Flexible Loads in Future Energy Networks

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ABSTRACT

We develop a vignette of an information-rich energy network with flexible and responsive electrical loads in the form of a domestic refrigerator augmented with a thermal storage system and a supply-following controller that responds to the availability of fluctuating renewable sources. We fully characterize our prototype thermal storage-enhanced refrigerator. Using this, we investigate the behavior of a network of such loads at statewide scale in the context of a dynamic model of deep penetration of renewable sources. Our results show that with 10% penetration of thermal storage across refrigeration and freezer load on the California electricity grid, peak fossil fuel load can be reduced by nearly a gigawatt. The approach naturally extends to similar applications in thermal management of buildings and would operate in concert with smart vehicle charging.

1. FUTURE ENERGY NETWORKS

The nature of the electricity grid is evolving from a relatively small set of fully dispatchable generators powering a massively distributed set of oblivious loads to a more integrated, cooperative network of sources and loads with a far more extensive data overlay of control and management. Numerous trends across the energy sector – among them, renewables portfolio standards, the emergence of inexpensive wireless sensors and actuators for dense monitoring and management of energy systems, and the explosion in availability of competitive renewable generation – are pushing a transition where maintaining the match between supply and demand changes from a completely centralized task managed by electricity providers to a distributed one involving providers as well as consumers. These policy and technological trends point to a future grid where large supplies of non-dispatchable renewable generation dominate. However, deeper renewables penetration increases supply variability, exacerbating the challenge of supply-demand matching.

Some future reports have begun to document this challenge, though specific assumptions in models of future grids vary widely. Previous work introduced a model of a future instance of the California electricity grid with 60% of its electricity generated from renewable sources [1]. This grid presents a different set of challenges than today's grid does: instead of heavy fossil fuel use in the summer to accommodate a large air conditioning load, the scarcity in a grid with heavy renewables penetration occurs in the winter; this is the time the fossil fuel resource gets used. With an inability to control renewables generation, mismatches occur more often; flexible loads can respond to these mismatches. In this work, we extend the model to analyze the grid-scale ramifications of a massively distributed, agile energy storage resource represented by a network of energy loads.

2. FLEXIBLE LOADS WITH ENHANCED STORAGE

The class of flexible loads that incorporate energy storage are an underused and potentially highly valuable resource for electric grids. These types of loads, primarily refrigeration and freezer systems but also electric vehicles or rooftop ice storage systems, are already widely deployed – for example, over 99% of U.S. homes have a refrigerator, and turnover is relatively fast, with more than half of refrigerators being replaced within seven years of purchase. Also, unlike battery storage, thermal storage has high turn-around efficiency and nearly infinite charge cycles.

To evaluate the energy storage potential of this type of load, we developed a prototype system that couples these relatively simple mechanical systems with information technology and communications systems. For our study, we employ a typical domestic refrigerator, a Whirlpool/KitchenAid unit with a 13.1 cubic foot refrigerator compartment and a 5.0 cubic foot freezer compartment. To better grasp physical system operation, we augmented it with a network of thermocouples and power sensors to monitor its environmental and electrical operation. This network is connected via a 6LoWPAN-compliant IPv6 edge router.

To enhance device flexibility, we designed and installed a thermal storage system to augment a domestic refrigerator. The prototype system consists of three sealed tanks added to the freezer compartment and filled with a phase change material (19.7% ammonium chloride) for energy storage. In an aqueous solution, this nontoxic substance freezes at -15.4 $^\circ$ C, just above the freezer operating range. To aid heat transfer, a low-freezing-point propylene glycol-based solution is circulated through the tanks to a heat exchanger in the refrigerator compartment by a small fluid transfer pump that is outside of the refrigerator. A comparison of the performance of the refrigerator with and without additional thermal storage is provided in Table 1. This is a prototype design; we believe that a commodity system would be integrated into the refrigerator and its internal control system, possibly providing insulation along with thermal storage capability while consuming minimal additional power.

e-Energy'13, May 21–24, 2013, Berkeley, California, USA.
ACM 978-1-4503-2052-8/13/05.

Fridge Configuration	Unmodified	Enhanced with Energy Storage
Mean Power	76.69 W	86.55 W
Duty Cycle	53.32%	60.14%
Mean Compressor Duration	1558 s.	1762 s.
Mean Defrost Duration	11.4 mins.	11.4 mins.
Mean Heating Post Defrost	13.5 mins.	3.1 mins.
Defrost Frequency	15 hrs.	13.7 hrs.

Table 1: Comparison of power consumption and cycle behavior of two fridge configurations. Values are calculated over a 12-day, unperturbed period.

3. EVALUATION

In this section, we examine the value of a network of flexible refrigerators to a large electricity grid, first presenting a prototype implementation of a supply-following refrigerator before modeling its effect at grid-scale. Rather than the traditional model where loads obliviously consume energy, the supply-following refrigerator is able to use its communicative ability to monitor grid conditions, consuming electricity when most advantageous and avoiding it otherwise. We implement a control algorithm that observes a real-time renewables generation feed from the California ISO and selects from among three operating modes. It operates in either low-supply mode (<2250 MW), avoiding defrost cycles while maintaining a slightly warmer temperature; medium-supply mode (2250-2750 MW), operating conventionally; or high-supply mode (>2750 MW), using shorter, colder, more frequent cycles. Figure 1 shows operation of the fridge over 24 hours and provides mean power consumption in each mode.

Looking at the results, we notice how dynamic a supply-following refrigerator can be as compared to a conventional refrigerator. The fridge is able to change its setpoint and curtail a defrost cycle automatically in order to reduce power. Further, the fridge operates on precisely the opposite pattern from what today's grid operators favor – it consumes little energy at night when renewables are scarce, but it consumes more during the day when solar energy is available. Also, note that medium-supply mode consumes nearly as much as high-supply mode – we believe this is an artifact of the particular day of operation and that in a longer deployment, medium-supply mode would approach its steady state consumption of 87 W, provided in Table 1. The stratification of power levels may also be enhanced with forecasting and response to grid demand. We acknowledge that the temperature ranges experienced by the compartments may be near the borders of their recommended ranges. We attribute this to the preliminary nature of the work and some bugs in control software. Nonetheless, we believe this is the first instance of a supply-following refrigerator, responding directly to real-time power availability.

The applications of such a technology are wide-ranging. A fleet of refrigerators could provide balancing to operate a renewable generation source as a baseload power plant. Instead, since utility expenses are often driven by high capital costs for underutilized facilities, flexible refrigerators could flatten duration curves of fossil fuel resources, relocating high-cost peak consumption to lower-cost times. Table 2 documents summaries of duration curves of natural gas generation in a 60% renewable grid with penetration of agile refrigerators ranging from 0% to the full capacity of refrigerators in California, 3 GW. Having even a fraction of the fridge capacity be agile provides extreme value; with 10% of the fridges agile, an entire gigawatt of supply can be obviated – nearly half the maximum possible peak natural gas reduction. Though very preliminary, these results highlight the potential of the emerging class of flexible electric loads.

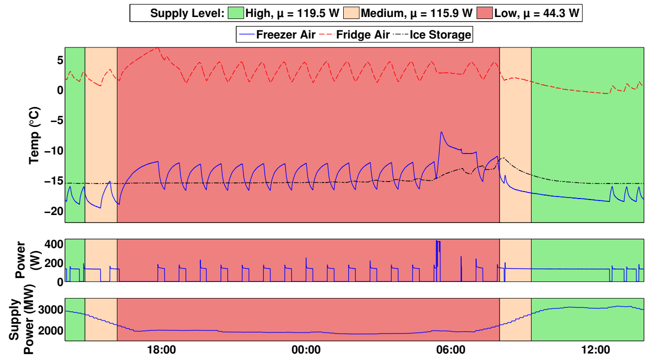

Figure 1: Operation of the thermal storage refrigerator as a supply-following load. The refrigerator operates in one of three power modes based on real-time grid availability of renewable power.

% of Hours	Fridge Penetration 0% (GW)	10% (GW)	25% (GW)	50% (GW)	100% (GW)
Max	19.528	18.628	18.108	17.757	17.235
0.1	16.693	16.457	16.290	15.928	15.385
0.5	14.569	14.252	13.962	13.734	13.597
1.0	13.905	13.633	13.382	13.099	12.971
5.0	11.314	11.238	11.106	10.969	10.982
10.0	9.588	9.567	9.532	9.574	9.482
50.0	0.000	0.000	0.000	0.000	0.000
100.0	0.000	0.000	0.000	0.000	0.000

Table 2: Summaries of duration curves for natural gas generation sources in a 60% renewable grid. Columns represent different penetration levels of thermal storage refrigerators in California.

4. CONCLUSION

In this work, we present an inexpensive augmentation to a domestic refrigerator that enables a common household appliance to become a critically valuable electricity grid resource. By adding minimal equipment, improved sensing, and simple control functionality, we can reduce peak electricity demand and accommodate increased renewables penetration, creating a more sustainable electricity grid. We intend that these lessons can be assist in designing thermal and other energy storage systems and more advanced modeling and control processes for managing them.

Acknowledgments

This work is supported in part by the National Science Foundation under grants CPS-0932209 (LoCal), CPS-0931843 (ActionWebs), and CPS-1239552 (SDB). We thank Albert Goto and Stephen Dawson-Haggerty for deployment help.

5. REFERENCES

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