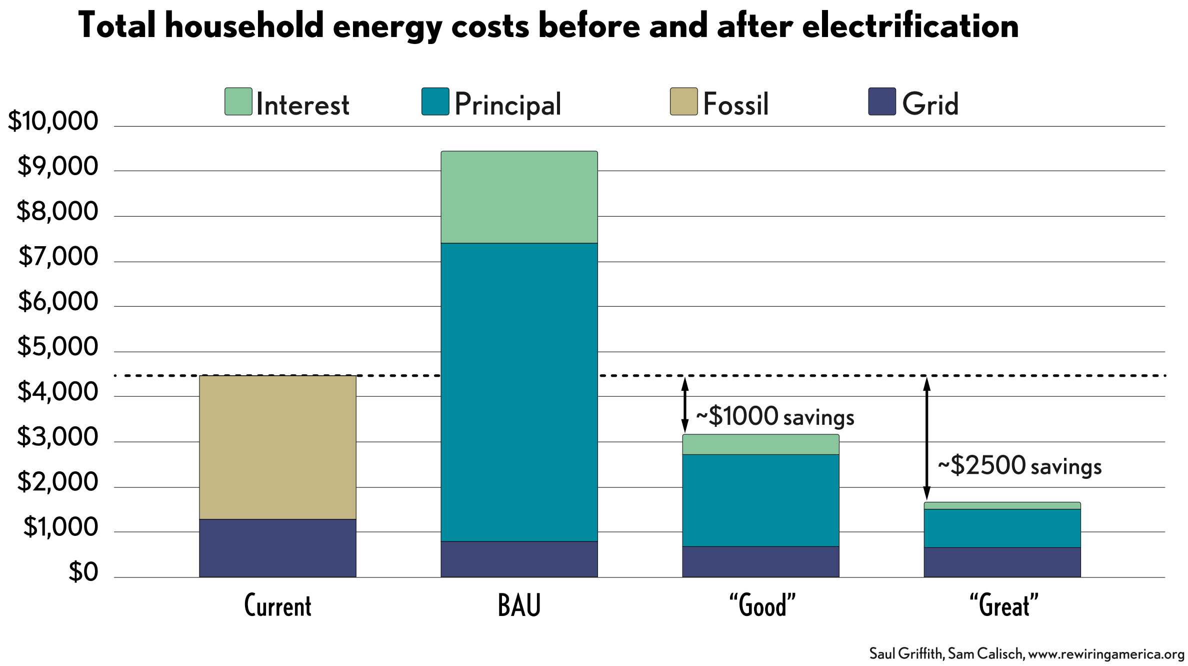

Figure 10: *Total costs of fuels and finance for all energy activities in a household udner current conditions and our 3 scenarios. Costs are divided into categories of capital cost (principal) and finance (interest) and extra energy purchases (grid)*

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The effect on capital cost for each model for each state can be seen in Figure 9.

This lets us compare current costs of energy, today's cost of a whole lifestyle electrical upgrade ("BAU") and our "Good" and "Great" models. We can see the results in Figure 10. Electrifying today would increase a household's annual costs from around $4,500 to around $9,500, a reality the few early adopters who have trod this path can testify to. With the "Good" model we see real savings in the national average, and in the "Great" model, savings significant enough to have a huge impact on the majority of households. The division of these costs into the principal payment, the interest payments, and the costs required spent on electricity from the existing grid are all show for context.

Expressed in terms of household savings, rather than total energy costs, we can see the value of electrification to the average U.S. household in Figure 11. Savings are categorized according to energy use category, and we see that the largest savings are driven by electric vehicles, and space and water heat. The lowered effective cost of electricity due to the rooftop solar is also noticeable.

We can look at more detail of state by state savings as per Figure 12.

In addition to average savings per household, we can look at accrued savings in billions of dollars to the U.S. economy as a whole as per Figure 13. Indeed, electrifying everything today with America's patchwork of expensive regulatory environment, inconsistent subsidies, high installation and permitting costs, and with high costs of not yet fully mature industries, adds an additional $600 billion dollars per year in energy costs. With the "Good" model

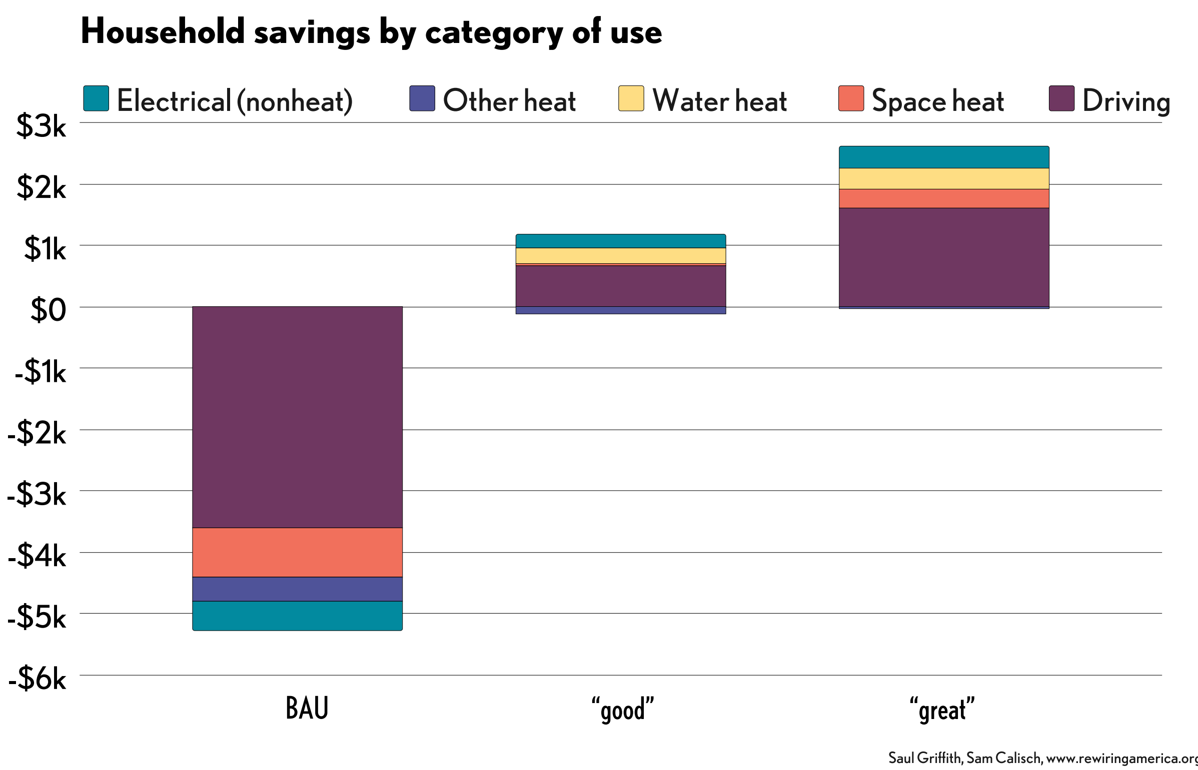

Figure 11: *Savings by category.*

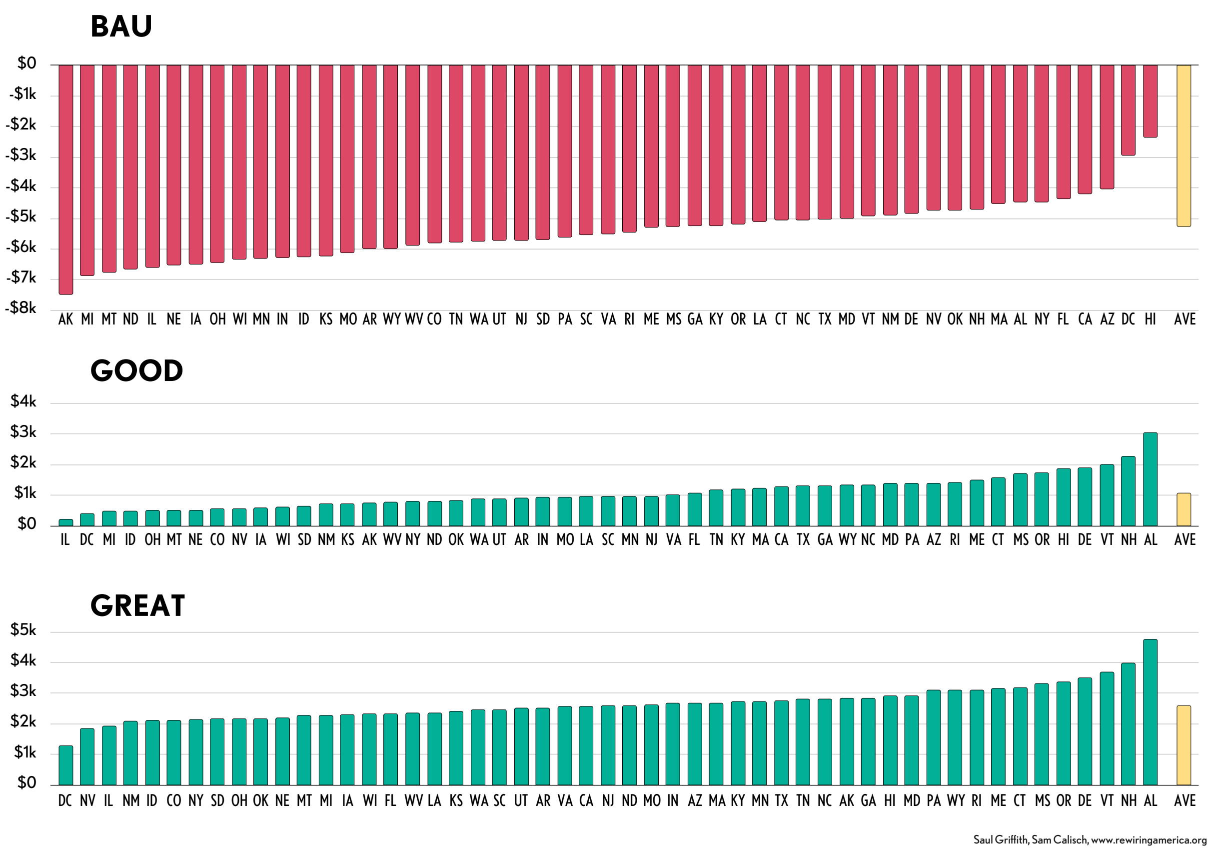

Figure 12: *State by state savings.*

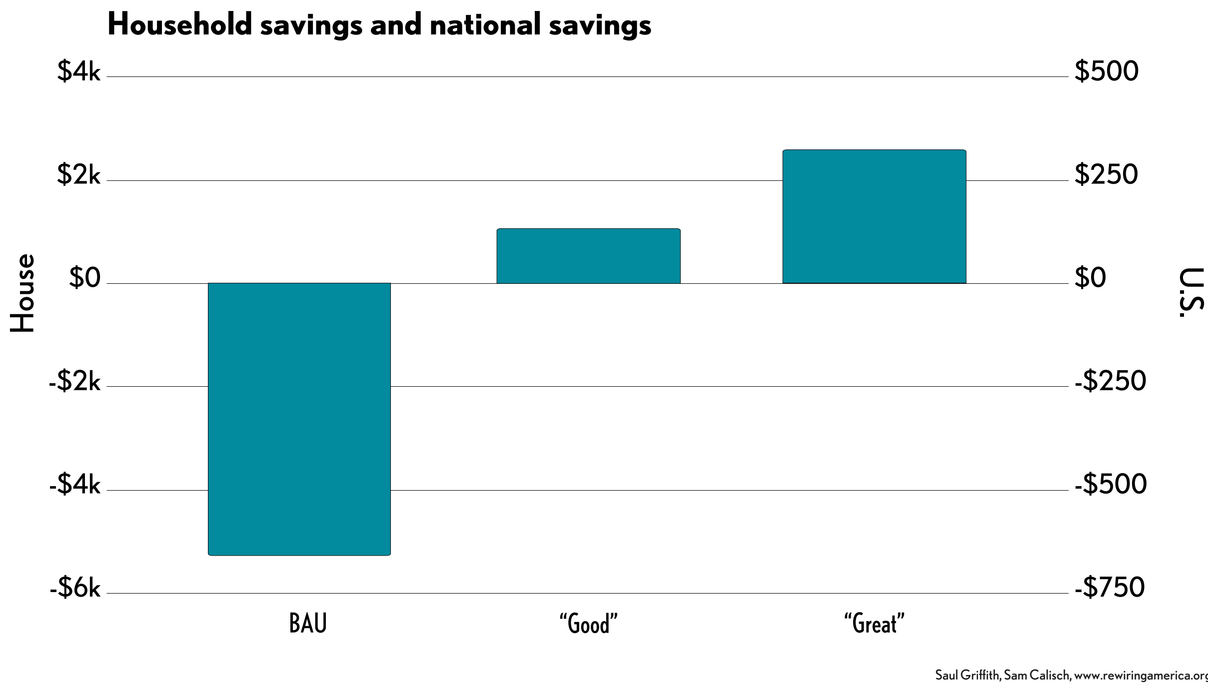

Figure 13: *Household and national savings.*

we flip the sign and recognize well over $100 billion dollars in savings per year and with the "Great" model, over $320bN per year in savings.

These results may seem surprising, but perhaps they shouldn't be. Currently, it is not economically rational to completely decarbonize, and it takes subsidies and incentives or wealth to make it a viable option for a household. The good news is that if we took the best practices from around the world today, on finance, regulatory environment, and technology, (the "Good" scenario) it is economically a win **tomorrow** to completely decarbonize. Without relying on major technology improvements, but with a more aggressive financing and regulatory environment and enormous scale, we could be saving more like $2,500 a year per household in short order. This would require an aggressive industrial policy centered around the critical industries that produce these household energy consuming devices, and a training and apprenticeship program that enabled a sufficiently large installer network.

4 Jobs

We previously did a full economy jobs study[9] that suggests as many as 25 million additional near–term jobs and 5 million sustained, permanent new jobs would be created by whole economy decarbonization, including the commercial sector, industrial sector, the remainder of the transportation sector, and the electricity generation and distribution network. This jobs section looks at the subset of jobs associated with these household electrification upgrades.

[9]See *Mobilizing for a zero carbon America: Jobs, jobs, jobs, and more jobs*, Rewiring America, 2020.

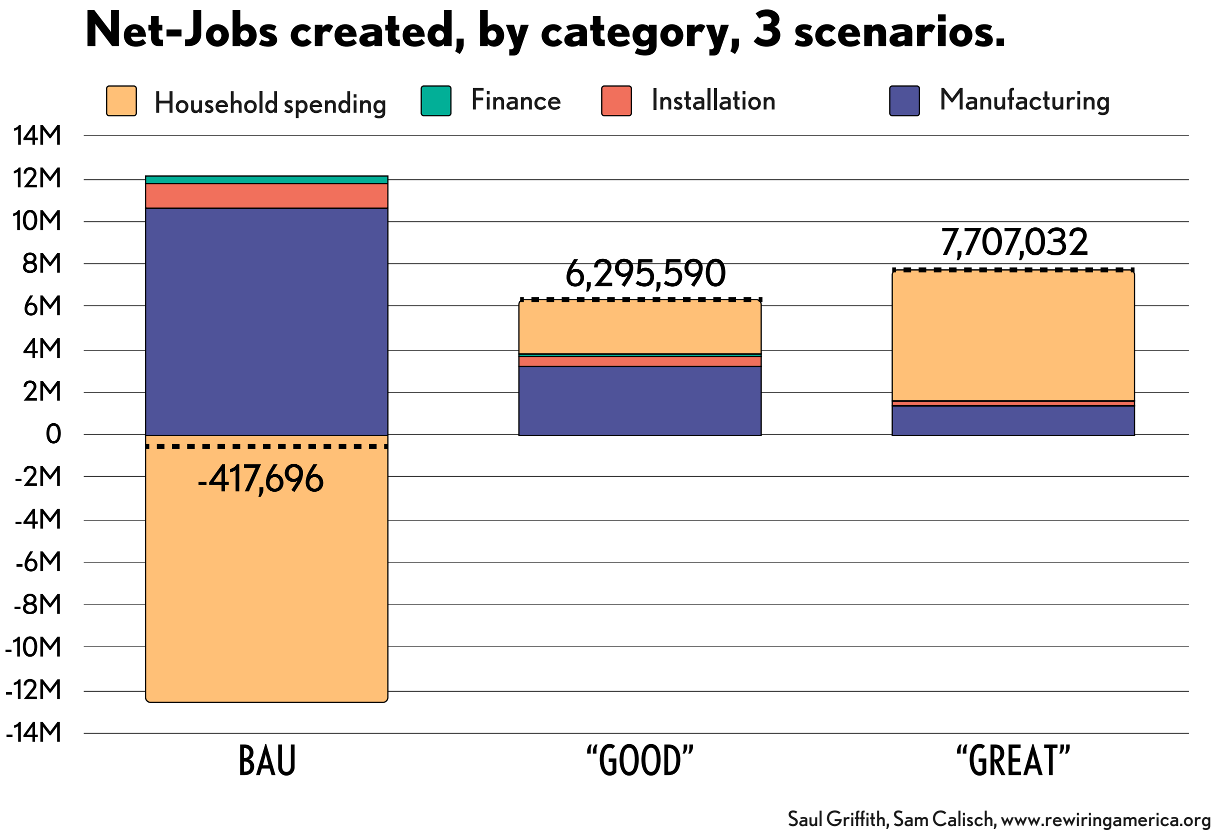

Figure 14: *Jobs created nationally, including the total number of net jobs.*

In Figure 14 we graph the jobs created by state for "Business as Usual," "Good," and "Great" models. The job estimates are based on 2018 Implan jobs creation coefficients by sector. The table of coefficients and source can be seen in Appendix G.

We use construction industry ratios for all jobs in the installation component. We use manufacturing industry coefficients for jobs in the capital cost component. We use finance industry ratios for money spent on interest and financing. We use the national average for the jobs created (or destroyed) by net positive or negative household spending.

We can see the number of jobs created in each state as per Figure 15. A number of important things can be said about these estimates. In the model of electrification under Business as Usual, more than 10 million jobs are created U.S. wide, but a slightly larger number are destroyed in decreased household spending, as electrification currently costs more than status quo fossil fuel consumption. We see in the "Good" scenario the creation of a total of more than 7.5 million net jobs. Many are in manufacturing and a similar number in increased local spending. It shouldn't be surprising that in the "Great" scenario, the fewest installation and financing jobs are created (though still tens of thousands in most states). This is because to keep the costs down, efficiencies in installation and low cost financing are modeled in. Similarly manufacturing jobs are far fewer in the "Great" scenario as capital costs are pushed down by manufacturing efficiencies. There will be critics of this, but it is actually good news. Because manufacturing jobs will go the lowest bidder, they won't necessarily be in every state. The geography of the manufacturing jobs is an industrial and trade policy question. The installation jobs by very definition are local jobs, as the installer needs to be on your roof or in your basement. Finance jobs will be a little local, but will likely skew towards traditional finance or insurance centers. Despite all of this, the jobs created by household savings are likely to create a lot of local jobs, and a lot of varied jobs. Working to maximize these jobs will create the most vibrant and robust local economies.

4.1 Comparing with carbon tax

In Figure 16 we compare the "stick" of a carbon tax on the household to the "carrot" of electrification. We assume $30 a ton for end–of–smokestack emissions such as those created in electricity generation. We assume $300 a ton for diffuse emissions such as tailpipe emissions from cars as well as furnace and natural gas emissions from home space and water heaters. Even with these (arguably) aggressively low carbon prices, they pose a significant cost to the household or the generator of those energy services. In all cases, it is nearly certain that these costs will be borne by the household in some manner. Without significant redistribution, a carbon tax becomes a major burden on households. Electrification, when done effectively, puts money directly in the pockets of households. There may still be a role in the world for a carbon tax, in particular for its market–shaping effect. This study, however, suggests more cost– effective methods for total decarbonization that could occur much faster, and on the timeline appropriate for hitting a 2° C/3.6° F climate target.

4.2 What interest rates make it work?

Due to the high capital costs of household upgrades, one method to make them accessible is to minimize the interest rate. This has precedent in the New Deal–era creation of the FHA and Fannie Mae to guarantee mortgages. Fortunately, the market has historically low interest rates in 2020, which makes very low interest rates seem possible, but we wanted to query how critical the interest rate is to success.

In Figure 17 we model the interest rate by state at which the endeavor breaks even for the household. We do this for the "BAU," "Good," and "Great" scenarios. We can compare these required interest rates with those currently available to households. Car loans are currently around 5%[10] and mortgage rates are commonly under 3%.[11]

Because of the unfavorable costs of the "BAU" scenario, negative interest rates would be required to complete the electrification. In the "Good" model we see a range of workable break-even interest rates between 4 and 12% which look like more traditional financial products, and are uniformly above current mortgage interest rates. Many are still below the financing rates for households with poor credit scores, or for financing consumer appliances. We would like to underscore the importance of creating low interest financing projects to enable LMI households to participate in this economic win.

We can see by the "Great" scenario that interest rates between 14 and 30% still allow break even household costs. These allowable interest rates are well above car loan rates,

[10] See the Fed's G19 Consumer Credit Report

[11] See the CFPB's Rate Explorer and Mortgage Market Activity and Trends

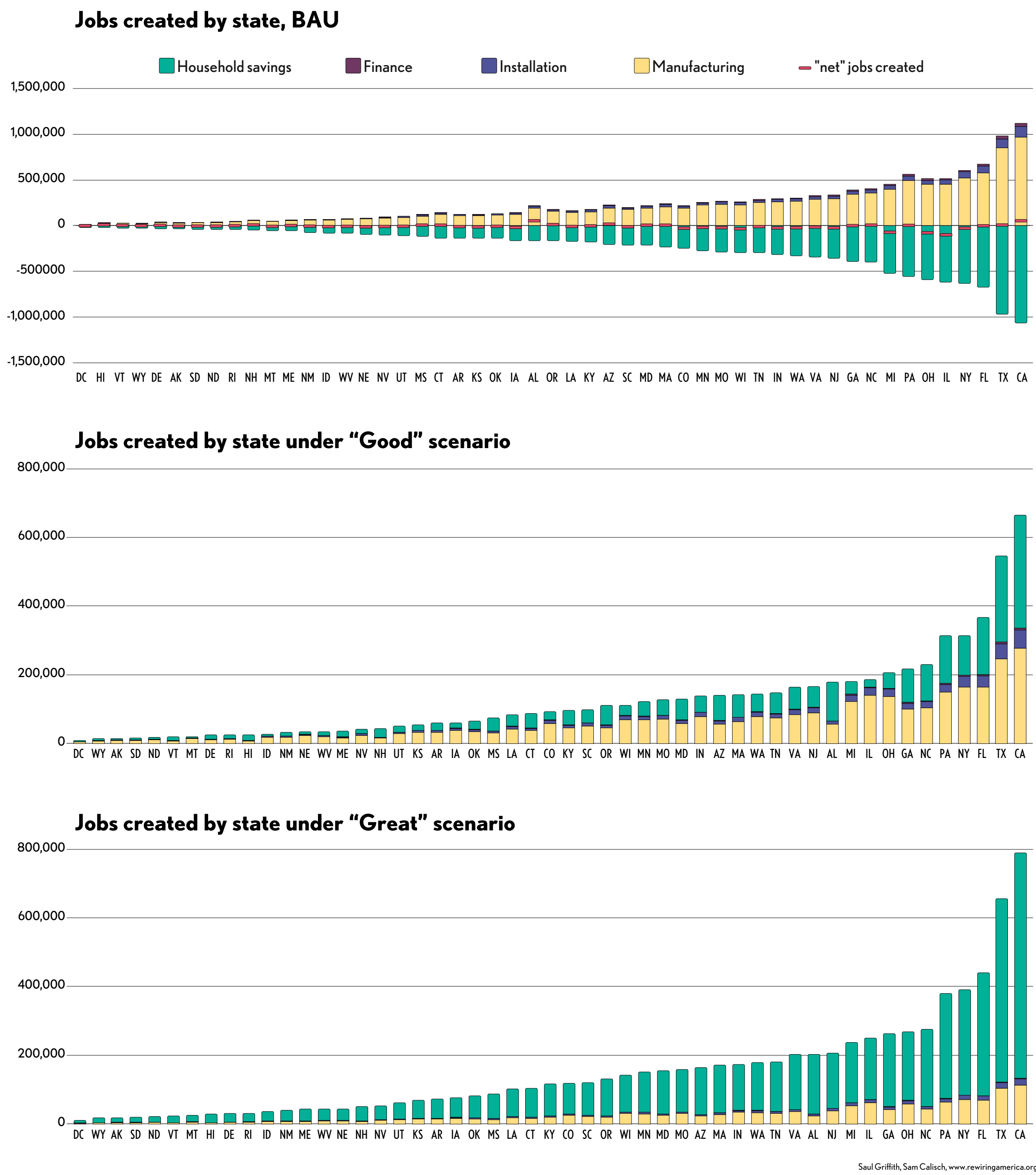

Figure 15: *Jobs created by state, and the composition of those jobs including jobs created in installation (construction), manufacturing, finance, and jobs created due to spending the money households save.*

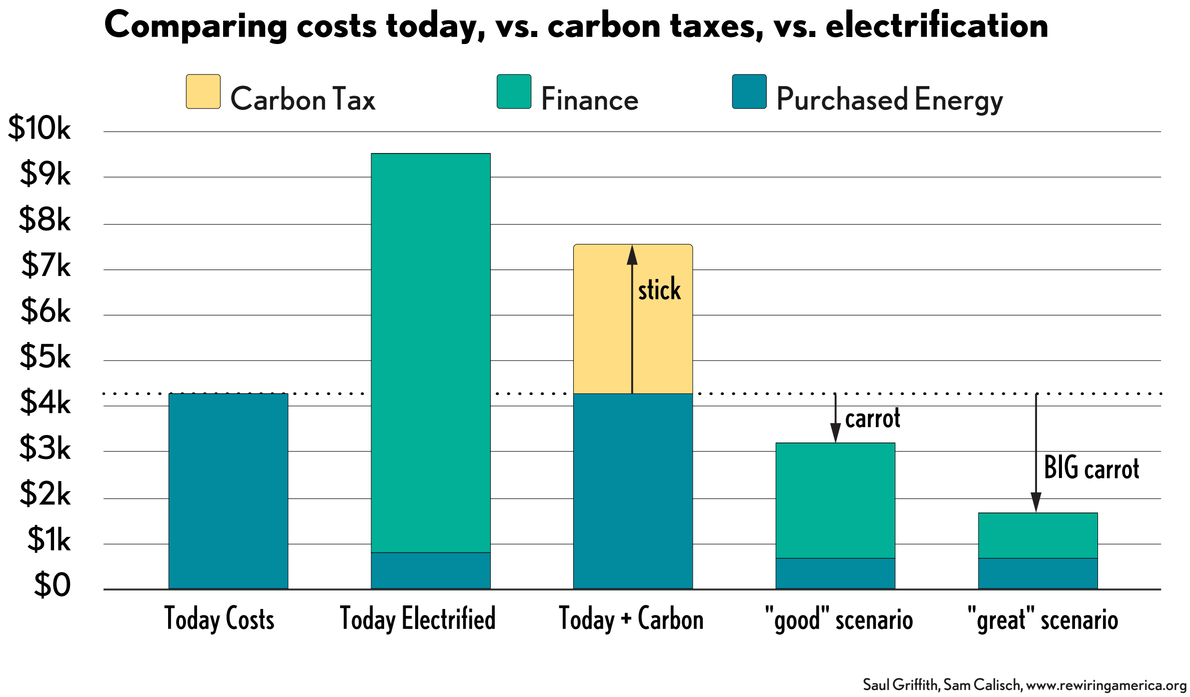

Figure 16: *Comparing the "stick" of a carbon tax on the household, with the "carrot" of electrification.*

with many in the realm of credit card rates. Once we have achieved the great scenario, we can see there is plenty of room for run–of–the–mill interest rates (i.e., those where lenders can make a sure profit).

The implications are interesting. In the short term, certainly for the initial ramp up, low–cost financing is critical. But as we see in the "Good" and "Great" models, there comes a time when costs have fallen enough that low–cost financing isn't critical any more. At this stage, a larger array of more conventional financial products could be used for these electrification upgrades.

4.3 Can this be accomplished with electricity from the grid?

A similar thought experiment to the break–even interest rate can be applied to the grid.

Much of the household savings comes from the very low cost of electricity enabled by cheap rooftop solar. But not every household is a detached single–family house with a large roof, so for many households the question will be whether this transition will be economically viable at the cost of grid electricity. To study this, we calculate the *break–even grid price*, or the price at which the grid would have to deliver electricity to have total household energy costs break even compared to today. In Figure 18 we show break even rates for every state, along with current grid prices there.

In the "BAU" scenario, the cost of grid–based electricity would have to be negative or far below today's grid prices. In the "Good" scenario, electricity prices in many states fall

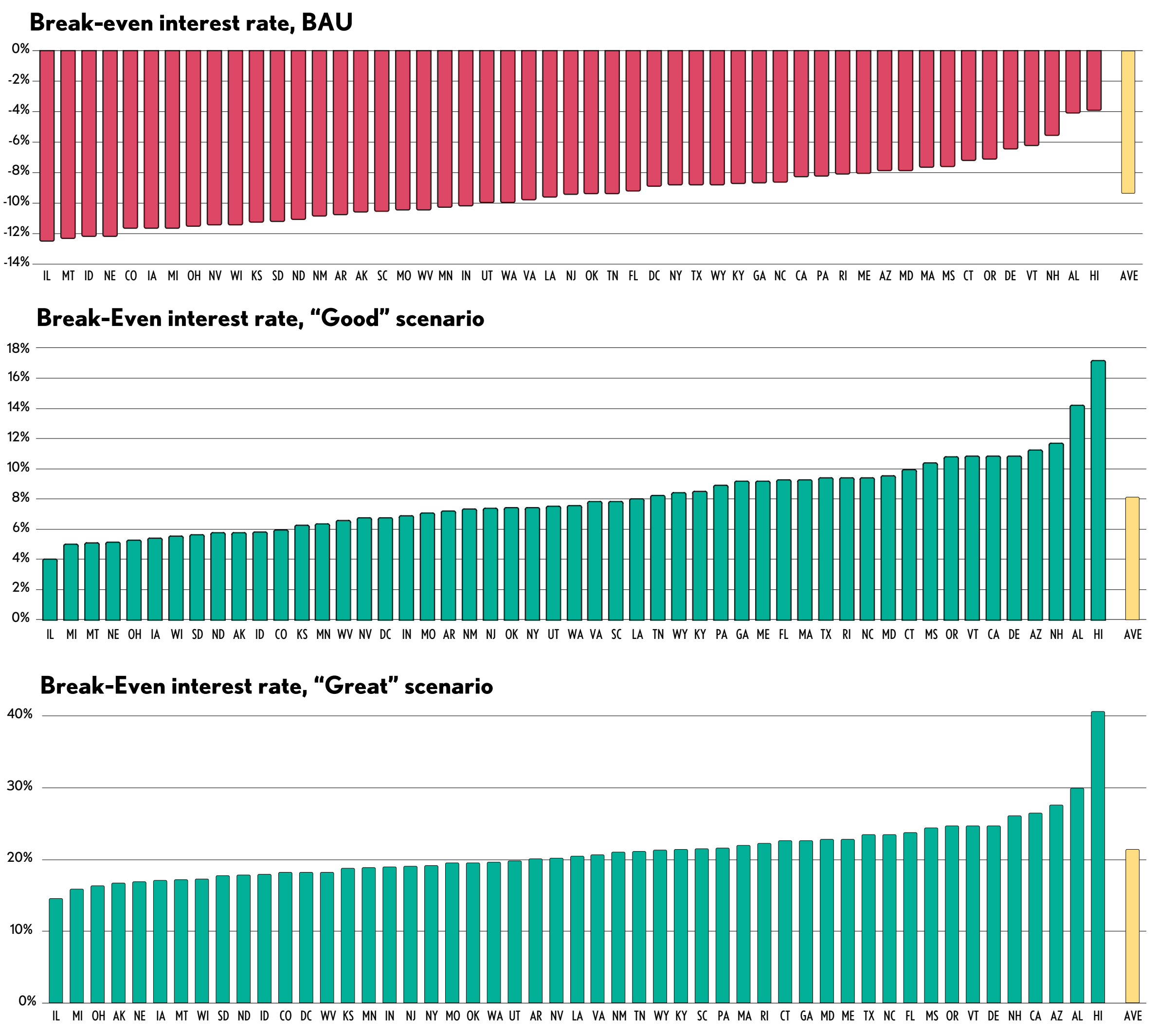

Figure 17: *Interest rates at which household economics are break even.*

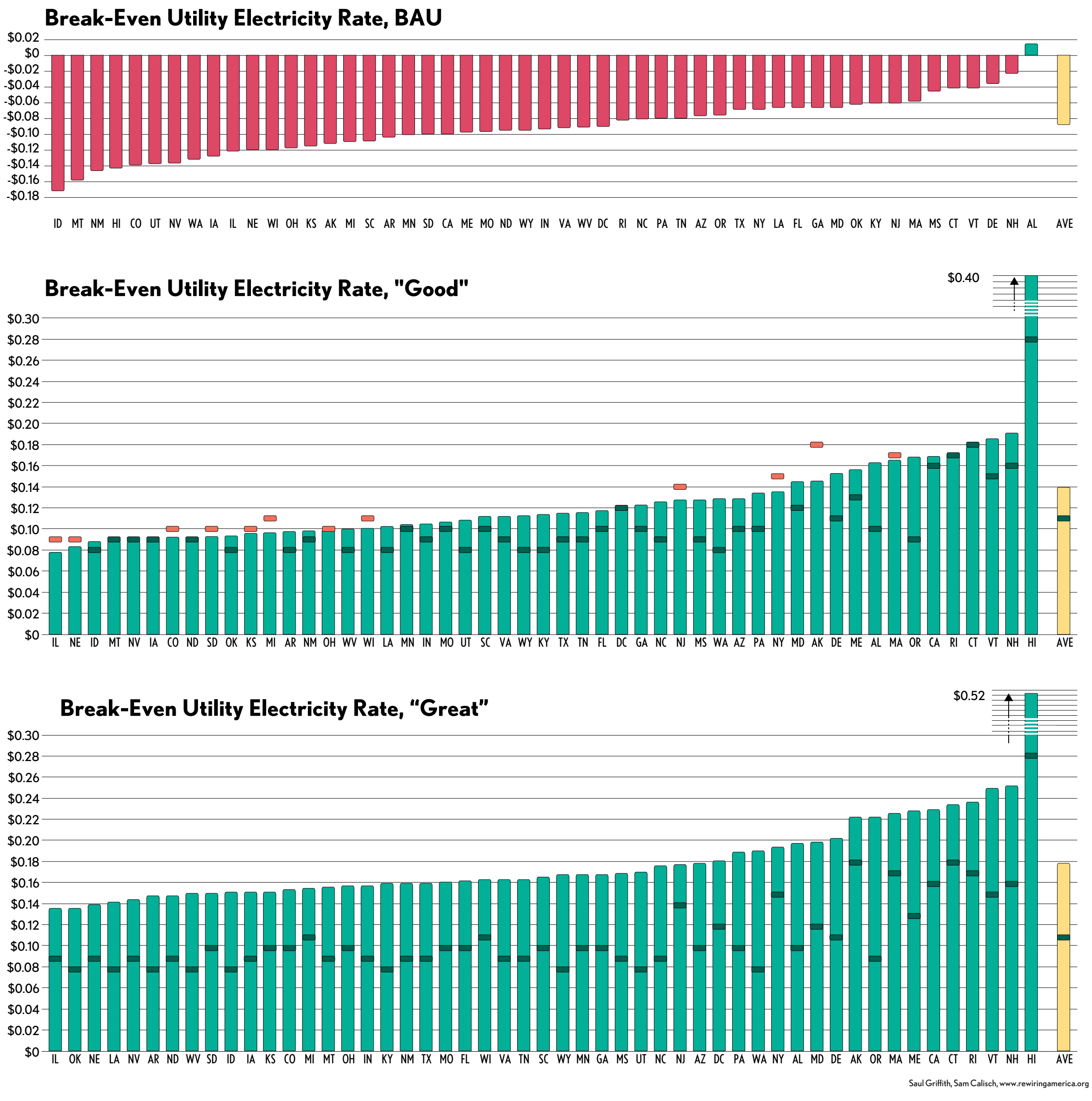

Figure 18: *Electricity prices at which household economics are break even, along with current state–by–state average electricity prices.*

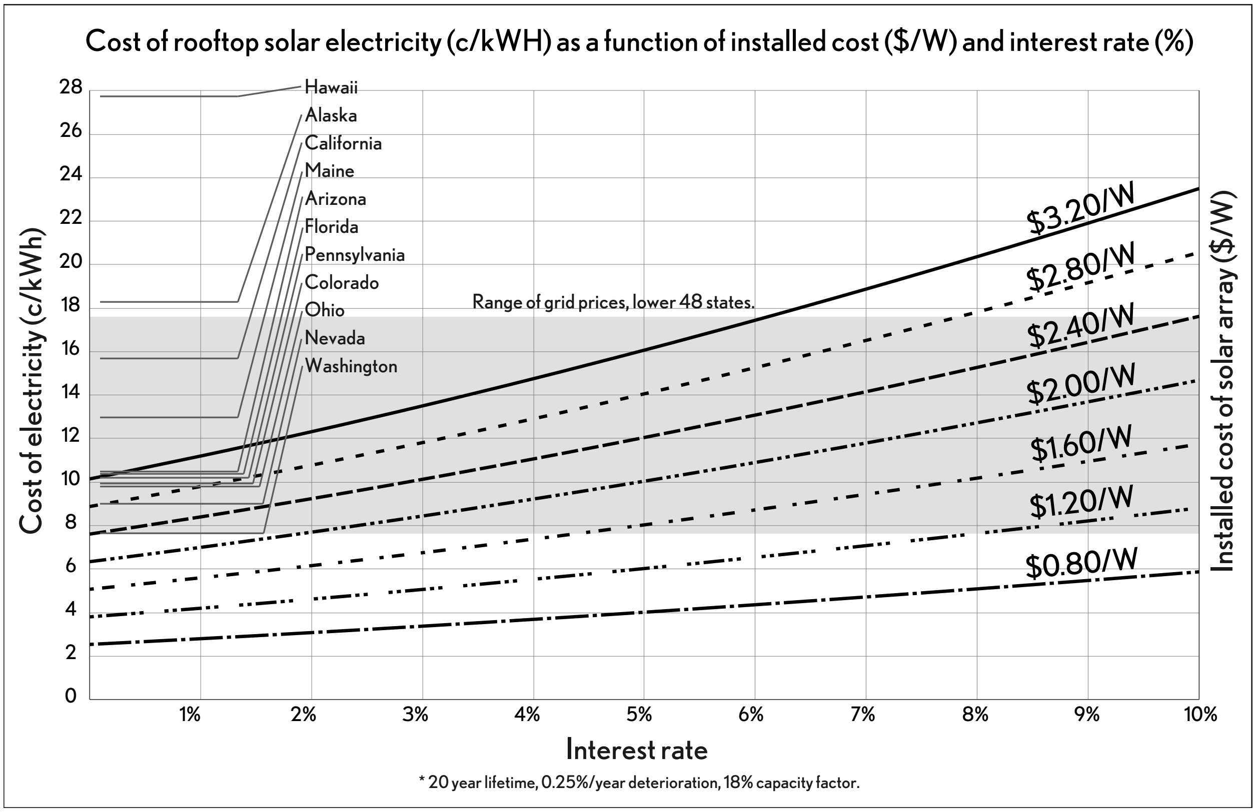

Figure 19: *Relationship between installation rates, interest rates, and delivered electricity prices of solar.*

below the break–even, allowing grid–purchased electricity to save the household money. In the "Great" scenario, households in every state can save money with electricity from the grid. On average across all states, the utilities have 3 and 7 cents per kWh of headroom in the "Good" and "Great" scenarios, respectively, to provide the household electrification upgrade as a service. This implies utility financing of the end–use electrical loads can work out once we have the cost reductions in place due to scale and regulatory reform. There is ample opportunity for utilities to be a critical, and profitable part of the solution.

Even so, rooftop solar will very likely be the cheapest source of electricity for those households that have the room and means to install it. This cheap electricity helps households save money on everything that is electrified. With low interest and low installation costs, rooftop solar beats the grid in every market, as shown in Figure 19. Australian solar is already at $1.20 a Watt installed. Regulatory reform, workforce training and certification, and optimization of permitting and inspection are key to getting those prices here in the U.S.

Under this total electrification model, and even with solar installed to the limit of the NREL technical potential, only about 2/3 of the future electric load will be met by the solar, the balance will need to come from the grid. This is in fact a similar number of delivered kWh as the existing amount of electricity, given that the total electrical load of households increases significantly. We show the installed solar capacity of this program in Figure 20 for each state. The approximate doubling of total delivered household electricity is reflected in

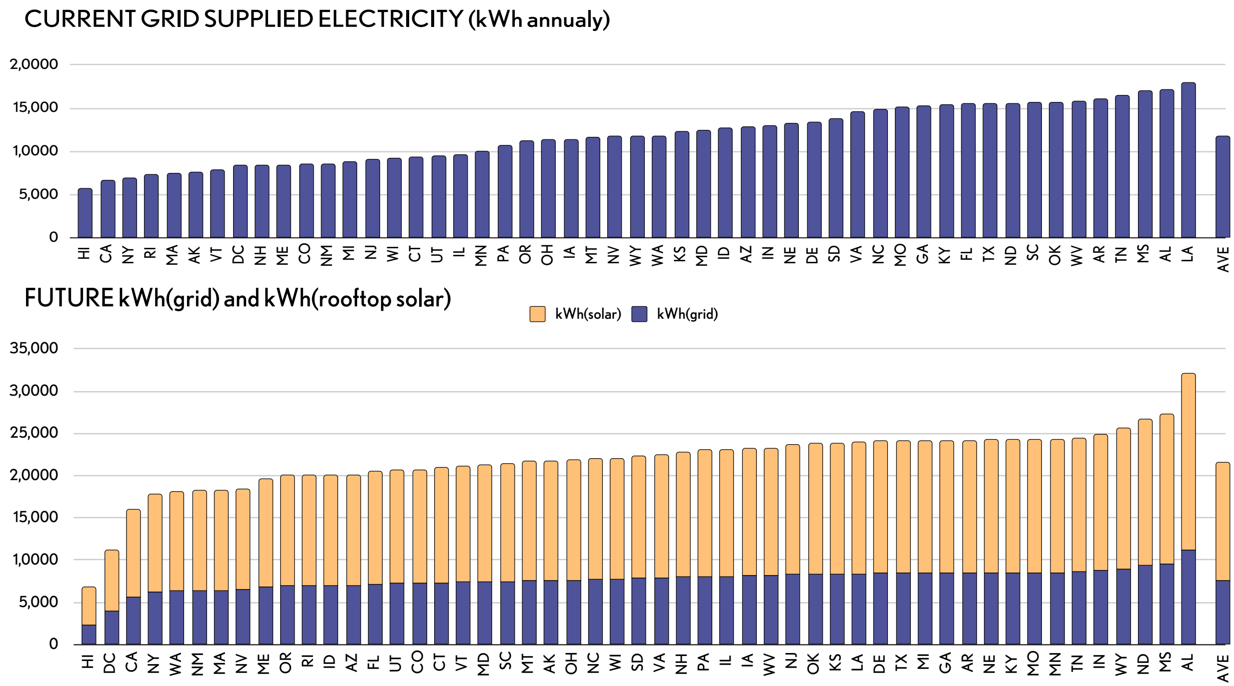

Figure 20: *Installed solar under this program, state–by–state.*

the chart.

4.4 Sensitivity Analysis and trends

In Figure 21 we look at the effects of critical variables on household savings. The cost of batteries is the most crucial factor in achieving maximum household cost savings, largely because of the high capital cost of two EV batteries per household. The interest rate is also a dominating factor. The cost of rooftop solar and the effective COP of heat pumps are other major contributing factors to achieving cost savings. The battery lifetime is important, because it impacts the financing period. Labor efficiency is important in eliminating soft costs in the installation process.

We also look at trends from factors that include (a) population density, (b) household historical heating load, (c) state price of gasoline;, (d) household vehicle miles traveled in Figure 22; and (e) state average electricity price, (f) state average natural gas price, (g) state average temperature, and (h) state average solar insolation in Figure 23. These trends are all charted here for the "Great" scenario, though can be generated for all scenarios. There are not a huge number of surprises here, but the analysis is interesting. The increasing population density of a state curiously has a positive effect on savings — though only a soft function. States that use more heat save more money once the COP is high enough, and electricity costs low enough, to beat natural gas or heating oil as a heating fuel. Not surprisingly, more expensive gasoline correlates with higher savings as do more household vehicle miles traveled. Higher local electricity prices today correlate with increased energy savings in this version of an electrified future because we have high penetration of low cost

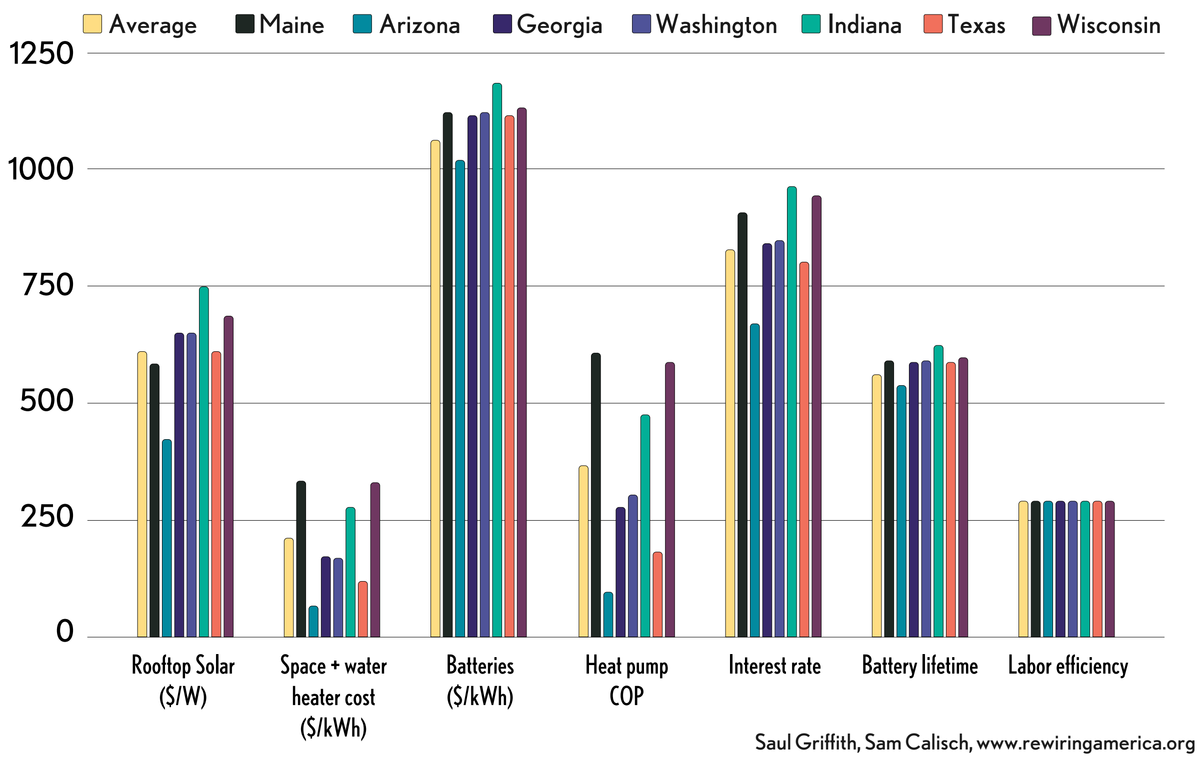

Figure 21: *Sensitivity analysis of critical variables effect on cost.*

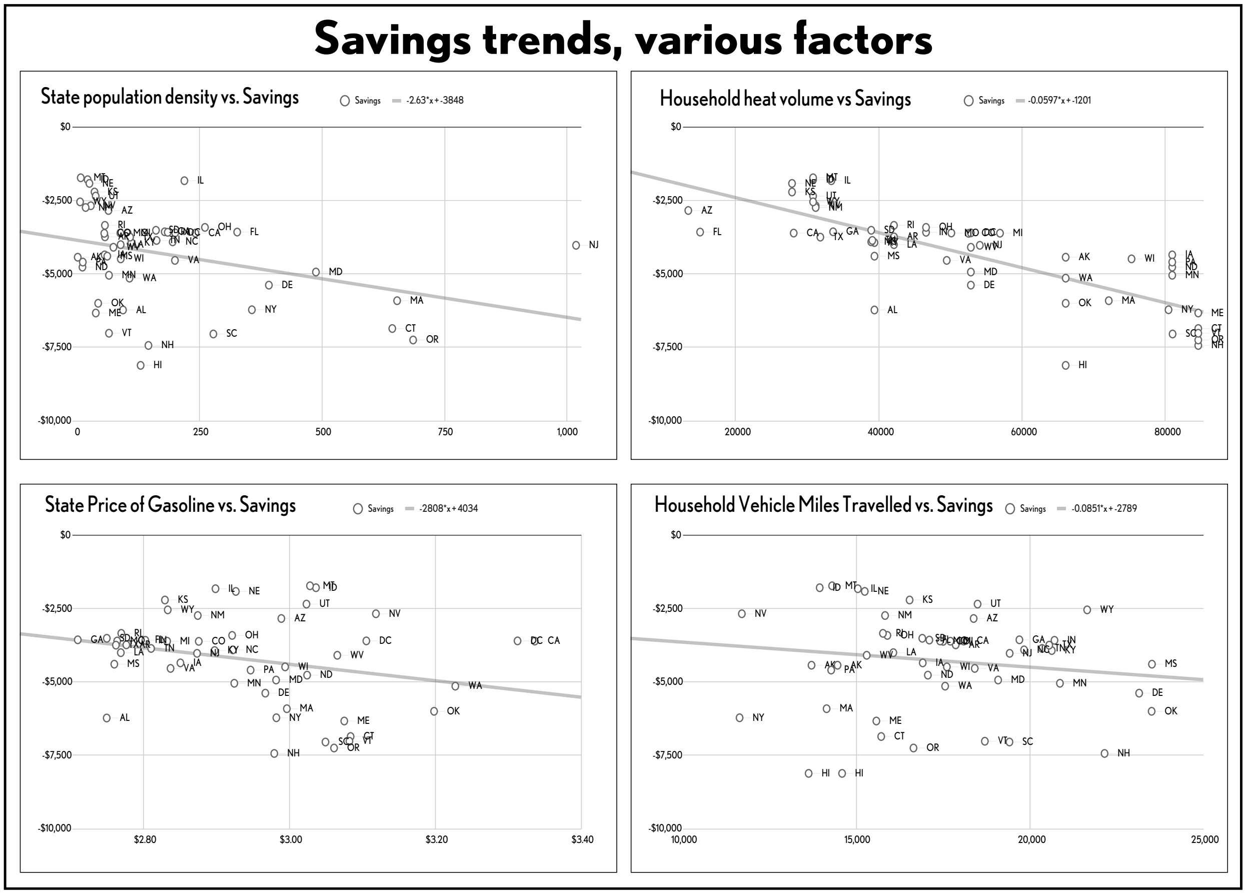

Figure 22: *Investigating nationwide trends by various conditions: (a) Population Density, (b) Household historical heating load, (c) State price of gasoline, (d) Household Vehicle Miles Traveled (VMT)*

rooftop solar, which easily bests current electricity prices in almost all locations. Similarly, higher future household savings correlate to higher current natural gas prices. Colder state average ambient temperatures only slightly correlate with higher savings, although colder places do save a little more money — the very high air conditioning running costs at existing electricity prices in hot places is improved with low cost rooftop solar–generated electricity. Intriguingly, once rooftop solar gets below a certain threshold, as is seen here, the savings are negatively correlated with average incident solar radiation. The places with lower insolation also have higher heating costs and typically longer driving distances and household VMT, which means they still save more in spite of requiring larger household solar installations.

5 Conclusions

- Without doubt, the three main pillars of this strategy are a low price of rooftop solar, a low price of batteries, and a low cost of financing.
- Regulatory reform that lowers the artificially high solar costs of U.S. solar should be a

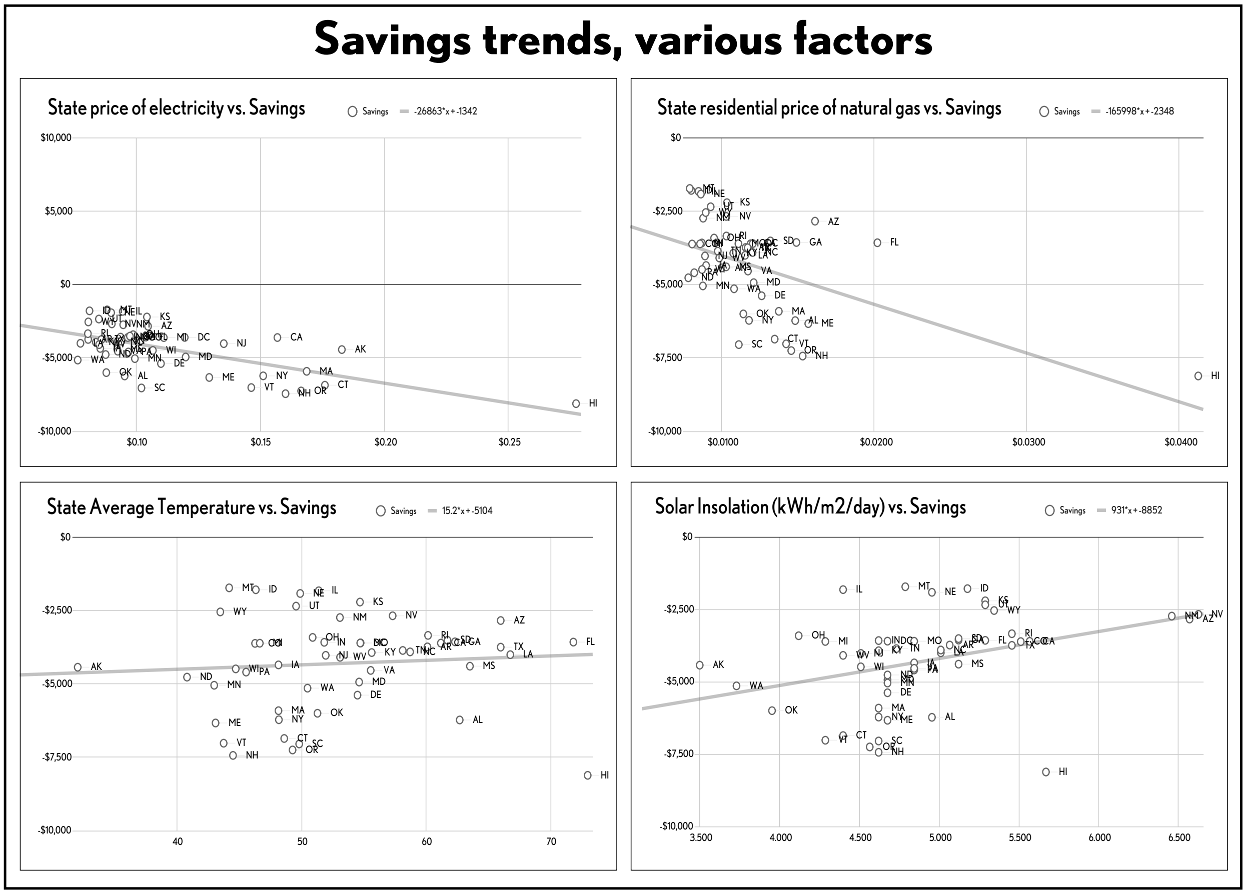

Figure 23: *Investigating nationwide trends by various conditions: (e) State average electricity price, (f) State average natural gas price, (g) State average temperature, (h) State average solar insolation.*

priority.

- Federal and state mechanisms for providing low–interest, guaranteed, or infrastructure style financing for the household retrofits will be critical.

- Mechanisms that work for all household income levels are important in achieving the penetration required to be meaningful on climate impact.

5.1 Additional Benefits

We can identify at least five additional sources of potential savings that we don't calculate here, but we wish to emphasize can make this an even bigger win for the American public than is commonly recognized.

These savings include:

- Lower maintenance costs of lower complexity electrical machinery

- Lower healthcare costs due to improved air quality particularly indoor air quality from stopping indoor combustion of fossil fuels

- Tax savings homeowners realize from the "stepped–up basis" of their homes from these retrofits

- Grid services that could accrue to households in helping to balance the national grid or taking advantage of time of pricing

- Savings realized collectively from higher water quality and environmental quality as we remove the toxins that result from fracking and other extractive industries contaminating our waterways and water tables

Income before taxes	**$78,635**	—
Food at home	$4,464	7.29%
Food away from home	$3,459	5.65%
Alcoholic beverages	$583	0.95%
Housing	$18,064	29.50%
Natural gas	**$410**	**0.67%**
Electricity	**$1,496**	**2.44%**
Fuel oil and other fuels	**$121**	**0.20%**
Apparel and services	$1,866	3.05%
Transportation	$7,652	12.50%
Gasoline, other fuels, and motor oil	**$2,109**	**3.44%**
Healthcare	$4,968	8.11%
Entertainment	$3,226	5.27%
Personal care products and services	$768	1.25%
Reading	$108	0.18%
Education	$1,407	2.30%
Tobacco products and smoking supplies	$347	0.57%
Miscellaneous	$993	1.62%
Cash contributions	$1,888	3.08%
Personal insurance and pensions	$7,296	11.92%
Average annual expenditures	**$61,224**	**100%**
TOTAL : All Fuels	**$4,136**	**6.76%**

Table 1: *2018 BLS Consumer Expenditure Survey breakdown of household spending.*

Appendices

A Baseline of current household energy costs

We must first start with an estimate of current household consumer expenditures on energy. In Table 1 we can see that in 2018 the post–tax expenditures per consumer household were $61,224, of which $4,136, or close to 7% was spent on energy — $1496 on electricity, $410 on natural gas, $2109 on gasoline or diesel and $121 on propane or fuel oil.

But there is much variation between households. We can look at the state–level expenditures that the Bureau of Labor Statistics (BLS) collates for California, Florida, New Jersey, New York, and Texas [11]. Households are broken down into quintiles by income. There is significant cost difference by household as a function of income, as is seen in Figure 24. As a percentage of spending by household, we see that low–income households can spend roughly twice as much as high income households on energy — 6–10% vs 5–6%.

We summarize the average historic costs per state in Table 2.

We need to make an estimation by state of all of the fuel costs by household. This includes gasoline[12] for transportation, and natural gas, propane, and fuel oil for heating systems as

[12] We actually include both diesel and gasoline under this heading for simplicity.

State	N-Gas (5yr) ($/1000Cu.ft)	Electric (5yr) ($/kWh)	Gasoline (10yr) ($/Gal)	Propane (10yr) ($/Gal)	Fuel Oil (10yr) ($/Gal)
Alabama	$14.83	$0.10	$2.75	$2.61	$3.18
Alaska	$10.01	$0.18	$3.72	$2.39	$3.18
Arizona	$16.13	$0.10	$2.99	$2.39	$3.18
Arkansas	$11.58	$0.08	$2.78	$2.14	$3.18
California	$11.91	$0.16	$3.34	$2.39	$3.18
Colorado	$8.06	$0.10	$2.88	$2.07	$3.18
Connecticut	$13.48	$0.18	$3.08	$2.91	$3.29
Delaware	$12.63	$0.11	$2.97	$3.04	$3.15
Dist.Columbia	$12.05	$0.12	$3.11	$2.39	$3.74
Florida	$20.22	$0.10	$2.80	$4.64	$3.18
Georgia	$14.91	$0.10	$2.71	$2.23	$3.18
Hawaii	$41.29	$0.28	$3.71	$2.39	$3.18
Idaho	$8.01	$0.08	$3.04	$2.37	$3.18
Illinois	$8.48	$0.09	$2.90	$1.62	$3.18
Indiana	$8.70	$0.09	$2.80	$2.12	$2.88
Iowa	$8.98	$0.09	$2.85	$1.42	$2.67
Kansas	$10.35	$0.10	$2.83	$1.49	$3.18
Kentucky	$10.76	$0.08	$2.90	$2.16	$2.78
Louisiana	$11.54	$0.08	$2.77	$2.39	$3.18
Maine	$15.69	$0.13	$3.08	$2.67	$2.95
Maryland	$12.11	$0.12	$2.98	$3.07	$3.21
Massachusetts	$13.75	$0.17	$3.00	$3.11	$3.20
Michigan	$8.58	$0.11	$2.83	$2.09	$2.86
Minnesota	$8.77	$0.10	$2.92	$1.72	$2.81
Mississippi	$10.30	$0.09	$2.76	$2.31	$3.18
Missouri	$11.10	$0.10	$2.76	$1.78	$3.18
Montana	$7.91	$0.09	$3.03	$1.88	$3.18
Nebraska	$8.64	$0.09	$2.93	$1.39	$2.68
Nevada	$10.31	$0.09	$3.12	$2.39	$3.18
New Hampshire	$15.32	$0.16	$2.98	$3.26	$3.05
New Jersey	$8.91	$0.14	$2.87	$3.59	$3.29
New Mexico	$8.78	$0.09	$2.87	$2.39	$3.18
New York	$11.80	$0.15	$2.98	$3.00	$3.42
North Carolina	$12.03	$0.09	$2.92	$2.75	$2.99
North Dakota	$7.81	$0.09	$3.02	$1.50	$3.18
Ohio	$9.50	$0.10	$2.92	$2.54	$2.85
Oklahoma	$10.31	$0.08	$2.77	$1.81	$3.18
Oregon	$11.42	$0.09	$3.20	$2.39	$3.18
Pennsylvania	$11.13	$0.10	$3.05	$3.00	$2.96
Rhode Island	$14.57	$0.17	$3.06	$3.58	$3.20
South Carolina	$13.20	$0.10	$2.75	$2.39	$3.18
South Dakota	$8.20	$0.10	$2.95	$1.53	$3.18
Tennessee	$9.75	$0.09	$2.81	$3.10	$3.18
Texas	$11.71	$0.09	$2.76	$2.33	$3.18
Utah	$9.28	$0.08	$3.02	$2.44	$3.18
Vermont	$14.23	$0.15	$3.08	$3.44	$2.99
Virginia	$11.73	$0.09	$2.84	$2.99	$2.99
Washington	$10.82	$0.08	$3.23	$2.39	$3.18
West Virginia	$9.84	$0.08	$3.07	$2.39	$3.18
Wisconsin	$8.71	$0.11	$2.99	$1.67	$2.82
Wyoming	$8.96	$0.08	$2.83	$2.39	$3.18

Table 2: *Average annual household retail prices for all household fuels. Data from: Electricity (2014-2018 average), Natural Gas (2014-2018 average), Gasoline (2009-2018 average), Propane (2009-2018 average), and Heating Oil(2009-2018 average).*

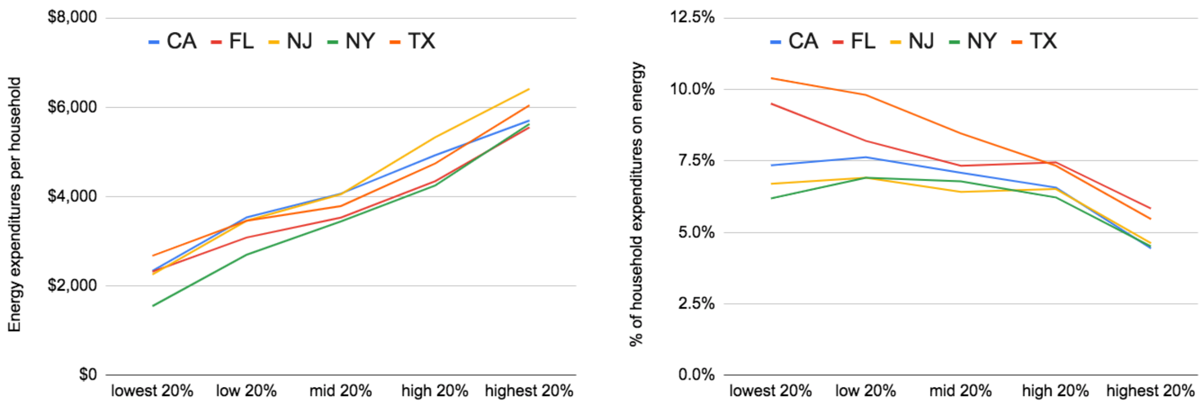

Figure 24: *a) 2017-2018 BLS Consumer Expenditure Survey breakdown of household energy spending by state and by income quintile. b) As a percentage of total household spending*

well as electricity for the everything else.

The State Energy Data System (SEDS) keeps detailed energy data by sector and by state[10]. This conveniently includes all residential fuels and electricity. It critically does not include the gasoline consumption by household, instead providing consumption per capita by state, including all uses of gasoline, such as commercial, industrial, and government uses in this figure.

We consequently address transportation fuels in subsection A.1, and all other household fuels in subsection A.2.

A.1 Household Gasoline Use

To estimate gasoline use by household, we first estimate vehicle miles traveled by household.

To get the best estimate of vehicle miles traveled per household, we compare four sources of data on how much Americans drive in a year. First, we look at the Department of Transportation's National Household Travel Survey (NHTS) [12, 13], which is released every eight years and surveys over 100,000 households across the country about their travel habits. We use the NHTS BESTMILE estimate from this survey, which is a carefully calculated and fitted figure of household vehicle–miles traveled [14]. The second source we use comes from the State Energy Data System (SEDS) [10], which records energy expenditures. We convert these to vehicle–miles by using the EIA-Derived 55/45 fuel economy estimate from NHTS on a state–by–state basis. The third source comes from the National Highway Administration's Traffic Volume Trends report [15] and Highway Performance Monitoring System [16] which samples data from 5,000 continuous traffic counting locations across the country and reports weighted statistics on road use. Finally, we use data from the Department of Transportation's Office of Highway Policy Information (OHPI) [17] which are often used for quoting insurance policies.

We compare data from these sources, state by state, in Table 3. We see that the NHTS estimate falls significantly below the other three sources. This is because this survey only counts miles traveled by an individual not for work purposes, whereas the other three count all vehicles out on the roads, including commercial driving and freight trucking. To maintain

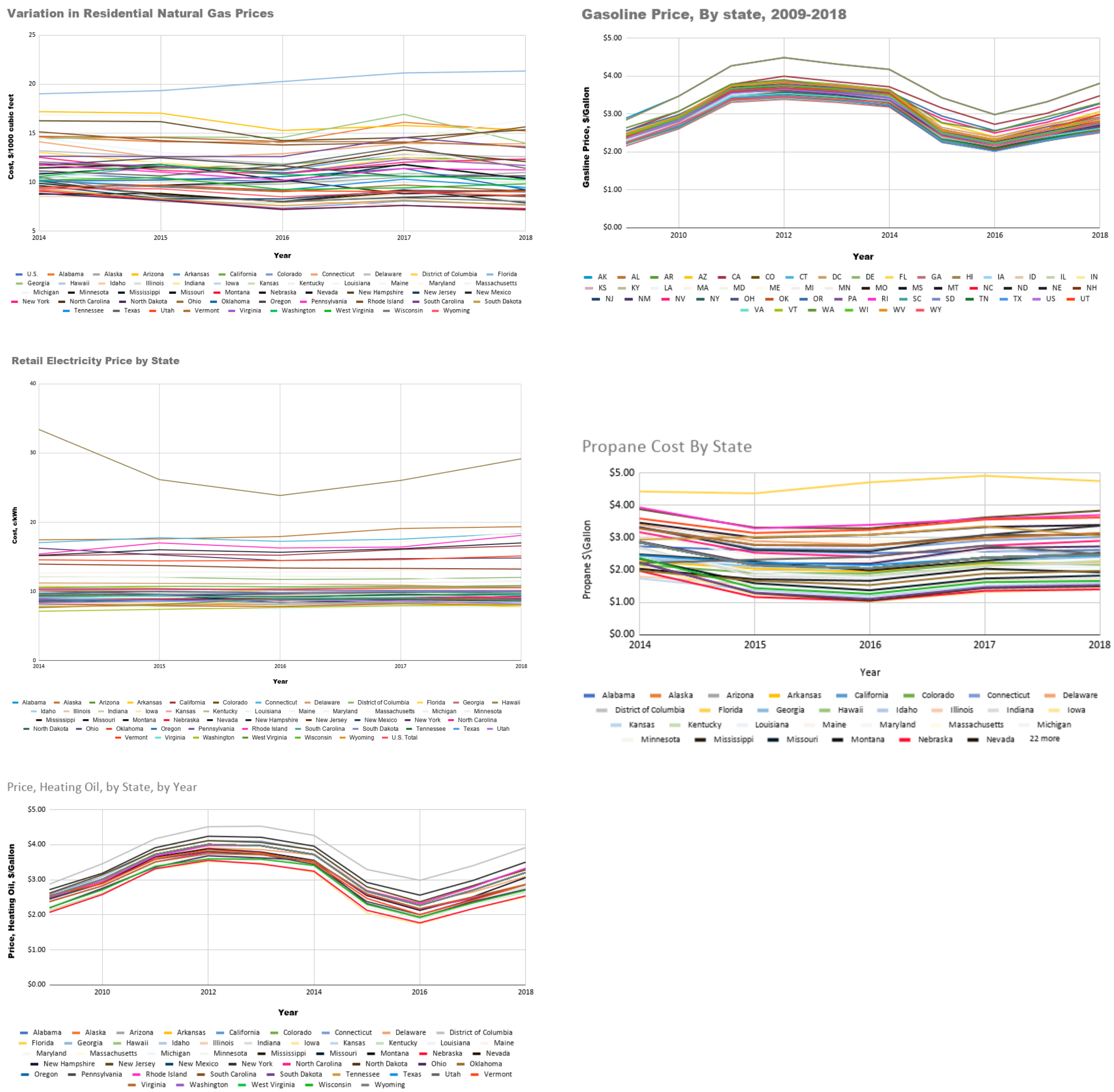

Figure 25: ***Retail prices of fuels to households:*** *(a) Residential Natural Gas Prices by state, 2014-2018, (b) Retail Gasoline Prices by State, 2009-2018, (c) Residential Cost of Electricity by state, 2014-2018, (d) Propane Prices by State, 2014-2018, (e) Heating Oil Prices by State, 2009-2018*

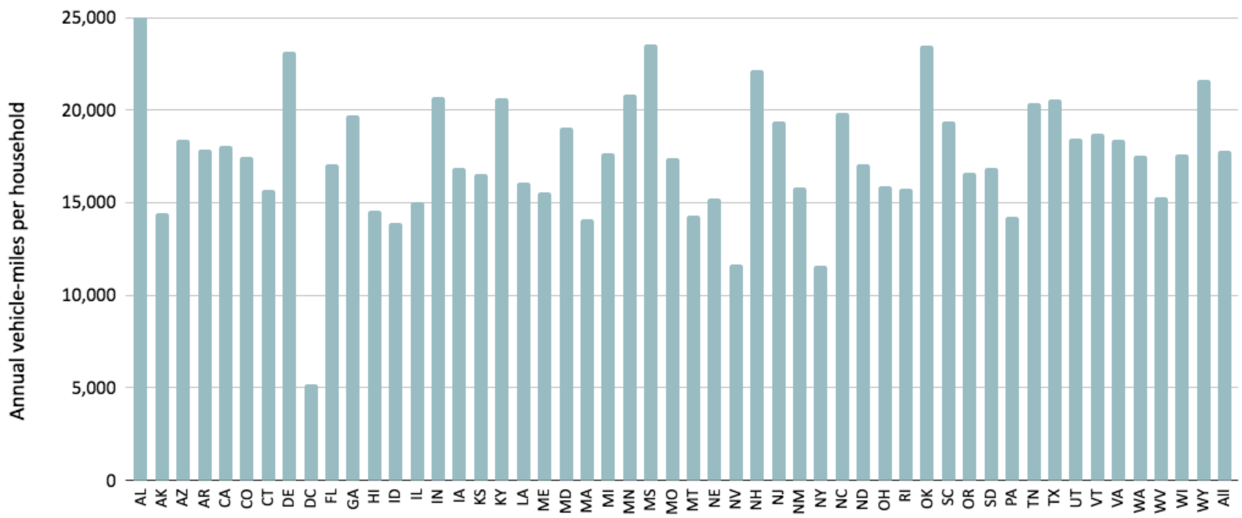

Figure 26: *NHTS VMT per household by state*

a conservative estimate for household electrification savings, we use the NHTS data (plotted in Figure 26). On average, this comes out to a bit less than 20,000 miles for every household. We check this number which gives a weighted average cost per household of ∼$2400 to the $2109 of the 2018 BLS survey which confirms the validity of the data.

We use the miles per household to estimate the number of gallons of gasoline per household using an average fuel economy value. To calculate this, we take the total amount of gasoline used for driving and divide by the number of miles driven. Using this approach, we find the average economy for all vehicles on U.S. roads is 18 miles per gallon (mpg), but if we restrict that just to the light-duty vehicles used by households, the average is 22 mpg [18].

The savings per household, as we will see later, are enormously influenced by VMT, because electric cars cost about 3 cents/mile to operate and ICE cars about 15 cents/mile. Our savings numbers are thus probably slightly conservative, as the real VMT per household is probably higher than our most conservative assumption.

A.2 Household fuel energy costs by state

To arrive at the current household fuel energy cost by state, we need to know the amount of each fuel used per home and we need to have an estimate of the cost of those fuels. The cost is determined from averaging the 5 or 10–year time series of historic costs by fuel.

For historical fuel costs we can look to data from the Energy Information Administration (EIA) for which we have the time–series for decades. Some care is necessary to reconcile missing data or states that don't have data for particular fuels (e.g. heating oil). We collate the data for all fuels in Figure 25.

Looking at the price variation for electricity [19] over the 5 year period 2014-2018, we see there is little variation in electricity prices.

Natural gas [20] shows substantially more variation, much of it from the rise of the fracking industry, and some from the increasing costs of maintaining natural gas distribution

	NHTS	SEDS	HPMS	OHPI
Alabama	36,018	31,838	34,978	27,307
Alaska	14,450	22,810	19,379	16,396
Arizona	18,376	24,233	24,039	24,865
Arkansas	17,859	28,219	29,141	26,516
California	18,090	26,274	25,136	26,152
Colorado	17,497	23,433	22,421	23,510
Connecticut	15,709	24,535	22,507	19,004
Delaware	23,151	29,684	26,312	26,800
District of Columbia	5,217	7,749	11,542	11,719
Florida	17,098	24,852	25,538	20,119
Georgia	19,696	29,481	30,146	32,952
Hawaii	14,581	22,586	21,972	18,567
Idaho	13,934	26,414	24,987	29,935
Illinois	15,035	22,633	21,507	22,057
Indiana	20,709	27,462	29,621	32,350
Iowa	16,908	27,446	25,330	26,001
Kansas	16,528	25,480	27,143	25,680
Kentucky	20,630	28,427	27,128	28,493
Louisiana	16,060	27,581	27,050	22,471
Maine	15,569	24,866	25,357	29,627
Maryland	19,083	27,552	25,401	25,604
Massachusetts	14,134	23,491	21,751	19,471
Michigan	17,704	26,306	24,395	24,036
Minnesota	20,865	26,067	25,341	30,460
Mississippi	23,520	34,686	35,116	29,211
Missouri	17,409	29,309	28,943	29,161
Montana	14,293	26,313	27,606	27,432
Nebraska	15,235	25,840	25,563	25,724
Nevada	11,689	23,626	22,557	21,036
New Hampshire	22,153	28,892	23,690	24,680
New Jersey	19,415	28,223	23,003	20,767
New Mexico	15,820	29,092	34,542	28,716
New York	11,623	17,283	16,265	17,574
North Carolina	19,832	25,893	26,881	26,973
North Dakota	17,056	29,294	30,422	26,427
Ohio	15,887	24,265	23,631	21,560
Ohio	15,760	27,897	31,110	31,953
Oklahoma	23,511	21,833	21,423	25,854
Oklahoma	19,409	21,976	19,397	21,194
Oregon	16,641	19,790	18,263	22,260
Oregon	16,894	31,938	25,518	28,392
Pennsylvania	14,266	29,522	25,611	25,872
Pennsylvania	20,350	29,102	28,404	26,558
Texas	20,557	32,660	25,460	29,532
Utah	18,490	26,825	28,903	31,572
Vermont	18,700	25,975	27,076	24,382
Virginia	18,408	28,740	25,265	27,014
Washington	17,554	21,442	19,976	22,228
West Virginia	15,291	24,456	26,773	24,167
Wisconsin	17,604	23,628	25,586	25,999
Wyoming	21,652	32,113	40,792	38,869
U.S.	17,815	26,018	24,757	24,769

Table 3: *Comparing estimates of vehicle-miles traveled per household, calculated from four data sources.*

infrastructure.

Gasoline prices [21] per state vary a lot more.[13]. Gasoline prices are subject to variations of the international price of oil as well as technology advances such as horizontal drilling and fracking over this period.

Substantial numbers of households still use propane [22] and heating oil [23], which both show variations that correlate with the price of gasoline since they are all oil derivatives. For states without reported data we use the national average.

From all of these historical data sets we can now build a state–by–state cost basis for our analysis. These historical prices are shown in Table 2.

From these costs, and from our estimates on energy consumptions by household, we can build the table of current household energy costs in Figure 5.

B Future household energy costs

To determine the future costs of energy per household, we need to know two things: (1) the effect of electrification of the household on the total energy consumption per household, and (2) the future cost of electricity to the household.

For future household energy consumption, we need to establish "Electrification Exchange Rates," or EERs, for each of the fuel uses within the homes. It turns out electricity is the great equalizer, the one "fuel" that can power all of our different activities.

Here we establish the equivalent units of the electrical energy services that will replace our current fuel–driven energy services. We do this for miles traveled in subsection B.1, for household heat in subsection B.2, and for everything else in subsection B.7.

B.1 Transportation: ICEs to EVs

In the case of comparing internal combustion engines (ICE) or gasoline vehicles to electric vehicles (EVs), let's look at real world vehicles to get a heuristic for converting gallons of gasoline to kilowatt–hours for the same number of miles travelled in a similarly sized vehicle.

Gallons to kWh

Very grossly, a small efficient electric vehicle, like a TESLA model 3, uses about 250 Wh/mile. That's 4 miles / kWh. The equivalent internal combustion engine (ICE) vehicle, like a Honda Civic gets an EPA 36mpg average [24].

A larger, heavier, faster electric vehicle, like a TESLA model S, uses closer to 333 Wh/mile. That's 3 miles / kWh. That would compare to a larger luxury car like a BMW 5 series that gets about 26 mpg [24].

Pickup trucks and SUVs comprise nearly half of America's auto fleet. An electric equivalent like a Rivian truck, will need around 500 Wh/mile [25]. That's 2 miles / kWh and will compare to similar sized trucks that get around 15–20mpg [24].

Using the **S**mall, **M**edium, and **L**arge vehicle models defined above, we can now translate between MPG and MPkWh which will give us a multiplier that converts household gallons of gasoline to required kWh of electricity. As shown in Table 4, this number is surprisingly

[13]It would be interesting to compare these to crowd–sourced datasets like `www.gasbuddy.com`

Vehicle Size	MPG	MPkWh	ICE vehicle	EV	Ratio kWh:G
Small	36	4	Honda Civic	Tesla Model 3	9
Medium	24	3	BMW 5 series	Tesla Model S	8
Large	17	2	Chevy Pickup	Rivian	8.5
Average	-	-	-	-	8.5

Table 4: *ICE to EV vehicle equivalencies*

similar for each of the vehicle sizes we consider — in the range of 8–9. We will use the average value of 8.5 to convert household gallons of gasoline consumption to the electric equivalent.

B.2 Heating Fuel Conversions

Heating is more complicated than vehicles for two reasons. The first is that not all homes are currently heated in the same way. Most are heated with natural gas, but many are electric and some use propane or fuel oil. The variation in heating equipment by climate region is shown in Figure 27.

Further, we need to determine which equipment we will include in our analysis, and which will need to be replaced as a capital expense and which not. The EIA's Residential Energy Consumption Survey [26] contains detailed estimates of the proportion that are already electric, and what proportion still burn fuels. We show these by end–use in Figure 28. We do not include in our capital estimates changing the equipment in homes or appliances that are already heated electrically.

The second complication is that for the large part we are going to model replacing the various pieces of equipment with electric heat pumps, and the Coefficient Of Performance (COP) of the heat pump is determined by the type of heat pump (air–sourced, or ground–sourced), as well as the local ground and air temperatures. We are going to make the simplified assumption that we will use air–sourced heat pumps for all retrofits as they are much lower in capital cost and retrofit cost than ground–sourced heat pumps. Ground sourced heat pumps can have higher COP in certain regions (like Maine) and may be the best economic choice in those regions, but that is a level of detail beyond this analysis and in any case renders our economic analysis once again on the conservative side.

As with heat pumps, the COP of existing infrastructure varies by region and existing fuel type. In the case of fossil burning space and water heaters, this number is also called AFUE, or annual fuel utilization efficiency. With use historical sales data from EIA[14] to estimate AFUE by fuel type for both space and water heating. These values are shown in Table 5. We then use the regionally specific breakdowns of fuel use for space and water heating to estimate the aggregate AFUE for each use by state.

For the conversion of household heating uses to their electrical equivalent we model the following:

1. We will determine, by state, a COP assuming air–sourced heat pumps with performance according to their manufacturers' specification sheets and historic TTY3 climate data.

[14] Residential End Uses: Historical Efficiency Data and Incremental Installed Costs for Efficiency Upgrades, U.S. EIA, June 2017.

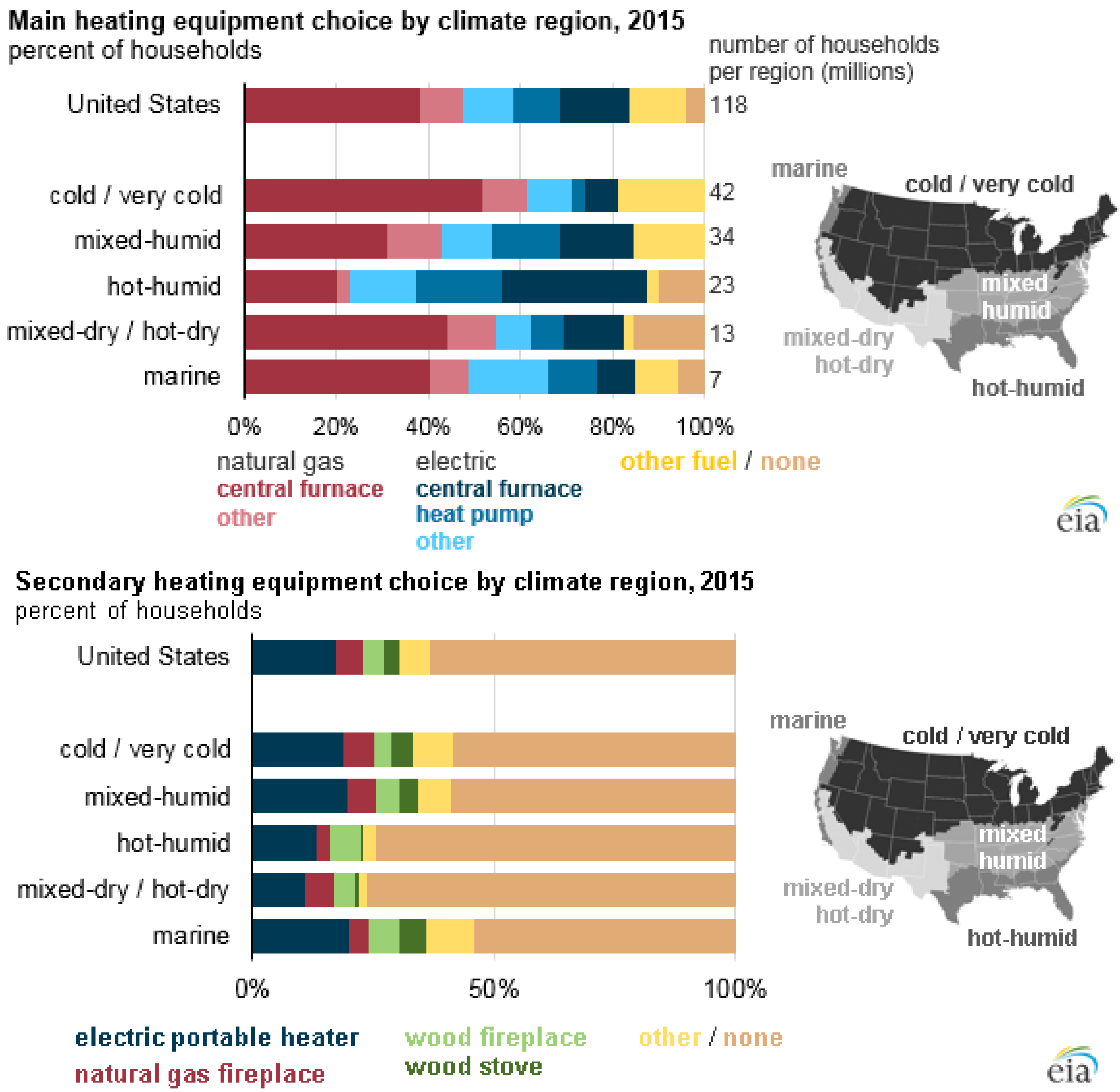

Figure 27: *Heating equipment by climate region for both primary and secondary heating equipment. From :* https://www.eia.gov/todayinenergy/detail.php?id=30672

	Natural Gas	Electricity	Propane	Fuel Oil
Space heat	0.88	0.99	0.88	0.82
Water heat	0.64	0.95	0.64	0.58

Table 5: *Calculated AFUE by fuel and use.*

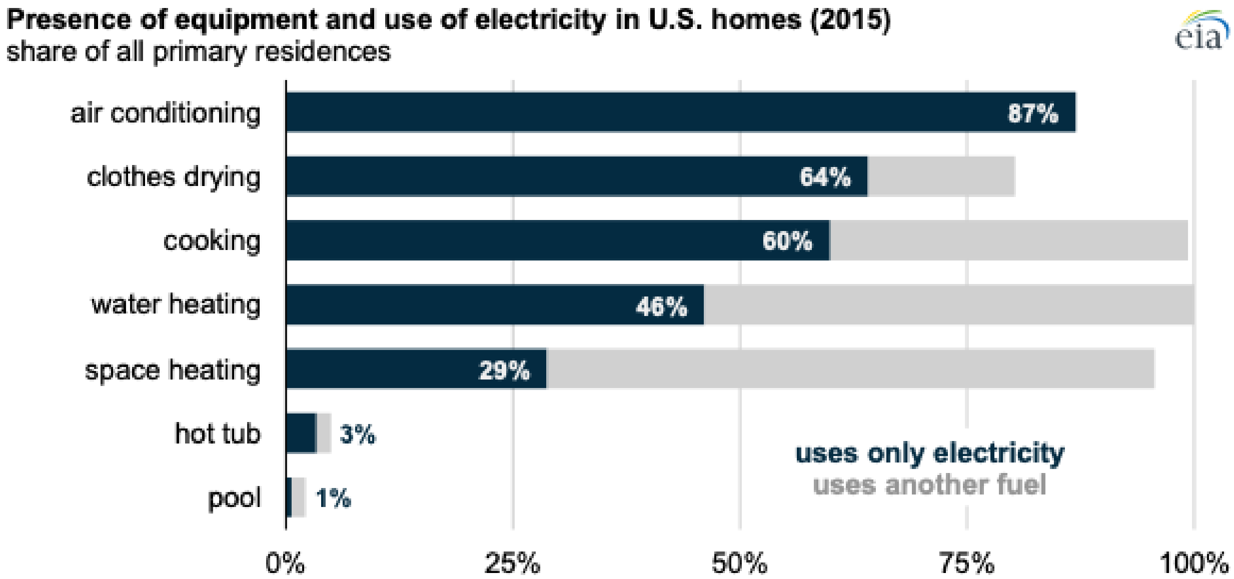

Figure 28: *Main energy consuming equipment in US homes and proportion of electric or fossil. From [27].*

This is a weighted average COP for the year that excludes periods where the air temperature is higher than 70 degrees and thus heating needs are low.

2. Replacing all natural gas cooking equipment with electric induction. The efficiency of these two forms will be considered equal (even though induction stoves are slightly more efficient).

3. Replacing all water heating with electric heat pumps. We will use the heat pump COP and AFUE of existing infrastructure determined as above. These reflect contemporary heating system efficiencies; many in older homes are much lower, again rendering our analysis on the conservative side.

4. Replacing all space heating with electric heat pumps. We will use the heat pump COP determined as above and assume the same representative COP of existing fuels as for water heating. This is probably going to report the total savings on the low side as many aged furnaces have COP (efficiencies) of 0.6–0.7. Once again the conservative assumption.

5. We will assume any natural gas use in the home is for the above uses and ignore clothes drying as it is majority electric already and a small load relative to space and water heating.

B.3 Fuel types by region

To arrive at by–state estimates we need to know which fuels are used where, and in what proportion. The EIA collects the data by region, and we assume all states in those regions to have the same ratio. This does mean, for example, in the western region that lumps

Fuel	USA	Northeast	Midwest	South	West
Gas	.51	0.55	0.65	0.32	0.67
Electric	0.41	0.25	0.29	0.65	0.28
Propane	0.04	0.03	0.05	0.02	0.05
Fuel Oil	0.03	0.17	-	-	-

Table 6: *Water Heater fuel type by Census Region*

California, Hawaii, and Alaska together, that we are mixing states with wildly different climates and heating types. In future studies we would hope to find by–state estimates of equipment fuel type for space and water heating.

B.4 Water heating

B.5 Space heating

To convert these regions to states we use U.S. census divisions [28]. In a better world we would do this by climate zone to avoid the California / Alaska / Hawaii problem. Climate Zones from EIA RECS : `https://www.eia.gov/consumption/residential/maps.php`. Unfortunately climate zones do not neatly align with state borders. This is a level of disaggregation that could be done in future studies.

B.6 COP by state

We use TTY3 climate data to determine COP by state using the performance curves for a typical Sanden brand heat pump. We choose the Sanden SanCo heat pump as it has a supercritical CO_2 refrigerant which has very low global warming potential (GWP). It is worth reminding ourselves of the importance of using low GWP heat pumps as a significant portion (7%) of current global emissions are from refrigerant leaks in heating and cooling and refrigeration. We only consider the COP for hours when the temperature is below 70 degrees (F) as the times when homes would be heated. This will skew our COP estimates low as the water heating component is still required on days above 70 degrees. The resulting average COP values can be seen in Table 8.

B.7 Other Household energy uses

There are two other uses of energy in households not covered under out household heat or miles of transportation EERs as calculated above. These are the non-heat uses of fuels, mostly cooking[15]. We assume that the incumbent technology has a COP of 1, and that the electrical machines that will replace it will have a COP of 1. In effect BTU per BTU or kWh per kWh these changeovers will be equivalent in energy use.

[15] Yes, cooking is heating, technically, but it's a different category to water and space heating which we only really need for comfort

Fuel	US	Northeast	Midwest	South	West
Natural Gas	0.49	0.52	0.69	0.32	0.55
Central Warm-Air Furnace	0.39	0.29	0.61	0.27	0.44
Steam or Hot Water System	0.06	0.21	0.07	0.01	0.02
Built-In Room Heater	0.02	0.01	0	0.02	0.04
Floor or Wall Pipeless Furnace	0.01	0	-	0	0.04
Other Equipment	0.01	-	0	0.01	0.01
Electricity	0.34	0.12	0.18	0.57	0.28
Central Warm-Air Furnace	0.17	0.01	0.09	0.33	0.12
Heat Pump	0.09	0.02	0.02	0.18	0.05
Built-In Electric Units	0.05	0.07	0.05	0.03	0.07
Portable Electric Heater	0.02	0	0	0.04	0.04
Other Equipment	0.01	0.01	0	0.01	0.01
Fuel Oil	0.06	0.27	0.02	0.01	0
Steam or Hot Water System	0.03	0.17	0	0	-
Central Warm-Air Furnace	0.02	0.09	0.02	0.01	0
Other Equipment	0	0.01	-	-	-
Propane/LPG	0.05	0.03	0.08	0.05	0.03
Central Warm-Air Furnace	0.03	0.02	0.07	0.03	0.02
Other Equipment	0.01	0.01	0.01	0.02	0.01
Wood	0.02	0.03	0.02	0.02	0.03
Heating Stove	0.02	0.02	0.02	0.02	0.02
Other Equipment	0.01	0	0.01	0	0
Kerosene	0	0.01	-	0	-
Other Fuel	0	0.01	0.01	-	-
No Heating	0.03	-	-	0.02	0.1

Table 7: *Percentage of homes with each type of Heating equipment by fuel type by Census Region*

State	COP	Current MBTU	Current (in kWh)	Future (in kWh)
Alabama	3.31	36.37	10,660	3,182
Alaska	2.43	30.45	8,924	3,614
Arizona	3.33	51.99	15,236	4,493
Arkansas	3.26	33.31	9,764	2,951
California	3.39	30.45	8,924	2,590
Colorado	2.94	51.99	15,236	5,076
Connecticut	3.1	75.16	22,028	6,848
Delaware	3.18	33.88	9,928	3,078
District of Columbia	3.12	33.88	9,928	3,132
Florida	3.4	33.88	9,928	2,876
Georgia	3.33	33.88	9,928	2,934
Hawaii	3.4	30.45	8,924	2,582
Idaho	2.91	51.99	15,236	5,130
Illinois	3.08	72.3	21,191	6,746
Indiana	3.03	72.3	21,191	6,855
Iowa	3.01	62.95	18,450	6,018
Kansas	3.14	62.95	18,450	5,769
Kentucky	3.19	36.37	10,660	3,302
Louisiana	3.4	33.31	9,764	2,832
Maine	2.93	75.16	22,028	7,242
Maryland	3.18	33.88	9,928	3,073
Massachusetts	3.12	75.16	22,028	6,795
Michigan	2.99	72.3	21,191	6,959
Minnesota	2.86	62.95	18,450	6,326
Mississippi	3.32	36.37	10,660	3,172
Missouri	3.16	62.95	18,450	5,720
Montana	2.88	51.99	15,236	5,183
Nebraska	3.06	62.95	18,450	5,909
Nevada	3.13	51.99	15,236	4,782
New Hampshire	2.96	75.16	22,028	7,164
New Jersey	3.19	67.94	19,911	6,096
New Mexico	3.2	51.99	15,236	4,677
New York	3.05	67.94	19,911	6,360
North Carolina	3.31	33.88	9,928	2,956
North Dakota	2.83	62.95	18,450	6,394
Ohio	3.1	72.3	21,191	6,715
Oklahoma	3.21	33.31	9,764	3,003
Oregon	3.1	30.45	8,924	2,833
Pennsylvania	3.08	67.94	19,911	6,315
Ohio	3.16	75.16	22,028	6,711
Oklahoma	3.3	33.88	9,928	2,962
Oregon	2.95	62.95	18,450	6,140
Pennsylvania	3.22	36.37	10,660	3,267
Texas	3.3	33.31	9,764	2,920
Utah	3.02	51.99	15,236	4,950
Vermont	2.92	75.16	22,028	7,282
Virginia	3.22	33.88	9,928	3,039
Washington	3.1	30.45	8,924	2,836
West Virginia	3.13	33.88	9,928	3,127
Wisconsin	2.94	72.3	21,191	7,082
Wyoming	2.87	51.99	15,236	5,207

Table 8: *COP by state, Annual current average MBTU per household, Annual current kWh equivalent per household, and future annual kWh projected from COP and mix of heating fuels and penetration of non-combustion equipment.*

The other energy in the household is the electricity we currently use for our devices, lighting, tools and entertainment. We assume these uses will not change and similar use trends will persist in the future.

C The future cost of electricity

We need a future cost of electricity to determine the future household cost of energy. There are two components to this: the cost of financed rooftop solar, and the cost of the grid delivered electricity. We make the mix fraction a global variable in our model. For the future cost of solar we use the $/W capital cost as calculated in Appendix D, a typical degradation rate for rooftop PV of 0.25% per year, and the financing cost as determined by the interest rate that we have as a variable in Appendix E. We find that after all of the electrification and the inherent efficiencies of electric vehicles and electric heat pumps that the total electrical load of the household approximately doubles. If 70% of this is provided by rooftop solar, the average rooftop solar installation required is approximately 9-10kW in nameplate capacity. Applied to all small buildings, this represents a total U.S. installed capacity of around 1100 GW, which is commensurate with the estimated technical potential as estimated by NREL [29].

C.1 Assembling the future fuel energy cost per household

We can now forecast total future costs to the household. We take historic energy consumption patterns, convert all loads to electric, multiply that future electrical load by the future cost of electricity, and we have a final cost of fuels for our decarbonized homes.

D Capital Costs

We need a simple capital cost model of converting our current households into zero–carbon electrified households. The main components are the conversion of the vehicles of the home to electric, the home heating systems to heat pumps, and installation of generous home rooftop solar systems. Associated minor costs such as an upgrade to the main electrical panel (load center), a home back–up battery, Level 2 vehicle chargers, electric cooking, and an estimate for the electrical upgrade labor (not technically a capital cost, but will be lumped with the installation) are included. Below we address each in order and the variables associated with them in the global cost model.

Vehicle Batteries. We only count the capital cost upgrade of the vehicle batteries ($capital_{batteries}$). The rest of the vehicle is assumed to be the same cost as the vehicles that the household currently finances out of its non–fuel costs. In reality this is a conservative assumption as the EVs will have lower maintenance costs, and falling capital costs over time in addition to the lowered cost of electric transportation. We use the number of vehicles per household as determined by the NHTS up to 2 vehicles per household (households with more than two vehicles don't need to electrify them all). We calculate the vehicle battery costs assuming a variable average vehicle range in miles ($range_{car-miles}$) for the household's vehicles and a cost of batteries in $/kWh ($cost_{batteries}$). Vehicle batteries are financed over a lifetime ($life_{car-batt}$). A residual value is assigned to the batteries at the approximate value of the raw materials of $40/kWh. In a future analysis it would be worthwhile to separate the effect of battery cycle life and battery cost. A 10,000 cycle battery, for instance, would lower the cost enormously of the storage, but would significantly lower the financed cost given the longer financing period that could be enabled.

Lithium-ion battery packs are already at around $150/kWh[7]. Viable paths to under $100/kWh have been forecasted by around 2026 (depending on rates of production and research) [6]. Exactly how low this price drops is a question of much debate, but as lithium-ion storage is projected to be the most cost-effective in the nearly all short-term storage applications[30]. We assume the batteries last 1000 cycles [31, 32].

Rooftop Solar. We size the rooftop solar according to the fraction ($fraction_{electrical}$) of total electrical load we expect it to supply to the household as dictated by the average loads per state. We determined a capacity factor by state for the solar based on the typical insolation per state. These numbers range from 13% (Alaska) to 24% (Arizona) and influence the size of the installation. We apply a variable $/W ($cost_{solar}$) to determine the capital cost. Solar is financed over a representative lifetime, ($life_{solar}$).

Home battery cost. We size the home battery by the (variable) number of hours of storage it should supply ($home_{battery-hours}$), and by the future electrical load of the household. We use this as the size basis and multiply it by the $/kWh capital cost ($cost_{batteries}$) of the battery pack. The home battery is financed over a representative lifetime, ($life_{home-batt}$). A residual value is assigned to the batteries that is a function of the cycle life ($cycles_{battery}$) and has a floor at the approximate value of the raw materials.

Heat pump space heating. We take the estimated future annual demand in kWh and use this in the estimated capital upgrade cost in dollars. The cost is determined by the annual load in (kWh) which is a proxy for system size multiplied by a factor ($SH_{goodness}$). With the goodness set at 1, this gives costs for the space heating retrofit of $1000-6000 which accomodates a broad range of systems from mini–split heat pump systems to central air systems. We scale the capital cost with the typical heating requirements by state determined by the historic heating load. The space heat is financed over a representative lifetime, ($life_{space-heat}$).

Heat pump water heating. Similar to space heating, we use the effective future annual demand in kWh as a proxy for system size, and a factor ($WH_{goodness}$)/2. This allows for the size of system and demand that varies by state to be crudely modeled in and gives upgrade costs between $300 and $800. The water heat is financed over a representative lifetime, ($life_{water-heat}$).

Load Center Retrofit. We have a variable upgrade cost set at $1000 per house for the load center ($capital_{load-center}$). The load center is financed over a representative lifetime, ($life_{load-center}$).

Electrifying Cookstoves / Ranges. The differential cost of installing an electric cookstove or range instead of a combustion cookstove is a variable that begins at $400 per house ($capital_{range}$). The range is financed over a representative lifetime, ($life_{range}$).

Vehicle Charging Retrofit. We have a variable upgrade cost set at $500 per household vehicle, up to two vehicles, including $100 for electrical upgrade work ($capital_{EV-charge}$). The vehicle chargers are financed over a representative lifetime, ($life_{EV-charge}$).

Electric upgrade labor. Beyond baseline installation costs for each appliance, we add an additional variable for extra labor required to retrofit the electrical system in the house for each high current device added. We assume a cost per appliance ($capital_{labor,appliance}$) for extra work over and above installation associated with electrical upgrades set at $100 each for the six appliances that are not solar and EVs (load center, space heat, water heat, battery, range or cook stove, and vehicle chargers).

Additional variables include estimates of the improvement of important technological performance characteristics. These include a multiplier on the COP ($COP_{goodness}$) to account for future improvements in heat pump performance should we focus our research and development efforts on this critical factor. We also include a multiplier on the capital cost of the space heat ($SH_{goodness}$) and water heat ($WH_{goodness}$) components.

E Financing Costs

We apply simple compound interest for each capital component in the household. There is 0% downpayment assumed (fully financed). The financing periods for each component is a variable, though we try to assume it is the lifetime of the object. There is zero residual value on all items except for the vehicle batteries and the home battery which are assumed to have a residual value roughly equivalent to the raw material costs ($40/kWh). Payments are calculated monthly to a fixed interest rate ($Interest_rate$). The total capital cost is converted to an annual payment by summing the annual payments that were calculated for each component.

We recognize the naivety of this financing model, and we anticipate that should the larger idea of this paper gain traction that much more nuanced and creative financing models can be performed to suggest more granular policy and regulation (or deregulation as the case may be).

F Cost Scenarios: BAU, Good, Great

We now have a working model of all energy expenditures for households and the decarbonization of about half of the energy economy (and consequently of the CO_2 economy as well).

We run three scenarios, (1) Business as Usual ("BAU") (2) "Good," and (3) "Great."

The results of the three scenarios are expressed in Table 9. The "Business As Usual" scenario represents values for the variables that are costs of all of the components in the U.S.A. in 2020. The "Good" scenario represents the best valuables available in 2020 including peer countries, financed at the current US federal mortgage rate of 2.9%. The "Good" scenario and "Great" scenario are reasonable scenarios of improving technology costs and lower again interest rates.

The good news is that the "BAU" scenario already shows us a pathway to fixing climate change being a wash on household finances, and the "Good" and "Great" scenarios demonstrate household cost savings of $1-2000 annually, with total U.S. economic savings of $75-300bN per year!

Item	**BAU**	**Good**	**Great**
CAPITAL COSTS			
ROOFTOP SOLAR ($/W)	3.00	1.50	1.00
FURNACE ($/kWh)	2.00	1.50	1.00
HOT WATER HEATER ($/kWh)	1.00	.50	.25
LOAD CENTER ($)	500	250	100
HOME BATTERY ($)	500	120	75
CAR BATTERIES ($/kWh)	250	120	75
CAR CHARGERS ($)	400	300	200
INDUCTION RANGE ($)	500	250	100
LABOR (Delta over existing)			
ROOFTOP SOLAR ($/W)	.20	.20	.20
FURNACE ($)	2,000	1,000	0
HOT WATER HEATER ($)	250	125	0
LOAD CENTER ($)	1,000	500	250
HOME BATTERY ($)	1,000	500	250
CAR BATTERIES ($)	0	0	0
CAR CHARGERS ($)	500	250	125
INDUCTION RANGE ($)	1,000	500	0
LIFETIME			
ROOFTOP SOLAR (years)	25	25	25
FURNACE (years)	15	20	25
HOT WATER HEATER (years)	15	20	20
LOAD CENTER (years)	15	20	25
HOME BATTERY (years)	10	12	15
CAR BATTERIES (years)	10	12	15
CAR CHARGERS (years)	15	20	20
INDUCTION RANGE (years)	15	20	20
TECHNOLOGY FACTORS			
COP GOODNESS FACTOR (unitless)	1.	1.1	1.2
HOME STORAGE (hours)	8	8	8
AVE. CAR RANGE (miles)	200	200	200
LOAD PROPORTION SOLAR (%)	65	70	70
LOAD PROPORTION STORAGE (%)	15	15	15
BATTERY ROUNDTRIP EFFICIENCY (%)	90	90	90
CAR CHARGE EFFICIENCY (%)	95	95	95
CAR BATTERY RESIDUAL VALUE ($/kWh)	0	40	40
FINANCE FACTORS			
INTEREST RATE (%)	5.0	2.9	2.0

Table 9: *Global variables in the cost model, Example Capital Costs, Labor costs, Lifetimes, Technological Factors, and Finance Factors.*

Sector	Direct Jobs	Indirect Jobs	Induced Jobs	Total Jobs	Annual Productivity improvement
Construction	6.63	3.36	10.05	20.04	0.0%
Manufacturing	1.92	3.98	8.18	14.08	2.0%
Electric Utilities	0.86	2.21	7.90	10.97	1.5%
Natural Gas Utilities	1.22	3.27	8.64	13.12	1.9%
Gasoline Sales	8.39	4.10	8.92	21.42	2.4%
Finance	4.15	3.68	10.16	17.99	1.8%
Automobile Sales	7.37	2.53	9.22	19.12	1.6%
Government Services	9.09	0.50	11.50	21.10	0.8%
All Other Sectors	6.22	3.43	9.80	19.45	1.30%
Household Demand	6.14	3.02	9.03	18.18	1.30%

Table 10: *U.S. Jobs coefficients (jobs per million 2018 USD invested) Source: John A. "Skip" Laitner, as estimated from the U.S. IMPLAN Data and the Bureau of Labor Statistics (October 2020)*

G Jobs

Table 10 are the U.S. job coefficients per million 2018 dollars of investment, including annual labor productivity gains for the representative industries used to estimate the jobs and job categories appropriate to this household infrastructure upgrade.

H Appendices

H.1 Cost per mile comparison of gasoline to electric vehicles

$$\frac{Cost}{Mile}_{(gasoline)} = \frac{1}{MPG} \times \frac{\$}{Gallon} \tag{1}$$

and

$$\frac{Cost}{Mile}_{(electric)} = \frac{\frac{Wh}{1000}}{mile} \times \frac{\$}{kWh} \tag{2}$$

This allows us to draw lines for the costs of transportation per mile with gasoline at 1,2,3,4 and 5 \$/gallon, and compare that for cost per mile of electric vehicles with electricity at 0.05, 0.10, 0.15, 0.20 and 0.25 \$/kWh we get the costs in Figure 29 per mile for our small, medium and large vehicles.

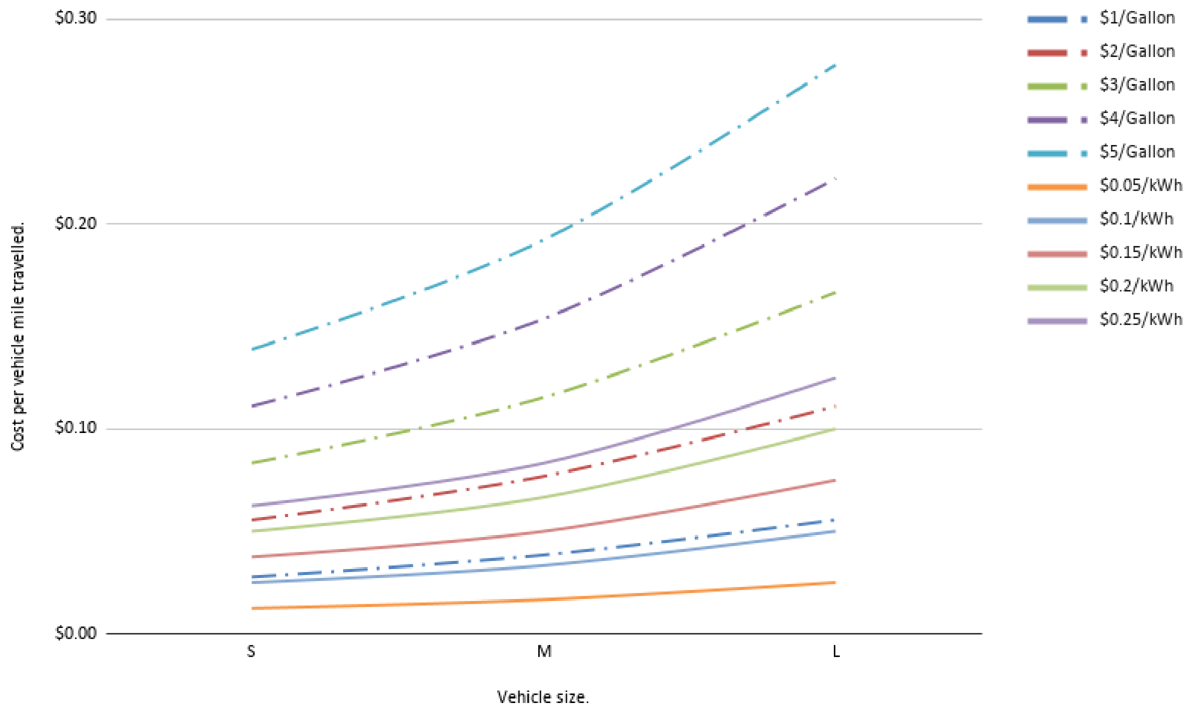

Figure 29: *Cost per mile for different vehicles according to retail cost of fuels.*

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