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On the Feasibility, Cost, and Carbon Emissions of Grid Defection

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***Abstract*—Distributed solar generation is rising rapidly due to a continuing decline in the cost of solar modules. Nearly all of this solar generation feeds into the grid, since battery-based energy storage is expensive to install and maintain. Unfortunately, accommodating unlimited intermittent solar power is challenging, since the grid must continuously balance supply and demand. Thus, governments and public utility commissions are increasingly limiting grid connections of new solar installations. These limitations are likely to become more restrictive over time in many areas as solar disrupts the utility business model. Thus, to employ solar without restrictions, users may increasingly need to defect from the grid. Unfortunately, batteries alone are unlikely to become cost-efficient at enabling grid defection for the foreseeable future. To address the problem, we explore using a mixture of solar, batteries, and a whole-home natural gas generator to shift users partially or entirely off the electric grid. We assess the feasibility and compare the cost and carbon emissions of such an approach with using grid power, as well as existing "net metered" solar installations. Our results show that the approach is trending towards cost-competitive based on current prices, reduces carbon emissions relative to using grid power, and enables users to install solar without restriction.**

I. Introduction

Distributed solar generation on rooftops has been rising rapidly due to a continuing decline in the cost of solar modules. Solar is already the fastest growing segment of U.S. energy generation, with capacity increasing by 40.5% in 2017 alone and accounting for 2% of U.S. generation, and much more in some states, including California (15%), Hawaii (12%), Nevada (11%), and Vermont (12%) [1]. Worldwide, solar capacity increased 50% in 2018 alone [2]. The rapid rise is due to the falling costs of solar modules, which are decreasing much faster than forecasted, and do not appear to be abating any time soon [3]. Thus, many expect solar power to become the dominate source of electricity by the end of this century [3]. Policies in some states are accelerating this trend. For example, California recently instituted a policy that *requires* new buildings to include rooftop solar [4].

The increasing amount of solar generation will profoundly change the grid's operation and the business model of utilities. In particular, while utilities operate and maintain the distribution network, they earn most of their revenue from generating electricity, which they currently can do much more efficiently than individual users. However, solar generation differs from fossil-fuel based generation in that it does not benefit as much from economies of scale. As a result, individual homeowners can install solar on their rooftops for closer to the same cost per watt that utilities can install large grid-scale solar farms. Even now, when amortized over a 25-year lifetime, solar power is cheaper than retail electricity rates in much of the U.S., assuming the solar power can be "net metered" and the utility credits users the retail rate for surplus power fed into the grid. Net metering enables consumers to connect solar power to the grid such that it acts as a negative load, causing their meter to run backwards when generating a net power surplus. When combined with government incentives, the payback period for net metered solar is now well under 10 years in many states.

Of course, the more individual users generate their own power, the less revenue utilities earn from generating electricity. Yet, utilities cannot simply decommission their generators (and take a capital loss), since they must still supply the grid's power at night when the sun is not shining. In addition, utilities may need to alter their mix of generators to handle increasing net metered solar installations, and their increased stochasticity, by employing more responsive but less efficient peaking generators. These changes may in-turn increase the cost and decrease the efficiency of grid generators. Thus, state governments and utility commissions typically place tight restrictions on users' ability to connect solar to the grid, as well as the compensation they receive for the energy it generates.

These restrictions vary widely by state. For example, in Massachusetts, the state places a hard cap on connected solar capacity under a state-sponsored incentive program. Upon reaching the cap, the legislature must pass a new law to raise the cap, and update the incentives, e.g., generally by steadily decreasing them over time. The process of drafting the legislation is highly political and involves negotiations among multiple stakeholders, including legislators, utilities, solar installers, environmental groups, etc. The last round of negotiations after hitting the cap in 2016 took more than 9 months during which time new installations were prevented from connecting to the grid [5]. Other states have a similar process. For example, Hawaii prevented residents from connecting solar for 2 years due to similar negotiations [6], [7].

While Massachusetts and Hawaii offer incentives to install and connect solar, some states actually penalize consumers for connecting solar. For example, Alabama requires residential customers with solar to either pay a fee of \$5/kW per month of installed solar capacity or pay 6× the standard electricity rate during peak summer hours [8]. In addition, unlike Massachusetts, Hawaii, and many other states, which credit consumers the retail rate for their surplus solar power, Alabama credits them 3-4× *less than* the retail rate. As a

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result of these solar disincentives, Alabama currently has only 48 residential solar customers statewide [8]. Many other states have similar policies that discourage solar adoption.

Clearly, the policies above directly influence solar energy's rate of growth. As solar penetration rises, utilities are likely to negotiate more strongly to reduce solar incentives, or even create disincentives, to preserve their revenue and business model, especially in states where utilities hold more political sway. Even in states, such as Massachusetts, that offer generous solar incentives, these incentives are decreasing over time as solar adoption increases, impacting utility revenue and operational costs. As these incentives decrease, we envision solar users considering partially or entirely defecting from the electric grid. Grid defection would enable users to install as much solar as they wish without limitations. Of course, the problem is that users can no longer rely on the grid to balance electricity's supply and demand, requiring them to store excess solar power and make up for deficits in solar power using batteries. However, even if a solar-powered home consumes net zero energy over a year, much of the energy is generated during the summer months, which leaves large deficits on many winter days. Installing enough battery capacity to shift summer solar generation to make up for winter deficits would be prohibitively expensive, likely requiring a battery with greater than 1MWh capacity for the average U.S. home.

Instead, we envision the likely path for grid defection to be using a mix of solar power, batteries, and a whole-home natural gas generator. The cost of generating power from natural gas generators has rapidly decreased due to the steep drop in natural gas prices over the last decade. In contrast, utilities are locked into multi-decade investments in large coal plants that are less efficient and incur high fuel costs. Grid defection differs from prior work on off-grid buildings, which does not consider using backup generators, since it largely focuses on remote regions not connected to gas infrastructure. In exploring the feasibility, cost, and carbon emissions of defecting from the grid, we make the following contributions.

Power Generation Tradeoffs We analyze tradeoffs of using different forms of generation and storage, including grid power, natural gas generation, solar power, and batteries, in terms of their average costs, carbon emissions, lifetime, reliability, and operational constraints (Section II).

Grid Defection Architecture We present an architecture for grid defection. The architecture enables a home to dynamically switch between a local/generator and solar/battery depending on its power consumption and generation. We define switching policies that capture a tradeoff between power switching and wasted solar: more switching leads to less reliability, but maximizes the use of solar energy. We then compare the cost and carbon emissions of grid defection for representative home with using grid power based on current cost estimates based on policies from multiple states (Section III).

Implementation and Evaluation We implement a trace-driven simulator to evaluate the cost and carbon emissions of grid defection for a wide range of homes that differ in their power consumption, solar generation, battery power and energy capacity, and generator capacity (Section IV).

Generator	*CapEx ($)*	*OpEx ($/kWh)*	*Life (years)*	*CO_2*
Grid Power	0	0.10-0.32	∞	0.45
Natural Gas	7,656	0.187-0.374	$\gg$10	0.45-0.90
Solar	21,980	0	25	0
Battery	4,550	0	10	0

TABLE I: Summary of current CapEx, OpEx, lifetimes, and carbon emissions (in kg-CO_2/kWh) of different generation options for grid defectors.

II. Background and Cost Estimates

To assess the feasibility of grid defection, we first need to understand the cost and carbon emissions of different forms of energy generation and storage, including grid power, local natural gas generation, solar power, and small-scale batteries.

A. *Grid Power*

The cost and carbon emissions of grid power are highly dependent on location, the local utility and its mix of generation sources, and the electricity rate structures, e.g., flat rate, time-of-use, peak demand charges, etc. The Energy Information Administration (EIA) estimates 62.7% of electricity generation comes from fossil fuels (coal, oil, and natural gas), 20.0% from nuclear, 17.1% from renewables, and 0.3% from other sources [9]. The total estimated generation from these sources was 4,015 billion kWh in 2017 with total associated CO_2 emissions being 1,821 million metric tons [10]. For this paper, we translate these averages to our own carbon emission estimate of 0.45 kg-CO_2 per kWh for grid power. Similarly, average grid electricity cost for residential users varies widely by region from a high of $0.32/kWh in Hawaii to a low of $0.10/kWh in Washington, with an average of $0.13/kWh [11].

B. *Whole-Home Natural Gas Generator*

Estimating the cost of a whole-home natural gas generator is more challenging than grid power. Standby generators capable of powering a home are increasingly common to provide power during grid outages. These generators are widely available at local home improvement stores at low cost. For example, a 11kW generator with an automatic transfer switch (ATS) currently costs ~$3100 [12]. These generators connect to a home's electrical panel via the ATS, which is able to sense a power outage, start the generator, and then automatically switch the home's power source from the grid to the generator. There is typically a 30 second delay between sensing an outage and switching to generator power, since the generator requires some time to start up after sensing an outage. The ATS also senses when grid power returns and automatically switches home power back to the grid, and then shuts down the generator. There is typically no loss of power when switching from the generator back to the grid. The generator connects directly to a home's natural gas pipeline, so there is no need for fueling the generator.

Unfortunately, standby generators are designed to only provide power for roughly 200 hours per year, or 3000 hours over their lifetime. In contrast, prime power generators are designed to provide reliable power continuously with an estimated lifetime for a natural gas microturbine being 50-80k hours, or 6-9 years continuous operation. Of course, since grid defectors will not operate generators continuously, they should last significantly longer. Currently, there are no home-scale (<20kW) prime power natural gas generators on the market to provide a cost estimate, which is currently an impediment to grid defection. As a result, we use the EIA estimate of $696 per kW of installed capacity for a prime power natural gas generator [13]. Thus, we estimate a 11kW prime power generator would cost $7,656 to install. We view this estimate as conservative, since EIA is a more expensive synchronous generator, which grid defectors would not require.

In addition to its capital cost, the generator also requires natural gas. The average price of natural gas in 2017 was $10.98 per thousand cubic feet, although this price varies throughout the year [14]. Generator efficiency varies based on load, and ranges from 10%-40% efficient, with higher loads being more efficient. Unfortunately, most homes operate at low load levels <1kW most of the time relative to their peak load, resulting in lower efficiencies near 10-20% [15]. This yields an average cost of $0.187-0.374/kWh of delivered electricity. Since this price is slightly above grid power prices, defection to a natural gas generator is not economically feasible. The carbon emissions of natural gas when burned as a fuel are 5.3 kg CO_2 per therm (or 29.3 kWh at 100% efficiency). At 10-20% efficiency, this translates to $0.45 - 0.90$ kg-CO_2/kWh. Thus, grid power is slightly cleaner and cheaper than a standalone natural gas generator due to operating its generators at higher load levels that are more cost- and carbon-efficient.

C. Solar Power and Batteries

Solar power costs also vary widely by region based on the amount of sunlight. The average Levelized Cost of Energy (LCOE) for solar in the U.S. for residential systems is estimated at $0.129-0.167/kWh without any government subsidies [16], although the precise cost is a function of location and size. LCOE represents the net present value of the unit cost of electricity over a solar installation's lifetime, including the hardware cost of the modules and inverters, as well as the labor cost to install the system. Solar's LCOE is steadily declining with the Department of Energy's goal as part of the SunShot initiative to reach $0.03/kWh by 2030 [17]. The LCOE amortizes solar's capital cost based on the energy it will generate over its lifetime, which is typically estimated at 25 years (based on manufacturer warranties). The capital cost of solar is currently estimated at $3.14 per watt installed, which translates to $31,400 for a system with 10kW rated generation capacity [18]. We reduce this by 30% based on the federal tax credit, resulting in a capital cost of $21,980. Of course, the operational cost of solar is effectively zero as it requires no fuel. Solar generation has zero carbon emissions.

Unfortunately, LCOE assumes that all energy is used regardless of when it is generated. Of course, solar generation varies over each day and throughout the year. To fully utilize solar without using the grid requires battery-based energy storage. The Tesla Powerwall 2.0 costs $6500 with installation and a 10-year warranty, is designed for daily charging and draining in conjunction with solar, and has a capacity of 14kWh with a round-trip efficiency of 89% [19]. As above, the Powerwall benefits from the 30% federal tax credit, resulting in a capital cost of $4,550. However, the Powerwall has a power constraint of 5kW continuous power and 7kW peak, which is not large enough to concurrently run high-power appliances, such as an air conditioner, clothes dryer, and electric oven. In addition, solar plus 14kWh battery capacity is not nearly enough capacity to defect from the grid, even for a net zero home. Net zero homes at higher latitudes, as in the United States, generate much more energy during the summer than in the winter. Thus, homes must either install enough batteries to shift summer generation to the winter, e.g., 1MWh or 71 Powerwalls, or over-provision solar to generate enough power over the winter. Either case requires over-provisioning, causing excessive capital costs for solar or batteries.

Summary Table I summarizes our cost and carbon emissions estimates for grid power, local natural gas, solar, and battery. The natural gas estimate is based on the 11kW prime power natural gas generator described above, the solar estimate is based on a 10kW solar installation, and the battery estimate is based on the Tesla PowerWall 2.0 with 14kWh capacity.

III. Grid Defection Architecture

Figure 1 depicts our grid defection architecture, which includes two power sources: a battery charged by a rooftop solar array, and a whole-home natural gas generator. The power sources connect to a smart ATS that is able to programmatically switch the home's power between the sources. While switching the power source from a battery to the generator requires some delay to start-up the natural gas generator, we assume this delay is brief, e.g., 1 minute, such that the battery can provide power over this time to prevent power losses at switch-over points. We assume the battery charges from solar, and not the natural gas generator, as charging the battery from the natural gas generator is inefficient. Functionally, our smart ATS is similar to those for backup standby generators already in use. The primary difference is that it requires a policy to determine when to switch between the two power sources.

The switching policy presents a tradeoff between minimizing the wasted solar power, and minimizing the switches between sources. We consider a few simple policies.

Minimizing Switches. Minimizing switches is important, since it decreases wear and tear on the generator, as frequent generator start-ups and shutdowns can reduce its lifetime and reliability. A switching policy that minimizes switches always waits until the battery is at full capacity before switching to the battery, and then waits to switch again until the battery is fully depleted. The problem with this policy is that it has the potential to waste solar energy. In particular, when the battery is at full capacity, and solar generation exceeds our power consumption, then there is no additional capacity to store surplus solar, and we must shed it. Solar charge controllers shed solar by increasing the applied voltage, which reduces the current and the resulting solar power generated to 0 [20]. As a

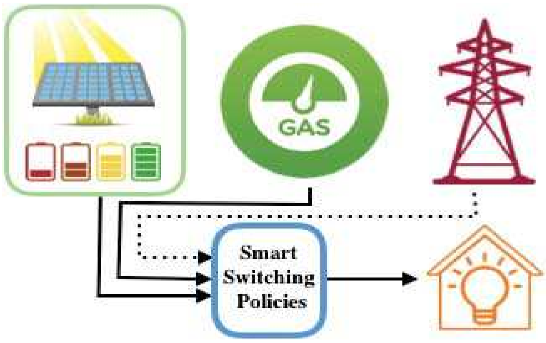

Fig. 1: Grid Defection Architecture

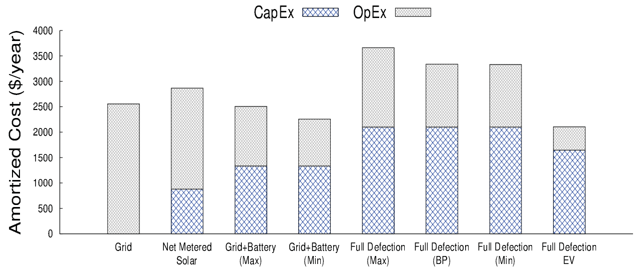

Fig. 2: Operational and amortized capital cost for different scenarios in $/year.

result, waiting until the battery is full to switch increases the likelihood of wasting solar energy, especially in the summer when generation may significantly exceed consumption.

Minimizing Solar Waste. In contrast, we minimize solar waste by *always* switching to the battery whenever it stores any excess solar power. This policy consumes solar energy whenever it is generated, significantly increasing the number of switches as we frequently switch to and from the battery and its state-of-charge remains near empty. In particular, cloudy days may incur numerous switches over the day.

Balanced Policy. We also examine a balanced switching policy that takes advantage of the regularity of solar energy, and switches based, in part, on the net rate of generation/consumption rather than the battery's state-of-charge. In particular, if there is any excess power in the battery once the sun sets, we drain the battery completely before switching to the natural gas generator. In the morning, we switch back to using the battery after the sun rises (assuming we depleted the battery overnight) once the rate of solar generation exceeds our rate of consumption. Our intuition is that the rate of solar generation will increase over the day, even when cloudy, such that once the generation exceeds consumption at the start of the day, it is likely to continue to exceed it until the afternoon.

Our intuition above also exploits typical electricity usage patterns, which experience peaks in the morning and evening (due to to the use of high-power kitchen appliances), and a lull in usage during the middle of the day. Once switching to the battery, we only switch back to the generator once the battery's capacity is depleted. We switch back to the battery again once generation exceeds consumption, which generally does not occur until the next day. Of course, our system must also switch when exceeding the power limit of the power sources. For our battery, unless otherwise specified, we use a 7kW limit based on the Powerwall's specifications, such that we switch to the generator if power exceeds 7kW. Likewise, our generator has a 11kW limit, such that consuming greater than 11kW triggers an outage that deactivates appliances.

IV. Implementation and Evaluation

The cost estimates from §II focus on capital costs. However, the amortized cost per kWh also includes operational costs, which are specific to each home's pattern of power consumption and solar generation. In particular, the more the generation and consumption are aligned, the less there is a need for battery-based energy storage and natural gas generation. Likewise, the less generation and consumption are aligned, the greater the need for battery-based energy storage and natural gas generation. Since natural gas generation incurs an operational cost and carbon emissions, using it increases the overall amortized cost and carbon emissions per kWh.

To examine these effects, we wrote a trace-driven simulator in python. The simulator takes as input a trace of solar generation and power consumption, and emulates homes with different power configurations, including using only grid power, using grid power with net metered solar, and grid defection using solar, a battery, and a natural gas generator. The simulator enables users to configure the battery capacity, peak battery power output, and peak natural gas generator power. In the latter case, the simulator implements each of the switching policies from §III, and tracks the energy each power source generates, the amount of wasted solar energy, and the number of hours each source is used. The simulator also tracks the number of switching events. It associates the operational cost and carbon emissions from Table I with each kWh of energy generated from each source. To compute the overall amortized cost per kWh, we add the operational cost and carbon emissions of natural gas generation with the capital costs from Table I amortized over their lifetime.

We use our simulator to analyze a representative home in the northeast region of the United States in depth, as well as compare with other homes in different regions with different climates. For each home, we use five years of historical generation data at a one-hour time resolution. In most cases, our experiments focus on a single year, since significant year-to-year variations are unlikely. Our default home has a 10kW capacity solar installation, and, in our default configuration, has a 14kWh Tesla Powerwall 2.0 and an 11kW prime power natural gas generator. As we discuss, since these default values are not necessarily optimal, we examine how optimally sizing these values affects cost. The home is near "net zero" in that it generates roughly the same amount of power that it consumes. We refer to the policies in the previous section as Minimizing Switches (Min), Minimizing Solar Waste (Max), and the Balanced Policy (BP). Since minimizing solar waste maximizes solar usage and switching, we label it as Max.

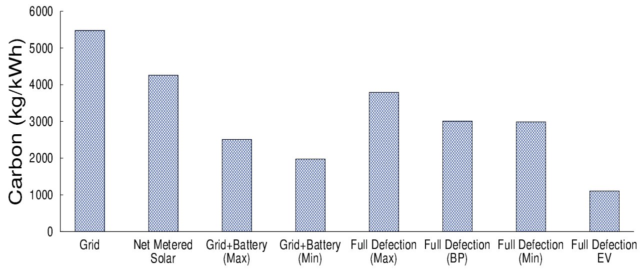

Fig. 3: Carbon emissions from the same scenarios as in Figure 2 for cost.

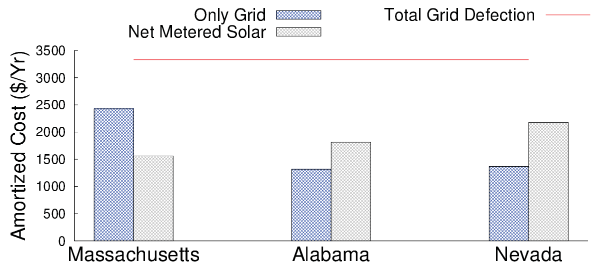

Fig. 4: Price Comparison for Different States

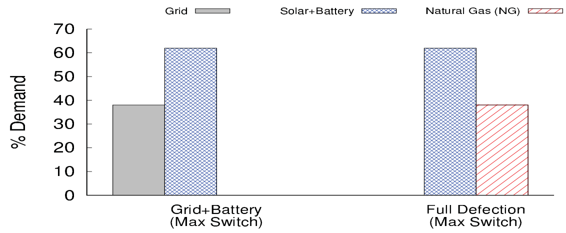

Fig. 5: Percent Demand Met by Different Sources

A. Cost and Carbon Emissions Analysis

Figure 2 shows the results for the *operational and amortized capital cost* (over 25 years) on the y-axis, and the different power scenarios and switching policies on the x-axis. We view these results as conservative, as they assume current costs are static with no technological improvements. As shown, full grid defection using a residential battery, such as a Tesla Powerwall, is more expensive than using grid power, while using grid power with net metering offers the cheapest option. However, as discussed earlier, grid power with net metering is likely to be disincentivized over time. Some states already enforce such disincentives that make net metered solar much more expensive than the current results. Under such scenarios, users may be forced to defect from the grid to use local solar energy. The graph also shows the tradeoff between the different switching policies with the policy that minimizes solar waste (and maximizes switching) resulting in lower costs than the policy that minimizes switching. The balanced policy from Section III has a similar cost as the policy that minimizes solar waste by maximizing switching.

The graph also shows an alternative where users leverage the battery in an EV rather than purchase a separate battery. In this case, we assume a battery capacity of 75kWh equivalent to the capacity of a Tesla Model 3 with extended range. If we exclude the cost of the EV from the system's capital costs, then this scenario already offers lower costs (by 17.6%) than using grid power. Thus, as EVs become more prevalent, the incentive for grid defection increases, especially if solar net metering policies become less attractive. Finally, given that full grid defection is still more costly than using grid power, we analyze an approach that keeps solar disconnected from the grid by switching between the grid and a solar-powered home battery. This approach, labeled grid+battery above, essentially removes the natural gas generator and uses the grid as a backup source of power. We apply the same switching policies from the Section III, and find that this partial defection approach also results in lower costs than using grid power in both cases.

Figure 3 then shows the equivalent graph for average *carbon emissions* over the same period under the same scenarios. As before, the graph shows each scenario on the x-axis and carbon emissions on the y-axis. As shown, even though the natural gas generator incurs slightly more carbon emissions than grid power, our grid defection scenarios use it much less than grid power resulting in a significant decrease (by 45.4%) in carbon emissions. Note that carbon emissions when using net metered solar are only $\sim$20% lower than with grid-only because net metering still requires importing a significant fraction of grid power, especially in the winter. As before, using the grid as a backup power source by partially defecting with a solar-powered battery results in even lower carbon emissions, since the grid's carbon emissions are less than those of the natural gas generator. Finally, using the EV as a backup battery results in the lowest carbon emissions, since the size of the EV battery is much greater than the 14kWh Tesla Powerwall. Note that carbon emissions show a different trend than cost, with the grid having significantly more carbon emissions. Thus, if governments were to price carbon emissions, the financial incentive for grid defection would likely increase.

Figure 4 differentiates the incentive for grid defection in different states based on their solar (dis)incentive policy for that state. Since Alabama and Nevada's policies do not incentivize solar, the cost of net metering solar in Alabama and Nevada is more than in Massachusetts. Interestingly, a higher cost for net metering solar implies a stronger incentive to defect from the grid. That is, the cost of net metered solar in these states is closer to the red line that indicates the cost of grid defection.

B. Solar Waste Analysis

We compared the solar energy waste using the default 14kWh battery capacity for the different policies from Section III, including minimizing switching (Min), minimizing solar waste (Max) and the balanced policy, assuming full grid defection. We found the following amount of solar waste for these three policies: Min (6483 kWh), Balanced (5327 kWh) and Max (5300 kWh). We see that the minimum switching results in the highest solar waste, since it always waits for the battery to be full before discharging. Thus, upon switching to

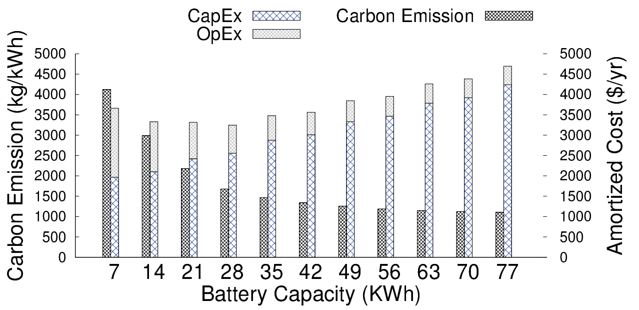

Fig. 6: Amortized cost and carbon emissions as battery capacity increases.

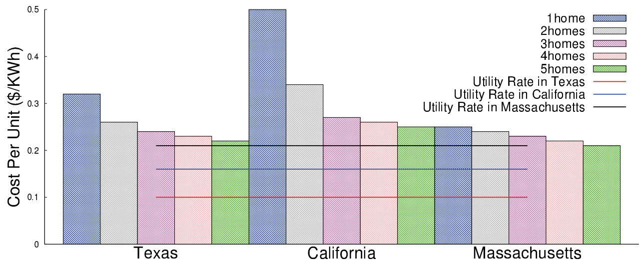

Fig. 7: Cost Per Unit Power for Grid vs. Total Grid Defection with optimal configuration for aggregation of homes in different states of USA

the full battery, if the rate of generation exceeds the rate of consumption, the excess cannot be stored in the battery and will thus be wasted. In contrast, the maximum switching and balanced policies have close to the same solar waste, since these policies focus on maximizing solar usage by always immediately switching to consume solar when it is available. In this case, all the policies waste a significant amount of solar, which demonstrates that a larger battery may be cost-effective.

Figure 5 then shows the percentage of demand met by the grid, battery, and natural gas generator under both partial grid defection (when using the grid as a backup source of power) and full grid defection (when using the natural gas generator as a backup source of power). In both cases, we focus on the maximum switching policy. The graph shows nearly 40% of the demand cannot be met by solar energy even though more than that amount of solar energy is being wasted – due to the asymmetry in solar generation between summer and winter.

C. Impact of Battery Size

Based on the results above, we also examined the impact of battery capacity on solar waste by increasing the capacity from 7kWh to 77kWh, assuming the same amount of solar generation and demand. Figure 6 compares the amortized cost and carbon emissions for these different battery capacities. As we increase the battery size, the carbon emissions decrease due to less use of the natural gas generator to satisfy demand. However, a battery capacity of 28kWh minimizes the amortized cost, where the increase in capital costs from the battery is more than offset by using it to reduce solar waste, which reduces the operating costs. The optimal amortized cost is closer to the grid power costs. In this case, full grid defection incentivizes the use 2 Powerwall batteries.

D. Impact of Aggregating Homes

We also considered the benefits of aggregating homes into small clusters, which are able to share solar energy and natural gas generation. These small clusters are akin to microgrids. To simulate this, we used data from multiple homes in different regions. For a set of homes, we create a cluster by aggregating the demand across the homes and aggregating their solar installations. We found that when considering multiple homes it is also important to consider the size of the solar installation and the capacity of natural gas installation, in addition to the battery size. We thus find the optimal feasible configuration of battery size, solar installation, and natural gas generator capacity to minimize the cost. The solar installation capacity is found by scaling (from $(0, 1]$) the combined available installation for the set of homes considered.

Figure 7 shows the effect of clustering 5 different homes in the states of Texas, Massachusetts and California, that have similar usage and solar generations. We observe that in comparison to a single home, a cluster of homes show a more competitive reduction in cost for full grid defection in comparison to using grid power. This is because we are not scaling the parameters linearly in proportion to the number of homes. For instance, the optimal parameters for a cluster of 5 homes in MA was found to be a 42kWh battery, solar scaling $0.6\times$ combined solar installation of 5 homes, and 33 kWh capacity of natural gas. Thus, these 5 homes are able to multiplex the available energy more effectively than any single home and also benefit from the smoothing of demand and generation due to the aggregation. Hence we can conclude that aggregating even a small number (5) of homes makes grid defection more feasible as compared to a single home. In particular the cost for grid defection for a cluster of 5 homes in MA is more favorable than the utility cost in MA.

Above, we ensured continuous power with no outages. However, if we permit some power outages, we can significantly reduce costs. To see how much, for a cluster of 15 homes, we calculate the amortized cost ($/kWh) for different percent of energy availability in Figure 8. We also show the flat rate utility price for three states, which have different grid costs. This shows that full grid defection could be cheaper than the grid cost if we allow for lower energy availability. We can see from the figure that at 75.75% energy availability, the $/kWh is lower than the utility rate in MA and CA, while at 95.60% energy availability the $/kWh is still lower than the utility rate in MA. The graph also shows that states with higher grid prices, such as MA, are closer to incentivizing grid defection than states, such as TX, with lower grid prices.

V. Related Work

Battery prices are dropping rapidly, which has made it already economical for many commercial customers to reduce their peak consumption levels. Grid defection is beginning to make economic sense both in industrial and residential

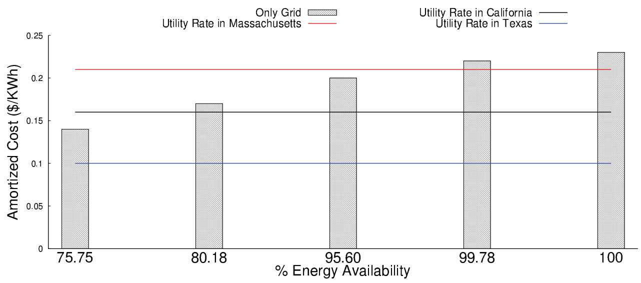

Fig. 8: Amortized Cost vs % Energy Availability for a 15 home cluster

sectors due to these drops in battery costs and studies have predicted that grid defection may become a viable option in only a few years [21]. Recent work [22], [23], similar to ours, compares a grid-tied residential solar system with an off-grid solar-plus-battery system at locations in the United States, and estimates the costs and carbon emissions. However, this work does not consider the use of a natural gas generator. Prior work also examines optimizing energy storage capacity and load scheduling to improve reliability in islanded operation in residential sectors [24], which we leverage in our analysis. Of course, our work does not consider the impact of grid defection on grid power costs. Prior work studies the implications of widespread disconnection from the grid using only solar [25] and examines policies to grid operators develop other sources of revenue rather than increasing energy prices.

VI. Conclusions

The declining cost of solar generation is leading to an increase in grid solar capacity. However, this is also leading to utilities restricting access to connect solar to the grid, and reducing the compensation for it. As a result, in the future, the most viable way to use solar energy may be to defect from the grid. Thus, in this paper, we proposed an approach for total grid deflection for residential homes using a combination of solar with/without battery, natural gas and electric vehicles. We presented different policies for smart switching between these power sources with tradeoffs in terms of number of switches, solar waste, reliability, carbon emissions and total cost. We analyzed these tradeoffs using a trace driven simulator for a single home as well as a cluster of homes. For these scenarios we considered homes from Massachusetts, California and Texas and compared the feasibility of grid versus total grid defection. Our analysis indicates that, based on the net metering policies in different states, complete grid-defection is financially attractive for a cluster of homes – even currently – in some states, and in all cases yields less carbon emissions.
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