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Dual-Fuel Hybrid Residential Water Heater – Technical and Laboratory Evaluation

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SUMMARY

This report presents a technical assessment and laboratory evaluation of the Navien Dual-Fuel Heat Pump Water Heater (DF-HPWH), a first-of-its-kind residential water heating system that integrates a 120-Volt (V) electric heat pump with a natural gas backup burner. The system is designed to reduce installation costs by eliminating the need for 240 V electrical upgrades while providing fuel flexibility and maintaining hot water availability during periods of high demand. The technical assessment establishes the foundation for the experimental evaluation by documenting the system architecture, major components, control strategy, operating modes, and mode-transition logic under varying demand and ambient conditions.

The laboratory evaluation included both standardized and advanced performance testing to comprehensively characterize system operation. Standard testing consisted of Uniform Energy Factor (UEF) and First-Hour Rating (FHR) measurements conducted in accordance with U.S. Department of Energy (DOE) test procedures[1], enabling direct comparison with commercially available water heating technologies. Additional testing included load-based evaluations and detailed performance mapping to characterize heat pump and burner performance across a range of inlet water temperatures, ambient conditions, storage temperatures, and representative hot water draw profiles. The resulting dataset was used to develop high-fidelity performance correlations that will support the creation of a physics-based dynamic simulation model capable of predicting real-world operation, fuel consumption, and efficiency under diverse residential conditions.

Table 1 summarizes the measured performance of the 40 MBH and 60 MBH DF-HPWH units under standard operating conditions. The 60 MBH unit achieved a FHR of 98.18 gallons, compared to 81.67 gallons for the 40 MBH unit, demonstrating the benefit of increased burner capacity on hot water recovery performance. In E-Saver mode, both units achieved nearly identical UEF values because the gas burner did not engage during testing and water heating was supplied exclusively by the heat pump subsystem. In Gas-Only mode, the units achieved UEF values of 0.88 and 0.93 for the 40 MBH and 60 MBH units, respectively, consistent with high-efficiency condensing gas water heater performance. Hi-Demand mode produced intermediate efficiencies, with UEF values of 1.22 and 1.85 for the 40 MBH and 60 MBH units, respectively, reflecting coordinated operation of the heat pump and gas burner to provide faster recovery and increased hot water availability.

Additional testing demonstrated that system performance is strongly influenced by ambient temperature, storage temperature, and operating mode. Under warm ambient conditions, the heat pump achieved high efficiencies and operated without gas assistance. As ambient temperatures decreased, heat pump performance declined, resulting in increased electrical consumption, longer recovery periods, and occasional gas burner operation. Testing at elevated storage temperatures with a thermostatic mixing valve demonstrated increased usable thermal storage capacity but also increased standby losses and reduced heat pump efficiency.

[1] https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-430/subpart-B/appendix-Appendix%20E%20to%20Subpart%20B%20of%20Part%20430

Performance mapping generated component-level correlations describing heat pump coefficient of performance (COP), compressor power consumption, burner capacity, and burner efficiency as functions of operating conditions. These correlations provide the basis for future dynamic modeling and annual performance simulations. Demand response testing further confirmed successful communication through the CTA-2045 EcoPort interface, although full operational responses to demand response commands were not yet implemented in the prototype firmware.

Overall, the laboratory evaluation demonstrated that the DF-HPWH successfully combines the efficiency benefits of heat pump water heating with the recovery capability and resiliency of a condensing gas-fired system. The technology offers a promising pathway for residential electrification by enabling high-efficiency operation on a standard 120 V electrical circuit while maintaining customer expectations for hot water availability. Future work will focus on dynamic model development, annual performance simulations, field validation, and verification of production-ready demand response functionality.

The FHR and UEF values reported herein are intended solely for research and product development purposes and do not represent certified performance ratings. Measured results agreed within 1% of the Canadian Standards Association (CSA) performance data provided by Navien, providing confidence in the testing methodology and experimental results.

Table 1: Standardized Tests summary for Dual Fuel Heat Pump Water Heater.

Parameter	40 MBH unit			60 MBH unit		
	E-Saver	Gas Only	Hi-Demand	E-Saver	Gas Only	Hi-Demand
FHR	81.67			98.18		
Recovery efficiency	4.27	0.89	0.95	4.18	0.998	1.84
UEF	3.86	0.88	1.22	3.79	0.93	1.85
Gas-to-electricity consumption ratio	0	107.81	3.92	0	93.50	1.66

Technical Assessment

The Navien Residential 120V DF-HPWH employs a hybrid water heating architecture that integrates a 120V electric heat pump with a natural gas-fired burner rated at either 40 MBH or 60 MBH. The system is designed to provide a flexible and resilient water heating solution that combines the high efficiency of heat pump technology with the rapid recovery capability of gas-fired heating. Figure 1 presents a schematic of the DF-HPWH and its major components.

A key feature of the system is its ability to operate from a standard 120V electrical circuit, eliminating the need for 240V electrical service upgrades commonly required by conventional heat pump water heaters. This design reduces installation complexity and cost while expanding applicability in existing homes. The integrated gas burner provides supplemental heating during periods of high hot water demand, low ambient temperatures, or other operating conditions that limit heat pump performance.

Both heating sources are coupled to a 50-gallon insulated storage tank, allowing the system to balance energy efficiency, recovery capacity, and hot water availability through coordinated control of multiple operating modes. Depending on user selection and operating conditions, the system can operate in heat pump-only, gas-only, or hybrid modes that utilize both heating sources. This integrated approach is intended to maximize energy efficiency during normal operation while maintaining reliable hot water delivery during peak demand periods and cold climate conditions. A summary of key system specifications and component ratings is provided in Table 2.

The heat pump subsystem incorporates a nominal 400 W compressor connected to a wrap-around condenser that surrounds the lower portion of the storage tank, promoting efficient heat transfer to the stored water. The natural gas burner is positioned approximately 22 inches above the bottom of the tank, allowing rapid heat input to the bulk water volume when supplemental heating is required. System operation is controlled through two temperature sensors located at different elevations within the storage tank. The lower temperature sensor primarily governs heat pump operation, while the upper temperature sensor is used to initiate burner operation. Heating source activation is determined by sensor temperatures relative to mode-specific control setpoints, enabling coordinated and dynamic operation of the heat pump and gas burner under varying load conditions.

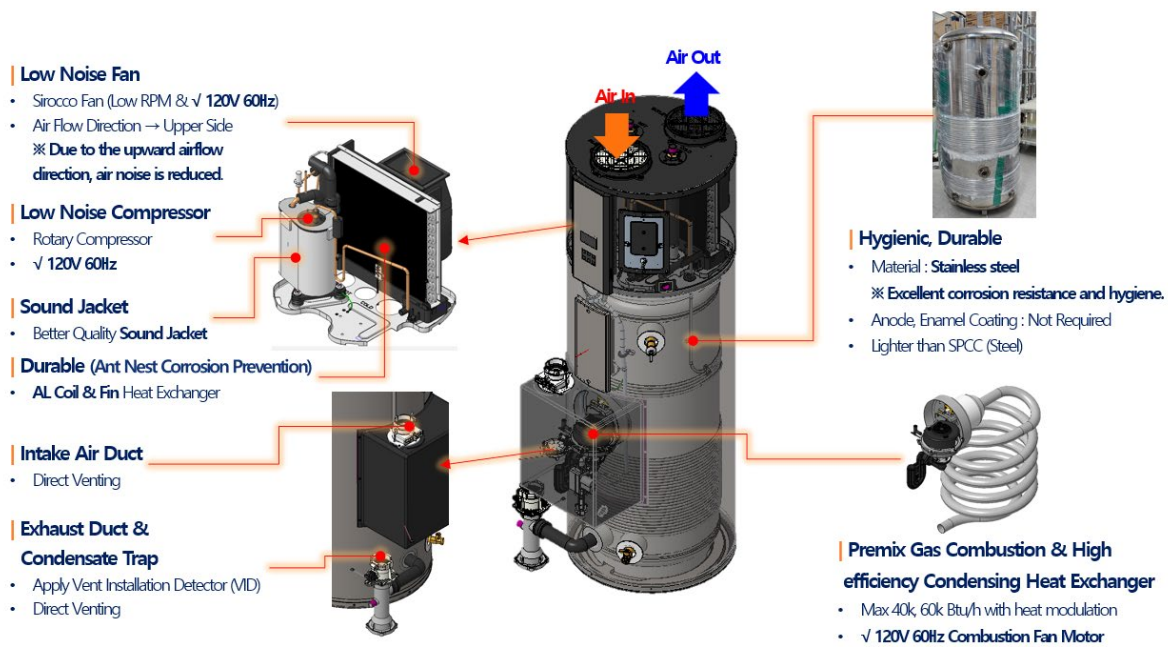

Figure 1: Detailed Schematic of the Navien DF-HPWH.

Table 2: Key Product Specifications.

Parameter	Value
Nominal Volume	50 gal
Gas Capacity	40 MBH | 60 MBH
Type of Gas	Natural Gas
Max. Water Pressure	150 PSI
Temperature/Pressure Valve	150 PSI, 210 °F
Electrical Rating	120V, 60 Hz, 1 Ph | Plug-in
Compressor	3.5 A

Parameter	Value
Fan Motor	0.22 A
Max. Fuse or Circuit BRK Size	15 A
Min Supply Circuit Ampacity	10 A
Refrigerant	R-134a
Refrigerant Factory Charge	800 g
Ambient Temperature Range*	37 °F to 113 °F
Water Temperature	50 °F to 149 °F
*** Final Product Specification pending**	

Operating Modes

The DF-HPWH offers four operating modes that allow users to balance efficiency, recovery performance, and hot water availability based on their specific needs.

E-Saver Mode (Default)

E-Saver mode prioritizes energy efficiency by maximizing heat pump operation. Under normal operating conditions, the heat pump serves as the primary heating source. The gas burner remains inactive unless required to support large hot water draws or accelerate recovery during periods of elevated demand. This mode is intended to maximize electrification and minimize fuel consumption while maintaining acceptable hot water availability.

Hi-Demand Mode

Hi-Demand mode operates similarly to E-Saver mode but incorporates a more aggressive burner engagement strategy. The gas burner is activated at higher tank temperatures and earlier during recovery periods, providing increased hot water availability and faster recovery rates during sustained or high-intensity demand events. This mode balances efficiency and performance by combining heat pump operation with selective gas assistance.

Gas-Only Mode

In Gas-Only mode, the system relies exclusively on the natural gas burner to maintain the storage tank at the user-defined setpoint temperature. The heat pump is disabled and does not contribute to water heating. This mode was implemented primarily for laboratory testing and performance characterization purposes and is not intended to be included as a customer-selectable operating mode in the commercial product.

Heat Pump-Only Mode

In Heat Pump-Only mode, water heating is supplied entirely by the electric heat pump while the gas burner remains disabled. This operating mode maximizes electric-only operation and system efficiency while eliminating direct natural gas consumption.

Laboratory Evaluation

An extensive laboratory testing program was conducted to characterize the performance, operational behavior, and demand response capabilities of the Navien DF-HPWH. The evaluation was designed to quantify standard performance metrics, develop component-level performance correlations for dynamic modeling, and assess the system's ability to participate in demand response programs.

The specific objectives of the laboratory evaluation were as follows:

1. **Quantify Standard Performance Metrics**: Determine the FHR and UEF of the DF-HPWH at a storage setpoint temperature of 120°F under both the default E-Saver mode and Gas-Only mode. The resulting performance metrics are summarized in Table 3 (Tests 1–4). Testing was conducted in accordance with applicable U.S. DOE procedures to enable comparison with commercially available water heating technologies. In addition to standard DOE conditions, supplemental UEF testing was performed at ambient temperatures of 95°F and 44°F to evaluate system performance under hot- and cold-climate conditions representative of outdoor installations.
2. **Develop Performance Correlations for Dynamic Modeling**: Characterize the thermal performance and transient operation of both the heat pump and gas burner subsystems through load-based evaluations and detailed performance mapping. Testing was conducted across a range of operating conditions, including varying ambient temperatures, inlet water temperatures, storage temperatures, and draw profiles. The resulting dataset was used to develop empirical performance correlations describing heating capacity, energy consumption, COP, and thermal efficiency as functions of operating conditions. These correlations will support the development of a high-resolution, physics-based dynamic model capable of predicting annual energy consumption, fuel utilization, and mode-dependent operation of the DF-HPWH under representative residential usage patterns.
3. **Evaluate Demand Response Functionality**: Validate the capability of the DF-HPWH to communicate with and respond to external demand response (DR) signals. Testing focused on verification of CTA-2045 communication functionality, command recognition, and system response pathways to assess the readiness of the platform for future grid-interactive and load-shifting applications.

The laboratory evaluation combined standardized rating tests with advanced diagnostic testing to provide a comprehensive understanding of system performance, operational characteristics, and grid-interactive capabilities across a broad range of operating conditions.

Table 3: Test Matrix.

Test #	Name	Ambient Temp., °F	RH, %	CWT, °F	Set Point, °F 120	140	150	Operating Mode E-saver	Gas-only	Hi-Dem	HP-only
Standard DOE Testing											

Test #	Name	Ambient Temp., °F	RH, %	CWT, °F	Set Point, °F 120	140	150	Operating Mode E-saver	Gas-only	Hi-Dem	HP-only
1-2	FHR†	67.5	50%	58	•			•	•		
3-4	UEF†	67.5	50%	58	•			•	•		
Load-based Evaluation											
5-13	UEF- draw profile	67.5	50%	58	•	•		•	•	•	•
14-15	UEF- draw profile	67.5	50%	58		•		•			
16	UEF- draw profile	67.5	50%	58		•			•		
17	UEF- draw profile	47**	50%	58		•		•			
18	UEF- draw profile	95**	50%	58		•		•			
19-22	UEF- draw profile X 1.75	67.5	50%	58	•			•	•	•	•
23-26	UEF- draw profile X 0.25	67.5	50%	58	•			•	•	•	•
27-28	UEF- draw profile	47**	50%	58	•			•	•		
29-30	UEF- draw profile	95	50%	58	•			•	•		
Performance Mapping											
31	COPhp-50	50	65%	50			•				•
32-33	COPhp-68	67.5	50%	50			•	•			•
34	COPhp-95	95**	50%	50			•				•
35	COPhp-95-dry	95**	20%	50			•				•
36	EEb-50	50	65%	50			•		•		
37	EEb-68	67.5	50%	50			•		•		
38	EEb-95	95**	40%	50			•		•		
DR Validation											
39	UEF-mid	67.5	50%	58	•						•

† = evaluated with the 40 and 60 MBH units.
** = or to maximum/minimum chamber or heat pump capability
CWT = city water temperature, RH = relative humidity, FHR = first hour rating, UEF = uniform energy testing, DR = demand respond, UEF mid = UEF mid profile test
UEF high x 0.25 = UEF draw profile (high draw) multiplied by a 0.25 factor
UEF high x 1.75 = UEF draw profile (high draw) multiplied by a 1.75 factor
COPhp-xx = No-draw COP of the heat pump at given ambient; EEb-xx = Energy Efficiency of the burner at given ambient

DOE Standard Tests

The DF-HPWH was installed and instrumented in GTI Energy's water heating laboratory, as shown in Figure 2, and evaluated in accordance with the U.S. Department of Energy (DOE) test procedures for residential water heaters (10 CFR Part 430). The instrumentation listed in Table 4: Instrumentation list. was used to measure all relevant energy streams, water temperatures, flow rates, and operating conditions required for performance assessment.

Testing was conducted under controlled laboratory conditions with regulated inlet water temperature, ambient air temperature, and relative humidity to ensure compliance with DOE requirements and repeatability of results. In addition to standard DOE rating conditions, supplemental tests were performed at elevated (95°F) and reduced (44°F) ambient temperatures to evaluate performance under climatic conditions representative of outdoor installations.

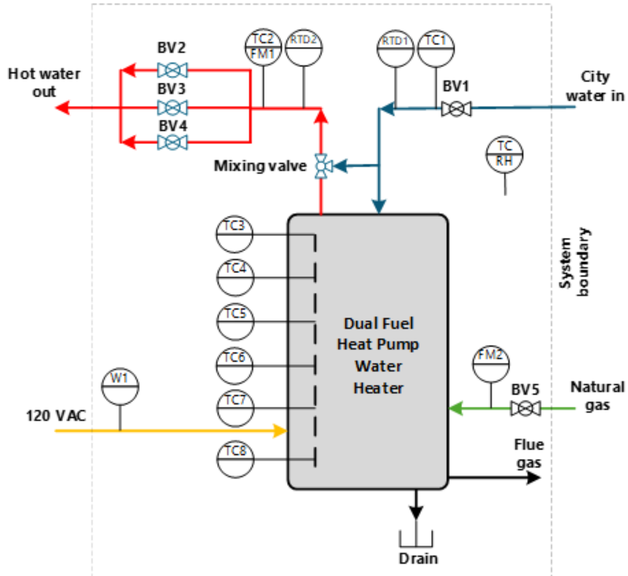

Figure 2: Plumbing and instrumentation diagram (P&ID) of the water heater.

Table 4: Instrumentation list.

What For	P&ID ID	Brand/Part No.	Accuracy
Gas meter	FM2	Alicat Whisper: Low Pressure	±0.8% of reading ±0.2% FS
Temperatures	TC1-2	TMQSS-125G-6	±1.0 ℃
Ambient Temp and RH	RTD3 RH1	Vaisala HMT 130	±0.2 ℃ ±1.5% RH
City water in	RTD1	PR-17L-3-100-1/8-6	Class A
Hot water out	RTD2		
Water loops	FM1	ifm SM6420 (0-9.5 GPM)	±0.8% of reading ± 0.2% FS
Electricity use	W1	Accenergy	0.5% reading

Results and Discussion

First-Hour Rating

Figure 3 and Figure 4 illustrate the temporal evolution of burner firing rate, average tank temperature, outlet water temperature, and hot water flow rate during the FHR tests for the 40 MBH and 60 MBH DF-HPWH units.

At the beginning of each test, a hot water draw of 3.0 ± 0.25 GPM was initiated, resulting in a gradual reduction in average tank temperature and outlet water temperature from the initial setpoint of approximately 120°F. In response to the draw, the gas burner operated continuously to recover the tank and maintain outlet water temperature. Each draw period was terminated when the outlet temperature declined by 15°F from its maximum value. Subsequent draw events were initiated after recovery was completed and the burner cycled off. This process continued until one hour had elapsed from the start of the test. The total volume of hot water delivered during this period represents the First-Hour Rating (FHR).

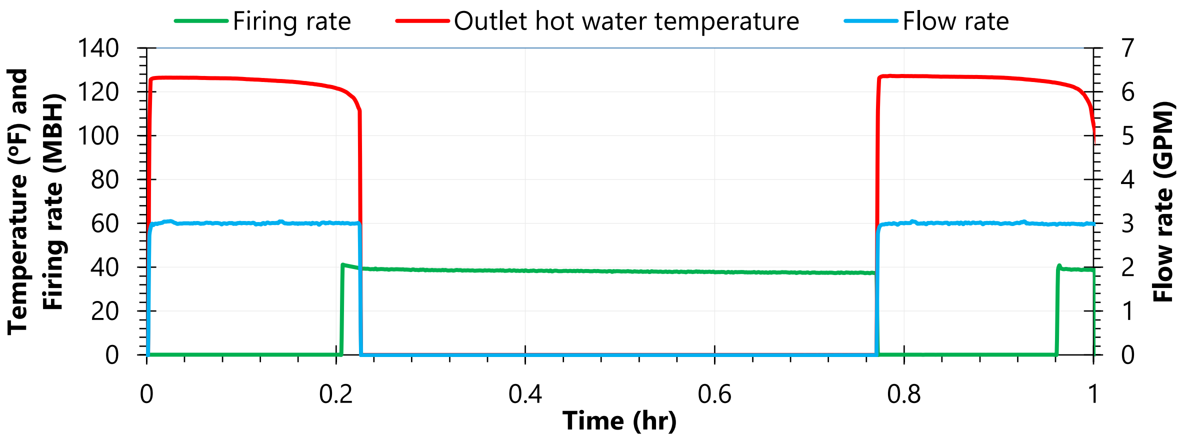

Figure 3: Dynamic operating of the 40 MBH unit during the FHR test.

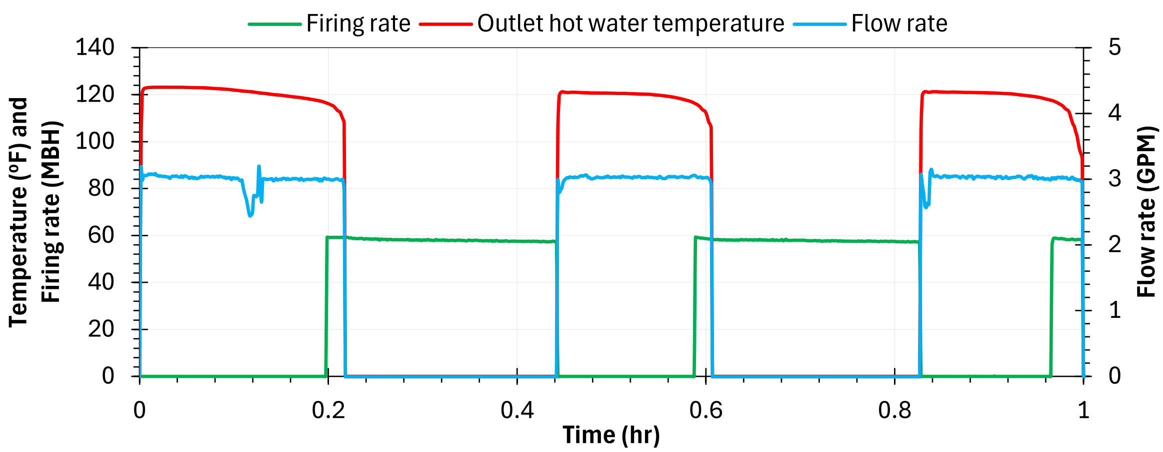

Figure 4: Dynamic operating of the 60 MBH unit during the FHR test.

Table 5 and Table 6 summarize the measured FHR results for both units.

The 40 MBH unit completed two draw cycles during the one-hour test period. Each draw delivered approximately 41 gallons of hot water over a duration of about 13.5 minutes while maintaining average outlet temperatures near the 120°F setpoint. The outlet temperature cut-off values were similar for both draws, ranging from 106.4°F to 106.0°F, resulting in a measured FHR of 81.67 gallons.

The 60 MBH unit completed three draw cycles within the same one-hour period due to its higher burner input and enhanced recovery capability. Individual draw volumes ranged from approximately 29.6 to 38.9 gallons, while average outlet temperatures remained above 119°F throughout the test. The outlet temperature cut-off values were consistently between 106°F and 108°F. The additional recovery capacity enabled a total FHR of 98.18 gallons, representing approximately 20% greater hot water delivery than the 40 MBH unit.

Overall, increasing burner capacity from 40 MBH to 60 MBH significantly improved first-hour hot water delivery by reducing recovery time and enabling an additional draw cycle while maintaining comparable outlet temperature performance.

Table 5: Summary of the FHR test for the 40 MBH unit.

Variables	Draw No. 1	Draw No. 2
Duration (min)	0:13:30	0:13:45
Average GPM	3.01	2.98
Volume Drawn (Gallon)	40.63	41.04
Average Inlet Temp (°F)	58.30	58.25
Average Outlet Temp (°F)	119.81	119.54
Max Outlet Temp (°F)	121.75	121.24
Cut-off Temp (°F)	106.42	106.02
FHR (Gallon)	**81.67 (High-Usage)**	

Table 6: Summary of the FHR test for the 60 MBH unit.

Variables	Draw No. 1	Draw No. 2	Draw No. 3
Duration (min)	0:13:00	0:09:50	0:09:50
Average GPM	2.99	3.02	3.01
Volume Drawn (Gallon)	38.85	29.71	29.62
Average Inlet Temp (°F)	58.38	58.27	58.30
Average Outlet Temp (°F)	120.38	119.03	119.23
Max Outlet Temp (°F)	123.15	121.20	121.27
Cut-off Temp (°F)	107.75	105.69	106.44
FHR (Gallon)	**98.18 (High-Usage)**		

Uniform Energy Factor

Based on the measured FHR values, UEF testing was conducted using the DOE high-use draw profile. Figure 5 through Figure 7 present the cumulative electrical energy consumption, natural gas consumption, and delivered hot water volume over the 24-hour test period for E-Saver, Gas-Only, and Hi-Demand operating modes, respectively.

E-Saver Mode

As shown in Figure 5, E-Saver mode relies almost entirely on the heat pump subsystem to satisfy both load and recovery requirements. Electrical energy consumption increased in discrete increments corresponding to major draw events and reached approximately 3.2 kWh by the end of the test period. No measurable natural gas consumption was recorded, confirming that all water heating demand was satisfied by the heat pump under standard DOE conditions.

Gas-Only Mode

Figure 6 illustrates the operating characteristics of Gas-Only mode. Electrical energy consumption remained minimal, reaching only approximately 140 Wh over the test period and consisting primarily of control, blower, and auxiliary loads. Natural gas served as the primary energy source, with cumulative consumption reaching approximately 44 kBtu. Step increases in gas consumption correspond directly to burner activation during major hot water draw events, demonstrating combustion-driven recovery independent of heat pump operation.

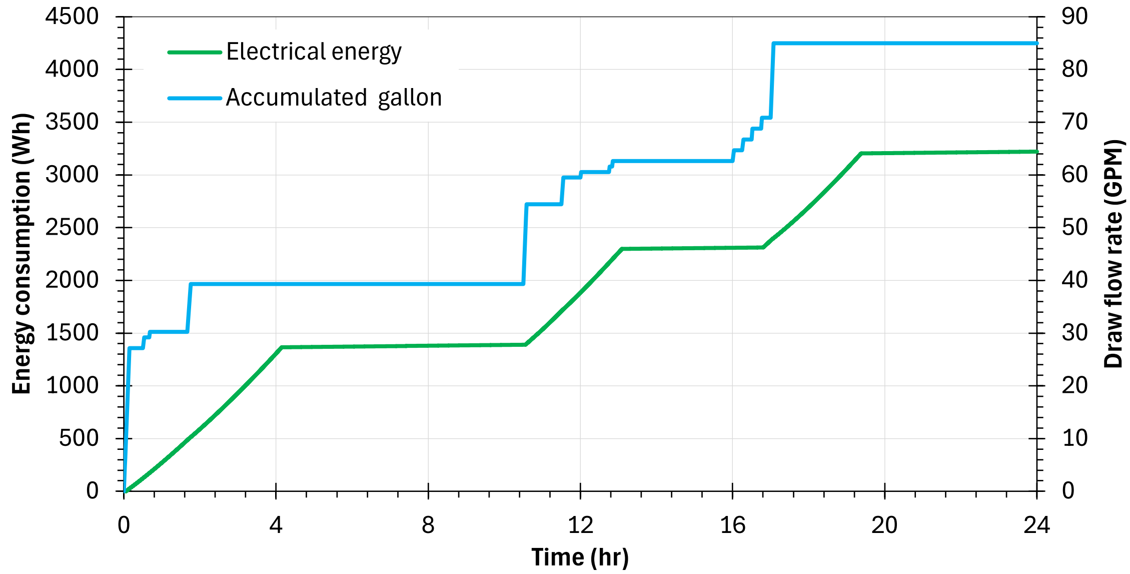

Figure 5: 24-hr profile of energy consumption and draws for E-Saver mode.

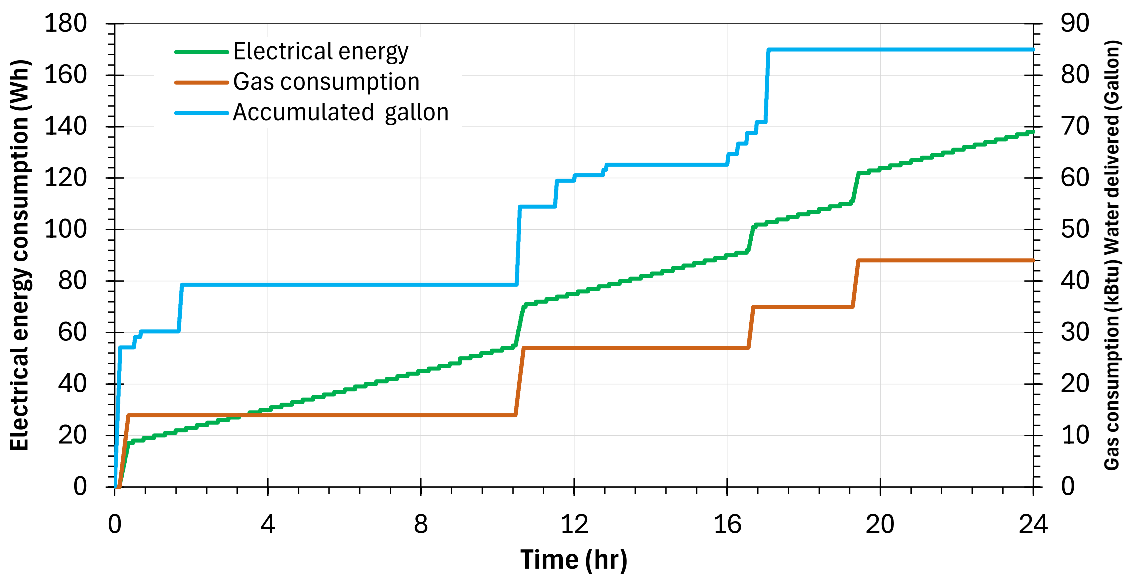

Figure 6: 24-hr profile of energy consumption and draws for Gas-only mode.

Hi-Demand Mode

Figure 7 demonstrates the hybrid operating strategy employed in Hi-Demand mode. Electrical energy consumption reached approximately 2.6 kWh while natural gas consumption totaled approximately 15 kBtu. The heat pump remained the primary energy source under most conditions, while selective gas burner operation occurred during large draw events to accelerate recovery and maintain hot water availability. Compared to Gas-Only mode, gas consumption was substantially reduced, illustrating the effectiveness of the dual-fuel control strategy.

Overall, the results demonstrate that the DF-HPWH effectively modulates between electricity and natural gas depending on operating mode and demand conditions. E-Saver mode maximizes efficiency and electrification, Gas-Only mode prioritizes recovery performance, and Hi-Demand mode balances efficiency and hot water availability through coordinated operation of both heating sources.

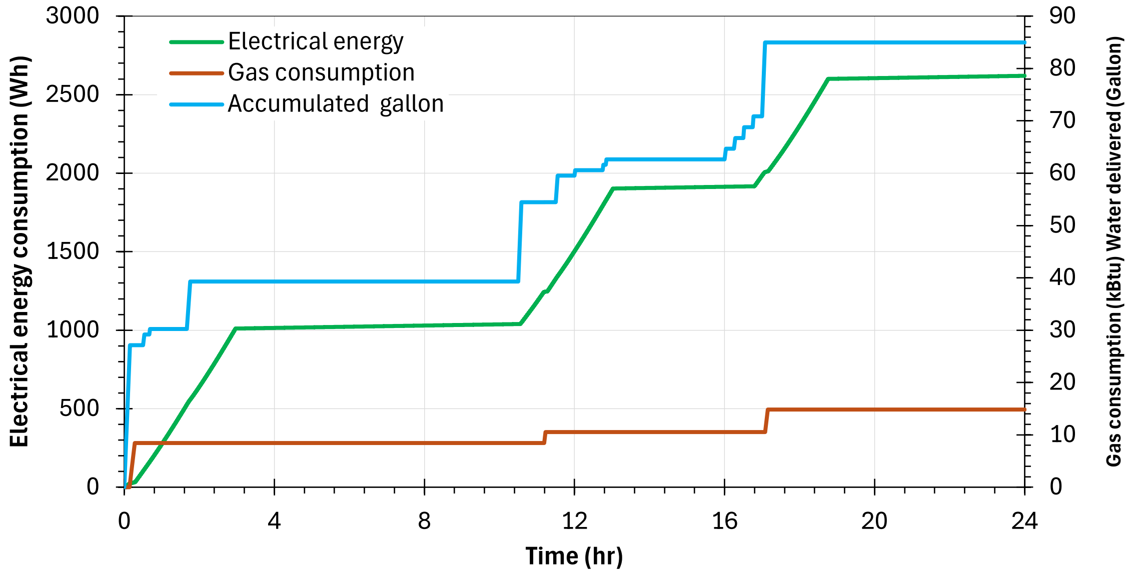

Figure 7: 24-hr profile of energy consumption and draws for Hi-Demand mode.

Performance Comparison Across Operating Modes

Figure 8 compares recovery efficiency, UEF, and standby loss coefficient for the 40 MBH and 60 MBH DF-HPWH units operating in E-Saver, Gas-Only, and Hi-Demand modes at a 120°F setpoint.

For both units, E-Saver mode achieved the highest recovery efficiency (approximately 4.2) and UEF (approximately 3.8), reflecting heat-pump-dominant operation without gas burner assistance. Because both units utilize the same heat pump architecture and the burner remained inactive during the test, their performance was nearly identical under these conditions.

Gas-Only mode produced substantially lower recovery efficiency and UEF values due to exclusive reliance on natural gas combustion. The measured UEF values were approximately 0.88 and 0.93 for the 40 MBH and 60 MBH units, respectively. These relatively high efficiencies are consistent with the condensing operation of the gas burner, which recovers a portion of the latent heat contained in the flue gases. During Gas-Only operation, the burner cycled four times to satisfy the prescribed draw profile.

Hi-Demand mode exhibited intermediate performance characteristics, reflecting coordinated operation of the heat pump and gas burner. UEF values of approximately 1.22 and 1.85 were measured for the 40 MBH and 60 MBH units, respectively. The higher efficiency observed for the 60 MBH unit is attributed to its greater recovery capacity and more effective utilization of heat pump operation during recovery periods. In this mode, the burner operated three times throughout the test to supplement heat pump operation during periods of elevated demand.

Across all operating modes, the 60 MBH unit consistently demonstrated higher recovery efficiency and UEF values than the 40 MBH unit, highlighting the benefits of increased burner capacity and improved thermal recovery performance.

To further illustrate the relationship between operating mode, energy source utilization, and overall efficiency, Figure 9 presents the corresponding natural gas consumption for each test condition. Although the delivered hot water energy remained relatively constant because inlet water temperature, ambient conditions, and draw profiles were identical, the energy source used to satisfy that demand varied substantially among operating modes.

In E-Saver mode, both units relied exclusively on electricity, consuming approximately 3.2 kWh (11 kBtu) with no measurable natural gas consumption. In Gas-Only mode, nearly all input energy was supplied by natural gas, while electrical consumption was limited to auxiliary loads such as controls and combustion air fans. Hi-Demand mode exhibited a hybrid energy consumption pattern, combining heat pump operation with selective gas burner assistance during peak demand events.

These results demonstrate that operating mode is the primary driver of fuel utilization and system efficiency. E-Saver mode maximizes electrification and energy efficiency, Gas-Only mode prioritizes recovery performance through combustion heating, and Hi-Demand mode balances both objectives by strategically integrating electricity and natural gas to satisfy hot water demand.

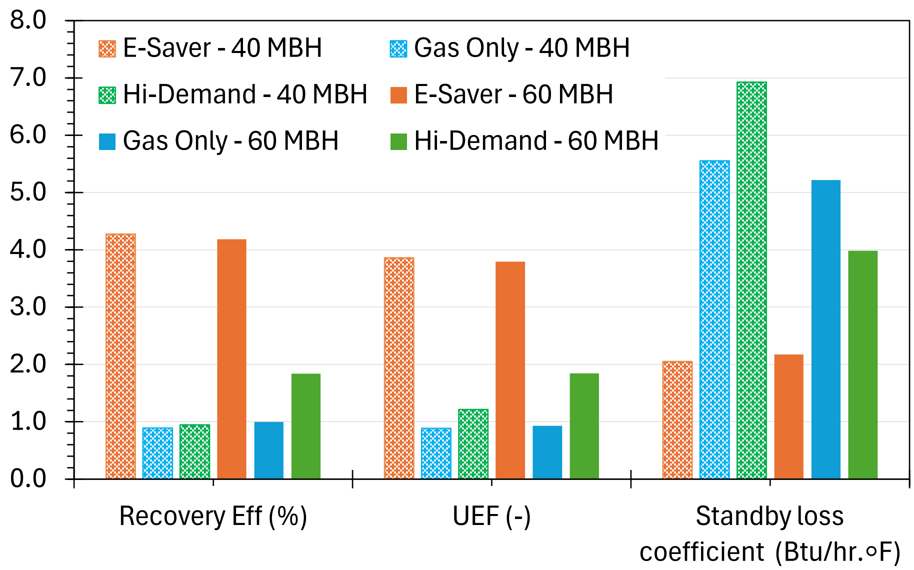

Figure 8: Recovery efficiency, UEF, and standby loss coefficient of the 40 and 60 MBH units.

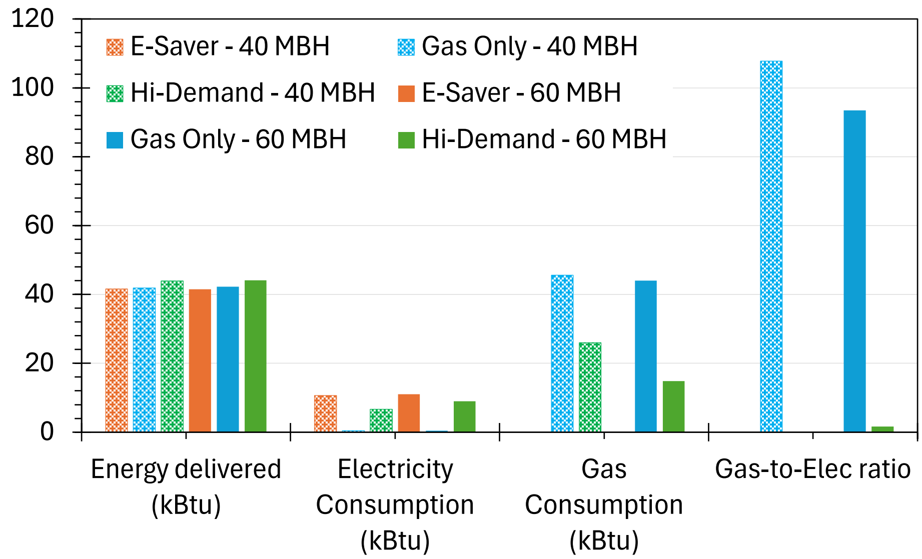

Figure 9: Energy delivered and energy consumed by the 40 and 60 MBH units.

Effect of Ambient Temperature

Because the 60 MBH unit demonstrated superior overall performance, additional testing was conducted to evaluate its sensitivity to ambient conditions. Figure 10 and Figure 11 summarize the results for E95, E50, and E44 test conditions listed in Table 7.

Table 7: Operating conditions of the optional tests.

Test Name	E95	E50	E44
City water inlet temperature (°F)	67	50	50
Ambient temperature (°F)	95	50	44
Ambient relative humidity	40	58	58
Setpoint (°F)	120	120	120
Draw profile	**High-usage**		

At an ambient temperature of 95°F, the heat pump operated under highly favorable thermodynamic conditions and achieved the highest measured recovery efficiency (approximately 5.4) and UEF (approximately 4.4). Electrical energy consumption was limited to approximately 2.2 kWh while fully satisfying the required hot water demand.

As ambient temperature decreased to 50°F and 44°F, heat pump performance degraded significantly due to reduced evaporator heat availability and increased compressor lift. Recovery efficiency decreased to approximately 1.5, while UEF declined to approximately 2.0 and 1.7 for the E50 and E44 tests, respectively. Under these colder conditions, the gas burner operated once during each test to support recovery and satisfy the required draw profile.

The standby loss coefficient increased from approximately 2.2 Btu/hr·°F at 95°F to approximately 4.7 Btu/hr·°F at both 50°F and 44°F. This increase reflects larger temperature differences between the storage tank and surrounding environment, resulting in greater thermal losses and longer recovery periods.

These results demonstrate that E-Saver mode delivers exceptional efficiency under warm ambient conditions but experiences reduced performance as ambient temperatures decrease. Nevertheless, the hybrid architecture maintains reliable hot water delivery through selective burner assistance, highlighting the value of dual-fuel operation in cold-climate applications.

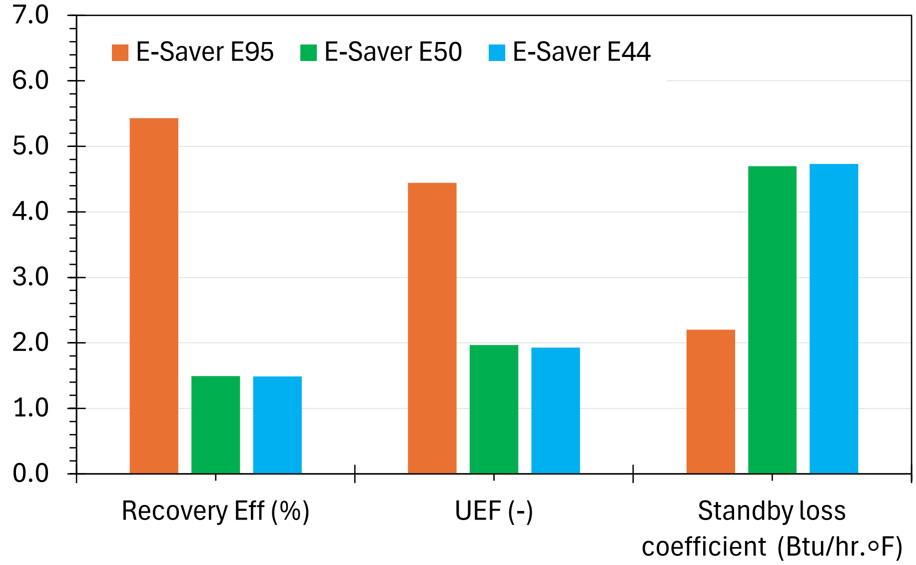

Figure 10: Recovery efficiency, UEF and standby loss coefficient of E-Saver mode during the optional tests.

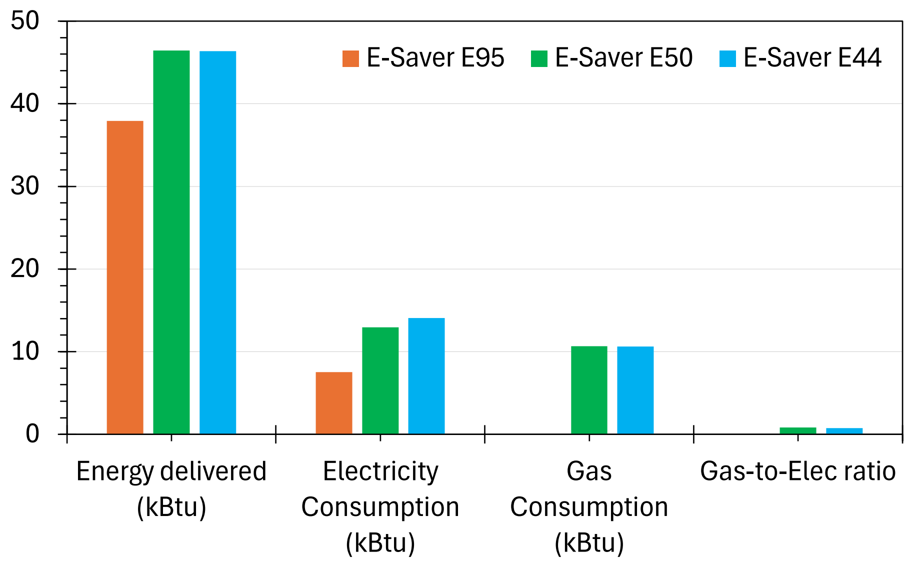

Figure 11: Energy delivered and energy consumed by E-Saver mode during the optional tests.

Elevated Storage Temperature and Thermostatic Mixing Valve Operation

Additional testing was performed with a thermostatic mixing valve (TMV) installed and the storage temperature increased from 120°F to 140°F. This configuration is commonly used to increase effective thermal storage capacity, improve load-shifting capability, and reduce the risk of Legionella growth.

Figure 12 and Figure 13 compare system performance at 120°F and 140°F storage setpoints.

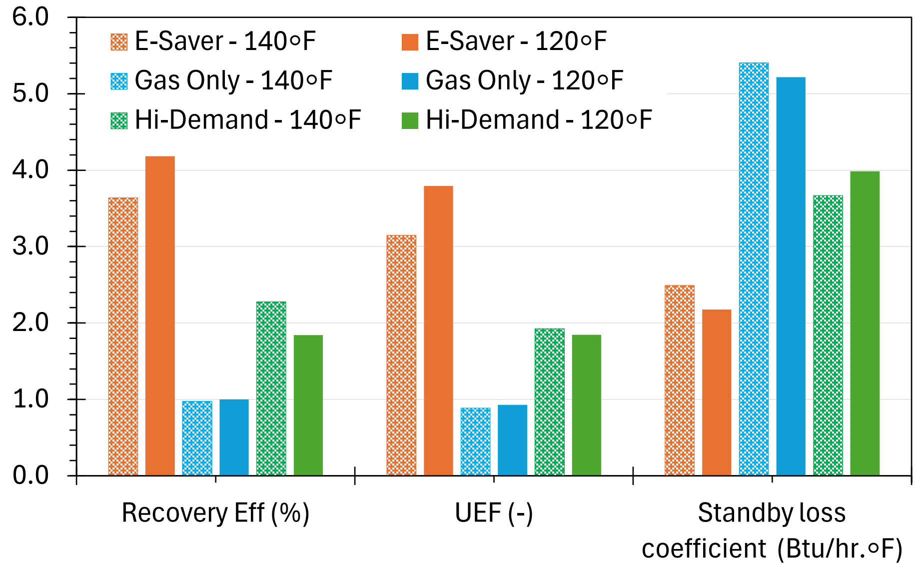

Figure 12: Recovery efficiency, UEF, and standby loss coefficient of the 60 MBH unit at 120 °F and 140 °F.

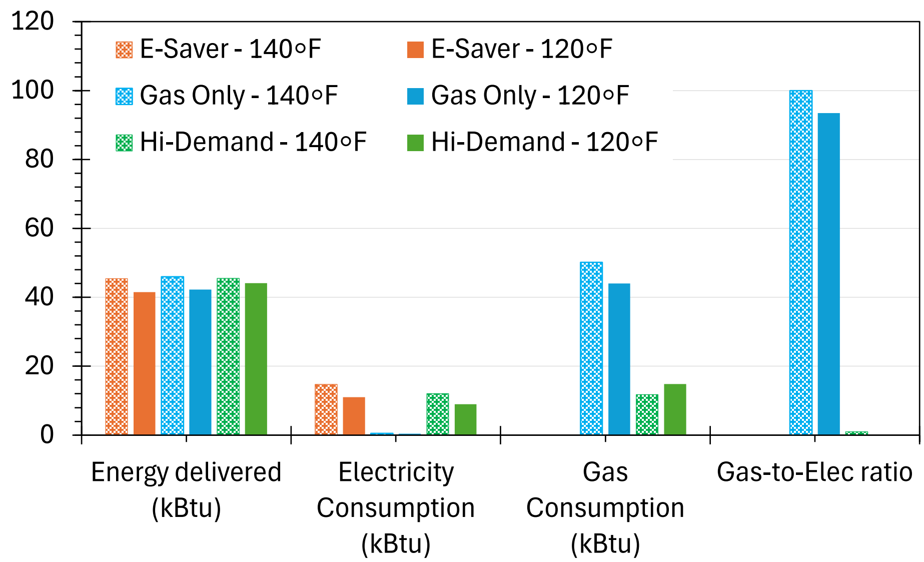

Figure 13: Energy delivered and energy consumed by the 60 MBH at 120 °F and 140 °F.

In E-Saver mode, increasing the storage temperature reduced recovery efficiency from approximately 4.1 to 3.6 and decreased UEF from approximately 3.7 to 3.1. These reductions are attributed to the larger temperature lift required of the heat pump. Electrical energy consumption increased accordingly, while standby losses also increased due to the higher average tank temperature.

Gas-Only mode exhibited relatively little sensitivity to storage temperature. Recovery efficiency and UEF remained near unity, although natural gas consumption and standby losses increased modestly due to greater thermal losses from the storage tank.

Hi-Demand mode displayed intermediate behavior. At the 140°F setpoint, a recovery efficiency of approximately 2.23 and a UEF of approximately 1.92 were measured. These values were slightly higher than those observed at 120°F due to reduced natural gas consumption and greater heat pump contribution.

Overall, increasing storage temperature increased total energy consumption and standby losses across all operating modes. However, E-Saver mode maintained the highest efficiency and electrification potential, supporting its application in grid-interactive and demand-response strategies.

Hot Water Dry-Out Test

Figure 14 presents the outlet water temperature and cumulative delivered hot water volume during a continuous 3 GPM draw test conducted in Heat Pump-Only mode.

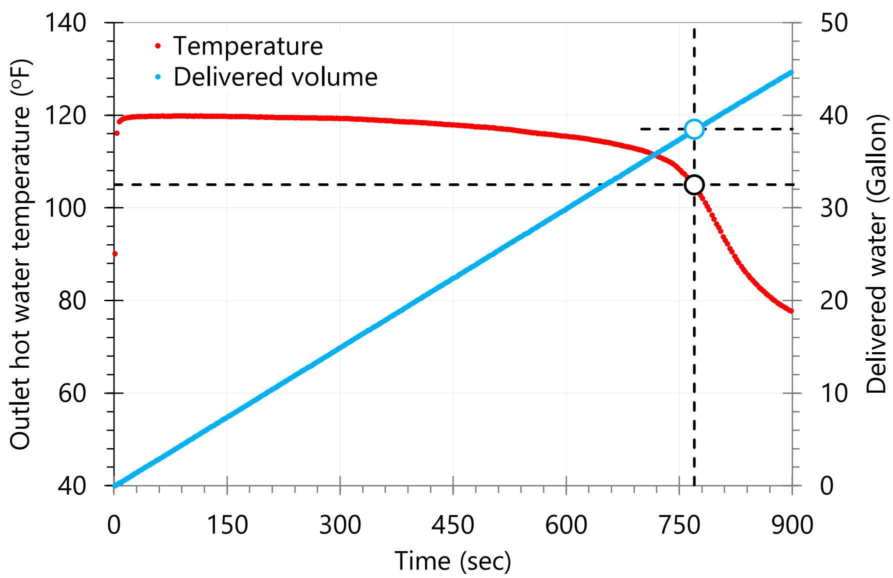

Figure 14: Temporal evolution of outlet water temperature and flow rate during a continuous draw (Dry out Test).

The unit delivered approximately 38.5 gallons of usable hot water before thermal depletion occurred. During the initial portion of the draw, strong thermal stratification within the storage tank maintained outlet temperatures near 120°F despite continuous withdrawal of hot water. As colder inlet water entered the bottom of the tank, the thermocline gradually moved upward while preserving the hot water layer near the outlet.

After approximately 700 seconds, outlet temperature began to decline as the thermocline approached the outlet location. Once the thermocline reached the outlet, thermal stratification collapsed and outlet temperature decreased rapidly below the usability threshold of approximately 105°F.

These results demonstrate that usable hot water capacity is governed not only by stored thermal energy but also by thermal stratification within the tank. The abrupt decline in outlet temperature confirms that the water heater becomes effectively depleted when the stratified hot-water layer is exhausted, even though residual thermal energy remains within the tank.

Load-based Evaluation and Performance Mapping

Heat Pump Mapping

In addition to the standard DF-HPWH performance testing, load-based evaluation and detailed performance-mapping experiments were conducted to generate a comprehensive experimental dataset. These measurements support the development of a high-fidelity, physics-based model capable of accurately capturing the system's dynamic operating behavior across a wide range of conditions.

To achieve this, the project team leveraged the GTI Energy's Virtual Test Home approach[2] (see Figure 15), a flexible and highly instrumented platform designed to perform standard tests and replicate realistic operating conditions while enabling controlled, repeatable testing. The VTH facility allows independent control of ambient temperature, inlet water conditions, setpoints, and hot water draw profiles, enabling systematic mapping of both heat pump and gas burner performance across a wide range of conditions representative of real-world residential and commercial water heating use. In addition to steady-state characterization, the test rig can impose time-varying draw schedules that emulate customer usage patterns, capturing transient behavior, control interactions, and mode switching under practical operating scenarios.

During these tests, high-resolution measurements of whole-system energy consumption, dynamic response, and component-level performance were collected, generating a comprehensive experimental dataset. This dataset supports rigorous model validation beyond single-metric efficiency comparisons by quantifying the relative contribution and runtime of the heat pump and burner under diverse conditions. More broadly, the VTH framework enables translation of laboratory results into actionable insights for multiple stakeholders: customers benefit from improved performance predictions under their specific usage patterns and climates; utilities gain credible data to assess load shape impacts, peak demand reduction potential, and demand response compatibility; and original equipment manufacturers (OEMs) can leverage the results to tune controls, optimize component sizing, and reduce development risk prior to field deployment. Ultimately, VTH testing provides a scalable, application-relevant basis for estimating system-level benefits across varying geographic locations, installation configurations, draw profiles, and utility rate structures, supporting both technology development and informed adoption at scale.

[2] Virtual Test Home

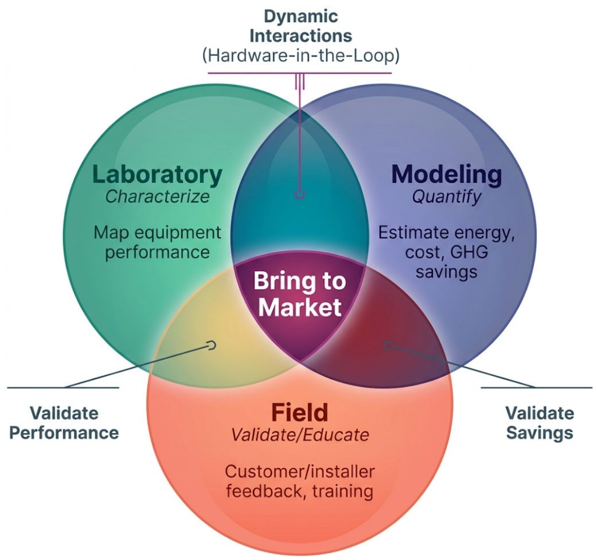

Figure 15: VTH holistic approach.

The tests outlined in Table 3 were conducted to quantify both the thermal energy delivered to the storage tank and the corresponding energy consumed by the unit. As an example, Figure 16 illustrates the temporal evolution of the average tank temperature and electrical energy consumption during Tests 23 and 33, highlighting the system's transient response and energy use during operation. The average tank temperature increased from 52 °F to about 140 °F in 7.0 hours (~12.6°F/hr [7.0°C/hr]).

The COP is a measure of useful energy transferred to the water (output) divided by the input energy to the system (supplied work). The equation used to calculate COP is:

$$COP_{HP} = \frac{Q_{thermal}}{W_{input}} = \frac{mc_p\Delta T_{tank}}{W_{input}} \quad (1)$$

Figure 17 illustrates the relationship between the heat pump's COP and electrical power consumption as a function of average tank temperature during Tests 32 and 33. The figure highlights the fundamental trade-off between efficiency and power input as the storage temperature increases. As the average tank temperature rises, the heat pump COP decreases steadily, dropping from around 5.5 at lower tank temperatures (~75°F) to about 2.4 at higher temperatures (~145 °F). This decline reflects the increasing thermodynamic lift required to transfer heat from the ambient air to warmer tank water, which elevates compressor work and reduces overall efficiency.

Conversely, electrical power consumption increases with tank temperature, rising from about 300 W to nearly 480 W over the same temperature range. This increase is driven by higher compressor loading and longer duty cycles as the system works against a larger temperature difference. The monotonic rise in power input, coupled with declining COP, indicates that additional electrical energy is increasingly converted into compressor work rather than useful heat delivered to the tank. The rated COP and rated compressor power are 3.49 and 400 W, respectively. The rated conditions are defined at an ambient wet-bulb temperature of 57 °F (14 °C) and an average tank temperature of 120 °F (48.9 °C).

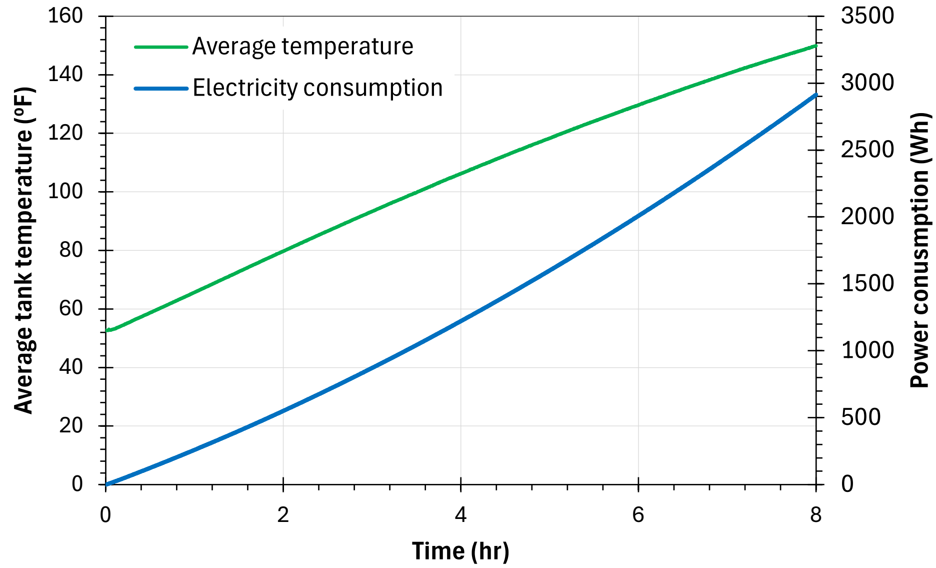

Figure 16: Temporal evolution of the average tank temperature and electrical energy consumption.

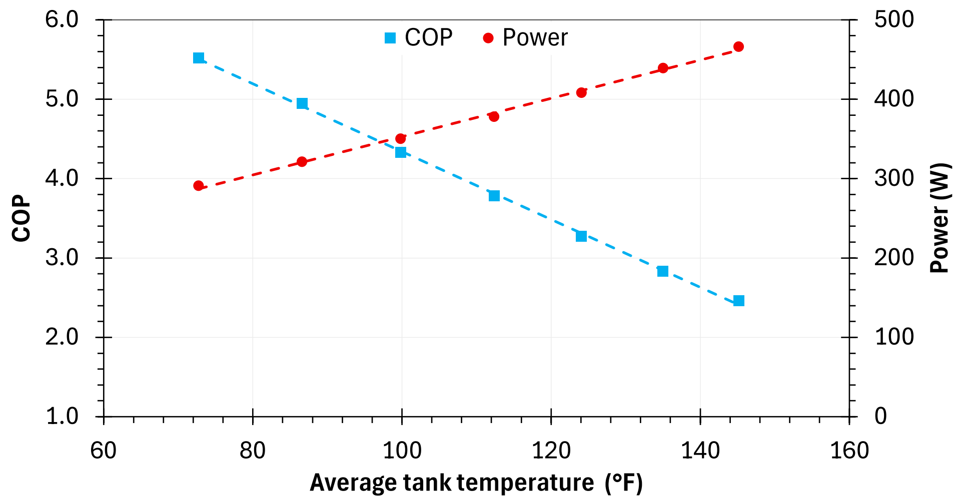

Figure 17: Heat pump's COP and power consumption as a function of average tank temperature at 68 °F ambient temperature.

Figure 18 illustrates the variation of heat pump's COP as a function of average tank temperature under different ambient wet-bulb (WB) conditions. A consistent trend is observed across all cases: COP decreases nearly linearly with increasing tank temperature. For example, at WB = 80 °F, the COP declines from about 7.6 at 70 °F tank temperature to about 3.4 at 140 °F, indicating a reduction of more than 50%. A similar proportional decline is observed for all other wet-bulb conditions.

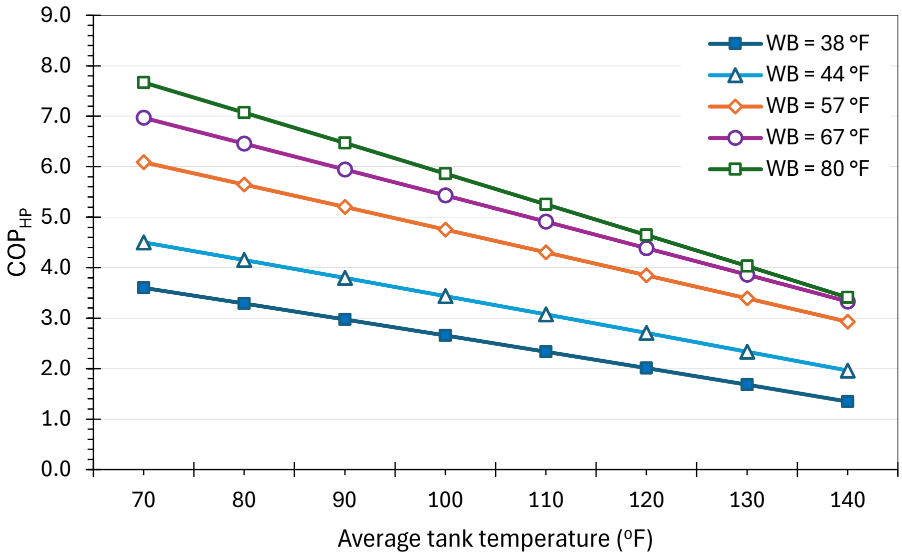

Figure 18: COP of heat pump at different average tank temperature and ambient wet bulb temperature.

For all tests, compressor power consumption and COP were mapped as functions of average tank temperature and ambient wet-bulb temperature using biquadratic correlations (Equation 2). This formulation enables straightforward integration of Navien's heat pump performance maps into building energy simulation tools such as EnergyPlus. Table 8 lists the equations' coefficients.

$$HP_p = c_1 + c_2.\bar{T}_{tank} + c_3.\bar{T}_{a,wb} + c_4.\bar{T}_{tank}^2 + c_5.\bar{T}_{a,wb}^2 + c_6.\bar{T}_{tank}\bar{T}_{a,wb} \quad (2)$$

Table 8: Coefficients of the biquadratic equations of the heat pump.

Parameter	c_1	c_2	c_3	c_4	c_5	c_6
Compressor (W)	590.6	-0.4054	-11.78	0.005	0.0745	0.03175
COP (–)	-4.335	-0.00242	0.3198	-0.0000181	-0.001484	-0.000683

where $\bar{T}_{tank}$ is the average tank temperature and $\bar{T}_{a,wb}$ is the ambient wet-bulb temperature in Fahrenheit.

Burner Mapping

For burner performance mapping, the burner firing rate and associated energy efficiency were measured over a range of operating conditions. Test 37 is presented as a representative example, illustrating the dependence of burner behavior on average tank temperature during operation. Figure 19 illustrates the variation of burner firing rate and burner thermal efficiency as a function of the average tank temperature during gas-fired operation at 68 °F ambient temperature. As the average tank temperature increases from 75 °F to 105 °F, the burner firing rate decreases slightly, from about 60.9 MBH to 59.8 MBH. In contrast, the burner energy efficiency remains relatively constant, hovering near 95–98% across the entire temperature range, with only minor fluctuations. This stability suggests that the combustion process and heat exchanger effectiveness are largely insensitive to tank temperature within the tested range. The high and nearly flat efficiency trend is consistent with condensing burner operation, where latent heat recovery from flue-gas condensation is maintained as long as return water temperatures remain sufficiently low at the heat-exchanger interface.

$$\eta_{th} = \left(\frac{mc_p\Delta T_{tank}}{Q_{burner\,input}}\right) \tag{3}$$

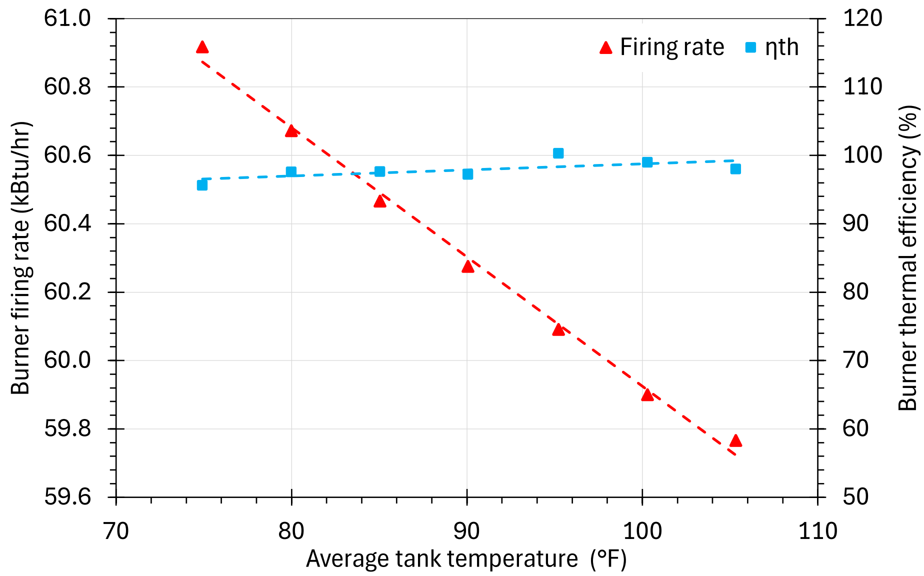

Figure 19: Burner firing rate and energy efficiency as a function of average tank temperature.

The gas burner performance was characterized using linear equations, as shown below.

$$C_b = C_{base} \times (a_1 + a_2\,\bar{T}_{tank})\left(\frac{T_{std}}{T_a}\right)^{a_3} \tag{4}$$

$$\eta_{th} = \eta_{base} \times (b_1 + b_2\,\bar{T}_{tank}) \tag{5}$$

Table 9: Coefficients of the linear equations of the gas burner.

Parameter	a_1	a_2	a_3	b_1	b_2	C_{base}	η_{base}
Burner capacity (C_b)	1.065	-0.00064	0.75	–	–	60	–
Burner efficiency (η_b)	–	–	–	0.0011	0.95	–	0.93

where C_{base} is the base burner capacity (60 MBH), $\bar{T}_{tank}$ is the average tank temperature in Fahrenheit, T_{std} is the standard temperature (528 R), T_a is the ambient dry-bulb temperature, and η_{th} is the burner thermal efficiency.

These equations form the basis of the system model, which will be developed and discussed in detail in the subsequent milestone.

Demand Response Validation

The prototype DF-HPWH provided to GTI Energy for laboratory evaluation was not initially equipped with a CTA-2045 EcoPort communication interface. Although the production design incorporates a CTA-2045 EcoPort and associated communication module, the DR control software was still under development at the time of testing. Consequently, the primary objective of the DR evaluation was to verify communication functionality and confirm that external DR commands could be successfully transmitted to and recognized by the water heater.

Upon completion of the performance testing program, Navien supplied the CTA-2045 EcoPort, interconnecting cables, mounting hardware, and developmental software required for functional verification. Installation of the hardware was straightforward and required minimal modification to the unit, demonstrating that the communication components are suitable for integration into a production-ready platform.

Navien provided the anticipated demand response operating logic for future production units, including the expected responses to CTA-2045 commands, as summarized in Table 10. These responses are intended to support utility load-management programs and future grid-interactive operation.

Table 10: Programmed Responses for CTA-2045 Signals.

Response to CTA-2045 Signal	Programmed Response
Shed load	Unit switches to gas-only heating
Critical Peak	
Emergency Shutdown	
End Shed, Critical Peak or Emergency	Return to normal operation
Load Up	Heat tank to normal setpoint in current mode
Advanced Load Up	Heat tank to above setpoint in current mode

Following installation, communication testing was performed using a SkyCentrics CTA-2045 EcoPort Cellular Module, as shown in Figure 20. The communication interface operated as intended, and command signals were successfully transmitted, received, and acknowledged by the DF-HPWH controller. The testing confirmed proper communication between the CTA-2045 module and the water heater control system.

At the time of testing, however, the prototype software did not implement the operational responses associated with the received DR commands. During both load-shed and load-add (load-up) events, the water heater continued normal operation without modifying its control strategy, heating source selection, or setpoint. Navien confirmed that the developmental software provided for testing was intended solely to validate command recognition and communication pathways rather than execute full demand response functionality.

Therefore, the testing successfully verified CTA-2045 communication compatibility and command recognition but did not validate the operational demand response behaviors outlined in Table 10. Implementation and validation of full DR functionality are planned for the commercial production version of the DF-HPWH. Future testing should evaluate the unit's response to load-shed, load-add, critical peak, and other CTA-2045 event signals to quantify the technology's capability to support utility demand response programs and grid-interactive water heating applications.

Figure 20: CTA-2045 Module installed on the DF-HPWH.

Conclusions and Next Steps

Conclusions

The laboratory evaluation demonstrated that the Navien DF-HPWH is a technically viable solution for combining high-efficiency heat pump water heating with natural gas backup in a 120 V platform. By integrating a low-power heat pump with a condensing gas burner, the system is capable of maximizing electrification under typical operating conditions while maintaining the recovery capacity required to satisfy high hot water demand, cold-climate operation, elevated storage temperatures, and future grid-interactive applications. This architecture directly addresses two significant barriers to broader heat pump water heater adoption: the need for costly 240 V electrical upgrades and concerns regarding hot water availability during peak demand periods.

Standard DOE testing confirmed strong heat pump performance in E-Saver mode, with measured UEF values of 3.86 and 3.79 for the 40 MBH and 60 MBH units, respectively. Under standard test conditions, the heat pump alone was able to satisfy the entire high-usage draw profile without gas burner operation. Gas-Only mode produced UEF values of 0.88 and 0.93, consistent with high-efficiency condensing gas water heater performance, while Hi-Demand mode provided intermediate performance through coordinated operation of both heating sources.

The first-hour rating (FHR) evaluation demonstrated the influence of burner capacity on hot water availability. The 40 MBH and 60 MBH units achieved FHR values of 81.67 and 98.18 gallons, respectively. The larger burner enabled an additional recovery cycle during the one-hour test period, increasing usable hot water delivery while maintaining comparable outlet temperature performance. These results indicate that burner capacity is a key design parameter influencing recovery performance and customer satisfaction, particularly for applications with high peak hot water demand.

The operating-mode evaluation highlighted the flexibility of the dual-fuel architecture. E-Saver mode maximized efficiency and electrification, Gas-Only mode prioritized recovery capacity, and Hi-Demand mode balanced efficiency and performance by selectively integrating gas burner operation during elevated demand periods. This operational flexibility allows the DF-HPWH platform to adapt to varying customer needs, installation environments, and utility objectives.

Supplemental testing further demonstrated that ambient temperature, storage temperature, and control strategy significantly influence performance. Heat pump efficiency increased under warm ambient conditions and decreased at lower temperatures due to increased compressor lift and reduced evaporator heat availability. Testing at elevated storage temperatures confirmed that larger thermal storage capacity can be achieved through the use of thermostatic mixing valves, although higher storage temperatures increase standby losses and reduce overall efficiency. These findings emphasize the importance of considering climate, installation location, inlet water temperature, storage temperature, and usage patterns when estimating annual performance.

The load-based testing and performance mapping activities successfully generated the component-level performance relationships required for dynamic modeling. Heat pump COP, compressor power consumption, burner capacity, and burner efficiency were characterized over a broad range of operating conditions. These datasets provide the foundation for developing and validating a physics-based simulation model capable of predicting annual energy consumption, fuel utilization, operating mode transitions, and demand response performance.

Demand response testing confirmed successful CTA-2045 communication and command recognition using the EcoPort interface. However, the prototype software evaluated during this project did not implement the intended operational responses associated with load-shed, critical peak, emergency, or load-add events. As a result, communication compatibility was verified, but full demand response functionality remains to be validated once production-ready firmware becomes available.

Overall, the laboratory results demonstrate that the DF-HPWH platform successfully combines the efficiency benefits of heat pump technology with the reliability and recovery advantages of natural gas backup. The technology shows strong potential to support residential electrification goals while maintaining customer expectations for hot water performance and providing a pathway toward future grid-interactive water heating applications.

Next Steps

The technical and laboratory evaluation presented above fulfills the tasks for the present contract. Additional work related to the Navien DF-HPWH will support several steps in preparation for market introduction.

The experimentally derived heat pump and burner performance correlations will be incorporated into a dynamic DF-HPWH simulation model. The model will represent tank stratification, heat pump and burner operation, control logic, operating-mode transitions, standby losses, fuel consumption, and hot water draw behavior. Calibration and validation will be performed using the laboratory data generated during this project. Particular attention will be given to accurately representing burner engagement thresholds and mode-transition logic because these controls strongly influence annual energy use, fuel mix, peak electrical demand, and hot water availability.

Subsequently, the validated model will be applied to evaluate DF-HPWH performance across a broad range of residential operating scenarios. Simulations will examine the impacts of climate zone, inlet water temperature, hot water usage patterns, storage temperature strategies, utility rate structures, and operating modes. These analyses will quantify annual electricity consumption, natural gas consumption, operating costs, greenhouse gas emissions, and peak demand impacts, providing a more comprehensive assessment of the technology than can be achieved through standardized laboratory testing alone.

Third, future testing should evaluate production-ready demand response functionality once the final firmware becomes available. Testing should verify that CTA-2045 event signals produce the intended operational responses and should quantify resulting impacts on electric demand reduction, gas substitution, recovery performance, hot water availability, and return-to-normal operation. Such testing will provide the information needed to assess the technology's value for utility demand response and grid-interactive building programs.

Finally, future field demonstrations are recommended to validate laboratory and modeling results under occupied-home conditions. Field deployments will provide insight into installation requirements, customer usage behavior, control performance, and long-term reliability while supporting the development of utility program guidance and deployment strategies. Together, laboratory testing, dynamic modeling, demand response validation, and field demonstration activities will provide a comprehensive foundation for product optimization, utility program design, and broader commercialization of dual-fuel hybrid heat pump water heating technology.

END OF REPORT