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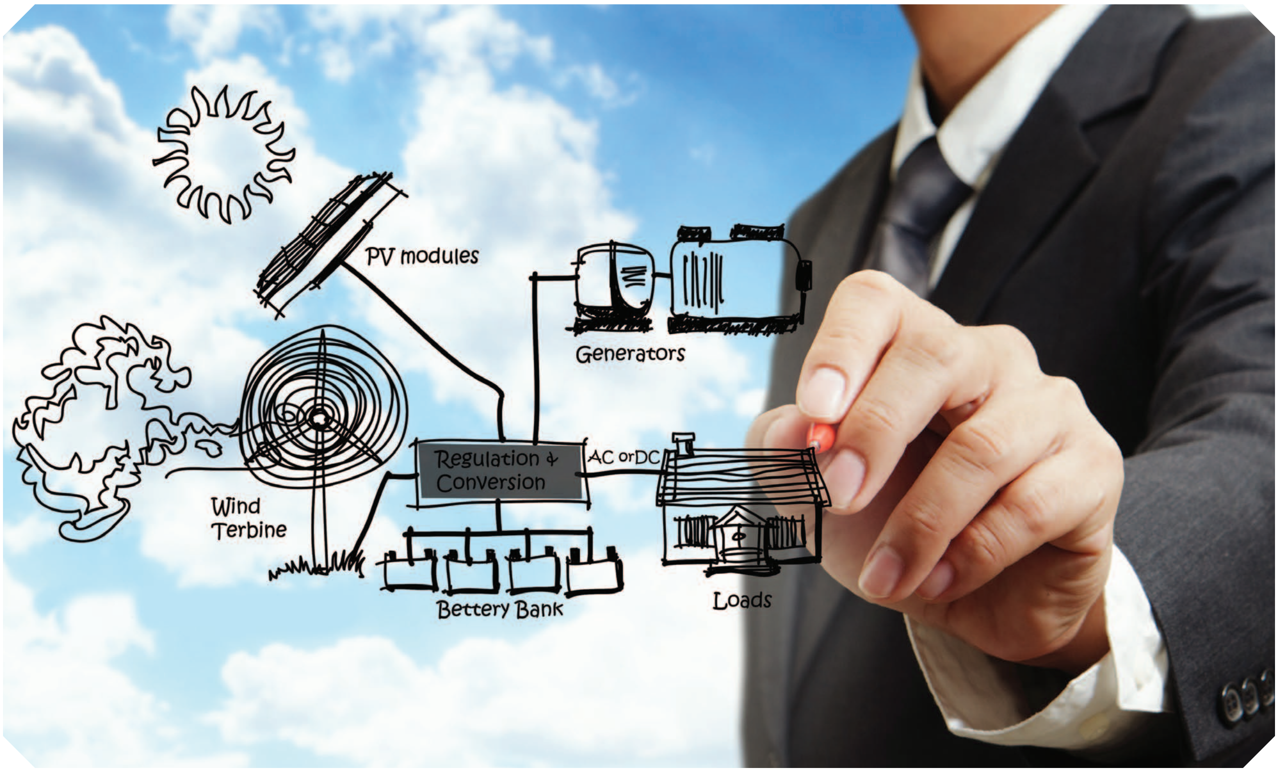


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# Solar Generation, Storage, and Electric Vehicles in Power Grids

## Challenges and solutions with coordinated control at the residential level.

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SOLAR ENERGY IS AN ABUNDANT RENEWABLE energy source that is available all around the world every day. Each hour, the solar rays that reach our Earth (if properly converted to electricity and other forms of energy) represent more than the total energy consumption of the entire human race over the course of one year. Wind energy is another important renewable resource available in large amounts every day. These two renewable energy sources are attracting significant investment as countries seek technology cost reductions to aid sustainability.

Improvements in the conversion and use of larger fractions of solar and wind energy would help in terms of supply security and satisfying societal energy needs for decades and even centuries to come without adding high levels of carbon dioxide and other greenhouse gases to the environment. Therefore, in several energy markets (such as in Brazil, Norway, Germany, England, and Australia), governments and regulators are emphasizing the need to increase the deployment of solar and wind energy sources as well as other measures to enhance monitoring, pricing, and control mechanisms in modern power grids.

The use of these renewable generation sources by themselves in power grids generally raises issues related to supply uncertainty, mismatch with system peak demand, and voltage and frequency regulation. For example, imagine the simple case of a household with installed solar panels that are used to produce electricity. In the daytime, the sun may be shining, and electricity can be produced without problems. But during this period, the household need for electricity is typically lower because  the users are away. This simple example can be extended to more complex and interconnected issues as the level of penetration of renewable energy resources increases.

In modern power grids, the use of devices ensuring the proper use of renewable energy sources is key as investments in wind and solar grow. Static batteries and other kinds of energy-storage devices are encouraged in these systems, and their employment helps to shift energy usage over time. Storage technologies are attracting the attention of investors, and there are plenty of successful applications of different storage devices alongside renewable energy sources. Government agencies and other regulators are also invested in exploring new opportunities for energy storage in energy markets. For example, in the United States, recently completed and ongoing projects can be found in the states of Massachusetts, California, North Carolina, Texas, and others (Figure 1).

Along with advances in modern power grids, the transportation sector is also significantly modernizing. New technologies are focused on developing environmentally friendly means of transport, such as plug-in electric vehicles (PEVs). PEV technology introduces a new link between the power and transportation infrastructures. These vehicles require electricity from the grid for battery charging, thus achieving the autonomy to transport people from place to place. But if the PEV is connected to the grid, the electricity stored in its battery can also be used to satisfy other household electricity demands. Because of PEVs' bidirectional capabilities, these transportation vehicles represent at once a load on the grid and a source of electricity for the grid, depending on when it is needed.

Because the use of solar energy panels, energy storage, and PEVs is ramping up, homeowners with both forms of storage can control and manage their equipment's operation in a coordinated way to reduce electricity/transportation costs and minimize other problems. The goal of this article is to offer an overview of solar PV generation, battery storage, and PEVs and highlight the benefits associated with the coordinated use of these technologies in energy management at the household level.

## Present and Future of Solar Generation at the Residential Level

According to the Solar Energy Industry Association, 2,227 MW of rooftop solar was installed in 2017 in the United States.

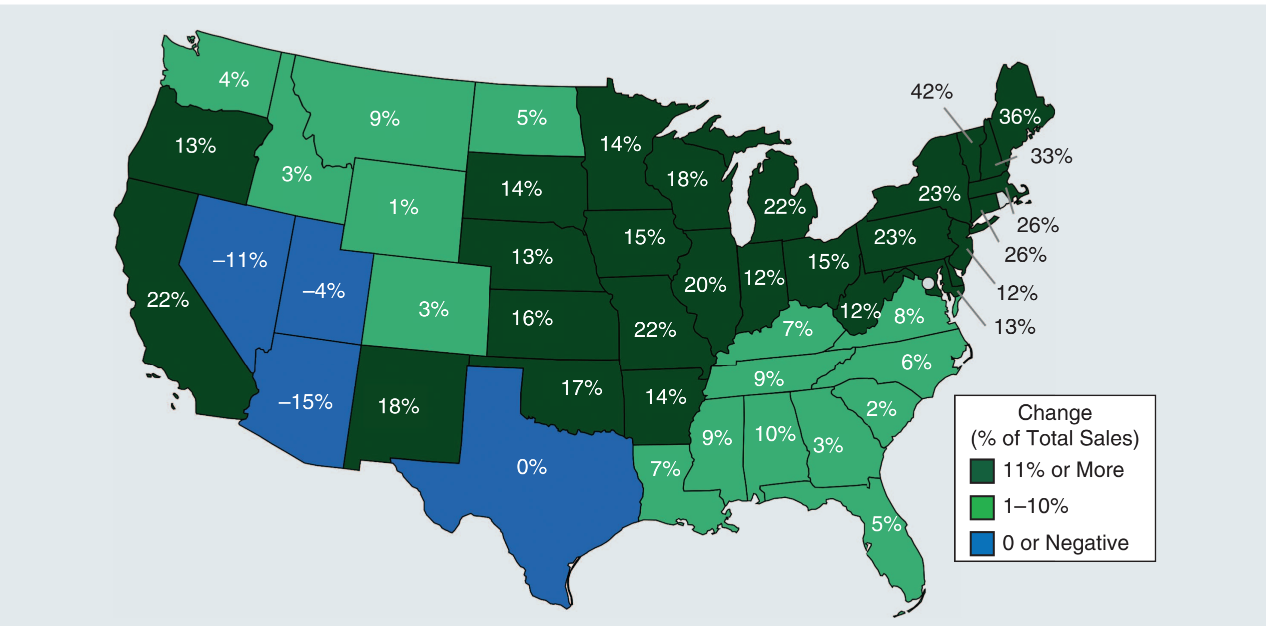


**Figure 1.** The change in the rooftop solar potential 2008–2016. (Image courtesy of the National Renewable Energy Laboratory, www.nrel.gov/docs/fy16osti/65298.pdf.)

Based on research by the National Renewable Energy Laboratory (NREL), rooftop solar could one day produce almost 40% of our electricity using the average efficiency of solar panels installed in 2015. The research report stated that there are over 8 billion $m^2$ of suitable roofs in the United States. It is possible to generate about 1,400 TWh of electricity each year, and two-thirds of this would come from small residential buildings. The analysis found that California could supply approximately 74% of its total electricity usage by covering its buildings with solar panels, while Wyoming (with fewer sunny hours) would achieve about 14% of its needs and New England around half.

In addition to the available potential generation capacity, the reduction in the cost of solar photovoltaic (PV) generation over the past five years is creating a significant shift on the supply side of power grids. According to recent estimates by the International Renewable Energy Agency, most homeowners were investing between US$2.70 and US$3.60 per watt to install solar PV in 2018. Furthermore, solar PV costs are expected to be cut in half by 2020, as reported by the same agency. The total price of solar PV panel installation varies from country to country and, in the United States, from state to state: in U.S. states, local governments and utilities offer rebates and other tax incentives that reduce solar generation investment costs. For example, a Greentech Media (GTM) research analysis showed that homeowners can save, on average. approximately US$38,000 in Portland, Oregon; US$63,000 in Boston; and US$90,000 in Los Angeles over 20 years, considering incentives. Currently, North Carolina homeowners can often spend fewer than US$2 per watt on installation.

In a household, the capacity of solar PV installation depends on the customer's needs and preferences and also affects electricity generation and overall cost. The size of the customer's PV panels has an impact on the existing grid infrastructure. Safety, reliability, and operational issues may not be evident at lower penetration levels of solar power, but higher penetration levels can create reliability challenges for the grid. These issues are not generally observed at the individual household level; as penetration levels increase, however, the effect is seen in the overall distribution circuit operation or even further upstream in the regional distribution or transmission substation. The reliability issue also plays a significant role in microgrids and isolated power grids.

For example, Hawaii is a prototype of the integration challenges associated with residential rooftop solar PV generation: in 2017, energy production exceeded 75% of the typical daytime gross electricity demand in the system on several islands. The state's high PV penetration has already created a real and unpredictable threat of large-scale overvoltage situations. Transient overvoltage events in Hawaii's grid have resulted in damage to grid equipment and customers' home electronics. In such situations, advanced solar PV inverters must be used to curtail solar generation produced at the household level and maintain outputs that will not affect system stability.

California is experiencing a sudden and excessive rise in power when rooftop solar systems are available online. In 2013, the California Independent System Operator (ISO) published a chart, now commonly known as the *duck-belly curve* (Figure 2), which shows the difference in electricity demand and the amount of available solar PV energy throughout the day. On 11 March 2017, the California ISO observed solar curtailment exceeding 30% of the solar production for an hour to maintain grid stability. On 4 March 2018, the solar peak generation reached approximately 50% of the total peak demand in California, which intensified the curtailment level.

Curtailing renewable energies is counterproductive and inhibits the achievement of environmental and economic goals. A large amount of carbon-free electricity production lost because of curtailment could otherwise be used to maintain the reliability and stability of the grid. In this circumstance, the net load drops faster during the daytime, and the afternoon-to-evening ramp-up grows rapidly steeper when there is no solar generation available. The problem is at its worst in springtime, when the sun shines longer each day, and fewer people are running their air conditioners because of temperatures being in the comfort zone.

In December 2017, electricity demand in California ramped up by approximately 13 GW, which represents 50% of the increase in demand, within three hours during the evening period. In situations like this, utility companies must prepare themselves to satisfy the peak demand and also sign several contracts with peak-power generation plants that will operate during the period to supply the additional demand. Thus, utilities are working with stakeholders and state leaders to innovate solutions to the rising trend

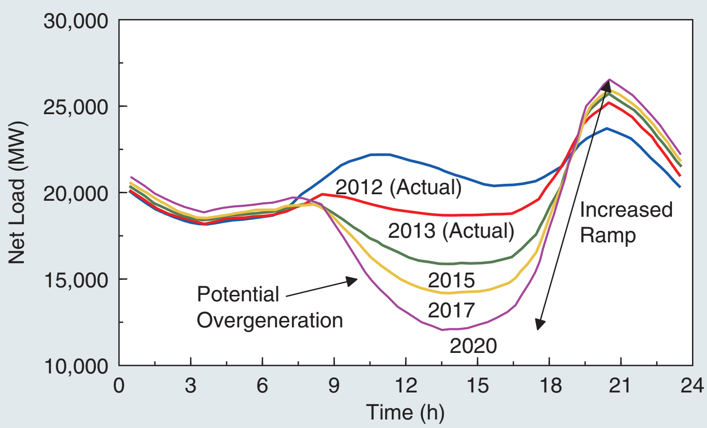


**Figure 2.** Load–solar PV curves (so-called duck-belly curves) from California. (Image courtesy of California ISO.)

of renewable curtailment and sudden load ramp problems. Energy-storage devices, along with solar PV panels at the residential level and PEVs with their storage capabilities, are considered emerging solutions to offset these problems.

## Solar PV-Storage Hybrid Systems at the Household Level

Energy-storage devices can be used to store the excess supply and so address some current grid management issues and overcome barriers during the transition to a greener, more cost-effective, and more efficient grid. The stored energy can be used later when demand is higher and available renewable energy is smaller. The energy in storage devices can also provide support for voltage and frequency regulation, congestion relief, energy arbitrage, and network upgrade deferral at the transmission and distribution levels. On the generation side, storage paraphernalia can be utilized to provide synthetic inertia to generators, peak capacity deferral, spinning reserve, flexible ramping, and frequency regulation.

Unfortunately, in the past, significant cost and value barriers were obstacles to the deployment of combined solar PV and energy-storage systems. But with the development of different storage technologies (more specifically, static lithium-ion batteries), the per-unit cost of devices is decreasing and their lifetime is improving. As a result, residential-level storage usage has recently started to grow. A significant uptrend took place last year when investments in residential energy storage scaled up. Global annual residential-level energy-storage deployment is expected to scale up from 94.9 MW in 2016 to 3,773.3 MW in 2025, as reported by Navigant Research.

According to recent data, in the United States, nine grid-connected home energy-storage systems were deployed per day through the third quarter of 2017, totaling 4.2 MW (amounting to a growth of 202% over the year). In Hawaii, which has the highest electricity rates in the nation, solar PV storage systems are making economic sense under the state's Customer Self-Supply program. In California, the Self-Generation Incentive Program, with its consideration for residential storage systems, has helped to drive growth.

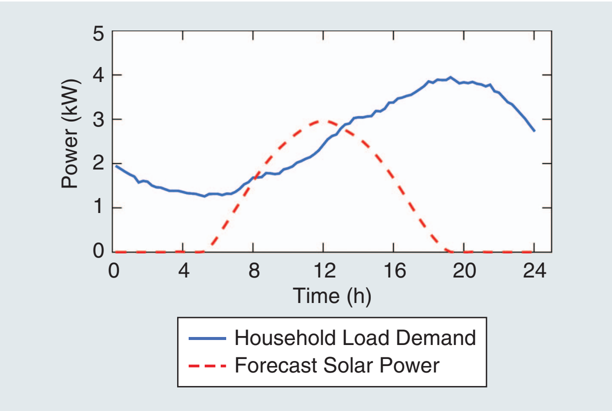


**Figure 3.** The household and solar generation profiles for a summer day.

Other states and utilities are trying out models to reduce the cost of batteries and power electronics over time.

The residential segment is expected to contribute about 10% of the storage market in 2018, and this value is expected to grow to 38% by 2022, as predicted by GTM. In most cases, homeowners are adding storage devices for backup power or monetary savings, while utilities encourage the deployment of the technology to mitigate the effects of high solar penetration on the grid. Today, U.S. residential energy storage is concentrated in a few markets with the right mix application and regulatory environment, such as Hawaii, California, and the Northeast region.

## Storage Device Control at the Household Level

Heuristic approaches are commonly applied for storage control, where the storage is charged when electricity demand is lower than solar PV generation and discharged when solar PV generation is lower than demand. As most customers pay electricity bills by following cost structures based on a time-of-use (TOU) rate, the reduction of electricity purchase costs is possible by controlling the storage device's charge/discharge scheduling by using dynamic programming (DP)-based advanced control strategies. DP approaches ensure that the global optimal path is reached considering all of the possible paths, which is exhaustive (for more details, see Hafiz et al. 2018).

A specific algorithm for DP is deterministic dual DP (DDDP), which considers a deterministic forward path. For systems involving stochasticity, such as those with solar PV generation and household load usage, stochastic dual DP (SDDP) methods can be used. SDDP helps to avoid DP's curse-of-dimensionality problem by constructing an approximation of the future cost function with piecewise linear functions. For convergence, a stopping criterion based on the desired level of a variable, such as the storage state of charge, is considered. These DP-based control strategies will always outperform heuristic approaches.

The impact of such advanced storage control strategies is shown in Figures 3–6 for a single-household energy-use case study (for more details, see Hafiz et al. 2017). A solar PV installed capacity of 3 kW, along with a 4-kWh energy-storage device capacity, is considered for the home. The household load and solar generation profiles considered for the case study are shown in Figure 3, and the Pacific Gas and Electric TOU rate structure is indicated in Figure 4. The heuristic approach (heuristic control) and DDDP- and SDDP-based control strategies were applied, focusing on reducing electricity purchase costs. The SDDP-based control strategy reduced electricity purchase costs per day because of the uncertainty of solar generation (Figure 5). The use of solar energy and peak savings also improved with the application of SDDP (Figure 6).

## Increasing Deployment of PEVs

At the residential level, another increasing form of energy storage is PEVs. Such vehicles use electricity to charge the

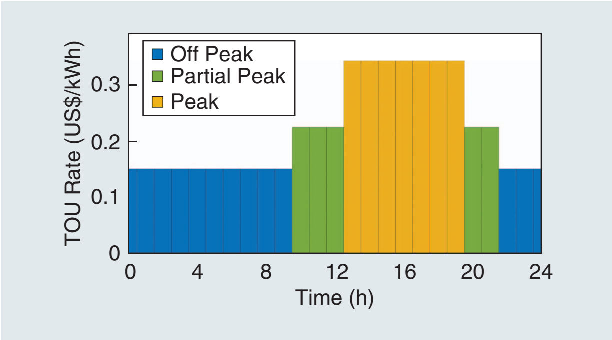


**Figure 4.** The TOU rate for summer.

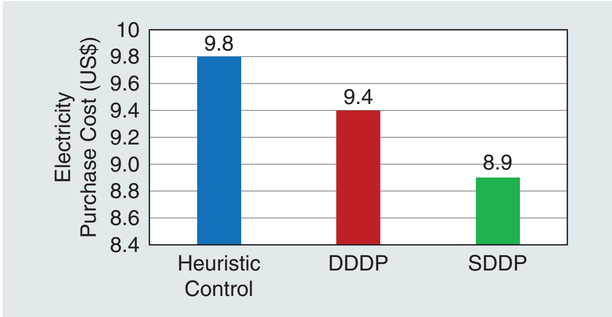


**Figure 5.** The electricity purchase costs per day (in U.S. dollars) for different control strategies.

on-board batteries instead of fuel (gasoline, ethanol, or diesel), unless the vehicle is a plug-in hybrid vehicle with a limited zero-emissions range. As mentioned previously, PEVs also have the potential to transfer power to the grid and so alleviate peak power demand and provide ancillary services in a way similar to other energy-storage devices. These PEV services are often said to have vehicle-to-grid power transfer capabilities. An emerging issue with PEVs is that, when a large number of vehicles are simultaneously connected to the power grid, they may cause a significant threat to its quality and stability.

According to a recent NREL report, the number of PEV users in California will grow to approximately 1.3 million by 2025, and annual sales of PEVs in 2025 will increase by more than 7% compared to 2017. Connecting and charging the large number of PEVs at the household level will significantly increase the system's electricity demand within a short period of time and require reconfiguration planning for the power distribution infrastructure. Based on the Electric Vehicle Infrastructure Projection toolbox developed by NREL, residential charging demand will be almost 900 MW at 8:00 p.m. each day by 2025 in California. On weekdays, the aggregate demand from all charging types (commercial and residential customers) will face an increase of approximately 500 MW between 4:00 and 7:00 p.m., with a maximum demand of nearly 1,000 MW before 8:00 p.m.

## PEV Charge/Discharge Control at the Household Level

The distribution system's modification and upgrading costs can be alleviated by coordinating the charging behavior of PEVs using either centralized or decentralized control schemes. To apply these techniques, an effective communication system is required, but owner privacy is an important issue that must also be addressed. The storage in the PEV provides various opportunities at the household level, such as electricity purchase cost minimization, voltage regulation, and load regulation. In this regard, a controller can regulate the PEV's charge/discharge actions considering different objectives. Typical owners would like to reduce their electricity purchase cost per day by controlling their PEV's storage device. If homeowners can be assured that they will have the required amount of charge in the PEV when leaving home, then, with an effective control strategy, the electricity purchase cost per day can be reduced.

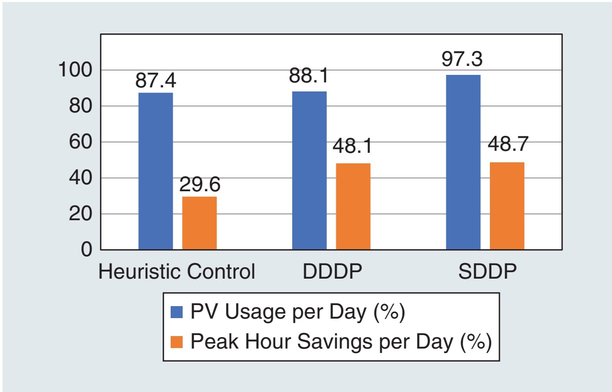


**Figure 6.** The improvements in solar PV generation usage and peak hours savings.

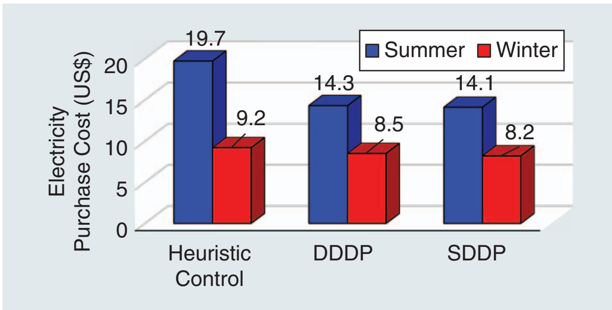


**Figure 7.** The electricity purchase costs per day in U.S. dollars for different PEV control strategies in different seasons.

Daily electricity purchase costs with different control strategies for different seasons are shown in Figure 7. For this case study, the PEV considered has a battery capacity of 85 kWh with a 10-kW charger. It can be seen that, if electricity demand uncertainty is considered when controlling PEV storage, then electricity purchase costs are lower compared to the deterministic control approach based on the DDDP and heuristic control methods for all seasons.

## Coordinated Control of Solar PV Generation, Storage, and PEVs at the Residential Level

As PV-based storage and PEV-deployed households are expected to increase in the next decade, both types of storage devices can be used by employing a coordinated control algorithm at the residential level that addresses security issues and communication requirements. Coordinated control of the two storage devices can provide benefits to both the customer and the utility. Customers will be able to control the available storage devices in their household according to their requirements and preferences, thus providing independence, an important factor for virtually everyone. The system overview with coordinated control is shown in Figure 8.

For coordinated control, a mathematical optimization model is possible, with the representation of the management problem through decision variables, parameters, objective function, and constraints. As an example, this model can be tailored to represent the owner's preference and behavior. Following the modeling step, data related to electricity demand, solar PV generation, storage device characteristics, and other factors need to be considered. If the goal is to control the storage devices for a particular day, then day-ahead data on these parameters need to be forecast. Based on these forecasts and optimal control decisions, the actions or operating policies for the storage devices on a particular day are defined. Depending on the characteristics of the overall optimization model, this can be handled by using off-the-shelf methods to solve linear programming, mixed-integer linear programming, quadratic programming, and DP. All of these methods can be applicable if electricity demand and solar PV generation are considered deterministic parameters for a particular day.

But, in the real problem, both solar PV generation and electricity demand are uncertain parameters. Also, for the transactive energy market, electricity per unit cost is uncertain. Thus, to ensure accurate coordination of system resources, these uncertainty sources must be considered when developing a robust and realistic coordinated control scheme.

Stochastic models can be optimized through model predictive control, the stochastic gradient descent method, stochastic DP, SDDP, approximate DP, and machine learning and mechanisms. In all of these cases, it is crucial to precisely model and represent the uncertainties associated with the random parameters. Based on available electricity demand and solar PV generation data, it is a good practice to compute the possible deviations around forecast values and integrate that information with the optimization process. However, in real-time implementations for controlling storage devices' inverters, rolling-window time horizons and rule-based control methods can be applied to achieve better management results.

## Benefits of Coordinating Resources to the Customers

One of the benefits of combined PV–battery hybrid systems and PEV battery usage at the residential level is energy security during distribution- or transmission-level power outages. If the grid experiences an outage for a few hours, as in the case of bad weather or rolling blackouts due to higher load demand in the grid, homeowners with PV–battery hybrids and PEVs can control energy usage and storage in a coordinated way, considering priority, availability, and outage duration. They also can be used to maintain power quality by smoothing out voltage fluctuation and voltage swell/sag, compensating for voltage harmonics distortion, and mitigating voltage unbalance. Moreover, households equipped with solar panels, along with energy storage and PEVs, can be protected from many grid vulnerabilities.

The increase in a household's electricity demand typically occurs when the power generated by solar PV drops

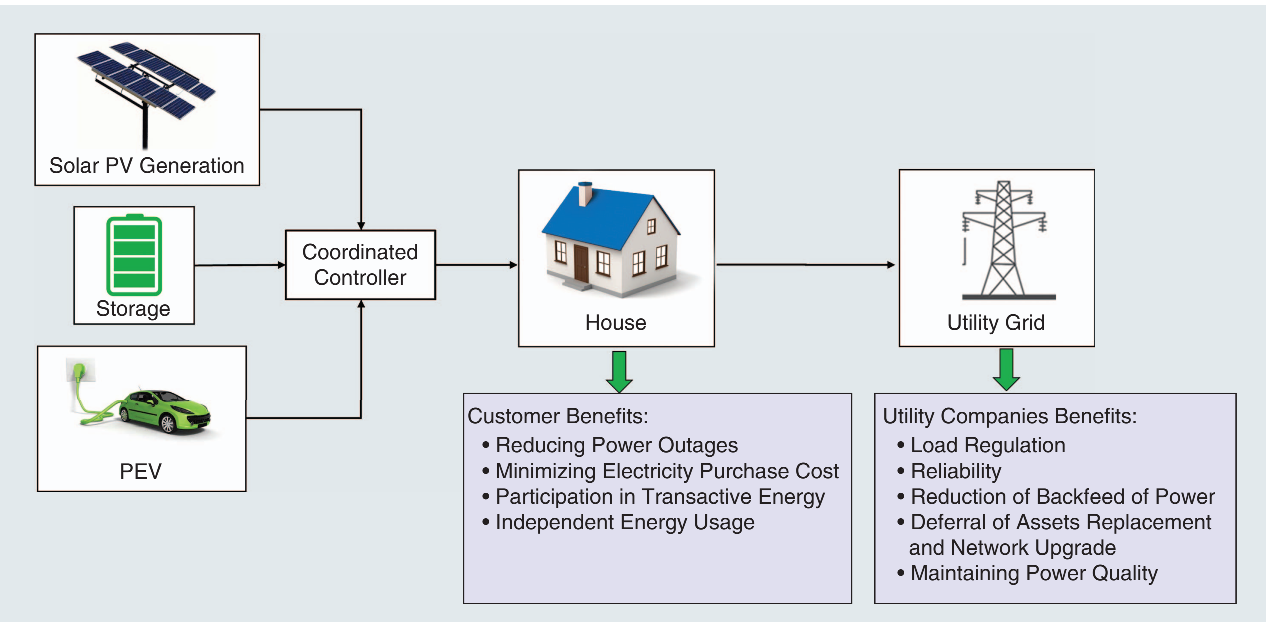


**Figure 8.** A system overview with coordinated control at the residential level and the benefits at different levels.

off at about the same time that PEVs plug into the grid as users return home from work. To mitigate rising demand, utility companies need to produce or purchase electricity at higher costs from more expensive power generation units, which impacts market electricity prices. Households with generation and storage devices can avoid electricity purchases from the grid during peak times and use the energy in the storage devices to minimize electricity purchase costs. Coordinated control of available storage devices can reduce electricity purchase costs per day compared to individually controlled methods. The electricity purchase cost reduction achieved through coordinated control between these two storage methods for different seasons is shown in Figure 9, based on a case study (for more details, see Hafiz et al. 2018).

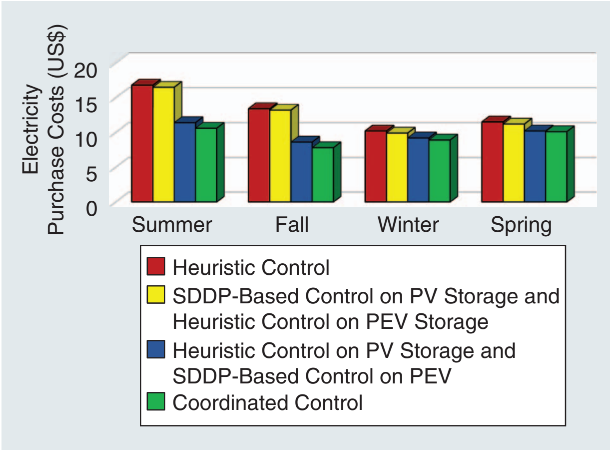


**Figure 9.** The electricity purchase cost-per-day reduction for different seasons.

## Benefits for the Overall Power Grid of Coordinating Resources

Spreading out household energy production/usage during the day to prevent large spikes in electricity demand from the grid is highly beneficial to the utility company. While reduced electricity demand during daytime may lead to overvoltage problems, a sudden demand increase during the night may cause low-voltage problems. It is thus helpful for utility companies if the overall load of a particular day is regulated so that any sudden decline of load or ramp-up of electricity demand can be avoided. Coordinated PV–storage hybrids and PEVs can be used to regulate and maintain a daily average household load demand that will help flatten the belly of the duck-belly curve, shown in Figure 2, when many household power demands are flattened with the coordinated control method.

The utility incentive mechanism can be developed to encourage customers to use coordinated control to maintain the average daily load in their household. The impact of load regulation with the coordinated control strategy is shown in Figure 10 for the household with the same capacities of a PV–storage hybrid system and a PEV as shown in Figure 9. If both storage devices are controlled in coordination, then the electricity demand variance reduces when compared to its value obtained by controlling them individually (Figure 11). The act of shifting demand at the household level may be viewed as a key alternative to alleviate issues in the distribution system while allowing homeowners to often avoid expensive peak load charges.

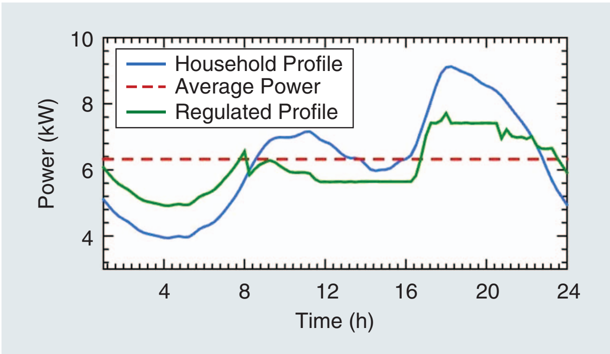


**Figure 10.** The regulated profile after control.

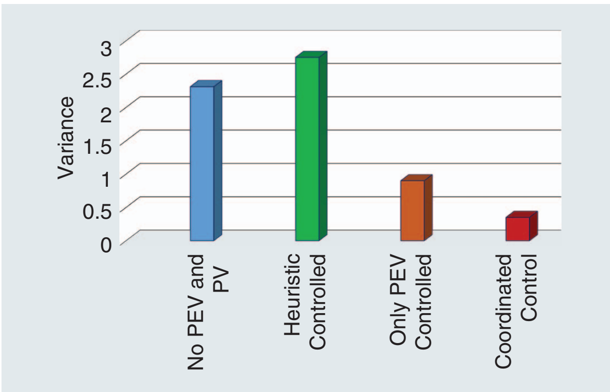


**Figure 11.** A comparison of different methods for load variation.

As distributed renewable energy resources increase in the system, one scenario may be that, after a certain level is reached, utilities will start to experience considerable losses in revenue. As a result, consumers without generation might need to pay more to make up the difference. Recent research recommends pursuing the idea of transactive energy to help mitigate such issues. Transactive energy will allow prosumers to buy and sell electricity and ensure the dynamic balance of supply and demand. Based on this scheme, end-user participation can be encouraged using various negotiation and bidding strategies for the customers' available capacity and resources until agreement with the utility is reached. By coordinating the available storage devices owned by households, customers can engage in this transactive energy market.

Another emerging issue is how to properly compensate the utilities for providing their assets and providing for the participation of customers in the grid and the transactive energy market. Therefore, novel smart-pricing mechanisms that take into account the complexity associated with this environment are necessary.

An additional problem for the distribution grid is associated with backfeeding solar PV generation and the potential voltage violations. To avoid backfeeding, either solar PV generation is curtailed by controlling the inverter, or storage devices are used to store the energy surplus. But, if the PV-based storage reaches its saturation level, the energy surplus should be curtailed. Instead of energy curtailment, the PEV's storage device can be used for charging if it is connected to the household circuit during the pertinent time period. Therefore, with coordinated control in the system formed by solar PV generation, PV storage, and PEVs, excess energy can be absorbed to avoid energy curtailment, reduce reverse power flow, and be used at appropriate times to optimize the use of the available renewable resources.

System stability and frequency regulation are two other aspects that must be properly ensured in power grids. Utility companies control frequency through automatic generation controls to adjust the grid frequency based on a reference level. But, because of the frequent variation of distributed energy resources, batteries, and PEVs in the grid, the distribution-level frequency can experience significant oscillation and violation. At the distribution level, electricity demand and distributed generation can be used to regulate frequency. Based on a defined frequency signal, prosumers and consumers that interact in the system can control the actions in their storage devices and so limit frequency deviations, providing the grid with a type of ancillary service. If homeowners can control their storage devices in a coordinated way to maintain reference frequency, a fast response to utility frequency control can be achieved.

As the number of PEVs on the road increases, their impact on the power grid infrastructure is likely to intensify. While there are relatively few PEVs presently circulating in the United States, if a small number of them (e.g., eight to 15 vehicles) are clustered in a given area dependent on a single distribution transformer, the additional load might reduce the life expectancy of that transformer by up to 50%. Despite being a transportation mode that is mostly not harmful to the environment, an escalated deployment of these vehicles may produce negative impacts on distribution system assets, such as distribution primary feeders, transformers, and secondary distribution lines.

As a result of these impacts, modification and upgrading of distribution system components may be required. This can be achieved by increasing distribution transformer sizes and adding new lines to the existing system, both expensive solutions. Similarly, because of the distributed generation during daytime, it is more frequent to observe the switching of existing online tap-changers and capacitor banks, which will reduce the lifetime of these components. However, upgrades in the distribution network can be deferred or postponed if resources are properly coordinated to satisfy the needs at the residential level.

## Conclusions

The task of preparing the grid for the seamless integration of solar generation, static storage, and PEVs while supporting customer preferences and creating benefits for utility companies is technically and economically challenging. Coordinated control between these devices at the residential level is important to both the customer and utility in several different ways. Some previous studies in this area analyzed using PEVs and evaluated possible reductions of solar PV generation at the grid level for large-scale penetration, but very few studies have considered the design of control strategies to properly facilitate coordination among them.

Several concerns arise, as simultaneous deployment of solar PV generation, storage, and PEVs at the residential level is likely to increase within the next decade. This article compared different control strategies for various objectives, highlighting the significance of coordinated control approaches at the residential level for renewables, storage, and PEVs. Coordinated control was shown to better provide benefits for customers and the distribution system.

## Acknowledgments

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## For Further Reading

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