ORNL/TM-2022/2679
CRADA/ NFE-19-07846

CRADA Final Report: CRADA Number NFE-19-07846 with Grid Fruit, LLC

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MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Prepared by
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1. Abstract

Cooperative Research and Development Agreement (CRADA) NFE-19- 07846 between Oak Ridge National Laboratory (ORNL) and Grid Fruit, LLC (Grid Fruit) focused on simulating, monitoring, and adjusting controls of commercial refrigerator and freezer systems to provide load flexibility and demand response services from these machines. Viewing these medium and low-temp coolers as thermal masses, the volumes of chilled air in these coolers make them time-shiftable loads ripe for deployment at optimal times. Grid Fruit is a startup company developing methods to schedule the chilling cycles (e.g., in "build load" and "shed load" grid events) to provide energy efficiency, peak shifting, and other benefits both to the grid and the broader environment. These benefits can be magnified by coordinating chillers with HVAC, lights, computers, and other loads. Grid Fruit completed simulations and then selected and ordered controls hardware to prove the technology were successful, but the diversity of chiller models in the field without digital controls, as well as limited market demand at present, make further exploration necessary before commercialization.

2. Statement of Objectives

The objectives of the CRADA and their relevant tasks are as follows.

1. Project management, equipment training, and maintenance

Facility walkthroughs and ORNL trainings were needed to secure lab access and to ensure safety throughout Grid Fruit's use of the premises. Technical project management was the main objective that covered these different components that constituted Task 1.

2. Optimization and algorithm development

2.1 Complete feasibility and economic analyses of an off-the shelf defrost controllers
2.2 Formulate numerical optimization problem with objective function
2.3 Develop algorithm to manage network of controllers

3. Software and Initial Testing

3.1 Write software implementing network management algorithm
3.2 Test algorithm in simulation
3.3 Test algorithm in pilot implementation

4. Processing Results and Reporting

4.1 Compile results to determine most promising approach
4.2 Use results to select control parameters
4.3 Write final report for this CRADA and submit

3. Benefits to the Funding DOE Office's Mission

Load flexibility and efficiency innovations in the energy market are difficult to implement at scale across the residential sector. These benefits can be provided from the commercial sector with far fewer buildings engaged. Collaborations with the Building Equipment Research Group and Building Technologies Research and Integration Center (BTRIC) at ORNL helped analyze and address these issues. The expertise by BTRIC in commercial refrigerators and freezers helped Grid Fruit learn standard controls typical in US supermarkets. In return, Grid Fruit's technology has the potential to assist BTRIC in its mission to integrate commercial chillers with the grid for demand flexibility benefits.

4. Technical Discussion of Work Performed by All Parties

This is a report based on the work performed in the aforementioned task list. Task 1 involved walkthroughs and trainings required by ORNL to secure lab access and to ensure safety throughout Grid Fruit's use of the premises. Grid Fruit completed these steps, including security and equipment-specific briefings, and officially registered to use ORNL's FRP-1 lab space. Grid Fruit also carried out program-level and technical project management throughout the project, as specified in Task 1.

As proposed, for Task 2 Grid Fruit did feasibility analyses of an off-the shelf defrost controller. The team went beyond the required task by analyzing and comparing two different off-the-shelf controllers from the two major manufacturers. The first, manufactured by Danfoss, is installed in ORNL's FRP-1 lab. The second, made by Emerson Electric, was loaned to Grid Fruit by a Nashville-based refrigerant data company called Trakref. Upon testing both controllers, Grid Fruit found they were designed to be closed systems that would not allow another company's software to run as a layer on their control system. Therefore, Grid Fruit began pursuing their own controller hardware as well as focusing on smaller stores that do not use Danfoss or Emerson controllers. The cost of the additional hardware required made the solution economically infeasible.

Also for Task 2, the Grid Fruit team developed an algorithm to manage network of refrigeration controllers, specifically focused on optimizing the timing of their defrost cycles based on the grid's seasonal on-peak hours. Grid Fruit published the optimization algorithm below with explanation of the variables (as well as other steps completed in Tasks 2, 3, and 4) in a conference article under titled, "Optimization of Refrigeration Defrost Schedules for Demand Shifting in Commercial Buildings" by Carolyn Goodman, Jesse Thornburg, and Javad Mohammadi. Jesse Thornburg presented the paper at the IEEE Green Technologies Conference in April 2021.

$$\min_x \quad a\hat{\rho}_{tou}^T \hat{P}_{tot}(x) + b\rho_{dcf} \max \hat{P}_{tot}(x) + \\ b\,\boldsymbol{M}\,\boldsymbol{W}\rho_{dct,on} \max\left(\boldsymbol{I}_{T_{on}} \cdot \hat{P}_{tot}(x)\right) + \\ b\,\boldsymbol{M}\,\boldsymbol{W}\rho_{dct,mid} \max\left(\boldsymbol{I}_{T_{mid}} \cdot \hat{P}_{tot}(x)\right)$$

where

$$\hat{P}_{tot}(x) = \hat{P}_{base} + \sum_{i=1}^{n_{cases}} \Big(circshift(R_{def,i}, x_i) \cdot \hat{P}_{def,i} \\ + circshift(R_{dd,i}, x_i) \cdot \hat{P}_{dd,i} \\ + circshift(R_{postdef,i}, x_i) \cdot \hat{P}_{postdef,i} \Big)$$

In the above equations

$0 \leq x \leq n$

$\boldsymbol{M} = 1$ if June through September, 0 otherwise

$\boldsymbol{W} = 1$ if weekday, 0 otherwise

$\boldsymbol{I}_{T_{on}} = (i_{on,1}, i_{on,2}, \ldots, i_{on,n})$

$\boldsymbol{I}_{T_{mid}} = (i_{mid,1}, i_{mid,2}, \ldots, i_{mid,n})$

$\boldsymbol{H} = (h_1, h_2, \ldots, h_n)$

where $I_{T_{on,l}} = 1$ if $h_l \in T_{on}$, $I_{T_{on,l}} = 0$ if $h_l \notin T_{on}$

where $I_{T_{mid,l}} = 1$ if $h_l \in T_{mid}$, $I_{T_{mid,l}} = 0$ if $h_l \notin T_{mid}$

$R_{def,i,l} = 1$ if $0 \leq l < L_{def,i}$

or $\frac{n}{2} \leq l < \frac{n}{2} + L_{def,i}$

$R_{dd,i,l} = 1$ if $L_{def,i} \leq l < L_{def,i} + L_{dd,i}$

or $\frac{n}{2} + L_{def,i} \leq l < \frac{n}{2} + L_{def,i} + L_{dd,i}$

$R_{postdef,i,l} = 1$ if $L_{def,i} + L_{dd,i} \leq l < L_{def,i} + L_{dd,i} + L_{postdef,i}$

or $\frac{n}{2} + L_{def,i} + L_{dd,i} \leq l < \frac{n}{2} + L_{def,i} + L_{dd,i} + L_{postdef,i}$

$\hat{P}_{base} = \hat{P}_{nodef} + 0.9\mu(\hat{P}_{ref} - \hat{P}_{nodef})$

Task 3 involved developing a physics-based simulation of a food retail store (specifically a 7-Eleven convenience store) with one of the chain's standard layouts of commercial refrigerators, freezers, and other loads. This simulation was developed by Grid Fruit using Energy Plus building modeling software. Grid Fruit developed further optimization and machine learning algorithms in Python.

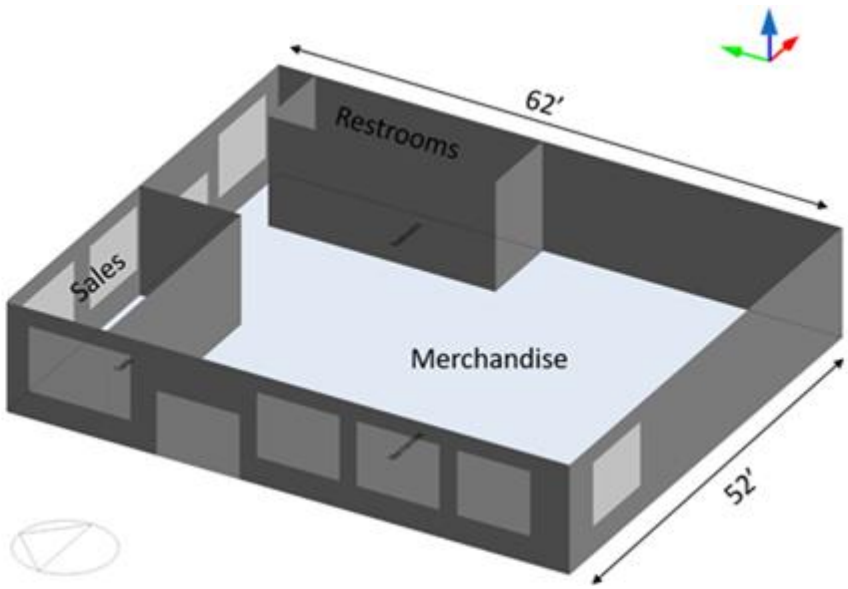

Figure 1: Convenience store floorplan and thermal zones modeled in EnergyPlus

For implementation on ORNL's main campus, Grid Fruit installed a microcomputer at the FRP-1 building and also tested manual controls of the refrigerator unit there. They were delayed coordinating the refrigerator with the onsite freezer for the rest of the proposed testing, since the freezer's compressor has been broken for around two years. Thankfully late summer 2022 ORNL's Buildings group repaired the freezer. The freezer has just started running correctly again, enabling the future collaborations described in section 7 below.

For pilot implementation as mentioned in Task 3.3, Grid Fruit added sensors and microcomputers to commercial refrigerators and freezers at two food retail stores (one a small grocery and restaurant, the second a general store and carry-out food provider). From this instrumentation, Grid Fruit collected data and developed an online dashboard that updates in real time with that data. Grid Fruit gave dashboard access to multiple stakeholders (our team, the store owners, and the utility partners seeking demand flexibility services). With the dashboard these parties can now monitor certain refrigerator and freezer cycles including defrost. Grid Fruit selected and purchased control hardware for the major refrigerators and freezers in these stores, namely walk-ins and open display coolers. Grid Fruit installed controllers at one of the stores, and they have a mechanical services provider engaged to install the controllers at the second store, so both can provide on-demand demand flexibility services. Once the second store is equipped, Grid Fruit will complete load scheduling tests (including defrost scheduling commands and more general shed load/build load signals).

Table 1: Annual benefits of optimized defrost scheduling in California climate zones 6 (containing Los Angeles) and 14 (containing San Bernardino)

	Climate Zone 6			Climate Zone 14		
	Staggered	Reference	Optimal	Staggered	Reference	Optimal
Time-of-Use Charge	\$173.1K +0.17%	\$173.3K +0.28%	\$172.9K -	\$170.2K +0.18%	\$170.4K +0.27%	\$169.9K -
Demand Charge	\$114.6K +6.23%	\$113.3K +5.02%	\$107.9K -	\$123.8K +8.48%	\$120.6K +5.60%	\$114.2K -
Total Charge	\$287.7K +2.50%	\$286.6K +2.10%	\$280.7K -	\$294.1K +3.52%	\$290.9K +2.41%	\$284.1K -
Emissions (tCO_2)	465.3 +0.50%	462.4 -0.14%	463.0 -	456.3 +0.52%	452.9 -0.21%	453.9 -

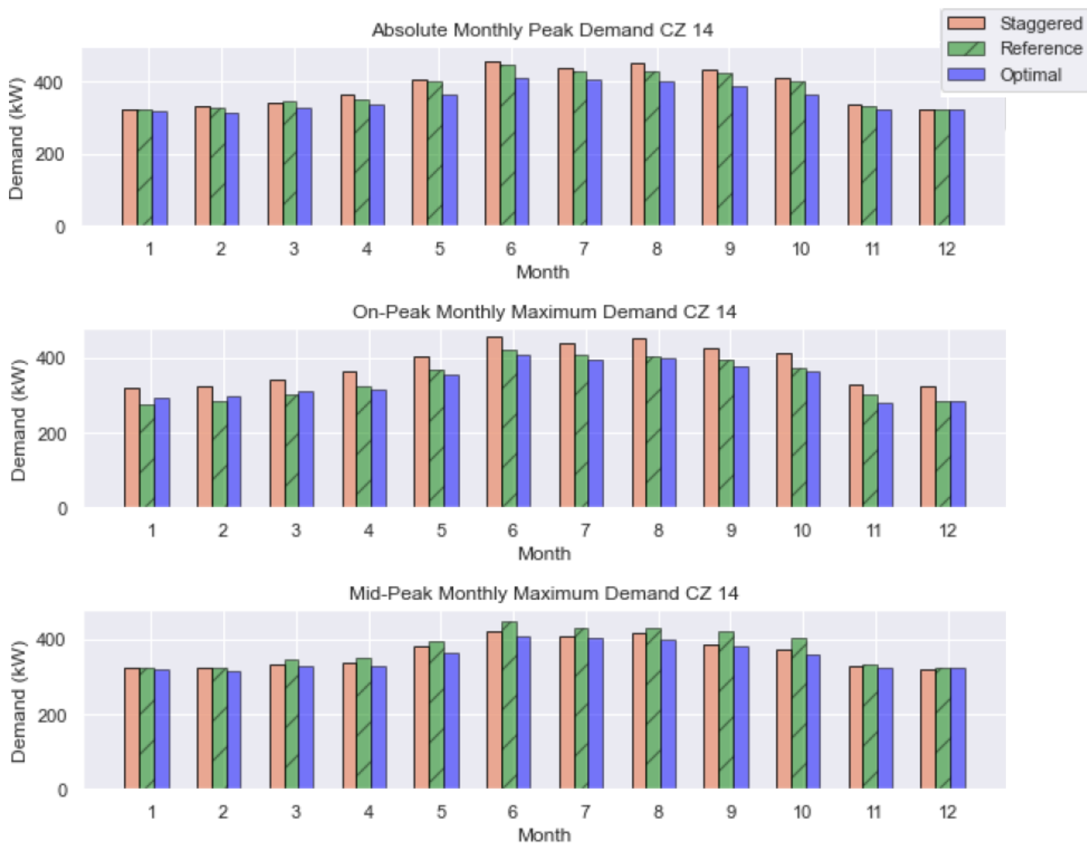

Figure 2: Graphed comparison of power demand (kW) for staggered, optimal, and reference cases by month of the year in California climate zone 14 (e.g., San Bernardino)

For Task 4, Grid Fruit applied the above optimization algorithm in simulation to the refrigerators and freezers of the standard 7-Eleven convenience store layout. The team then computed annual cost benefits (see Table 1) and monthly demand reduction benefits (see Fig. 2). In addition to being presented by Jesse Thornburg in the conference mentioned above, these results were published in the following book chapter.

C. Goodman, J. Thornburg, S. K. Ramaswami, and J. Mohammadi. “Building Power Grid 2.0: Deep Learning and Federated Computations for Energy Decarbonization and Edge Resilience,” in *Deep Learning Applications, Volume 3*; M. A. Wani, B. Raj, F. Luo, and D. Dou, Editors. Basingstoke, UK: Springer, 2021.

The results in Table 1 and Fig. 2, together with the control adjustments applied in simulation, fulfill Tasks 4.1 and 4.2. The writing and submission of this report to ORNL constitutes the final proposed step, Task 4.3.

5. Subject Inventions (As defined in the CRADA)

None.

6. Commercialization Possibilities

Grid Fruit projected commercialization possibilities in light of he results presented above, together with the learnings from the hardware controllers (concluding that additional hardware was necessary). From specifying and ordering the additional hardware required, Grid Fruit found that the hardware cost per refrigerator or freezer was

7. Plans for Future Collaboration

Further research into integrating commercial chillers into the grid would be an effective use of the FRP-1 building’s chiller equipment, which often sits dormant. Testing on these machines would also build the credibility of Grid Fruit’s technology, instilling confidence in food store owners and managers to implement the technology in their retail buildings. Therefore, a research plan for collaboration with the Building Equipment Research Group has been developed as an ORNL subcontract in Grid Fruit’s Phase II SBIR with DOE’s Office of Energy Efficiency and Renewable Energy. This SBIR project was approved and is now running, with the subcontract expected to be carried out in the coming year. Grid Fruit hopes to continue collaborations with the Building Equipment Research Group at ORNL as the company continues to explore energy efficiency and load flexibility applications.

8. Conclusions

During this CRADA, Grid Fruit developed a robust simulation model of commercial chillers in food retail was developed. The controls technology developed by Grid Fruit was successfully installed and commissioned in a food retail store for testing and validation. The industry standard of closed controllers plus additional, unexpected costs for installing Grid Fruit hardware, as well as the involvement of service people on the ground from multiple disciplines, helped Grid Fruit conclude that this technology is not economically feasible for commercialization or scaling at present. Grid Fruit intends to continue developing energy efficiency and load flexibility technologies and to expand collaboration with ORNL scientists through Grid Fruit’s SBIR Phase II project with DOE.