# Flattening the Duck:

A smart home algorithm to demonstrate the value in reforming utilities to enable a more efficient, cleaner grid

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Contents

## Abstract

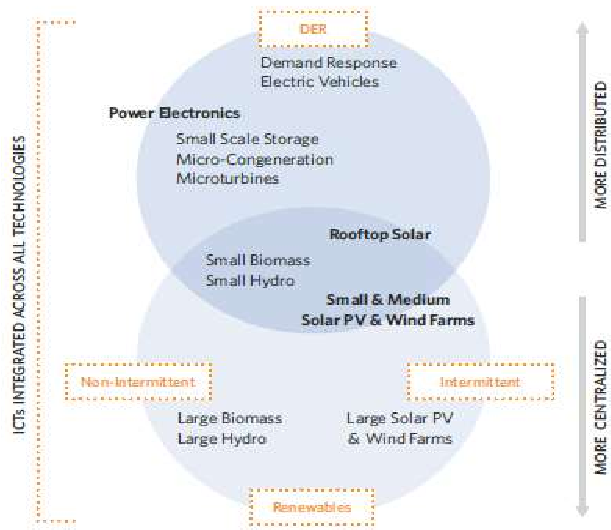
In an effort to address the interdependent nature of electricity utility reform and technology deployment, this paper presents case studies of New York's and California's attempts to integrate distributed energy resources (DER's) into the United States electricity grid. Based on the experiences of those two states, this paper then proposes a series of regulatory reforms based on an analysis of the relevant literature. This analysis concludes that regulatory reform and technology adoption are self-reinforcing, that adopting policy recommendations without the proper technology infrastructure is impossible, and that adopting technology piecemeal, without accompanying regulatory reforms, will hinder the adoption of low-carbon technologies and produce sub-optimal social, environmental, and economic outcomes. The paper then presents an original algorithm for controlling a smart home with multiple DER assets, including solar photovoltaics (PV), home batteries, electric vehicles, and programmable appliances. This demonstrates some of the practical applications that might be encouraged by those regulatory reforms through the development of an algorithm for smart home asset management, and a discussion of how a connected, smart home might interact with the grid of the future. The paper concludes by proposing next steps for study and for technological development.

## Introduction

Over the last 15 to 20 years the grid has become more distributed, digital, flexible, and less carbon-intensive. Coal use has declined significantly in the U.S., renewable technologies have accelerated capacity additions every year, driving costs down as manufacturing methodologies are improved and business models are refined. Last year, solar and wind power accounted for 2/3rds of new capacity additions (Lazard, 2017). This is driven both at the utility scale and by residential solar deployments. In a development that would have shocked energy forecasters a decade ago, solar and wind power have now reached unsubsidized cost competitiveness in many markets, and experts are predicting that by the 2020s solar and wind energy will be by far the cheapest option for additional capacity (Lazard, 2017). Batteries are following a similar cost curve, opening the potential market for home energy storage devices. Advanced metering, smart home and "Internet of Things" devices have opened up enormous potential for consumers to participate in energy markets, adjusting usage to incentives. Other tools are available to utilities to make grid management more efficient. Electric vehicles seem poised to overtake internal combustion engines. But despite these positive trends, deep decarbonization faces structural limiting factors – barriers in the way we regulate energy production and the structures we have devised for electricity markets. Deep decarbonization will therefore require deep re-regulation in order to adapt these structures to new technology.

**Distributed Energy Resource (DER)** is defined as any resource capable of providing electricity services that is located in the distribution system. DERs include small solar or wind generation, demand response, energy storage, and energy control devices. ES include not just electricity but also grid monitoring and ancillary services, such as frequency regulation (MIT, 2016).

**Figure 1.1: Illustrative Taxonomy of Distributed and Renewable Energy Resources**




In order to understand the scope of this challenge, this paper will review the history of utility regulation from the invention of electricity, and cover the deregulatory efforts that stalled around 2002. Broadly, investors in utilities are used to earning a consistent, predictable rate of return above and beyond their expenses. This has incentivized them to build as many capital assets as possible, working with regulators to spread those fixed costs to ratepayers, in the form of fixed charges and volumetric rates (i.e., $/kWh). In exchange for this monopoly, utilities have the obligation to serve every customer, residential, commercial and industrial, in the geographic area of their monopoly. That low-risk, noncompetitive model worked very well in the middle decades of the 20th century, when the goal was to incentivize utilities to build out the grid as fast as possible, and generation was only possible at large, central power plants.

Yet the need to address anthropogenic climate change has thrust a new set of imperatives on society, while at the same time communication technologies have advanced far beyond what anyone writing the Federal Power Act in 1920 could have imagined. As Peter Fox-Penner, a pioneer in Smart Grid development, wrote in 2010: “The future will be filled with a tension between the forces for change propelled by the Smart Grid and energy efficiency policies on one side and the perception that keeping the current structure may be more reassuring to investors, CEOs, and policymakers on the other.” (Fox-Penner, p. 20)

The solution will be reforms that enable DER’s to “plug into” the right parts of the Smart Grid, allowing innovation in low-carbon technologies, providing grid flexibility, and allowing consumers to save money by responding to real time prices, while at the same time preserving the regulation and oversight that ensures reliable electricity for everyone connected to the grid. Electricity markets are consumed by a tension between competition and cooperation, and walking this tightrope of energy transition requires both regulatory reform and enabling technologies. Failure to do so may result in grid defection as wealthier early adopters utilize new technology to reduce their reliance on the grid, leaving poorer consumer footing the fixed costs of the grid. This would undermine the regulatory compact that has ensured reliable access to energy for all.

## Methods

This  paper is broken into four primary sections. First, a discussion of the historical context of power market regulation. For this section, I relied primarily on Peter Fox-Penner’s *Smart Power* (2010) and Travis Kavulla's article in *American Affairs* titled, "There is No Free Market for Electricity: Can There Ever Be? (Kavulla, 2017)."

Second, case study analysis of two states that are at the forefront of the energy transition, New York and California is presented. This section relies on a combination of source documents from regulatory bodies in both states, academic and industry commentary on the proceedings of regulatory policy, and journalism from industry-focused outlets such as *Greentech Media* and *Utility Dive* as well as traditional newspapers such as the *New York Times* and the *Los Angeles Times.*

The third section is focused on recommendations for enabling DER innovation and pulls from these same sources ,since New York and California are taking many beneficial steps towards this aim. It also relies heavily on academic literature, primarily MIT's *Utility of the Future Study*, but also many other contributions from industry such as the Electric Power Research Institute, Electric Light & Power, Accenture, Deloitte, the Smart Electric Power Alliance (SEPA), and others. The ideas in this section are not my own, but are rather a synthesis from the literature available on the topic of power market regulatory reform.

The fourth section focuses on the design for a smart home controller algorithm for optimizing a smart home with multiple DER assets and is my own work. It reviews the existing literature for smart home optimization, and takes as an assumption that a smart home will be interacting with a DER aggregator in a "many to one" auction for scheduling appliances. These auctions may use game theory-derived algorithms to calculate optimal  energy usage, consumer costs, and a grid-wide Peak-to-Average ratio (PAR).

# Historical Context

## The Electricity Industry Has Always Welcomed Regulation

In order to understand how to integrate customer-sited low-carbon technologies in the form of distributed energy resources (DERs), we need to understand the basics of the current system so we can know what needs to be changed. According to Travis Kavulla, a utility regulator serving on Montana's Public Service Commission, "Electricity has never fit the paradigm of business verses regulation" (Kavulla, 2017). Electricity is unique because it is a primary economic input, from which other forms of economic activity are dependent. Its consistent availability and relative affordability makes it a driver of economic activity. These two societal demands for reliability and affordability  have tradeoffs between them. Recently, environmental and social considerations have been added to this list of policy and tradeoff demands. Because of these unique characteristics, few products are regulated in such a "command and control" manner as electricity. Electricity markets have become incredibly byzantine and balkanized.  But, there are a few common characteristics that help illuminate why electricity reform is such a Sisyphean project.

## COSR: Build More, Earn More

For over a century, the paradigm in electricity has been "exclusive franchise for the new monopoly utility [in a bounded geographical area], in return for the regulation of rates and the provision of service by the government." (Kavulla, 2017).  This model is known as Cost of Service Regulation (COSR).

$$RR = r(C) + D + OE + T, \textit{ where}$$

RR = the annual "revenue requirement"
$r$ = the regulator-authorized rate of return
C = "rate base," the total amount of undepreciated capital investment made by the utility
D = depreciation, or the return of the utility's capital investment
OE = operating expenses, such as labor, fuel, etc.
T = taxes, including all income taxes the utility will pay on its share holders' return

(Kavulla, 2017)

In the left side of the above equation, RR, represents is the *revenue requirement*, or the total returns expected from the utility's perspective. This number is then carved into individual slices and boiled down to a per-kWh rate, agreed upon with state-level regulators in public utility commissions (Fox-Penner, p 15). Rates remain fixed until the regulator revisits them every few years, or when the utility determines that it needs more revenue.

The primary thing to take away from this formula is that while capital expenditures earn a regulated rate of return *on top of* their costs, operating expenses do not receive this profit-making bonus. Operating expenses flow into consumer rates, but do not earn the utility any extra return. According to Kavulla and others (Borenstein 2015), Cost of Service Regulation "suggests to the utility that it should spend as much as possible, even when less might do. The barometer for whether an investment is wise for a utility is not capital productivity, but whether expenditures will be disallowed by the regulator. This seldom occurs." (Kavulla, 2017) The estimated expenses and sales volumes are built into the rate-making process but are not reconciled to the utilities' actual revenue. This provides an incentive to earn more than the regulated rate of return by reducing cost, or by providing more electricity. "Utilities often boast that they are 100% regulated...Regulation…is a profitable enterprise." (Kavulla, 2017)

The different treatment of capital and operating expenses is a key to understanding utility reticence to adopt innovative technologies for DER's and smart grid control systems, and it helps to explain exactly how Innovation and the utility's profit motive are frequently misaligned. Innovations often reduce fixed or operating costs, and in doing so reduces the utilities' rate of return. The example Kavulla uses in his article happens to perfectly capture the utility hostility to new technologies which this paper attempts to address: Cloud computing. Cloud computing, or software as a service (SaaS), has been transformative for some enterprises because, as subscription services, they require less investment by the enterprise, and are classified as operating expenses. Compared to the previous capital intensive model of software development, which necessitated purchasing more capital infrastructure, SaaS products are often cheaper and more adaptable than solutions developed in house. Under COSR, however, a custom, in-house solution, which is nearly always more expensive, fragile, and prone to security breaches, earns a rate of return, while SaaS expenditures are only recouped, without a rate of return. This perversion of incentives causes utilities to be allergic to the experimentation that leads to innovation. Further, under COSR, shareholders lose value when a third party provides services that a utility could have provided itself through a capital expenditure that increases its rate base. Utilities are therefore are incented to push for ownership of all smart grid infrastructure, regardless of whether owning these assets is the most cost-effective option. This incentive may not only create cost inefficiencies, but could also lead the utility to foreclose competition in new energy services markets that are enabled by grid modernization (Aas-Boyle, 2017).

COSR delivers on the policy goals of affordable, abundant and reliable supply. It fails on customer choice and environmental considerations. Customers bear the risk for poor decisions by the utilities. Deadweight in the form of poorly allocated capital, is *built-in and guaranteed* by the COSR model.  Therefore, the question when considering the utility of the future then becomes, how can we align utility incentives towards innovation and deep decarbonization, while maintaining the incentives for cheap, abundant, and reliable power?

It is also important to understand some of the physical characteristics of the electricity system in order to grasp the opportunities and challenges we face in this energy transition. First, and perhaps most importantly, unless it is stored, power is generated and consumed instantaneously. In modern grid systems, supply is directly responsive to demand and therefore it has to ramp up and down power production quickly in order to meet demand. There must be enough generation capacity to meet peak demand. Traditionally, there are few windows that a utility has into predicting consumer demand other than modeling the past daily, seasonal, and annual demand curves. In typical power systems, there is a one-way flow of energy from generators to consumers, utilizing direct current (DC) for transmission, and alternating current for distribution systems. The important thing to understand is that at a small percentages of the power mix, solar owners, can reverse the power flow by pushing power into the grid. But many users in a single grid doing this at the same time can force the utility to engage in expensive grid upgrades in order to maintain reliability (Fox-Penner, 2017)

## Early Deregulation to Today's Haphazard Patchwork

Before the 1990's, most electricity customers in the United States were served by regulated, vertically-integrated monopolies delivering power on a one-way grid. These monopolies handled every aspect of the power system: generation, transmission, local distribution, and billing/collections. Even in instances where generators were owned by an entity other than the utility, the utility exerted buyer-side control – monopsony power (Kavulla, 2017).

In the 70's and 80's, failing to anticipate flattening consumer demand, utilities across the country made several over-investments and regulators, for the first time, denied several large and unnecessary projects' costs from being passed on to consumers. The consensus at the time was that it still made sense for monopoly control of the distribution grid (Kavulla, 2017). But people began to ask why it was necessary for both generation and customers, those that plug into the grid, to be monopoly-regulated? (Kavulla, 2017). Thus, Congress empowered the Executive branch via the Federal Energy Regulatory Commission (FERC) to take on the responsibility of managing  the break up of vertical integrated utilities , if states chose to follow a deregulatory path (Fox-Penner, 11).

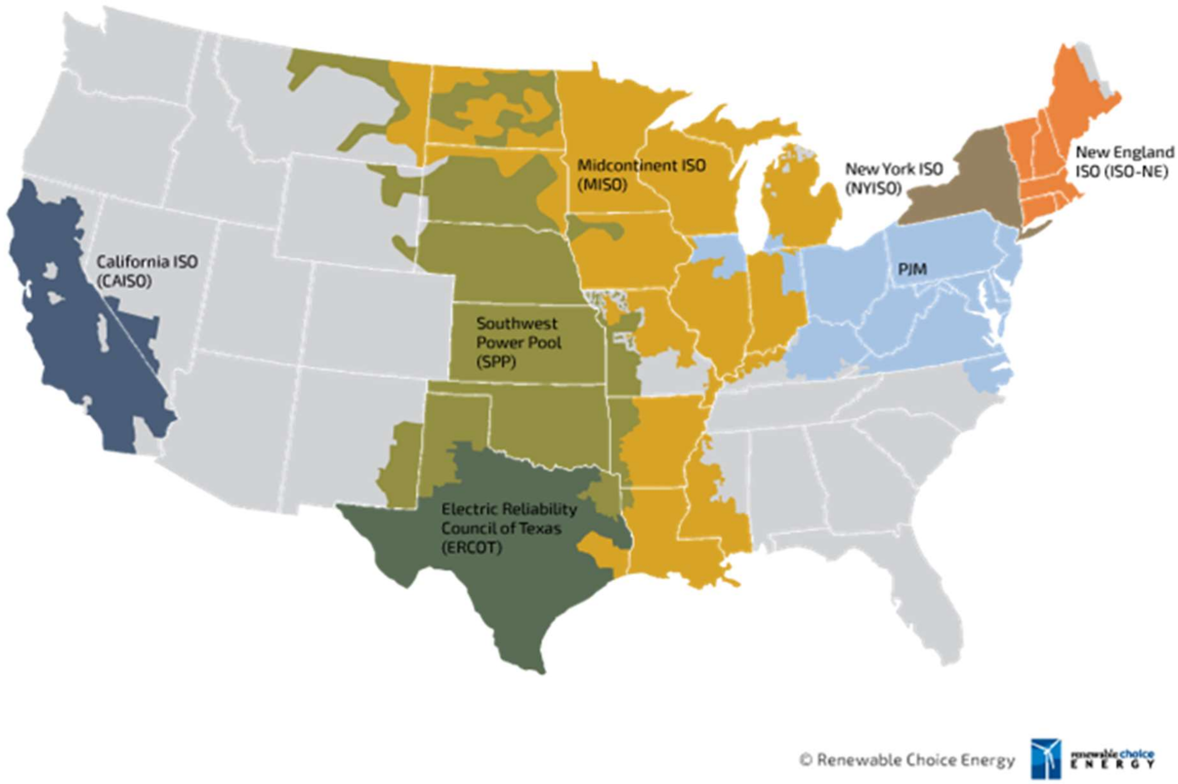
Currently, roughly half the country gets its power from *vertically-integrated monopolies*, mostly in the Southeast, plains states and mountain states (Fox-Penner, p. 19). The other half of the country, this vertical integration is broken. In those states, FERC creates the rules by which generation assets compete in wholesale markets in order to provide power. In these states, utilities are "*poles and wires firms* "across whose physical architecture unfolds a complicated auction process where power plants compete with one another upstream and customers downstream have a choice of retail supplier (Kavulla, 2017)." It is precisely this federalism in energy policy that has led to such a tangled structure for power markets in the U.S.

## Deregulated Market Design

In deregulated markets, traditional utilities retain ownership of the grid but relinquished daily operational control to an Independent System Operator (ISO) (Kavulla, 2017). Utilities responsible for maintaining the distribution system, commonly known as "Poles and Wires" firms, still follow COSR regulation in this model, but just for the maintenance of the physical grid infrastructure.

The ISO can be thought of as a traffic controller and auctioneer for a system with private generators bidding into daily and hourly markets. They also maintain capacity auctions looking several years out, giving generators' investors assurance that there will be demand for a new plant if it is built. The ISO is therefore responsible for ensuring daily and long-term reliability of the grid, managing wholesale bidding processes to allocate adequate supply to meet projected demand.

**Deregulated Markets – Governed by Independent System Operators (ISOs)**



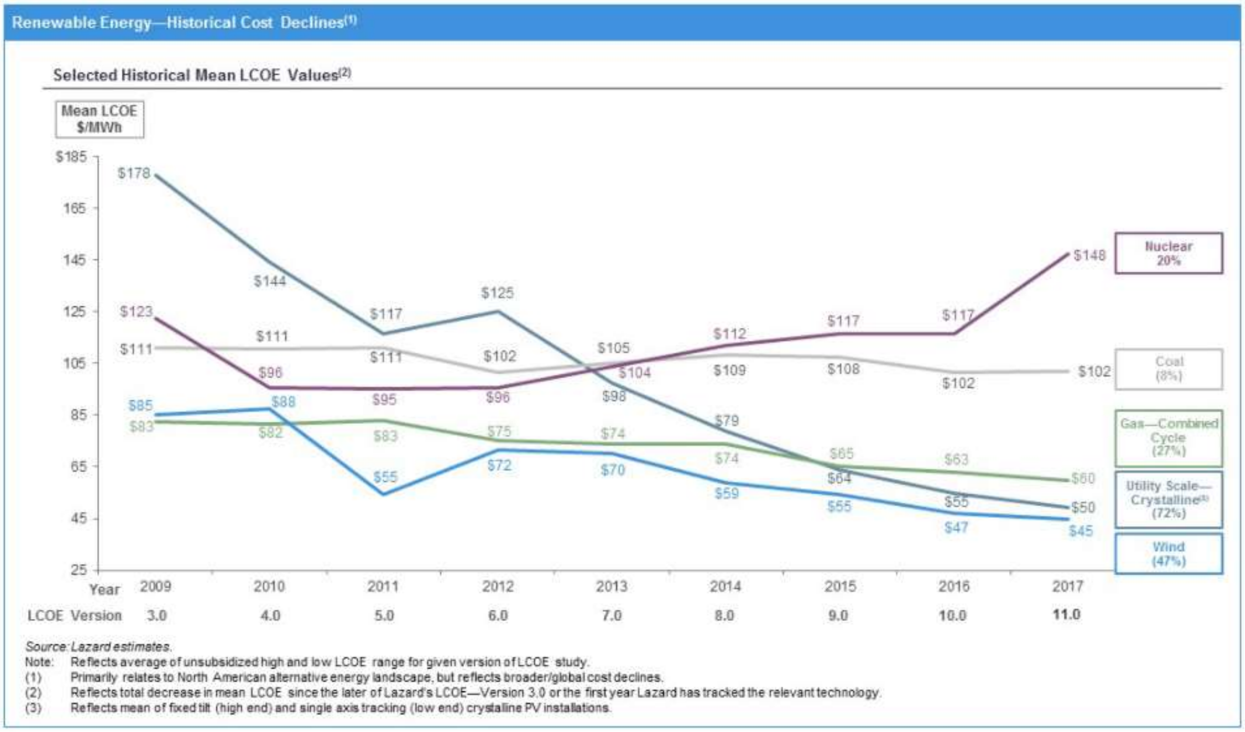

("Regulation", 2016)

ISO wholesale auctions are typically day-ahead. Usually it works like this. Prospective generators submit bids for each time increment of the next day (usually an hour but sometimes more frequently, and the ISO accepts enough bids to meet the next day's projected demand. Another auction is typically run "closer to real-time to further optimize the match of supply and demand (Kavulla, 2017)." Once bids are awarded, the ISO manages real-time operations to match supply and demand, issuing orders to generators to start up, shut down, ramp up or ramp down generation.

The key thing to understand about this auction is that the *highest bid* in the auction sets the market clearing price, which *all generators* are paid. Therefore, the ISO auction's market clearing price usually reflects the operating expenses– primarily fuel– of the highest-cost bidder. This is because rational generators usually submit bids of a bit more than their operating costs, without incorporating the fixed costs of building and financing the power plant. This dynamic rewards the lower-cost bidder by awarding them the same amount as those with higher costs.  Because renewable technologies such as wind and solar do not burn fuel, they have very low marginal operating costs, and therefore nearly always bid near zero, knowing that they will take the higher prices of traditional generators. In the case of rooftop PV systems owned by individuals or companies, which do not bid into wholesale markets, the effect is to reduce the total demand for wholesale electricity. As we will see in the case of California, a significant percentage of mid-day solar generation outside of the wholesale market paradigm can have major impacts on these markets' operations.

## Renewables and DERs: Early Evolution and Policy Support

Renewable energy has traditionally been supported in the United States by four primary policy levers. First, state-level Renewable Portfolio Standards (RPS's) are mandates that utilities must respond to in order to deploy renewable energy up to certain percentage of total power generation by a certain date. States where legislatures have passed RPS's have higher percentages of utility-scale wind and solar energy in their energy mix.  Second, Renewable Energy Credits (REC's) provide an additional reimbursement mechanism for generators of carbon-free energy. Third, Federal Investment and Production Tax Credits, ITC and PTCs, have incentivized investment by providing tax breaks for investors. In the earliest days of renewable deployment, these incentives provided enough tax equity benefits to bring renewable investments close to competitive rates with fossil fuels. Third, many states have implemented Net Energy Metering regimes, which allow customers with on-site solar or wind (mostly solar) power capacity to be reimbursed for pushing this electricity back into the grid. (Shallenberger, 2016).




(Lazard, 2017)

These four policies combined to support the nascent renewables industry when fixed costs were high, supply chains were still being formed, business model experimentation was high, and failure rates for clean energy companies were high.

## Renewables as a Base Cost

Renewables are entering a new phase in their development where, in many places of the country (and the globe), they are the cheapest form of new capacity additions, on a levelized cost of energy (LCOE) basis (Lazard, 2017). [1]

[1] LCOE a metric used to compare the unsubsized full-life unit costs energy produced by different technologies. It is often taken as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime.


(Lazard, 2017)

The International Energy Agency drastically updated International Energy Agency IEA its global renewables forecast, in 2017, and predicted that the world's renewable electricity capacity is set to rise sharply over the next five years, expanding 43% from today's levels. Renewables have accounted for almost two-thirds of net capacity additions in 2016, with almost 165 gigawatts (GW) coming online, the IEA adds. It forecasts that an additional 920GW of renewable capacity will be installed by 2022 (Timperly, 2017). These are global figures, and the global market they represent will continue to drive the costs of hardware down. Further renewable deployments will refine supply chains and deployment business models and, over time, financing will then become cheaper as the industry continues to establish itself. All of these factors will continue to push down both the hard and soft costs of renewables.

We are now entering a world that Michael Leibriech of Bloomberg New Energy Finance (BNEF) called in 2017 "base cost renewables" where solar and wind are the cheapest cost for new generation.

BNEF data predicts that by 2030 renewables will make up the majority of energy investment and 40-50% of capacity (Timperly, 2017).

## DERS: Benefits and Limiting Factors to Growth

However, the transition to renewable energy will require much more than simply plugging in renewables and then taking fossil fuel plants offline. There are limiting factors to growth in renewables that will need to be addressed if renewables are to make up the majority of the generators in the electricity system. While initial renewables support policies provided a stable base for the renewable industry to start, not allof these policies are widely considered beneficial. And the reality is that renewables pose a unique challenge to both grid operation and the functioning of markets, fundamentally changing the physical requirements for operating reliability without new flexible capacity.

At the same time, consumers are able to go around their utility in many states to procure solar, storage, and other DER's. With or without utilities, DER's are proliferating. It is a reality that utilities need to get in front of. If they do not, break down of the regulatory compact and a balkanization of the grid, whereby individuals or communities break off and form their own separate microgrids, is a real possibility. There are many possible ways for the utilities to incorporate DER's in order to get ahead of these issues, but all of them require allowing distributed resources to participate in a fair way.

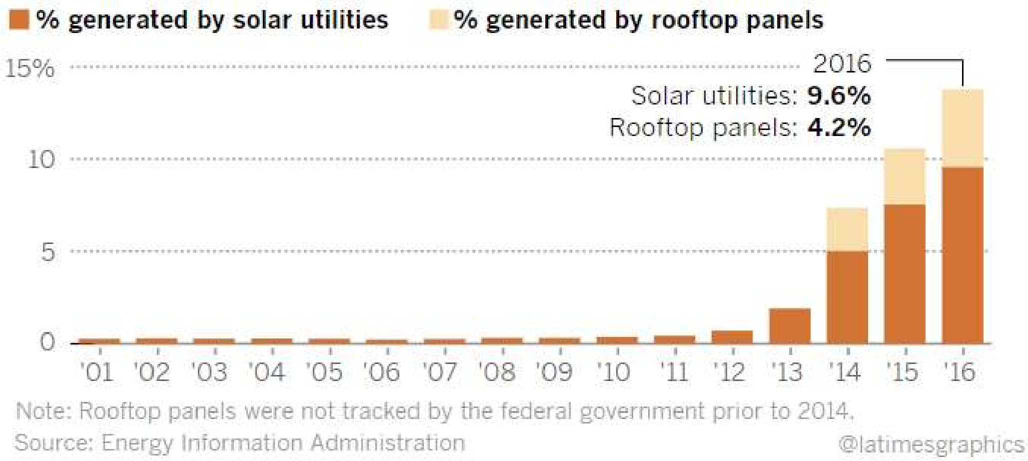
The good news is that, especially in the case of energy, markets are an entirely human construct, and can be remade by humans to meet a new technological reality in a way that meets society's needs. The examples of California and New York are illustrative of the immense challenge in reregulating energy markets and, at the same time, point towards possible solutions.

## Case Study: California

California has long been, for better and worse, the poster child for evolution in electricity markets. Thanks to the fraudulent actions of Enron, it was where the deregulation movement in the 1990's met its end. In the years after the 2000-2001, the resulting electricity crisis in California's restructured market – the movement for electricity deregulation - encountered a significant backlash (Fox-Penner, p. 16), and deregulatory momentum stalled nationwide. Since then, California has focused on consumer choice and environmental policy goals and it has become a leader in the energy transition, attempting to tackle decarbonization through mandates. The state passed aggressive Renewable Portfolio Standards (RPS's) in the early 2000's, dictating that renewables meet 33% of the states electricity needs by 2020, and 50% by 2030 (Penn, 2017). The state has defined renewable and storage as "preferred resources," compelling utilities to prove they are *not* cost competitive before choosing another. In the last few years the state has passed additional mandates in order to create a wholesale market for battery storage, essentially creating the first market for utility-scale batteries in the country. Most recently, in October 2017, Governor Jerry Brown signed a bill requiring utilities to plan carbon-free alternatives to gas generation for meeting peak demand. From the perspective of the renewables industry, and those convinced deploying current technologies are the best approach for carbon mitigation, these policies have been narrowly successful. Today, there is a high percentage of wind and solar on the grid. However, these policies are not without tradeoffs. California is now facing three key issues caused by the high penetration of renewables – the "duck curve," negative wholesale prices, and curtailment.

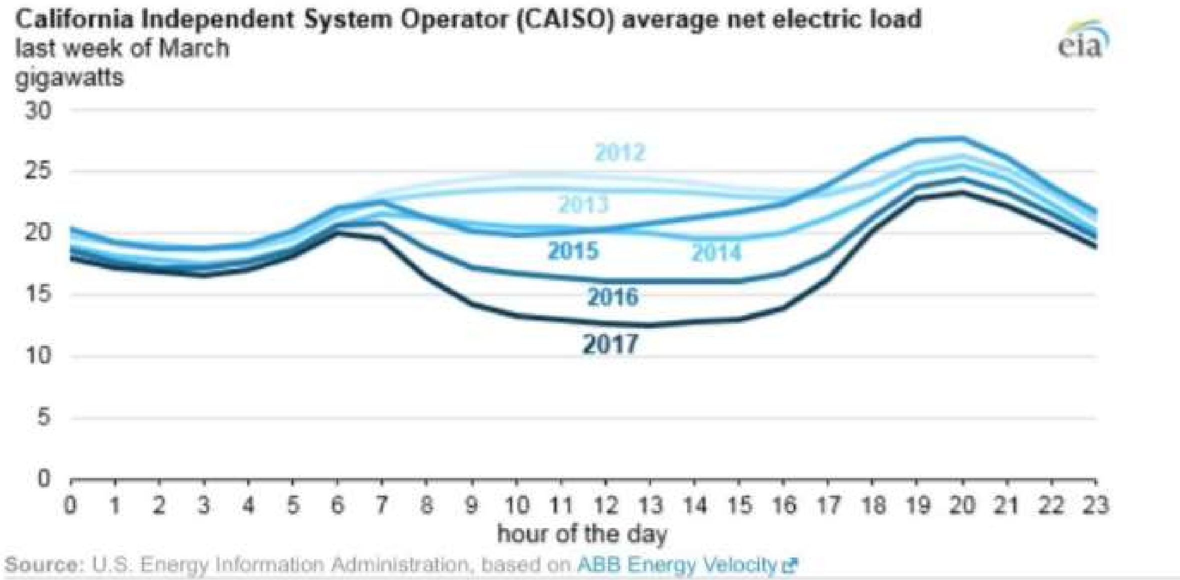
### The "Duck Curve"

In California, there is now so much mid-day solar energy produced outside of the utility's purview, or "behind the meter," that on sunny day this solar accounts for nearly all power demand, and the utilities need to call on very few natural gas, nuclear, and coal plants in the wholesale markets to meet demand.




(Penn, 2017)

However, when the sun starts to go down, the California Independent System Operator (CAISO), must coordinate an extraordinarily fast ramp-up of dispatchable resources in order to meet peak evening demand. The "duck curve," which is a graph of *net* utility generation, is so named due to the deepening "belly" and elongated neck that this high-solar scenario creates when graphed out. The Duck Curve was first predicted to become an issue in 2013 and has grown into a problem even faster than predicted as solar deployment has exceeded expectations.




Values along the duck curve are  measured by a metric known as the “Peak to Average Ratio” (PAR), which is defined as the difference between average net load and peak load. Midday solar brings down the average net load, but does nothing to bring down the peak hours after sunset. This is an inherently physical challenge for grid operators, who are now finding that only *flexible* dispatchable resources are capable of meeting this steep ramp up in needs. That requirement can largely only be met by combined cycle natural gas generators,and is forcing the slow-ramping nuclear technology off the grid. Natural gas now represents 46% of electricity generation in California, and is used largely to meet this evening peak demand (Penn, 2017).

## Negative Wholesale Prices and Renewable Policies

Thus far, federal and state incentives have successfully incentivized renewables deployment and created exponential growth in the technologies, but have led to unintended consequences in power markets. Namely, a result of the high deployment of solar in California is more frequent instances of extremely low wholesale prices, when there is so much solar generation that only the generation with the very lowest marginal operating costs are awarded bids in a sunny mid-day hour. On the one hand, lower wholesale prices are an unalloyed  good, as they should be passed on to consumers. However, as discussed above, variable and intermittent renewables do not have the capability to meet consumer demand at all hours of the day. Dispatchable generation must therefore be available to meet demand in these times. This has led to an overbuilding of both renewable and natural gas capacity, with many of the costs passed on to consumers. Therefore, lower wholesale rates have not led to lower bills for the average Californian. But extremely low wholesale prices may push too many of these generators out of the market, thereby risking the reliability of the entire system.

To be sure, policies supporting renewables have played a part in this problem. Because the PTC is based on production, and REC's are likewise only created with generation, renewable plants can have a *negative* marginal cost equal to the inverse of the value of the PTC plus REC's. Therefore, utility-scale solar plants are willing to *pay* consumers to take their energy output in order to ensure they capture the value of the PTC/REC's (Kavulla, 2017).

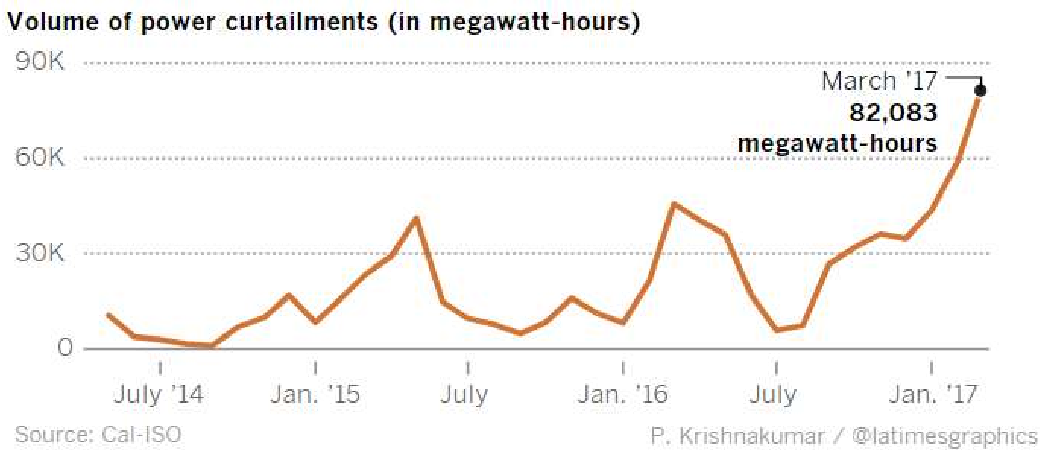
At small levels of renewable penetration in the market, this is not an issue, because the wholesale market-clearing price is set by the highest bid. So, in an hypothetical example, a wind farm may bid a negative price into the auction, but the clearing price will be determined by the more expensive nuclear or coal plant that provides the last bit of capacity the ISO determines will be needed. The renewable plant's negative price is irrelevant, as all bidders are renumerated the highest bid price. However, as the market share of renewables increases, there are times when non-dispatchable power (renewables but also the tough-to-ramp-up nuclear), generate more than consumers demand. When this happens, electricity prices go negative as every other generator is pushed out of the market.

The negative pricing threatens market revenues for traditional generators, sparking concern from some that the flexible gas plants that are needed to balance out wind and solar production may have to shut down, as the La Paloma plant did last year. Combined with the desire to maximize renewable energy output lost output of renewable energy to curtailment, the concerns have policymakers discussing ambitious market fixes to keep power prices positive and dispatchable merchant generators profitable. (Trabish, 2017).

## Curtailment

The result of these market realities is that California is now in the position of needing to balance the competing priorities of decarbonization and running the grid reliably. The unfortunate result is that California's ISO (CAISO) frequently chooses to maintain dispatchable natural gas generation to meet demand, while wasting or "curtailing" available renewable power. Since electricity storage is still limited, and too much unused electricity could hurt the grid, CAISO must either buy less electricity from wind and solar farms, letting unused capacity go to waste, or actually pay certain wholesale consumers to use more energy. CAISO predicts that if the build-out of solar continues at this pace, by 2024, California will have an overabundance of energy midday nearly every day, forcing exports to other states or curtailment.

This is not an abstract concern to be dealt with in the future, but rather a very real wasteful feature of the system today. CAISO curtailed 82,083 megawatts of energy in March 2017, nearly all of it wind and solar power. As the figure below shows, this is a rapidly accelerating trend, and is tightly coupled with increased solar deployment.




(Penn, 2017)

## Flexibility Is Now a Key Attribute

Due to these issues, CAISO has identified flexibility as an important attribute future electricity systems with high percentages of renewables . In 2016, CAISO defined reliability as the following:

- Sustain upward or downward ramp;
- Respond for a defined period of time;
- Change ramp directions quickly;
- Store energy or modify use;
- React quickly and meet expected operating levels;
- Start with short notice from a zero or low-electricity operating level;
- Start and stop multiple times per day; and
- Accurately forecast operating capability (CAISO, 2016)

The key takeaways from this list is that while there is flexibility required on the *generation* side of the energy equation, the electricity grids of the future will also require more storage and flexibility on the *demand* side. This will serve to shift both generation and load profiles. The way to measure flexibility, then, in part, is by measuring the extent to which a resource contributes to flattening the peak-to-average (PAR) ratio in demand curves,

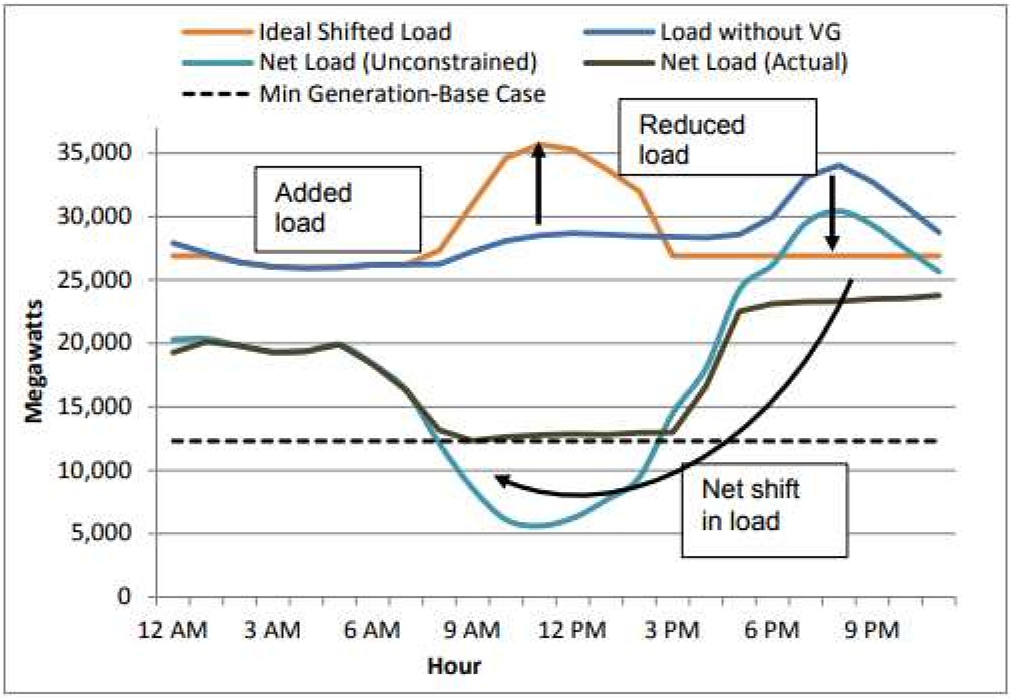



**Figure 20. Accommodation of increased penetration of PV by flattening the duck (increasing mid-day demand)**

The question for regulators looking to variable renewables decarbonization efforts is therefore: how to induce flexibility at every stage of grid management, from planning, design, to deployment and operation. Latest planning by CAISO attempts to bring DER owners into this herculean effort. CAISO plans to induce this flexibility in DER's, and is the planning process of considering how to do so also.

## Conclusion

Utilities are now facing numerous threats to the traditional paradigm. The addition of variable renewable energy (VRE), storage technologies, and other distributed energy resources (DER's)[2] provides avenues for customers to sidestep their utilities in procuring electricity. This distributed, variable, and intermittent two-way flow of electrons also introduces additional complexity into this system (CAISO,

[2] Defined as energy assets sited within distribution systems, e.g. residential solar, microgrids, EV's, (spell out) heat pumps, batteries, or other storage technologies.

2014). These developments are grafted onto an already fragmented patchwork of utility business models, regulatory regimes, communication and control systems, and rate structures, all of which restrict the sector's freedom to adapt and innovate. Anything that reduces consumer demand, such as energy efficiency programs, commercial renewable procurement, or residential solar, is considered a threat to utility revenue streams. This is true even in "deregulated" markets with competition at the generation or retail levels, and this is why utilities have resisted demand-suppressing innovations. Clearly, in this instance, society and utility goals are misaligned. This paper will briefly explore in some detail the reasons why these new technologies are a poor fit for the traditional linear, command-and-control business model that power systems have operated under for over 100 years.

Somewhat ironically, environmentalists find themselves arguing for the expansion of free, unfettered markets, while defenders of fossil fuels are arguing for more strict command-and-control mechanisms in order to ensure the profitability of coal, natural gas, and nuclear plants.

From this inflection point, there are many possible futures for the electricity system. There is no agreed-upon solution or way forward for how to accommodate DER's or VRE growth without breaking the utility business model, and thus breaking the regulatory compact.

In summary, we need to design a flexible, demand-driven system that allows nodes in the network to be sometimes producers and sometimes consumers of electricity services. We need a system exhibits properties of both competition *and* cooperation. Competition will drive the innovation we need to break through current limitations in decarbonization technologies, thereby finding efficient means of delivering electricity services that customers need while dealing with the climate change threat. Cooperation is vital for the system to function with high reliability and connectivity, ensuring we phase out carbon-intensive generation, while still meeting the progressive goal of energy access for all. How will we build markets maximize our utilization of the cheapest, cleanest power available? How do we make sure the assets we need to ensure reliability are paid for? How will we build the flexibility needed into our power systems in order to adapt to future innovations that have not yet reached their commercialization stage? And how will we do all this without imposing undue burdens on ratepayers?

## Case Study: New York

### NY REV – Too Soon to Tell

In 2014, New York governor Andrew Cuomo, seeing the potential opportunities and threats that DER's pose to electricity business as usual, and looking to build resiliency into the state's electricity system after Hurricane Sandy, began to form a policy called as Reforming the Energy Vision (REV). NY REV attempts a wholesale transformation of policy, after seeing the challenges California and others with high percentage of renewable generation have faced.  In constrast to California's tendency to advance its clean energy transition through technology mandates, NY REV plans to encourage deployment of DER's to socially optimum levels and location of deployment by establishing market rules and rate structures that will foster utility participation in innovation.

NY REV operates from the understanding that DER's are a novel feature of the electricity landscape that was not anticipated when utility regulation was first codified in the early 20$^{th}$ century. DER's can be a threat to utility business models if the regulations governing those utilities are not updated. With the right reforms, however, DER's can instead enable a new type of utility, one that serves as a platform for many nodes on the network serving as both producers and consumers of electricity. As set forth in Track 1 of the REV proceeding, the state's overarching goal is to "transition from the historic model of a unidirectional electric system serving inelastic demand, to a dynamic model of a grid that encompasses both sides of the utility meter and relies increasingly on distributed resources and dynamic load management (Auck ,2017)."

From this platform, NY REV anticipates many potential future business models, and does four important things in attempting to foster those models.  First, REV creates a Distribution Service Provider (DSP) to manage and aggregate DER activity. Second, it seeks to move beyond net energy metering (NEM) (define) as a policy mechanism for compensating DER's, and seeks to update rate design to something more closely resembling "real time" prices. Finally, REV compels utilities to consider implementing DER's, including those provided by third parties, in lieu of traditional upgrades when deciding on new large-scale infrastructure projects.

## Envisioning the Utility as a Platform

NY REV is attempting to move away from the classic COSR utility business models suitable for centralized power systems, and toward providing  a new funding mechanism for utilities by which they can serve as Distributed System Platform (DSP). Under the order, utilities will be responsible, and compensated, for setting up markets by which many DER operators, such as solar, geothermal, wind, fuel cells, combined heat and power, battery storage, energy efficiency, and other advanced energy services such as demand response (DR), can participate in procuring *and* supplying energy services. The idea is that by providing this platform, utilities can foster innovation in DER's, energy efficiency, and flexible capacity tools by giving all players an equal playing field on which to transact, and by determining the value of DER's through this platform, ("New York Adopts," 2016).

## Net Energy Metering is a Blunt Instrument

As explained  above, traditionally DER's such as solar have been compensated for adding electricity to the grid through a policy known as Net Energy Metering (NEM), by which a tariff is set by the utility for any excess energy pushed on the grid from, for example , a residential solar PV system. NY REV attempts to move away from this model and towards a more accurate method for assessing the true value of a DER.

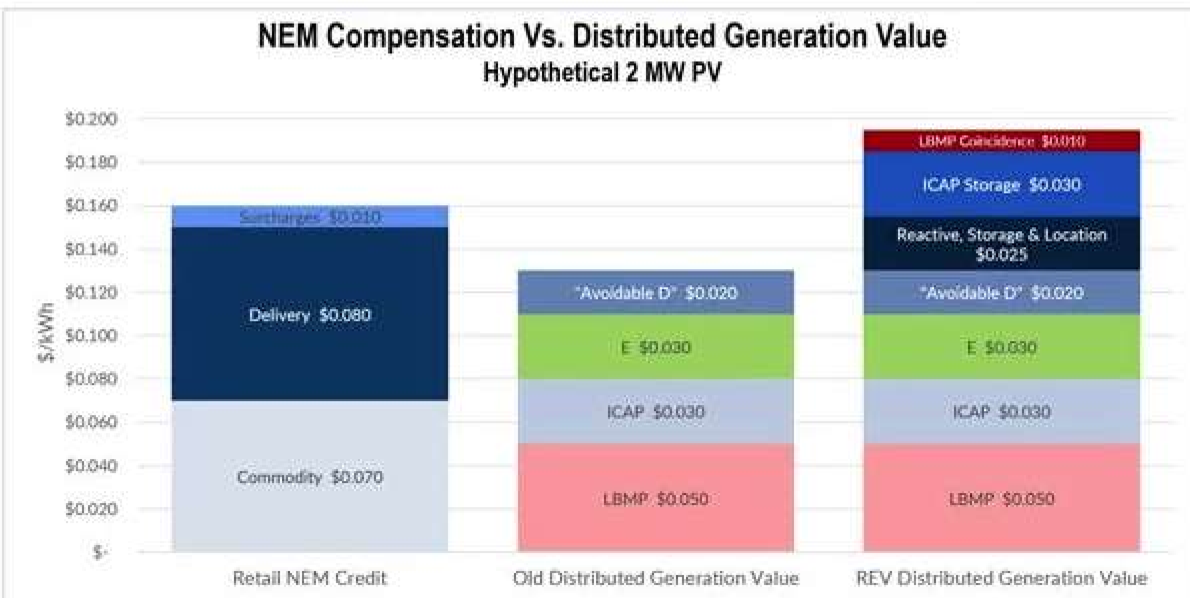
NEM in particular has become a political lightning rod in many states, and for good economic reasons. While initially, the policy provided compensation for solar owners' electricity supplied to the grid, as its adoption has grown the market distortions that this creates have become more problematic. Therefore, NEM is now understood as a "blunt instrument" for incentivizing DER deployment (Kuser, 2017). In 2017, the New York Public Service Commission summarized the issue, calling NEM "inaccurate mechanisms of the past that operate as blunt instruments to obscure value and are incapable of taking into account locational, environmental, and temporal values of projects." Because all NEM customers are reimbursed the same amount, above and beyond wholesale prices generally, a few customers are able to reduce their overall liability to the utility, and therefore reduce their contribution to paying for the utilities' fixed costs of operating and maintaining the grid. The Commission continued: "By failing to accurately reflect the values provided by and to the DER they compensate, these mechanisms will neither encourage the high level of DER development necessary for developing a clean, distributed grid nor will they incentivize the location, design, and operation of DER in a way that maximizes overall value to all utility customers (Kuser, 2017)."

A recent study by Energy+Environmental Economics ("E3") analyzed NEM in New York State's investor-owned utilities, and found that with current NEM compensation schedule DER's had higher costs than benefits. Many see this as a simple fairness issue and there is a regressive nature to any policy that compensates wealthier early adopters of a technology while pushing those adopters' costs to other customers. This is such a major issue that approximately two dozen states have begun to examine ways to modify their NEM policies resources to address this issue (Tierney).

Therefore, NEM policies do nothing to target DER's to places on the grid where they can avoid or defer distribution-related capital costs. A more precise method for valuing DER's can shift the benefit-cost ratio to positive. A better solution involves doing the work to identify, with greater granularity, the locational and temporal value that DER's are providing the grid. This is an extremely difficult task, and in addition to lawmakers and regulators, there are academics (MIT Utility of the Future, 2016) and industry (Tierney, 2016; Rodgers, 2016) attempting to resolve this question.

## Finding the True Value of DER's

NY REV's first attempt to develop an alternative to NEM through, what is calls, the "Value of DER" (VDER). The first attempts to determine the exact value of DER's came out in May and September, 2017, to mixed reactions from industry and academic observers.




| *New York Public Service Commission Staff Report on Value of DER Proceeding, Oct. 2016*

One thing VDER attempts to do is assess the entire "value stack" of DER's, by compensating DER owners, not just for electricity provided to the grid, but by putting a value on other ancillary grid services that a battery, smart inverter, or other device might provide to the grid. This value stack includes:

- Energy value, based on the day-ahead hourly zonal LMP's, including losses. According to MIT's Utility of the Future study (2016), "Mathematical and computational techniques exist such that the price of electricity can be computed at any given time and location within the network. These prices are defined according to the wellestablished theory of spot pricing, which, conceptually, can be extended to every corner of the electric grid through locational marginal prices.  To our knowledge, nodal prices are presently not used at the distribution level in any power system;

- Capacity value, based on retail capacity rates for intermittent technologies and the capacity tag approach for dispatchable technologies based on performance during the peak hour in the previous year;
- Environmental value, based on the higher of the latest Clean Energy Standard Tier 1 renewable energy certificate procurement price or the federal government's social cost of carbon; and
- Demand reduction value and locational system relief value, based largely on utility marginal cost of service studies and performance during 10 peak hours (St. John, 2016).
- Ancillary grid reliability services, including (Garcia, 2017):
    - Frequency regulation
    - Ramping and Balancing
    - Voltage support

## Conclusion

Clearly, in a system as complex and critical as the electricity grid, with such high social value placed on reliability, change will only come incrementally. The dynamic of tentative progress seen in New York and California is likely inevitable, and the most likely scenario for policy development involves a lot of muddling through. While this process works itself out, it can be helpful to take a step back and assess whether we are designing a system for the future from first principles. A suggestion for those principles is laid out below.

Broadly, does the electricity system of the future encourage innovation in low-carbon grid technologies (competition) while still supporting enough dispatchable power to reliably meet the regulatory compact (cooperation)? Specifically, does the system:

- Optimize the development of distributed energy resources (DER's) locally, and across the system as a whole? In other words, does the system capture as much primary solar energy as possible?
- Account for the social cost of carbon emissions?
- Incentivize utilities away from over-building fossil fuel and other expensive infrastructure to deliver one-way bulk power, and towards consumer-centric, efficient, low-carbon electricity services?
- Value dispatchable and variable generation appropriately, and provide a mechanism to allow that prices to respond to real world dynamics over time and location?
- Utilize modern technology to build flexibility to meet reliability goals?
- Allow consumers to adjust their electricity use in response to times of peak demand, rather than requiring turning on expensive, centralized power plants?
- Allow consumers to exercise their choice of energy sources, based on cost and/or energy source?
- Allow price discovery mechanisms in markets to value new technologies that have not been invented yet, and provide a tech-neutral way to integrate innovations?
- Line up utility and consumer incentives for innovations in deep energy efficiency?

## Recommendations

When assessing the system goals outlined in the section above, it is clear that New York and California, along with the thousands of people in academia, government, and industry contributing to the energy transition, are on the right track. There is no straight line from our current system to the optimal future, so some amount of muddling through is necessary in this type of systemic change. For example, there will certainly be a period of time where grids have an overbuilt capacity in both renewables and fast-ramping dispatchable resources. This next section attempts to distill the experience of New York and California thus far into recommendations that will build enough flexibility into the grid of the future, so that we can minimize the types of inefficient allocation of resources that is now endemic to energy transition.

## The Independent Distribution System Operator (IDSO): **Traffic Cop and Auctioneer for the Distribution System**

The first and most important reform is to create an **independent Distribution System Operator**, to serve an important market-making function, serving as middleman between dispatchable generation and consumers, with or without DERs, communicating price information and tightly matching supply and demand.  This is not an entirely new idea. Back in 2010's in *Smart Power* Peter Fox-Penner described an entity he termed the "Smart Integrator," and it was described  as, "a utility that operates the power grid and its information and control systems but does not actually own or sell the power delivered by the grid. Its mission will be to deliver electricity with reliability from a wide variety of sources, from upstream plants to in home solar cells, all at prices set by regulator-approved market mechanisms. It must keep all generation plugged in to its system in balance with demand and its customers fully empowered to shift their use in response to price signals (Fox-Penner, 175)."

This is essentially an IDSO, (spell out) and is similar in function to the DSP's that NY REV is compelling utilities to create. However, the early experience of NY REV suggests that utilities are still disincentivized from making the most of this transition. This paper argues that utilities should *want* to avoid this responsibility. According the Fox-Penner, "The first financial advantage for utilities would be shedding a major cost center. The second technical advantage would be less concern about managing a complex network of distributed generation and intelligent energy efficiency assets. Those two benefits would create a third opportunity for all: more competition and a fairer set of rules."

This is the crux of the issue in New York. Rather than relying on a utility to figure out the value of distributed resources, as NY REV is currently attempting to do, the IDSO and the local regulatory commission would be responsible for establishing incentive structures that accurately reflect their contribution to the network. And since the goal of the IDSO would be to create a market of independent distributed resources, their value would likely be accurately determined through pricing mechanisms, and truly valuable innovative products would see their value increase as time goes on.

Under an IDSO regime, the physical infrastructure of transmission and distribution ("poles and wires") whould stay in the hands of a regulated utility, as this is a natural monopoly, and will hold an important role in developing a platform to match supply from competing generators with consumer demand.

## Accurately Valuing DERs

The question of how to accurately value DER's comes down to two words: it depends. There are many factors that are relevant to determining the locational and temporal value of DER's, so it is difficult to generalize given the complexity of parameters involved (Rodgers, 2016).

There are numerous cost-benefits methodologies that have been developed, by regulators, academia, and industry. All of them find that the value of DER's is based not only on the value of the electricity services provided, and the important value of avoided costs in terms of infrastructure investment that the DER allows to be deferred, but *where and when* those services are called upon, and the cost of those investments that are deferred. According to MIT's *Future of the Utility Study*, "Well-designed prices and charges can incentivize investments in and operation of DER's in ways that yield lower costs for customers and the system as a whole. Ill-designed prices and charges can incentivize outcomes that yield lower costs for some customers, but may not necessarily yield lower costs system-wide ("MIT Future", 2016).

There are some groups that argue that regulatory cost-benefit analyses are bound to be inaccurate, instead advocating for "market-based mechanisms (e.g., competitive procurements) to set prices and performance obligations for DER's selected to provide services to the electric system (Tierney, 2016)." Others, such as the MIT *Utility of the Future Study*, argue that utilities should have enough information to accurately value DER's, using a concept known as "Locational Marginal Pricing,"which accounts for both the temporal and spatial components of pricing electricity services ("MIT Future," 2016).

An exact valuation of DER's is therefore, not only outside the scope of this paper, but may not even be possible in any kind of top-down, regulatory analysis. This reality should inform market and regulatory design in the future.

## DER Aggregation – from Demand Response to Flexible Capacity

More well understood is the power of DER aggregation to deliver real benefits in terms of providing grid flexibility, flattening the duck curve by reducing PAR (spell out), and allowing responses from individual DER's which are inconsequential alone to be orchestrated into behavior which can greatly improve grid operations. Primarily, aggregated DER's can be coordinated, using Advanced Metering Infrastructure and modern cloud computing technologies, into delivering the kind of flexible demand that the high-renewables grid of the future requires. Demand Response (DR) exists today, though largely for commercial and industrial customers. There are very few DR programs are in use for residential customers (Boynuegri, 2013). Yet residential customers represent 40% of the market for electricity (MIT Futures 2016), so there is a huge untapped market of demand just waiting to be made flexible.

Essentially, an aggregator allows the energy system to build cooperative models for interactions between many DERs and the IDSO. This aggregator could be the IDSO itself, or it could be another third party. Regardless, there are massive scaling issues in coordinating DER's into a demand response event. Solving these scaling issues is the role of an aggregator. Therefore, this proposal sits directly at the intersection of policy and innovation.

There is a lot of work going on in the electrical and computer engineering domains towards solving these scalability issues and optimizing models of aggregator-DER interaction. Already algorithms based on game theory models of interactions have been proven in small prototypes to optimize these potential interactions between aggregator and DER-enabled smart homes or DER nodes Reka et al., 2016).

In essence, one can think of flexible demand management as a “game” in which participants try to optimize the scheduling of appliances. This is obviously a game that no one is likely interested in playing. And since, from the aggregator’s perspective, this game needs to be played with many homes as players, this “game” can and should be handled by automation, with human users perhaps providing price thresholds or other constraints to guide the automated players of the game. Each player, or automated smart home, in the game is acting independently of the others, and seeks to optimize the home’s comfort with saving money.

The aggregator, on the other hand, is seeking to reduce the Peak-to-Average (PAR) ratio of total grid demand for the day. The aggregator uses hourly or real time pricing to nudge the network of smart homes into utilizing its DER assets and its shiftable load in such a way that it uses more power when renewables are plentiful and therefore when wholesale prices are cheap, and uses less power during peak times when (…) . Together, these automated systems would be hell-bent on flattening the duck curve.

## Dynamic Pricing: Time-variable, Location-based, Cost-reflective

This type of residential demand response, utilizing smart home-controlled DERs interacting with an aggregator, is simply not possible without prices that reflect the real time cost of generating that electricity. The regulatory mechanism to enable all this intelligence should therefore be “dynamic pricing,” in which electricity prices can vary hourly (or even more frequently) to more closely track the real-time marginal cost of power generation and distribution. With dynamic pricing, smart meters, inverters or controllers can read and adjust their behavior to prices that reflect present conditions on the grid (“Electric Vehicles as DERs” 2016).

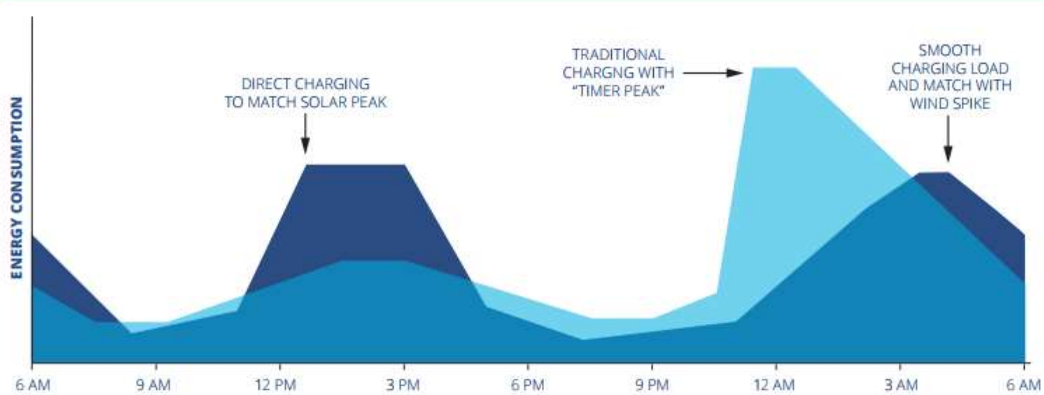
Remember, a key assumption of electricity systems with a high penetrations of renewables is that during boon times of renewable generation, operating costs of generation and thus wholesale prices are low. Prices are high when dispatchable generation is called upon to meet peak load. Therefore giving consumers transparent exposure into these prices, will allow them to optimize their use of solar, batteries, electric vehicles, and smart appliances at the times of day with lower prices.

| TABLE 8: TYPES OF DYNAMIC PRICING | |
|---|---|
| **TIME-OF-USE (TOU) PRICING** | TOU programs set prices for specific periods of time. Electricity prices for energy consumed during these periods are known to the consumer, allowing them to adjust their usage. |
| **REAL-TIME PRICING (RTP)** | RTP programs reflect the real-time cost of electricity. These rates most often change on an hourly basis, though in some cases they can change more frequently. |
| **VARIABLE PEAK PRICING (VPP)** | VPP programs are a hybrid between TOU and RTP; specific periods of electricity price fluctuations are defined in advance, but the price established during a peak period varies by utility and market conditions. |
| **CRITICAL PEAK PRICING (CPP)** | CPP programs raise the price of electricity during periods of anticipated high wholesale market prices or excessive demand. This rate can either be predetermined, or designed to vary based on the need to reduce load on the grid. |
| **CRITICAL PEAK REBATES (CPR)/ PEAK TIME REBATES (PTR)** | CPR/PTR programs anticipate high wholesale market prices or excessive demand, and price critical period consumption at a set rate. Customers receive refunds or credits for any reduction in energy consumption relative to expected consumption. This gives customers the benefit of saving through conserving without the risk of increased peak prices. |

This change in the grid will become even more important if electric vehicles (EV’s) proliferate as expected. This coming wave of potential demand could be a massive boon to utilities, or could exacerbate the same issues discussed above. It all depends on how vehicle batteries are charged and discharged, and when. EVs pull a lot of power; a typical home EV charging station will have a larger peak load than the home itself (Kann, 2017). Without proper dynamic rate structures, electric vehicle commuters will have no qualms about charging their vehicle right when they return home from work. This will exacerbate many of the issues already facing the grid by increasing system peak demand. This would require costly new infrastructure and potentially increase carbon emissions in the form of new peak fossil fuel capacity. However, with intelligent dynamic electricity rates, customers can be incentivized to charge their vehicles and home batteries when power is at the margins is cheap and abundant -- in the middle of the day in solar-heavy markets or at night in the markets served by lots of wind. By enabling EVs and batteries to communicate and respond to price signals, the system could alleviate over-generation and curtailment as renewables grow in popularity, and to mitigate the ramp up requirement to meet the evening peak. Evidence suggests that dynamic rate structures are effective for this purpose (MIT Utility of the Future, 2016).

In fact, a successful multi-year pilot in California of EV’s as a flexible grid resource recently demonstrated that not only did customers respond effectively to price signals by charging their vehicles during off-peak and super off-peak hours, but they did so increasingly over time. The program was designed to run without much direction from customers, and returned a 98% satisfaction rate, while 93% said they would be likely to participate again.

FIGURE 18: OPPORTUNITIES FOR ELECTRIC VEHICLE MANAGED CHARGING




Note: The light blue area illustrates the impacts of a hypothetical TOU residential charging rate with the lowest rate period beginning at 11 pm. The dark blue area shows how managed charging loads with peaks in renewable energy generation.

Source: BMW of North America 2016 with edits by Smart Electric Power Alliance, 2017[31]

(“2017 Utility Demand)

The pilot program incentives included $1,000 for signing up and up to $540 for ongoing participation, but it is interesting that PG&E's report said "participants indicated that helping to manage load on the electrical grid and promoting the reuse of BMW Group 2nd life batteries as more important than the ongoing incentive.” (Walton, 2017)

## Conclusion

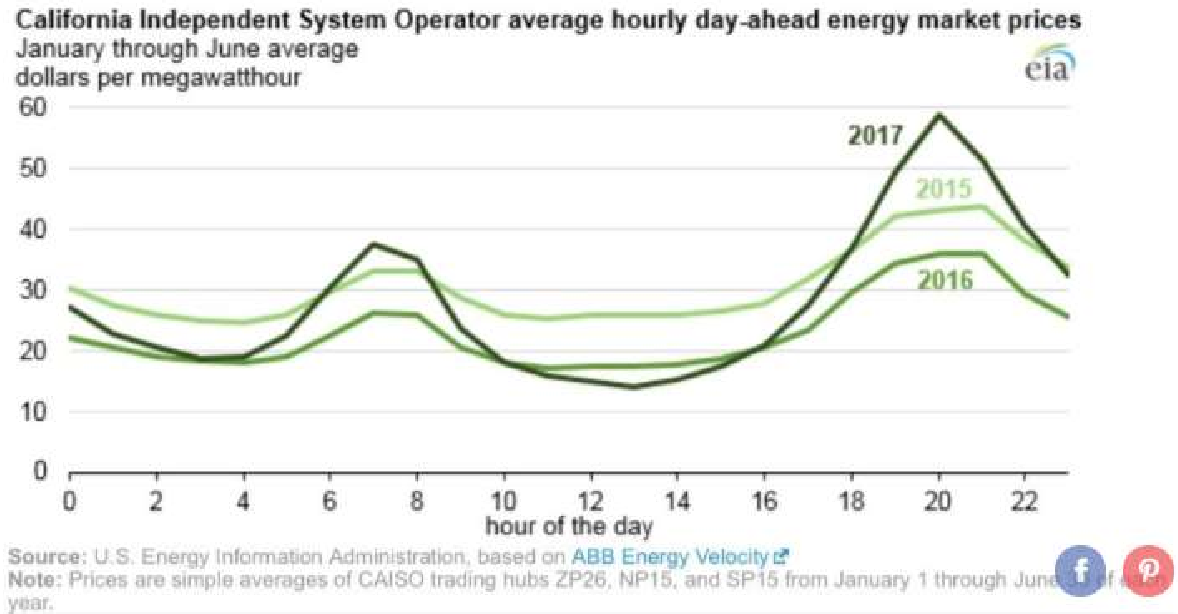
This is certainly a massive shift in the way that consumers interact with the electricity market. To be clear, this shift  would not possible without massive investment in advanced metering infrastructure (AMI), or smart meters. Smart meters provide data very frequently, and can be integrated with smart home controlling systems, that together can help with the implementation of dynamic pricing programs and move utilities beyond traditional pricing.

Some have suggested, therefore, that utilities begin with opt-in structures for customers with on-site generation, storage or load control, and over time, as Advanced Metering Infrastructure (AMI) continues to be rolled out, eventually implementing dynamic pricing to all customers (Kann, 2017).

# Algorithm for Smart Home Asset Management: Future Use Case

This section describes, in practical terms, the type of interaction that the regulatory reforms discussed above may enable and serves to show that there is value in those reforms. This next section attempts to demonstrate how, if the above proposed market reforms are enacted, a future smart home energy management system (SHEMS) can interact with the grid, and other smart homes, in a new way.

Smart Home Energy Management Systems (SHEMS) have been discussed extensively in the electricity literature (Wang, 2012, Garcia et al, 2014). The challenge is to find the optimal balance between saving money, buying clean energy, and living comfortably. The good news is that with the declining cost of renewables, plus their naturally low operating expense characteristics, this means that real-time pricing regimes would feature very low prices in times of the day when wind or solar are producing most of the electricity the grid needs. Research using large randomized field trials have found that households informed by “smart” thermostats “achieve impressive reductions in consumption during on-peak periods of up to 48 percent, but also engage in substantial load shifting to off-peak hours.” (Harding, 2016).




*Typical fluctuation of wholesale market prices in California. This algorithm assumes consumer exposure to similar price curves, but with higher maxima and minima*

To summarize, enabling DER innovation in order to deliver flexible capacity, while maintaining grid reliability and fulfilling the regulatory compact involves the following four reforms:

- Creation of distribution system operators (DSO’s) to provide a platform for DER’s, whether owned by utilities or third parties, to communicate supply and demand status and orchestrate supply and demand optimization initiatives.
- Dynamic Pricing: Real time pricing plus peak demand charges, communicated to smart devices by the IDSO, which would enable smart devices to respond to price signals and
- Value of DER methodology: that embraces the reality that DER’s’ value to the electricity system, is geographically and temporally unique, and compensates or charges DER’s according to their true value to the grid.
- DER Aggregation: individually, each DER’s participation in electricity services is minimal. If DER’s are able to be aggregated, however, they can be an effective source of flexible capacity, enabling load shifting to reduce PAR and address ramping issues caused by the duck curve..

## Use Case

Bringing these four primary recommendations together, this section demonstrates how a home of the future, equipped with multiple DER's, can rely on a smart home controller to optimize the usage of those devices while participating in hourly auctions for electricity services orchestrated by the IDSO. In this scenario, the home modeled is just one set of DER's which are being aggregated to perform grid services at a larger scale (Burger, 2016).

Numerous contributions to the literature of integrated DER's suggests an algorithm from game theory, called a "Generalized Tit for Tat game" that can be played in an automated many-to-one auction with the utility/DER aggregator. (Wang et al., 2012; Gao et al., 2014; Reka et al., 2016). This game, conducted entirely between automated devices, can optimize utilization of electricity services in response to demand and price conditions. Peak to Average Ratio (PAR) reduction is the thus name of the game.

This paper presents a simple algorithmic model of a smart home controlling multiple DER assets. In this case, the sample home has a 5 kW solar PV system, a 13.5 kWh lithium-ion battery capable of discharging 2kW of steady power, one electric vehicle, and a set of appliances with electricity load scheduling capability. In this way, the algorithmic model developed here demonstrates how this model can feed the "preferences" for a smart home communicating with other devices via web services. We have known that this is possible to do for some time, (Matsumoto et al., 2003), but only after implementing the proposed regulatory reforms to communicate real-time prices and allow households to participate in markets can these auctions create the incentives for residential demand shifting.

This algorithm therefore demonstrates that there is value in individual connected DER's to be aggregated. If formalized in future iterations, it can serve as a policy tool for decision makers to evaluate sensitivity to prices swings, consider rare edge cases (such as extreme weather events), measure system resiliency, and model the cumulative effect of aggregated DER's against real-world distribution system conditions. If refined to incorporate real asset performance attributes, the model can further be used as the basis for evaluating financial performance and payback period for those assets.

Further, this algorithm can be used in scaling experiments of a DSO-orchestrated real time auction for energy with many virtual DER's, each having unique asset attributes and locational value, participating in the Generalized Tit for Tat game of load scheduling.

## Assumptions and Modeling Constraints

- Use case: Predictive modeling for utility aggregator auction using game theory-based electricity scheduling algorithm.

- Recommended regulatory reforms have been enacted
    - NEM has been replaced by VDER via LMP and value stacking
        - Assume excess solar valued at wholesale price
    - Dynamic Pricing revealed through DSO: hourly pricing charges to encourage load shifting
    - DER Aggregator integrated with DSO sends signals to smart home controller to
    - initiate Demand Response (DR) and Ancillary Service events

- Model results based on a typical weekday load curve

- Home DER components
    - Electric Vehicle – home from 6 pm – 8 am every day
    - Rooftop PV (5kW system) in a place
    - Home battery (13.5 kWh capacity, 5 kW continuous power)
        - Simplified model assumes no round-trip losses
    - Connected appliances capable of demand shifting/scheduling
    - Smart thermostat
    - Advanced Metering Infrastructure (AMI) is widely adopted
    - Smart home controller communicating with web services

- PV output and EV charge needed determined stochastically within data-backed ranges[3]

[3] "The new grid requires a far more thorough treatment of the variability and uncertainty of supply and demand in a system where more and more energy is effected by the vagaries of sun and wind. This switch from deterministic to stochastic models is a bit like gaming out the odds of every possible

    - EV = 1-10 kWh, one hour charge
        - This assumes commuter behavior

- Rates are transparently derived from wholesale rates, are updated by DSO hourly.
    - Baseline case is extrapolated average 2017 CAISO day-ahead wholesale market data.

- Solar PV output is governed in the model by a combination stochastic process by which, in any hour the solar output of the system, is assigned a random kWh value within a Bayesian range of historical average output for that hour in the summer in California.
- The algorithm does not attempt to assess the state of deferrable load. Instead, as a simplification of that process, a Demand Response event will simply reduce the total load of the system at that time by 10%. This is a gross simplification that under new prototype iterations should be refined.

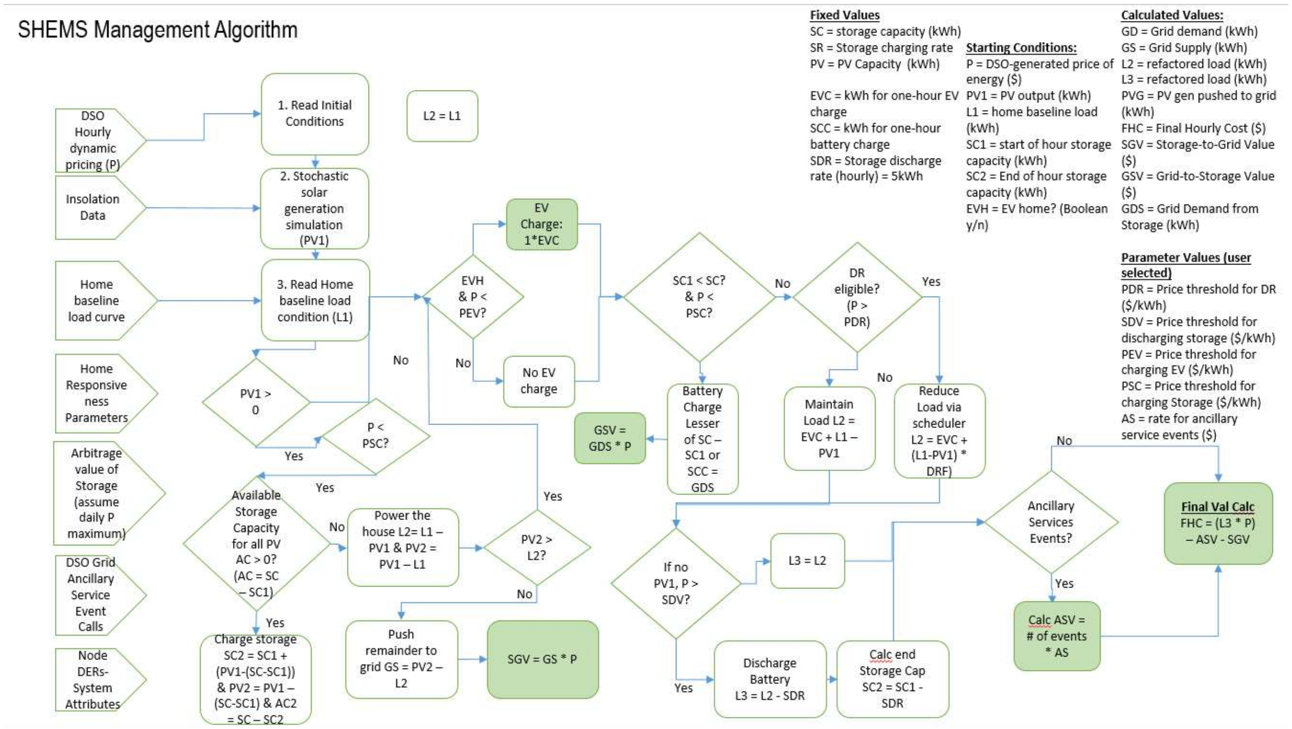
- The algorithm is stateless, in that it does not consider past or future conditions of the system. It simply reads initial system conditions, performs its calculations, and outputs ending conditions stored in variables to be used the next time the algorithm runs.

- Hardware and software protocols for device integration are not considered.

## Algorithm Design

As modeled in this paper the algorithm runs hourly, and follows a decision tree model to adapt the smart home's behavior to current system conditions. It assesses self-supply via PV generation and total load demand according to the current asset conditions of the system (such as available capacity in the home battery), solar generation conditions, prices, and asset status.

combination of outcomes -- a task that requires a lot of computation power and clever ways of applying it." ("Doing the Hard Math..", St. John, 2016)




Algorithm Process Flow

While this algorithm can be tweaked to anticipate future states of the system, by incorporating expected price values based on historical data, or weather predictions, as currently designed the algorithm takes into account only the current state and utilizes stochastic functions to determine variables such as PV generation[4]. This is a positive feature of the design for its stateless nature allows it to function at different frequencies, be it daily, hourly, or closer to real time.

A key feature of this algorithm is that its decisions rely heavily on four parameterized thresholds. This means that the parameters can be selected by a user on a mobile app, or can be determined by machine learning techniques as the algorithm optimizes itself. These thresholds determine at what price level the system will make certain decisions. They are as follows:

[4] Developing learning algorithms that do not rely solely on the day-ahead predictions such as in [other algorithms]. To do so, one can adopt techniques from stochastic games to model the demand-side management problem with storage (Saad et al., 2012).

- PDR = Price threshold for to initiate Demand Response (i.e. shift deferrable loads) ($/kWh)
- PLS = Price threshold for adding load ($/kWh)
- SDV = Price threshold for discharging battery ($/kWh)
- PSC = Price threshold for charging battery ($/kWh)
- PEV = Price threshold for charging EV ($/kWh)

Based on these four parameterized thresholds, the system determines the optimal use of solar generation, EV charging, battery storage or discharge, and demand response activity to shift non-critical appliance loads. It is helpful to consider example scenarios in order to understand how the algorithm would work in the larger process of orchestrating DER behavior. A homeowner, the automated processes of the smart home controller, or a combination of the two, will determine what the system should charge an EV if it happens to be charging at home *and* the price of electricity is less than $0.15/kWh. When the price is greater than $0.40/kWh, the home should initiate "demand response load shifting "as well as using power stored in the battery. There is far more complexity that can be built into a parameterized threshold model. The fact that this model uses only four simple thresholds shows the power that a few rules can have in a complex system. Adding more parameters may produce even greater system sensitivity to price and deliver complex behavior as the system begins to generate data that machine learning algorithms can seek in optimizing behavior.

Some algorithm designs instruct the system to only charge the battery when the PV system is generating electricity (Boynuegri, 2013). Anticipating a world of high renewable penetration and thus frequent mid-day oversupply from solar, this decision tree allows the battery to charge in such cases. A data element the DSO sends to networked DER's could indicate when renewable supply exceeds, or is about to exceed, the demand on the grid and will trigger the battery to pull electricity from the grid. An independent DSO, as not only the traffic cop for the grid but also the middleman between dispatchable power and transmission on the one hand and the distribution system on the other, would be in position to communicate this information to the many DERs that are participating in these many to one (DER-IDSO) auctions. That is getting ahead of ourselves, however. The algorithm models shown here describes a simple process, which begins at the start of each hour by reading the following Initial Conditions:

**Initial Conditions:**

- **P** = Price of energy ($): in the real world that would be DSO-generated, in this case modeled according to extrapolated 2017 California wholesale prices .
- **PV1** = PV output (kWh): modeled stochastically at run time.
- **L1** = Home baseline load (kWh): modeled according to default load curves for the average residential home, slightly modified to anticipate the presence of EV's.
- **SC1** = Start of hour storage capacity (kWh): determined from previous hour's simulation.
- **SC2** = End of hour storage capacity (kWh): determined from previous hour's simulation.
- **EVH** = EV home (Boolean y/n): assumed to be home from 6pm to 8 am every weekday.

The process first considers the presence of solar PV output, and then determines whether to store that electricity in the home battery or consume it to meet household load. If stored in the battery, any excess is used to meet household needs and any further excess is pushed to the grid. Then the system assesses the presence of an EV and evaluates the price signaled by the IDSO, against the parameter threshold selected to determine whether it is a good time to charge the car. If the car is to be charged, the model stores the data of the amount of charge and stores the value of energy consumed. The process then considers whether there should be further battery discharge or charge, based on price conditions, and evaluates whether prices are high enough to shift load from that hour to another time of day with more favorable prices.

Finally, because the assumption is that DER's are compensated for the full value of the electricity services they provide, the system considers whether there are any compensating ancillary services requested by the DSO, such as frequency or voltage regulation, and aggregates the value of those services. For simplicity's sake, these events are determined stochastically[5].

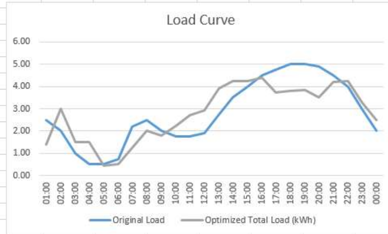
This is a very basic version of the algorithms that may control a home of the future, but even in their simplicity, these few rules can produce optimal results. For example, this system addresses several key issues in integrating DER's into the grid.

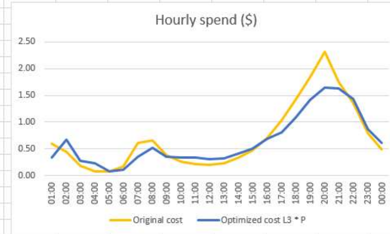
- It consistently allows solar energy to be stored during the daytime and used during peak times when prices are high.
- Ensures that the EV is always charged, and a potential new cost for a household is hedged by charging at cheap times.
- This energy arbitrage opportunity can improve the financial performance of DER assets. It maximizes the utilization of both storage and solar. Together they form a symbiosis that make each more robust and viable.
- Carbon reduction, because a lower peak demand means that there is less demand that must be met by fossil fuels. This example perfectly demonstrates the impact that aggregation can have. Individually, the each house may shave off a bit of peak usage. But added together, this can be the difference in a fossil fuel plant of x megawatts shutting down for the evening or may even prevent the need for entire fossil fuel plants.

Typical results of simulations using the algorithm can be seen in the figure below. Using the same amount of electricity, the smart home is able to optimize its DER assets to shift load, paying less for one day's worth of energy than it would without utilizing the optimization algorithm.

[5] For modeling: should be a random baysean distribution around local insolation data.

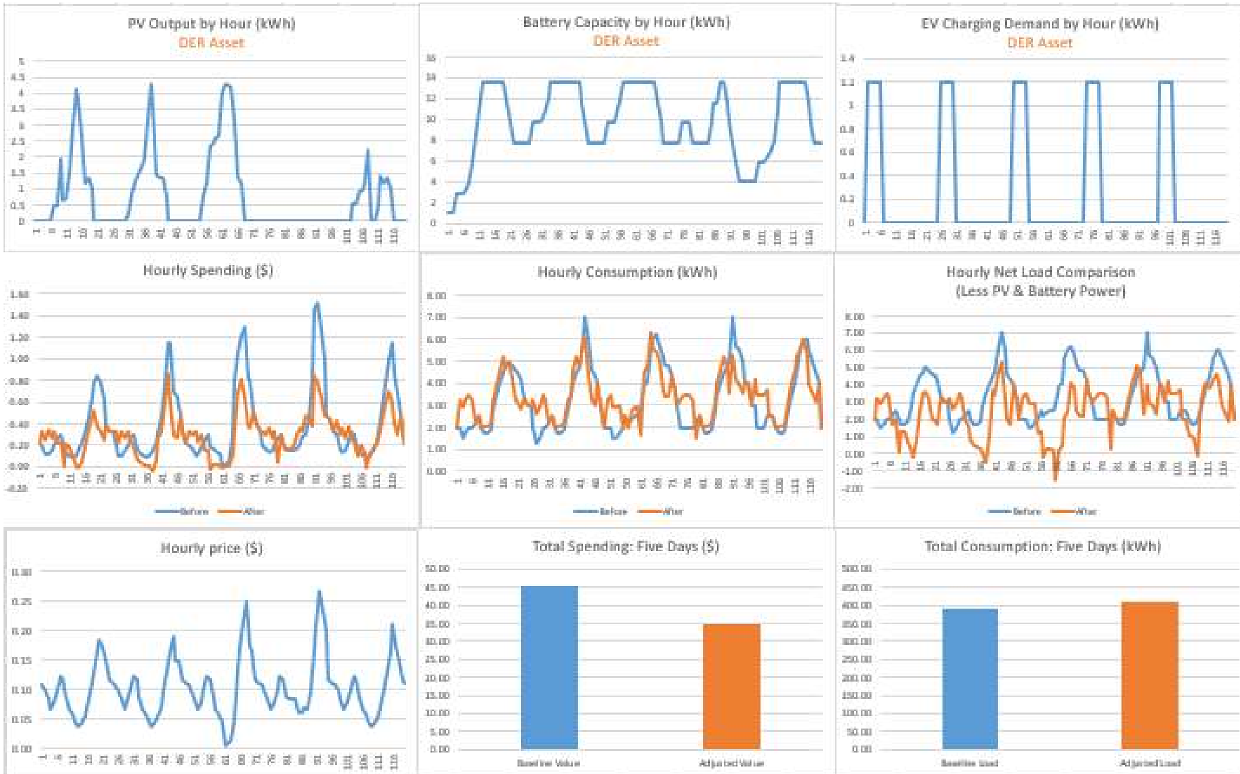
| Hour | DSO - Price ($/kWh) | Original Load | Optimized Total Load (kWh) | Original cost | Optimized cost L3 * P |
|---|---|---|---|---|---|
| 01:00 | 0.24 | 2.50 | 1.40 | 0.60 | 0.3 |
| 02:00 | 0.23 | 2.00 | 3.00 | 0.45 | 0.7 |
| 03:00 | 0.19 | 1.00 | 1.50 | 0.19 | 0.3 |
| 04:00 | 0.15 | 0.50 | 1.50 | 0.08 | 0.2 |
| 05:00 | 0.17 | 0.50 | 0.45 | 0.09 | 0.1 |
| 06:00 | 0.23 | 0.75 | 0.50 | 0.17 | 0.1 |
| 07:00 | 0.28 | 2.20 | 1.25 | 0.61 | 0.3 |
| 08:00 | 0.26 | 2.50 | 2.00 | 0.66 | 0.5 |
| 09:00 | 0.20 | 2.00 | 1.80 | 0.39 | 0.4 |
| 10:00 | 0.15 | 1.75 | 2.25 | 0.26 | 0.3 |
| 11:00 | 0.13 | 1.75 | 2.70 | 0.22 | 0.3 |
| 12:00 | 0.11 | 1.90 | 2.94 | 0.20 | 0.3 |
| 13:00 | 0.08 | 2.75 | 3.90 | 0.23 | 0.3 |
| 14:00 | 0.10 | 3.50 | 4.25 | 0.34 | 0.4 |
| 15:00 | 0.12 | 4.00 | 4.25 | 0.48 | 0.5 |
| 16:00 | 0.16 | 4.50 | 4.40 | 0.71 | 0.7 |
| 17:00 | 0.22 | 4.75 | 3.75 | 1.03 | 0.8 |
| 18:00 | 0.29 | 5.00 | 3.80 | 1.43 | 1.1 |
| 19:00 | 0.37 | 5.00 | 3.85 | 1.84 | 1.4 |
| 20:00 | 0.47 | 4.90 | 3.50 | 2.32 | 1.7 |
| 21:00 | 0.39 | 4.50 | 4.20 | 1.76 | 1.6 |
| 22:00 | 0.34 | 4.00 | 4.25 | 1.35 | 1.4 |
| 23:00 | 0.26 | 3.00 | 3.30 | 0.79 | 0.9 |
| 00:00 | 0.25 | 2.00 | 2.50 | 0.50 | 0.6 |
| | | | | | |
| | Original | Optimized | | Original | Optimized |
| Daily Load | 67.25 | 67.24 | Daily Costs | 16.66 | 15.38 |






Extrapolating the model for a full work week, we find even more interesting results in automated system behavior. Modeling stochastic solar PV generation, the system adapts to changing price conditions to optimize DER asset usage, while shifting load to times of the day with the best price. A sample dashboard of the model's output is shown below. In these graphs, users can track the status of their DER assets (solar PV, home battery, and EV) while comparing optimized usage against the baseline. In the sample below, over five days the household consumed the same total amount of electricity, but was able to save money by pushing more of that demand from peak times. Given that peak production is currently supplied primarily by fossil fuels, this type of automated demand shifting will have a net positive effect on carbon emissions.




## Next Steps

This initial algorithm design is intended as a prototype to demonstrate that there is value to be realized in utility reform that will enable DER aggregation for electricity services. Next steps would involve improving each step in the algorithm, and incorporating weather and price data that is more realistic. Further, teams working on this type of automated system will want to calculate the carbon emissions savings from shifting load from peak, and using solar power stored in batteries to cover the rest of peak times. Other next steps are listed below.

- Build a team including software developers and electrical engineers.
- Prototype software.
- Improve the model.
    - Improve accuracy of inputs.
    - Expand model duration.
    - Measure and compare hourly carbon emissions.
        - Hypothesis: optimized home will have lower emissions due to lower peak (fossil fuel) usage.
- Pilot project.

    - Many to one auctions within microgrids.
    - Pilot business models for aggregator systems[6]
- Aggregator models can integrate into an "end to end" value model.
    - LMP/VDER comp ranges from utilities.
    - Asset valuation.
    - Weather prediction data.
    - Wholesale prices across multiple time scales.
- Iterative prototyping web services auctions using game theory optimization models to test:
    - **Many-to-one auction to automate load scheduling : optimized by Generalized Tit-For-Tat Game.
    - Parameter sensitivity.
    - Scalability comparison between algorithms.

## Conclusion

In a few short years, the conventional wisdom regarding renewable energy has undergone a profound shift. The argument used to be that renewables had to get cost competitive before they could be taken seriously. In 2017, though, renewables are already cost competitive in many places, and that trend will continue until renewables are the cheapest option nearly everywhere.

But this is not the final obstacle to overcome, because there is now a new conventional wisdom, which questions whether renewable energy and adjacent technologies are going to pose a threat to the stability of the grid. Cost is no longer the primary limiting factor to renewable growth, but it is now grid integration. Yet, one of the reasons that that is the prevailing wisdom is that the regulations governing the trade in electricity do not allow these new technologies to deliver the flexible capacity that a grid with high percentages of variable and intermittent renewable technology requires. Markets haven't adapted to allow residential storage, electric vehicles, demand response, and other potential new technologies in grid management hardware and software to provide central reliability services and resiliency. They have the capacity to do that already today, from a technological stand point, but the markets do not reward it.

[6] (DERMs) DER Management Systems

In short, you cannot win if you cannot play. What this paper demonstrates is that with the right tweaks to electricity markets – creating an independent distribution system operator to communicate real time price conditions, aggregated, distributed energy resources at the residential can deliver the flexibility that is required to power our low-carbon energy future.

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## Appendix A: Glossary (Work in Progress)

PUC – Public Utility Commission

IDSO – Independent Distribution System Operator

ISO – Independent System Operator

FERC – Federal Energy Regulatory Commission

DER – Distributed Energy Resource

EV – Electric Vehicle

PBR - performance based regulation

Rate base

Rate case

C&I: commercial and industrial customers

COSR: Cost of Service Regulation

IOU: investor owned utility

Reserve Margin

Resource Adaquacy

Market-clearing price

Renewable Portfolio Standard

Investment and Production Tax Credits

MOPR - minimum offer pice rule

PAR: peak to average ratio

SaaS – Software as a Service

SHEMS – Smart Home Energy Management System

IEA – International Energy Agency

EIA - Energy Information Administration