Optimizing Device Operation with a Local Electricity Price

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Abstract

Making optimal use of available electric power is important for efficiency, functionality, and to reduce capital costs, particularly in developing countries. This paper shows the results from simulating the behavior of refrigerators and freezers that vary their operation according to a local price and price forecast. The price is set to the availability of local photovoltaic (PV) power and is used to adjust the temperature setpoints of the devices. For off-grid systems, this can be used to concentrate consumption during times of PV availability, to increase efficiency and reduce battery size. Our simulations show a reduction of up to 26% of the energy used by the devices at night.

Keywords: Off-grid; nanogrid; local price.

Introduction

In electricity systems of many scales, matching supply and demand is a critical need. This is a basic function of any grid—utility grid, microgrid, or nanogrid (Marnay et al., 2011). For energy access deployments, there are often significant limits on system capacities for energy and power, and these may vary from day to day. This paper demonstrates that a local price of electricity can be used to shape demand to use it more optimally. The context addressed is a standalone system powered with local photovoltaic (PV) power backed up with a battery. Refrigerators and freezers are modeled to show how price can be used to better match their consumption to electricity availability.

Research Objectives

The purpose of this study was to explore the general principle of using local prices as a way to control devices — or rather, so devices can control themselves. This is a core principle of the technology of Local Power Distribution (LPD) (Nordman, 2012; Nordman et al., 2012; Nordman et al., 2013). LPD is based on a network model of power, rather than the conventional single unitary grid. A network of local grids can be attached to a large scale utility grid, a small mini-grid, or a local micro-grid. The basic unit of power distribution in LPD is the nanogrid, and each nanogrid has its own local price and price-forecast. This paper considers only a single nanogrid, including integral storage, plus a connection to local photovoltaic power.

Data Sources

With the purpose of this study being exploratory, it was not necessary to be detailed in our modeling. For example, the efficiency of storing energy into and out of a battery is assumed to be constant, and we do not consider the interaction between charge level and capacity to store or withdraw power. The details of compressor operation are not modeled; each minute of operation is assumed to have an identical effect on reducing temperature in our refrigerators and freezers.

For PV data, we used sample data from a convenient source[1]. The loadshape of produced power was simply scaled to match our system needs and the hourly output linearized. Figure 1 shows one day of PV system output, unscaled, along with a price signal trivially derived from the PV output. For batteries, we assume that 10% of electricity is lost in the charge/discharge roundtrip.

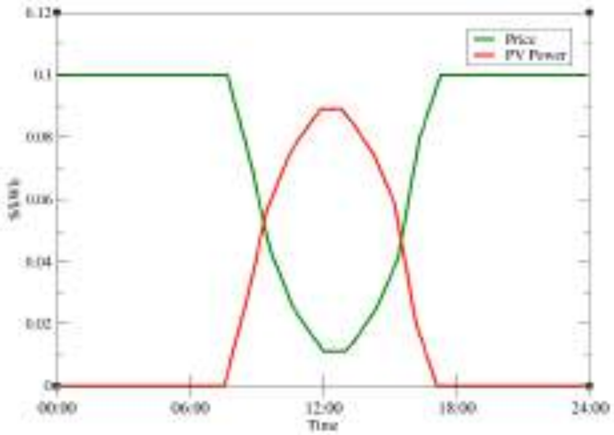

Figure 1. PV daily electricity loadshape and local price

Our base case of device operation was modeled on typical behavior of a recent models of refrigerators and freezers[2]. Our units are manual defrost so there is no automatic defrost cycle to schedule (though these could be readily set to be at times of high electricity availability). We did not model door openings.

Prior Work

Matching supply and demand is not only of concern for off-grid systems, but arises in most electricity systems. For improved operation of conventional utility grids, a project at U.C. Berkeley (Taneja et al., 2011; 2013) demonstrated a phase change material used in the freezer compartment of a typical refrigerator (with integral freezer) to shift demand. Energy is required to "charge" the material as it freezes; it later absorbs heat as it melts.

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[1] Adapted from http://www.seia.org/research-resources/potential-impact-solar-pv-electricity-markets-texas

[2] Personal communication from Lloyd Harrington, 2013.

They considered how such a system would behave in the context of a fixed time-of-use price regime. They also operated it to follow renewable generation in the local utility grid and select among a few different temperature setpoints to shift energy demand to the desired times.

Our project builds on this concept but with different context and goals. We take the appliances as-is, without physical modification; a local price forecast is the only information considered; and the setpoint is directly manipulated in a continuous manner.

Individual Device Operation

Figure 2 shows a six hour period of our basecase freezer operation. There is a constant setpoint (-10 C) so that the compressor cycles do not vary, with compressor on-times and off-times of about 20 minutes each. The unit turns on the compressor when the internal temperature reaches 0.5 C above the setpoint, and turns off the compressor when 0.5 C below the setpoint is reached. Our basecase of refrigerator operation is similar. We assume that the freezer setpoint can range from -3 C to -18 C, and the refrigerator setpoint from 1 C to 6 C. These are to give the system maximum flexibility without compromising the integrity of the units function.

The units can change their setpoint in response to the local price. This can happen at any time, so that a setpoint change may lead to immediate change in compressor state, or may cause the expected duration of compressor operation (or period of non-operation) to be longer or shorter than would have occurred without the setpoint changing. Compressors have a 10 minute minimum cycle time as short cycles are energy inefficient.

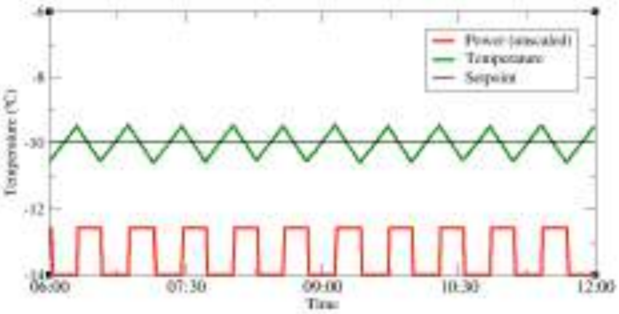

Figure 2. Constant price freezer operation

Optimizing Demand Patterns

When the sun is shining, power is more available than when it is not. Consuming at night requires storing power in a battery which entails capital cost for the battery and associated hardware, as well as energy losses from the round-trip through the battery. Thus, it is advantageous to concentrate electricity demand during the day, and to match as well as possible the loadshape of PV output. Doing this can reduce the size of the battery needed as well as the energy losses.

The context of our analysis is a system with a nanogrid controller which assesses available electricity supply (from solar and battery), current demand, and past history, to set a current price and forecast of future prices. The system reduces the price of electricity in accordance with actual and forecast solar output, with the lowest price corresponding to the highest output, as shown in Figure 1. Devices can use the price to concentrate their consumption in the middle of the day.

In general, the price and forecast can change at any time. Periods of constant price can be of any length and do not need to be the same as other periods. When the price or forecast changes, then devices may adjust their operation.

We used periods of 10 minutes for the price forecast, so that the setpoint for each unit also changed every 10 minutes. In our analysis, we did not change the actual price trajectory from that in the forecast; however, a nanogrid controller can change the forecast at any time. The shape of the price should match the supply/demand condition, so in this case it is simply the inverse of the supply.

Compressor operation is based only on the setpoint value (and minimum cycle time) so is not directly a function the electricity price. Similarly, the setpoint is based only on the price so it not directly a function of the PV output (or supply/demand balance generally). Each step of the process is as simple as possible, to enable more complex systems while keeping the complexity contained.

Figure 3 shows these distinct steps of operation in this system. In this case, the effect of changing the initial signal has a clear and direct effect on the device behavior, but this separation of functionality enables much more complex systems as described later in the paper.

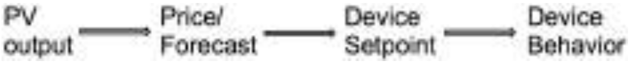

Figure 3. Basic sequence of control operations

Dynamic refrigerator operation is similar to that of a freezer, except that with a smaller temperature range available, the degree that consumption can be concentrated during the day is reduced.

Single Device Results

Figures 4 and 5 show freezer operation with a dynamic price. Figure 4 presents the entire day. Figure 5 is a close-up to show incremental setpoint changes and the how the unit changes operation from night (compressor mostly off) to day (compressor mostly on). Figure 6 shows the power consumption of the freezer operation from Figure 4; it is plotted as average power over each cycle of compressor on-time and off-time. For the variable price case, the freezer understands that there is a ‘day mode’ and ‘night mode’ of operation, where prices are lower during the day. It detects which mode it is in and for how long it will remain in that mode by looking at the trajectory of future prices. In night mode, it sets the setpoint to linearly move from its current point to its maximum point over the course of the night. In day mode, it adjusts the setpoint non-linearly, to have the greatest change in setpoint when the price is lowest, at the middle of the day.

Multiple Device Results

Nanogrids enable power to be exchanged locally within a building or community. Exchanges occur when prices are different in adjacent nanogrids, indicating different availability. Sharing power evens out the spikes of consumption that individual device operations produce.

To explore this, we simulated fifteen freezers (and fifteen refrigerators), with power levels and rates of temperature increase and decrease similar to our basecase units, but slightly randomized. The starting condition (internal temperature and compressor status) were also randomized. We did not want many units to change operation simultaneously, and so updates to the price/forecast was delayed by up to nine minutes to that at most two receive the update each minute. The compressor cycling of ten freezers is shown in Figure 7; the overall pattern is consistent—more on-time during the day—but their cycling details are random.

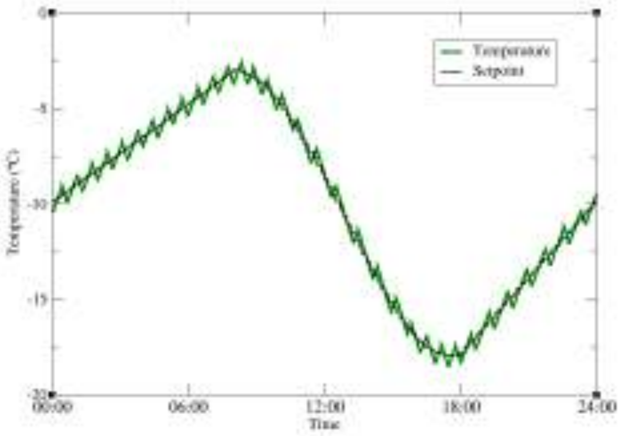

Figure 4. Variable price freezer operation – one day

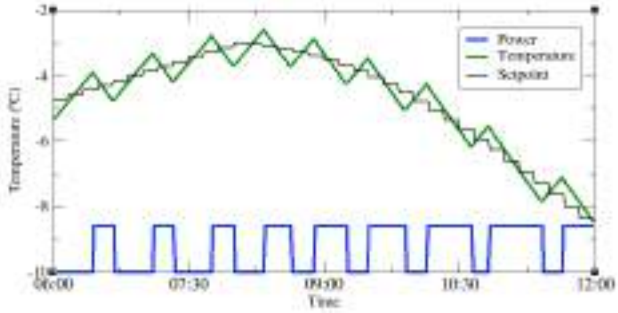

Figure 5. Variable price freezer operation – six hours

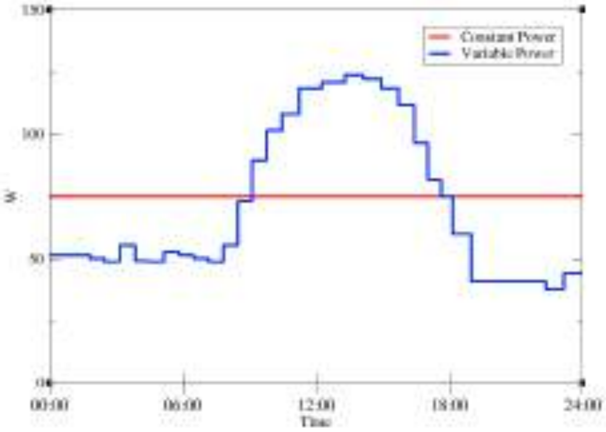

Figure 6 . Variable price freezer operation – power

The total energy use for the fifteen units of each type are shown in Figures 8 and 9. These are plotted as averages for each hour to eliminate short-term variations which obscure the overall pattern. We simulate both a constant price a (and so constant setpoint) and a variable price. Also on these figures we show the PV output required for the constant price scenario. The power under the PV output curve but above each total power line is stored in the local battery, to be withdrawn for use in the night hours, minus the round-trip energy loss. There is a greater difference between the two cases for freezers since they have more ability to shift energy use.

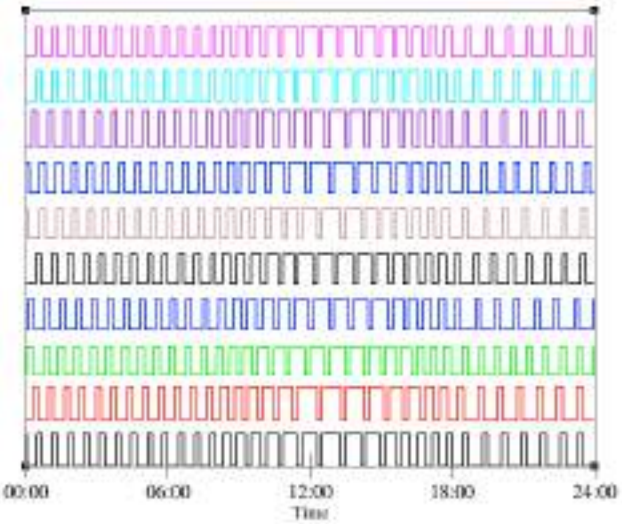

Figure 7. Compressor cycling for ten (of 15) freezers

Discussion

In principle, the night-time total power should be relatively flat from midnight until 08:00; we also did simulations with hundreds of freezers and refrigerators and produced that result. That the total in Figures 8 and 9 is not flat is due to the small number of units. For the evening hours, the cycling of refrigerator power is a result of most units being in compressor off mode after the setpoint has stabilized, since most were on as the setpoint was dropping. Then, as the setpoint begins to rise, most of these start their compressors, creating the pattern. Further randomization could avoid this alignment.

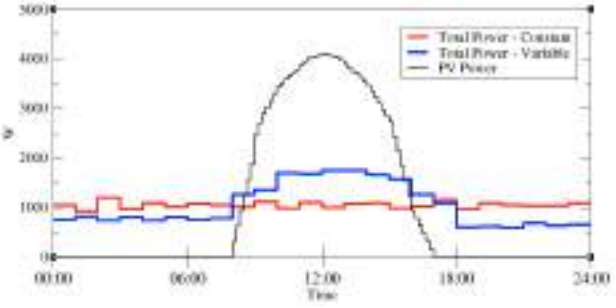

Figure 8. Constant and variable 15-freezer operation

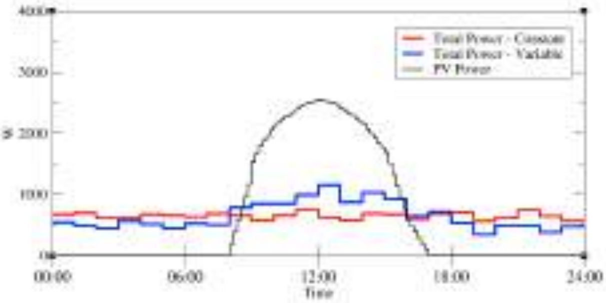

Figure 9. Constant and variable 15-refrigerator operation

Table 1 shows the primary quantitative results, which compare each constant price case with the percent change that occurs when variable prices are introduced. The table shows absolute energy values for the constant price case, and the percent change when moving to the variable case. Direct PV energy is the amount used directly from the PV panels by the units. Generation in excess of what the units consume is stored in the battery. Battery energy is the amount required from the battery. Excess PV consumption must be 10% greater than the energy drawn from the battery. The total unit consumption between the constant and variable cases is nearly identical.

With a time-varying price, the devices still consume power during the night and so rely on batteries, but less so than for the constant price case. With a constant price, about 35% of daily energy is consumed directly from the PV system. 16 and 10 kWh of battery output are needed, with 10% of these values lost in the charge/discharge cycle. So, the PV system would need to be 1.4-1.6% larger in the constant price case to deal with the additional battery roundtrip losses. With a variable price, about 50% of energy is consumed directly from the PV system output, and the battery size (and corresponding energy loss) is reduced 21-16%. .

These energy and battery capacity savings are the most obvious and valuable benefits of this change in device behavior, but not the only ones. The rate at which PV power must be absorbed by the battery is also reduced. For these cases, the maximum hour of excess PV power has is reduced by 24% and 21%. Battery chemistries have different limits on energy densities, charge rates, and discharge rates, so that being able to reduce this is an advantage.

Table 1. Results for one day for 15 units of each type
all values except % are energy in kWh/day

	Freezer		Refrigerator	
	Const.	Var.	Const.	Var.
Device energy	25.1		15.5	
Direct PV energy	8.6	12.8	5.4	7.5
Direct TV fraction of total	34%	51%	35%	48%
change constant to variable	49%		37%	
Battery energy	16.4	12.2	10.1	8.0
change constant to variable	4.2		2.1	
change constant to variable	-26%		-21%	
Battery loss (kWh)	1.64	1.22	1.0	-.8
change constant to variable	0.42		0.21	

There are two ways to interpret these benefits. One is that less hardware is needed to accomplish the desired tasks—less generation, conversion, and storage. The other is that for the same infrastructure, more benefit can be obtained — more energy available, and more storage available.

This analysis is for simple and fixed variations in generation and hence supply/demand balance, but the ability of devices to respond to changing prices can be used in complex grid topologies with many sources and end-use devices. All that is required is for each local grid to set a local price to reflect its own conditions, and use that in exchanges with other grids to help shape the local prices of adjacent grids.

Figure 10 shows a more general flow of information for a local grid context. The grid controller may have multiple potential sources of power, and may be able to transfer power to other grids. Each of these has a price/forecast associated with it to take into account. The battery state-of-charge will also affect price determination, depending on whether the controller is actively seeking to charge the battery, or let it discharge. Some of the information flows are actually bidirectional, such as with other sources. Power can also flow along many of these links, and in some cases, such as with the battery and other local grids, can reverse direction.

Figure 10. Information flows in local grids

Additional Issues

Varying the temperature in a refrigerator or freezer is not the normal mode of operation, but should not impact general food storage. There are limits that should not be passed certainly: temperatures that are too cold can freeze vegetables; temperatures too high can lead to premature spoilage, particularly in sensitive items such as milk. Users of a refrigerator and freezer can use knowledge of what they are putting in it to select appropriate limits, and to change them over time as their usage changes.

Given the high cost of electricity in many energy access contexts, attention has been given to making devices that are more efficient than might be economically justified for a unit that faces low electricity prices. These would most likely be different from more conventional units in having much better insulation. This would reduce the total electricity requirement, but would also mean that temperatures would rise more slowly, which would enhance the ability of a price-modulated control to concentrate energy use during the day. Using DC power also has efficiency advantages when coupled with local DC generation and/or storage (Garbesi et al., 2011).

Further Work

Any local grid will have a variety of devices, with electronics and lighting being among the most common. All of these can take a price and forecast into account in their operation. Lights might dim as prices get high, and turn off entirely when a threshold is reached. Electronics can modulate consumption, such as dimming displays or powering down to sleep more quickly. Water pumps can similarly serve as storage, operating when electricity is inexpensive and storing the water in tanks for use at a later time. The local price and forecast will drive decisions about when to charge and discharge a battery, and battery capacity in turn can help shape the local price.

While this project had price a simple function of local PV power, the forecast can be more complex and variable. With more complicated price trajectories, a more sophisticated algorithm would be needed to shape demand across multiple periods of high and low price during one day. In addition, for units with automatic defrost, defrost cycles need to be scheduled about once a day and can be set to occur at a time of relatively low cost. To avoid many units defrosting at the same time, they should randomly select a defrost time across a range of times where the cost is reasonably low.

If power suddenly becomes scarce during the day, the local price and forecast will be changed to quickly rise in response. This could then cause refrigerators to stop dropping their setpoint so that units that have their compressor off will delay turning them on, and units that are on will turn off more quickly. When the situation reverses, devices will automatically change operation.

The refrigerator characteristics used were from commercial units in industrialized countries. In the energy access context with more expensive power, it could be beneficial to insulate the units to a greater degree; this would reduce energy use overall, and would also enable a higher proportion of concentrating energy use during the day due to less energy needed at night to maintain the setpoints.

Conclusion

A local electricity price is a simple and universal mechanism to reflect the local supply/demand condition. Our analysis showed that such a price can be used to change freezer and refrigerator operation to make better use of local generation, and reduce hardware needed for battery power and losses associated with using battery storage.

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