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Commercial Heat Pump Tumble Dryers – Efficiency Testing, Operations Considerations, and Energy Savings

Prepared For NEEA:
Wendy Preiser, Sr. Product Manager

Prepared By:
Suzanne Foster Porter, Principal

Kannah Consulting
521 Road Avenue, Suite F
Grand Junction, CO 81501

Northwest Energy Efficiency Alliance
PHONE
503-688-5400
EMAIL
info@neea.org

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Glossary of Terms and Acronyms

Term/Acronym	Definition/Meaning
AHAM 100% cotton	AHAM-HLD-2010 specified 100% cotton load of flat sheets, pillowcases, and kitchen towels.
AHAM	Association of Home Appliance Manufacturers
Appendix D2	US DOE's amended test procedure for residential clothes dryers, specified in 10 CFR Part 430, Subpart B.
CA IOUs	California investor-owned utilities
Cap Ex / Op Ex	Capital expenditure / operating expenditure
CBSA	NEEA's Commercial Building Stock Assessment
CEC	California Energy Commission
CFR	Code of Federal Regulations
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Cost-effective	For the purposes of this analysis, heat pump CTDs are considered cost-effective if the payback period is 10 years or less (three percent or higher expected ROI).
CTD	Commercial tumble dryer
cu ft	Cubic foot or cubic feet
DOE	US Department of Energy
EF	Energy Factor: the bone-dry textile weight per kWh of energy consumed (excluding standby power).
ENERGY STAR® program	A partnership between private and public sector organizations and the federal government. The name and mark are registered trademarks owned by the US EPA. Through this partnership, organizations may receive authorization to use one or more of the ENERGY STAR trademarks to identify and promote their certified products and/or to highlight their partnership with ENERGY STAR.
EIA	US Energy Information Administration
EPA	US Environmental Protection Agency
FMC	Final Moisture Content
FTE	Full-time employee
GDP	Gross domestic product
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air-conditioning
IMC	Initial moisture content
lb	Pound or pounds
NEEA	Northwest Energy Efficiency Alliance
OPL	On-premise laundry
Payback period	The point at which the incremental upfront and ongoing maintenance costs of an energy efficiency investment (the heat pump CTD) equals the total value of the accumulated operating savings.
QPL	Qualified Product List
ROI	Return on investment

Executive Summary

For over a decade, the Northwest Energy Efficiency Alliance (NEEA) has championed the market adoption of residential heat pump clothes dryers with technical and market-based efforts. NEEA recently turned more attention to commercial tumble dryers (CTDs) as research revealed significant opportunities to improve their efficiency and that CTDs will deliver improved choices to Northwest consumers through NEEA's Market Transformation efforts. Around this time, an international hotel company approached NEEA to help assess the opportunity and viability of the heat pump CTDs for its low greenhouse gas (GHG) hotels since a European manufacturer has been bringing its higher capacity heat pump CTD to the US market.[1] In collaboration with these market actors, NEEA developed this research project to support its goals of increasing the adoption of energy-efficient CTDs and advancing more efficient commercial dryer technologies. NEEA also provided information on the heat pump's CTD energy efficiency and performance to the hotel company and the manufacturer. With the information generated in this study, the manufacturer is adjusting the heat pump CTD design to serve US hotels better. The research included a lab investigation, a model for hotel capital and operational expenditures (Cap Ex / Op Ex) to evaluate cost-effectiveness, and estimates of regional and national l energy and GHG savings associated with heat pump CTDs.

NEEA's lab findings include:

- The modified Appendix D2 approach is effective for CTD testing.
- The heat pump CTD saves 60 percent of CTD site energy relative to the conventional CTD with 15 to 25 minutes of additional drying time (an increase of 50 to 80 percent).
- The heat pump effectively dried hotel cotton towels with a 15-minute longer cycle time.
- The heat pump CTD did not effectively process the US hotel-specified bedding load: It dried unevenly, leaving damp spots, wrinkled sheets excessively, and ran inconsistently long cycles.
- Conversations with one hotel using heat pump CTDs revealed some issues with bedding that may be addressed by considering the complete laundry process instead of just focusing on drying alone.

NEEA's Cap Ex / Op Ex analysis of seven locations demonstrates:

- Heat pump CTDs are not a cost-effective replacement for natural gas CTDs. The heat pump has higher capital and operational costs, so it is impossible to recover the incremental capital costs during the expected life of the dryer.
- Using a heat pump CTD for hotel cotton towels is currently cost-effective for all-electric hotels in the seven locations evaluated. The laundry processing labor hours are the same, but work shifts are staggered to accommodate longer cycle times. The financial payback period varies.
- More cost-effective energy savings are possible in all locations using alternative bedding textiles or an updated heat pump CTD design.
- Heat pump CTDs save carbon dioxide (CO_2) relative to natural gas dryers in all seven locations in the analysis. Excluding utility incentives yields a high cost of saving CO_2.

NEEA's regional and national energy and GHG modeling reveal:

- Two-thirds of CTD site energy can be saved.
- GHG emissions of the electrical grid have an impact on GHG savings. The Northwest saves more than 70 percent of GHG emissions, while the US GHG savings is approximately 35 percent.
- Heat pump CTDs <u>increase</u> electricity use while reducing natural gas use.

[1] The largest US heat pump CTD available is 44 lb, while conventional CTDs can be as large as 200 lb.

To support the success of this nascent technology, NEEA plans to continue working with the heat pump CTD manufacturer toward an improved design that more effectively dries US hotel bedding. Future research could include identifying efficiency opportunities for vended CTDs, investigating emerging technology for natural gas CTDs, and refining the two models (the Cap Ex / Op Ex model and the energy and GHG savings model).

1. Introduction

1.1. Background

The Northwest Energy Efficiency Alliance (NEEA) is an alliance of more than 140 utilities and energy efficiency organizations working on behalf of more than 13 million energy consumers to increase the adoption of energy-efficient products, services, and practices. To do this, the alliance identifies and removes market barriers to energy efficiency to drive permanent change throughout the supply chain. NEEA pools resources and shares risks to transform the market for energy-efficient products and services to benefit all consumers in the Northwest.

For over a decade, NEEA has championed residential heat pump clothes dryers through seminal technical, lab, and field research, policy efforts for standards and voluntary programs, and support of utility incentive programs. This includes a half-dozen reports, multiple comment letters to the US Department of Energy (DOE) and the ENERGY STAR program, and the effort to develop a test procedure for a Qualified Product List (QPL) so that utilities could offer incentive programs for efficient residential dryers. See Section 6.2. for a list of resources and relevant NEEA efforts through the years.

While historically focused on residential clothes dryer efficiency, NEEA recently turned more attention to commercial tumble dryer (CTD) efficiency when research (Foster Porter et al. 2022) revealed that addressing the efficiency of commercial laundry is essential to delivering improved choices to Northwest consumers through NEEA's Market Transformation efforts in the Northwest:

- Nearly one-fifth of US households use a commercial laundry facility (i.e., laundromat or central multifamily facility).
- Households with lower income and families of color are more likely to use centralized commercial laundry facilities.
- Using a laundromat over the long term may cost more than owning and operating in-dwelling laundry equipment.

The higher costs of commercial laundry disproportionally affect lower-income households, so CTDs offer NEEA and other stakeholders the opportunity to achieve energy savings and set objectives extending benefits to an often-overlooked demographic.

Currently, there are no energy efficiency specifications for CTDs, and little information is available to purchasers to inform them about their equipment choice. At the time of this writing, ENERGY STAR is considering including CTDs in its specifications, an essential first step to providing consumers with energy efficiency information on this product category. An ENERGY STAR commercial dryer specification also requires the creation of a test protocol that considers the technological differences from residential products and distinctions in use patterns.

In 2023, an international hotel company approached NEEA to conduct a feasibility study of heat pump CTDs in new construction properties. Phase I of this research showed that heat pump CTDs could be a viable strategy in low greenhouse gas (GHG) hotel properties. This report summarizes findings from Phase 2, which included a lab investigation, a model for hotel capital and operational expenditures (Cap Ex / Op Ex) to evaluate cost-effectiveness, and energy and GHG savings estimates for all CTDs.

1.2. Heat Pump Commercial Tumble Dryers (CTDs)

CTDs use forced air circulation to dry clothing, sheets, towels, pillowcases, and other textiles as they tumble in a drum. These appliances are commonly used after processing textiles in a commercial washer. They operate in apartment buildings, coin-operated laundromats, hotels and motels, health clubs, nursing homes, jails and prisons, universities and colleges, fire and law enforcement stations, hospitals, restaurants, dry cleaners, and laundry service companies.

CTDs are generally rated by capacity (pounds (lb) of dry textiles) and maintain a cubic foot (cu ft) range from approximately 18 lb (<7.5 cu ft) to 400 lb (145 cu ft). They operate on natural gas and propane (with electric controls and motors), electricity, or steam (with electric controls and motors) (CA IOUs 2016). With conventional dryers, outdoor air comes in through the top of the dryer and into the electric or gas burner box, as illustrated in Figure 1. The air is heated, travels through the drum to pick up moisture from the wet textiles, and then is exhausted outside through a large duct on the back of the unit.

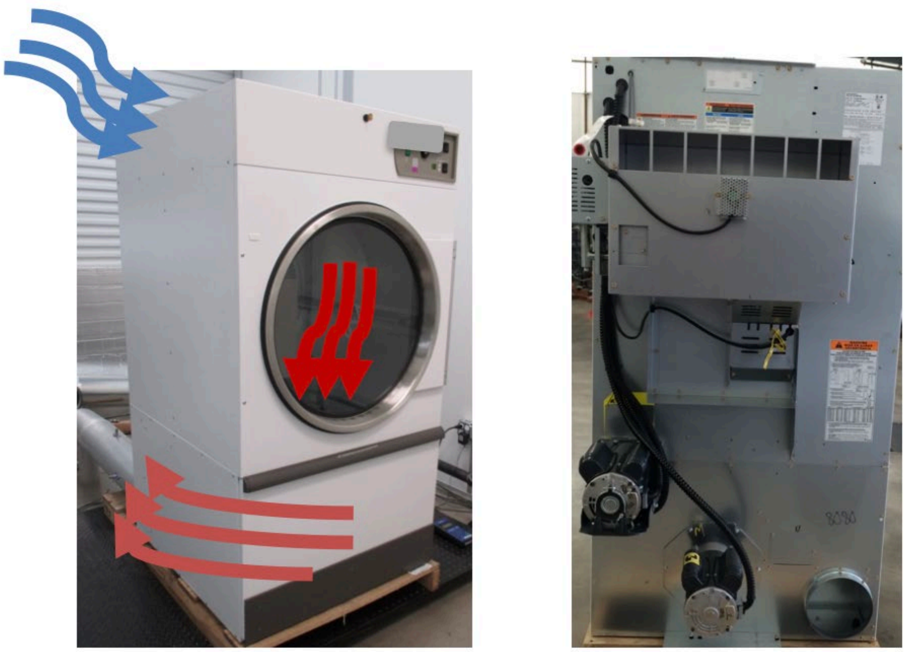


Figure 1. Airflow through a conventional CTD (image left) and rear of CTD (image right)
Source: CA IOUs (2016), page 9.

Figure 2 illustrates how heat pump CTDs available in the US today differ from conventional dryers in two ways:

- A heat pump increases the air temperature in the drum instead of an electric resistance element or a gas burner.
- Heat pump dryers do not have a conventional exhaust duct and employ a closed air loop for drying instead.

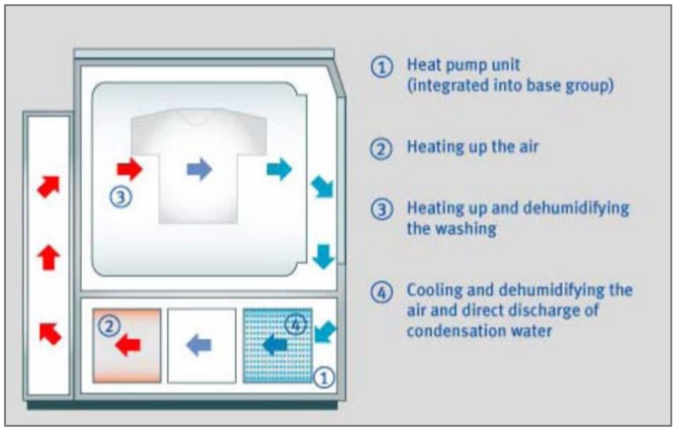


Figure 2. Airflow through a heat pump tumble dryer
Source: Meyers et al. (2010)

Further details on the design and operation of CTDs can be found in CA IOUs (2016).

1.3. Project Objectives and Scope

This project supports two NEEA objectives:

- To increase the adoption of energy-efficient CTDs and
- To advance more efficient commercial dryer technologies.

Furthermore, this project enabled NEEA to develop relationships with key market actors and stakeholders, which initially included the heat pump CTD manufacturer and the hotel company. During the research process, NEEA later connected with Hotel Marcel (New Haven, CT), which employed heat pump CTDs in its laundry operations.[2] The research herein benefited from the collaboration and information exchange with these important stakeholders. This engagement informed the research approach and presented an unusual opportunity for an early market intervention that may ultimately ensure product satisfaction with heat pump CTDs in the US market.

The project scope included three technical research areas with specific objectives for each. These investigations are summarized in the following sections:

- **Section 2—Commercial Tumble Dryer Lab Investigation**: Methodology and Results, including test procedure development and dryer energy measurement.
- **Section 3—Hotel Cap Ex / Op Ex Model**: Methodology and Results**,** detailing capital and operational expenditures of heat pump CTD use in a 100-room hotel.
- **Section 4—Energy and GHG Savings Model: Methodology and** Results, estimating regional and US energy savings opportunities using commercial heat pump tumble dryers.

The report concludes with **Section 5—Summary of Project Conclusions, Outcomes, and Future Opportunities**, which identifies notable opportunities and next steps. Also attached are four appendices with additional project details.

[2] https://www.hotelmarcel.com

2. *Commercial Tumble Dryer Lab Investigation: Methodology and Results*

2.1. Overview and Objectives

In May and June 2024, NEEA tested three types of CTD technology: heat pump, electric resistance, and gas. Specifications for the three CTDs tested are summarized in Table 1. The purpose of the testing was threefold:

- Assess energy savings of the heat pump CTD to support ENERGY STAR's emerging technology award for CTDs and a possible future ENERGY STAR program,
- Provide recommendations on testing parameters needed to modify DOE's Appendix D2 (CFR 2013) for CTD testing and
- Gather information to inform cost-effectiveness modeling and hotel operational parameters of a heat pump CTD.

A total of 27 tests were conducted in an ISO 17025-certified lab with test conditions controlled to achieve consistency in energy results. Methodology details and summarized test results follow next, with full test results available in Appendix A.

2.2. Methodology

2.2.1. CTDs Tested (Laboratory Sample)

Table 1 summarizes the specifications of three CTDs tested, providing technology type, rated capacity load weight, drum size, input voltage (V), and other notable characteristics. Testing included a 44 lb capacity heat pump model, a 55 lb capacity electric resistance model, and a 55 lb capacity gas model from two manufacturers.

Table 1. Three CTDs tested

Dryer	Rated Capacity Load Weight		Drum Size		Input Voltage (V)	Other Characteristics
	(lb)	(kg)	(cu ft)	(liters)		
Electric Heat Pump	44	20	12.7	360	240	Condensing, no intake duct
Electric Resistance	55	25	17.3	490	240 /3-phase	Vented, no intake duct
Natural Gas	55	25	17.3	490	240	Vented, no intake duct

2.2.2. Modified Appendix D2 Test Procedure

Standardized energy testing of CTDs is relatively new in the US, so NEEA developed an approach based on Appendix D2, DOE's test procedure for consumer clothes dryers, and modified it to consider the characteristics that differ from residential products. Version 2.6 of *the Energy Efficiency Test Procedure for Commercial Tumble Dryers*—developed by the California investor-owned utilities (CA IOUs 2017)—and the European standard BS EN 50594 (BSI 2018) also informed the testing method. Table 2 summarizes the specific modifications made to Appendix D2 and suggests adaptations to effectively accommodate future testing of these larger dryers.

Table 2. Summary of modified Appendix D2 test parameters for CTD testing

<table>
<tr><th>Test Parameter and Divergence from Appendix D2</th><th>Discussion</th></tr>
<tr><td>Drum Volume: Measuring drum volume with water is impractical.</td><td>NEEA used the manufacturer's rated volume.</td></tr>
<tr><td colspan="2">Drum Volume Measurement Suggestion: Use rated volume from the manufacturer, verified using Section 6 of Version 2.6 of the Draft Commercial Dryer Test Protocol. [a]</td></tr>
<tr><td>Load Size: 1:25 filling factor (kg of textile to liter of drum size).</td><td>Given the wide range of drum volumes for commercial dryers, a fixed load size is inappropriate.
A more representative approach uses a load size increasing with the drum size.
Manufacturers commonly recommend a 1:25 filling factor, which worked well for all dryers in the sample.</td></tr>
<tr><td colspan="2">Load Size Suggestion: 1:25 filing factor for testing commercial dryers.</td></tr>
<tr><td>Exhaust Simulator: A larger exhaust simulator is needed for larger dryers.</td><td>The AHAM exhaust simulator in Appendix D2 does not address larger exhaust duct diameters.
The Draft Commercial Dryer Test Protocol outlines exhaust and intake simulators based on the AHAM simulator and accommodates a range of duct diameters.</td></tr>
<tr><td colspan="2">Exhaust Simulator Suggestion: Use the exhaust simulator defined in Section 5.1.2 of the Draft Commercial Dryer Test Protocol. [a, b]</td></tr>
<tr><td>Textile Load Preparation: Load prepared in commercial front load washer.</td><td>The top load washer specified in Appendix D2 does not accommodate larger commercial dryer load sizes.
Testing ensured the textiles were wetted evenly, and then the water was extracted to the required IMC.
Although not required for this testing, larger commercial dryers may need loads prepared in two batches and combined.</td></tr>
<tr><td colspan="2">Test Load Preparation Suggestion: Use a larger front-load commercial washer for test load preparation; consider Section 5.7 of the Draft Commercial Dryer Test Protocol for instructions on combining washer loads. [a]</td></tr>
<tr><td>Dryer Preconditioning: Dryers were preconditioned to simulate serial load operation.</td><td>Representative of commercial serial dryer use.
Pre-warming the dryer improves efficiency and reduces the cycle time.
For comparison, one “cold start” test was performed on the heat pump using preconditioning requirements in Appendix D2 (see Figure 4).</td></tr>
<tr><td colspan="2">Suggestion to Add Dryer Preconditioning: Precondition dryers using BS EN 50594: 2018, clause 6.5.3. Precondition the heat pump dryers per the procedure (two preparatory runs).[c] Conventional dryers may use one preparatory run instead.</td></tr>
<tr><td>Ambient Conditions and Input Voltage:
1. Ambient conditions differed from established tolerances.</td><td>Labs are not yet routinely equipped with a test chamber and dedicated power supplies for larger dryers.
73˚F $\pm$ 3˚F was used for ambient temperature.</td></tr>
</table>

Test Parameter and Divergence from Appendix D2	Discussion
2. Ambient humidity was only sometimes within tolerance levels. 3. Could not control voltage input averages and ranges.	• 85% of tests always met Appendix D2 ambient humidity requirements; 11% maintained ambient humidity 75 to 80% of the time. • Recorded input voltage instead of controlling it to a tolerance.
Suggestion for Ambient Conditions and Input Voltage: Consider more relaxed tolerances until there is enough testing volume for labs to invest in equipment.	
Standby Power Measurement: NEEA did not test the standby power of the dryers.	• NEEA did not include standby power testing as it was not requested by the hotel organization that NEEA worked with on the project.
Suggest No Change to Standby Power Measurement: Measure standby power of CTDs per Appendix D2 requirements.	

Notes: [a] Version 2.6 of the *Energy Efficiency Test Procedure for Commercial Tumble Dryers*, which was developed in 2017 by the CA IOUs for California Energy Commission (CEC) consideration (CA IOUs 2017).
[b] Some CTDs with capacities greater than 75 lb may also have air intake ducts. The exhaust simulators could also be used as intake simulators in those cases.
[c] The European standard *BS EN 50594: Methods for measuring the performance of tumble dryers intended for commercial use* (BSI 2018).

Due to the timing of this research, NEEA could not obtain Appendix D2-specified momie textiles with fewer than 50 runs, as required by DOE-developed policy (US DOE 2023), due to product shortage. To address the issue, NEEA substituted expired Appendix D2 textiles (with more than 50 runs) for project testing. While these expired textiles are highly unlikely to affect the energy comparison of the dryers in this study, we recommend that possible impacts of the expired test cloth be considered when comparing the results to dryers outside of it.

2.2.3. Hotel Operation Test Procedure

In addition to testing the CTDs with the modified Appendix D2 test procedure, NEEA designed some tests to represent hotel operations. This testing component was also based on Appendix D2 but had more extensive test parameter adjustments to enable hotel operation-specific testing and evaluation. The hotel test parameters were developed in collaboration with the hotel company. They included hotel-specified towels (bath towels, hand towels, bathmats, and washcloths) and bedding (flat sheets, fitted sheets, pillow protectors, and pillowcases). Some other test loads employed textiles specified by the Association of Home Appliance Manufacturers (AHAM) test protocol for household tumble dryers ANSI/AHAM-HLD-2010 (AHAM 100% cotton). The following Appendix D2 modifications were the same as those outlined in Table 3: drum volume, load size, exhaust simulator, textile load preparation, dryer preconditioning, ambient conditions and voltage, and standby power measurement. The additional modifications to Appendix D2 are summarized in Table 3 and detailed in Appendix A.

Table 3. Summary of additional changes to Appendix D2 test parameters for hotel operation tests

Test Parameter	Divergence from Appendix D2	Discussion
Textile Type	Hotel-specified towels Hotel-specified bedding AHAM 100% cotton	• Three alternate textile loads to assess cost-effectiveness and confirm operational hotel needs when using the heat pump dryer. • Hotel-specified terry towels and washcloths (100% cotton) and bedding (tight weave, 52% polyester and 48% modal). • 100% cotton load of flat sheets, pillowcases, and kitchen towels specified by AHAM-HLD-2010.[a]
Load Size	Same as Table 1 with one exception	• The singular exception was the hotel bedding load in the heat pump, which was tested as a partial-size 22 lb load (filling factor of 1:36) to mitigate observed issues with tumble action (see Section 2.3.3 for more details).
Initial Moisture Content (IMC)	Hotel-specified towels: 56.3% IMC Hotel-specified bedding: 38.2% IMC AHAM 100% cotton: 53.7% IMC	• The IMC is the percentage of moisture content of the load going into the dryer. • The IMCs of these three textile loads were intended to simulate the operation of a best-in-class front load washer/extractor. • IMC is optimized to be as low as possible for each load type without overly extending the wash-extraction time, resulting in shorter dryer cycles and increased dryer efficiency relative to Appendix D2.
Final Moisture Content (FMC)	FMC between 3.0 and 4.0%	• NEEA understands that this FMC is acceptable for these hotel loads.
Dryer Settings	Timed dry for all dryers, including the heat pump model that had automatic termination	• Dryer setting requirements for the conventional dryers matched Appendix-D2 requirements; they do not have automatic termination, so they were tested with timed dry. • The heat pump had automatic termination, but timed drying was used because commercial dryers are highly programable (operators can repeatedly use custom cycles for each common load type in that facility). • Furthermore, laundromats and multifamily laundry facilities tend to sell drying in time increments, which does not enable automatic termination.

Notes: [a] AHAM (2010). ANSI/AHAM HLD-1-2010: Household Tumble Type Clothes Dryers.

2.2.4. Summary of all Laboratory CTD Tests Performed and Values Recorded

Table 4 summarizes the 27 test runs performed on the three dryers. All tests were conducted in an ISO/IEC 17025 certified laboratory (Figure 3). Multiple runs were performed and averaged for the hotel-specified textiles to improve the repeatability of the testing. Standard test loads (Appendix D2-specified momie and AHAM 100% cotton) were typically not run multiple times because of research supporting the repeatability of these textiles for energy testing (Gluesenkamp 2014).

Table 4. Number and type of tests performed on each CTD model

Test Type		44 lb Heat Pump (Dryer 01)	55 lb Natural Gas (Dryer 02)	55 lb Electric Resistance (Dryer 03)
Modified Appendix D2 Test[a]		2 tests: 1 warm, 1 cold [a]	1 test	3 tests [b]
Hotel Operation Tests [c]	Hotel-specified towels	3 tests	3 tests	3 tests
	Hotel-specified bedding	3 tests	3 tests	3 tests
	AHAM 100% cotton	1 test	1 test	1 test
	27 TOTAL:	**9 tests**	**8 tests**	**10 tests**

[a] See Section 2.2.2 describing the modified Appendix D2 test procedure in detail.
[b] Multiple tests were performed to reach the FMC target. Only one test that was within the FMC target was used in the analysis.
[c] Hotel operation tests as described in Section 2.2.3.

Figure 3. Project laboratory testing of the two electric CTDs

NEEA recorded test parameters (e.g., energy use, load weights, ambient temperatures, cycle time, etc.) for each test and calculated the Energy Factor (EF), which is the weight of the bone-dry textile per kWh of energy consumed (excluding standby power). Next, test results offer essential insights into efficiency differences and operational considerations for heat pump CTDs.

2.3. Results and Discussion

2.3.1. Lab Investigation Results Overview

NEEA's lab investigation confirmed that the modified Appendix D2 testing approach could be used for similar commercial dryer testing in the future. Testing revealed that the heat pump CTD delivered 60 percent energy savings relative to the other technologies with 15 to 25 minutes of additional drying time, and effectively dried 100% cotton towels with a 15-minute longer cycle time. However, it did not effectively dry a full-size synthetic hotel bedding load: Drying was uneven and the cycle length was inconsistently extended. Even when the load size was reduced to mitigate inconsistent cycle length, it still resulted in uneven drying for bedding textiles.

2.3.2. Modified Appendix D2 Test Results

Test results found that the heat pump CTD was more than two times more efficient than the conventional models, even when operating with a cold start (no warm-up cycle). Heat pump CTDs deliver 60 percent energy savings relative to conventional technologies. Heat pump efficiency improves by 20 percent when running a serial load compared to starting cold without a load preceding it (heat pump cold start, Figure 4).

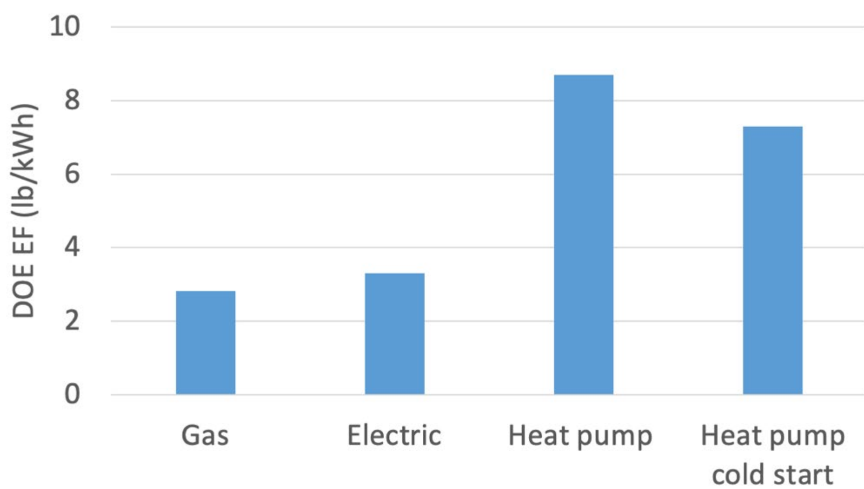


Figure 4. Comparison of Energy Factor (EF) for gas, electric resistance, and heat pump CTDs tested with a modified Appendix D2 (filling factor 1:25)

2.3.3. Hotel Operation Test Results

Under lab conditions designed to mirror hotel operation, the heat pump CTD energy use results, shown in Figure 5, were highly similar to those in the modified Appendix D2 test procedure:

- The heat pump model delivered an average of 60 percent energy savings per cycle compared to conventional electric and gas technologies.
- The heat pump efficiency (EF) was two to three times that of the conventional technologies.

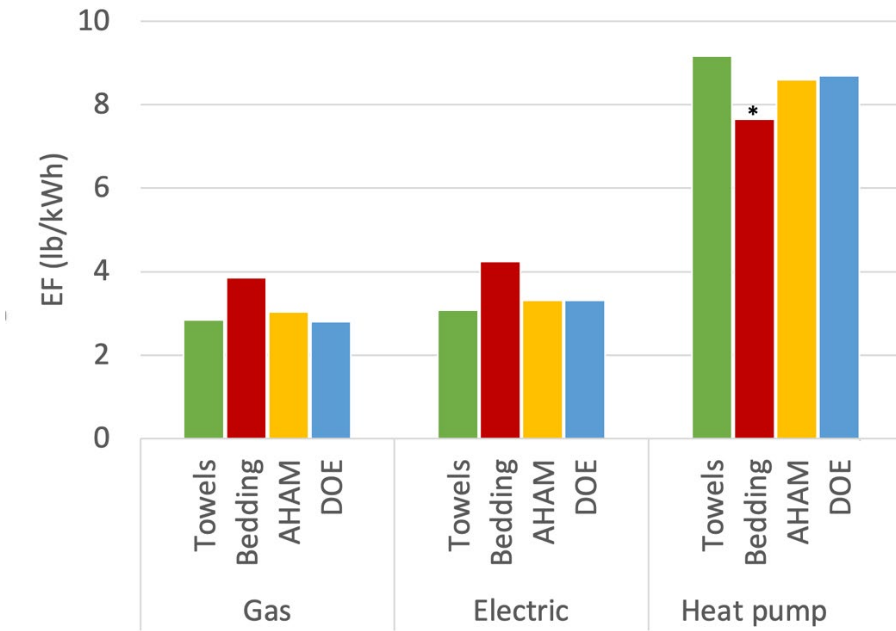


Figure 5. Comparison of Energy Factor (EF) for gas, electric resistance, and heat pump CTDs tested for three full-sized test loads (filling factor 1:25)

Notes: *Partial-size load (filling factor 1:36)

Performance results of the operational test loads, however, were mixed:

- The heat pump dryer effectively dried the hotel-specified 100% cotton towel load with a cycle 15 minutes longer than the conventional CTDs.
- The heat pump CTD unevenly dried and excessively wrinkled sheets, resulting in damp spots on many of the bedding items. Furthermore, the cycle length was long and inconsistent from cycle to cycle.

NEEA attempted to mitigate this issue by utilizing a partial load size instead (filling factor of 1:36). The reduced size improved drying time consistency but still resulted in unevenly dried, wrinkled sheets. NEEA shared these results with the manufacturer for its internal product research and development efforts.

NEEA's conversations with Hotel Marcel—which uses the same heat pump CTDs in the US—confirmed they initially experienced heavy wrinkling of synthetic cotton blend pillowcase loads. Some of these issues were addressed by considering the complete laundry process instead of just focusing on drying alone. Shortening and slowing the washer spin cycle for the pillowcases mitigated the wrinkling and enabled the processing of the pillowcases exclusively in the CTD (with no ironing).

2.3.4. Laboratory Investigation Opportunities and Next Steps

After learning of and assessing the challenges with the heat pump CTD for the bedding load, the manufacturer found that the hotel-specified bedding textile (tight weave of 52 percent polyester and 48 percent modal) is uncommon in the European market where it has historically designed and sold commercial heat pump CTDs. In Europe, flat sheets with 100% cotton content are damp-dried and finished with an ironer. US hotels rarely use ironers and finish the textiles in a CTD.

NEEA identified the following possible solutions to address the uneven performance of the hotel company bedding load in the heat pump model:

- **Use an electric resistance dryer for bedding.** The hotel could employ one heat pump dryer for towels and one electric resistance dryer for the existing bedding textile. This solution is used in Scenario One in the Cap Ex / Op Ex model described in Section 3.2.4.
- **Consider alternative bedding textiles.** The hotel could employ a less tightly woven bedding textile with higher cotton content that will likely dry better in heat pump CTDs. Replacing fitted sheets with flat sheets may also improve performance. Together, the drying results may be more like the AHAM 100% cotton load, which had better overall drying performance with a larger load. A synthetic cotton blend bedding textile—as the Hotel Marcel uses —could also be considered. This solution is included in Scenarios Two and Three in the Cap Ex / Op Ex model described in Section 3.2.4.
- **Future heat pump dryer design change.** The heat pump manufacturer is considering a dryer design change to accommodate this bedding textile type, and a future product may better accommodate this hotel-specified bedding load. This solution is included in Scenarios Two and Three in the Cap Ex / Op Ex model described in Section 3.2.4.

NEEA's efforts to collaborate with the heat pump manufacturer illuminated these market differences between the US and Europe, with positive results to date. The manufacturer is researching and planning for design changes to its US heat pump CTD product line to accommodate hotel operations more effectively. An update on progress is expected in 2025. Regardless, this activity demonstrates the benefit of NEEA's Emerging Technology program with critical performance information as an early market intervention to support the future successful adoption of heat pump CTDs in the US market.

Another consideration for future heat pump CTD research and market adoption efforts is to target other applications (such as vended laundry) for US market entry points.

3. Hotel Cap Ex / Op Ex Model: Methodology and Results

3.1. Overview and Objectives

The purpose of the capital and operational expenditure (Cap Ex / Op Ex) model was to:

- Identify whether commercial heat pump dryers were a cost-effective measure for hotel operations in key climate zones in the Northwest and other US locations specified by the hotel company.
- Support the hotel company in achieving its stated GHG reduction goals by providing detailed cost-effectiveness information on energy and GHG savings associated with heat pump CTDs.

3.2. Methodology

3.2.1. Hotel Baseline Operational Parameters

Working closely with the hotel company to inform the approach, NEEA developed a hotel laundry model with the following parameters used for the baseline laundry facility (both natural gas and all-electric):

- 100-room hotel
- 2 washers and 2 dryers, each with a 30-minute cycle
- Towels are separated from bedding for laundry processing

- Towels represent 50 percent of the total laundry processing loads and bedding the other 50 percent
- 590 lb of laundry processed per day (216,000 lb of laundry processed per year)
- 1.5 full-time employees (FTE) in a single 8-hour shift per day is the assumed staffing model

NEEA selected this operational and staffing approach for the purposes of this model. However, variation is expected across different hotels depending on occupancy rates, beds per room, hotel amenities (e.g., guest pool and spa), and other attributes.

3.2.2. Hotel Types

The model includes incremental capital and operational costs associated with selecting electric heat pump CTDs instead of conventional commercial gas and electric CTDs for new construction hotel properties. The model analyzes two hotel types:

- **All-electric,** where the baseline CTD technology is electric resistance and
- **Conventional,** where the baseline CTD technology is natural gas, given that both natural gas and electric utility services are available.

These two hotel types provide two new construction baseline scenarios in the model.

The heat pump CTDs in this study create additional heat in the room because they are ventless and condensing (see Appendix B). For the heat pump scenarios, the added capital construction cost of higher capacity heating, ventilation, and air-conditioning (HVAC) equipment is included in the analysis to ensure extra cooling to the laundry area. Energy use associated with this additional energy use is included in the ongoing energy costs. Furthermore, for Scenario Three in **Error! Reference source not found.**, extra floor space is required for the third heat pump, which is included in the cost analysis.

3.2.3. Dryer Efficiency and Cycle Time

The project team used CTD efficiency, cycle time, and drying performance from the lab investigation detailed in Section 2 to inform the baseline and replacement (heat pump CTD) scenarios. Other parameters in the model were developed from available literature and market data. When data were unavailable, the project team used its best professional judgment. To reduce complexity, the model does not consider utility incentives nor the co-location of synergistic equipment (such as a heat pump water heater).

3.2.4. Three Heat Pump CTD Replacement Scenarios

Heat pump CTDs are not a one-for-one replacement with conventional CTDs, requiring operational changes due to the longer cycle time and HVAC impacts. The model includes capital and operational expenditures for additional HVAC to accommodate these differences. (For more information about installation approaches for conventional dryers and heat pump dryers, please see Appendix B.) The model assumes the conventional CTDs operate with a 30-minute cycle time, while heat pump dryers take 45 minutes per cycle instead.

Also, as discussed in Sections 2.3.3 and 2.3.4 above, NEEA observed that the currently available heat pump CTD showed the need to improve performance when drying the hotel bedding load. To consider this constraint for a US hotel and to process the same amount of laundry with a longer drying time, the model considered the three scenarios described in **Error! Refere**Table 7**nce source not found.**.

Table 5. Three heat pump CTD replacement scenarios

Scenarios	Technology Approach	Staffing and Shift Impacts
One: Mixed Technology	• One heat pump CTD for towels • One conventional electric resistance CTD for hotel-specified bedding	• Increases laundry processing time: 10-hour shift covered by 1.5 FTE [a] • The 0.5 FTE starts near the completion of the first 8-hour shift
Two: Alternative Bedding or Dryer Design Change	• Uses two heat pump CTDs • Assumes a bedding textile change or heat pump CTD design change	• Same as Scenario One
Three: Scenario Two + Capital Investment	• Uses two washers and three heat pump CTDs • Assumes a bedding textile change or heat pump CTD redesign • Higher capital investment than in Scenarios One and Two	• 1.5 FTE over an 8-hour shift maintains current processing time • Staff divide the full-size wash loads across the heat pump CTDs; the drying cycle completion is staggered throughout the shift

Notes: [a] Hotel staffing and laundry processing time baseline is 1.5 full-time employees (FTE) over an 8-hour shift.

Note that for Scenarios One and Two, the hotel company indicated there would be no increase in labor cost per hour for the adjusted shift. Therefore, the model uses the same hourly labor rate for all scenarios.

3.2.5. Hotel Locations

Seven hotel locations are included in the model, including:

- **Three in the Northwest:** Portland, Oregon; Spokane, Washington; and Billings, Montana. Efforts were made to include different climate zones as conventional dryer efficiency is impacted by the outdoor air temperature (see Section 4.2).
- **Four in other parts of the US:** San Francisco, California; Detroit, Michigan; Phoenix, Arizona; and Houston, Texas. The hotel company selected these US locations.

Baselines for the all-electric and conventional hotels were considered at all seven locations.

3.2.6. Approach to Cost-effectiveness

For this analysis, a heat pump CTD is considered cost-effective if the simple payback period—the point at which the incremental upfront and ongoing maintenance costs of an energy efficiency investment equals the total value of the accumulated operating savings—is 10 years or less, which is slightly shorter than the dryer lifetime of 12 years. A 10-year payback period provides a six percent return on investment (ROI) with no inflation adjustment (Pearce et al. 2009 p. 8). When adjusting for a three percent inflation rate, the 10-year payback period yields an ROI of three percent. These returns are assumed to be acceptable to a commercial hotel.

Cap Ex / Op Ex model results are discussed next.

3.3. Results and Discussion

3.3.1. Quantitative Results

This section includes summary results from two locations—Spokane, Washington, and Detroit, Michigan—to enable a discussion of findings. Summary results from the other five locations are provided in Appendix C.

Table 6 summarizes results from Spokane, Washington, which had a median payback period of five years for heat pump CTDs in place of conventional electric resistance. The greenhouse gas (GHG) emissions for heat pump dryer scenarios are also substantially lower than natural gas dryers (3 to 5 tons of carbon dioxide equivalent (CO_2e) per year for heat pump dryers versus 16 tons for natural gas).

Table 6. Cap Ex / Op Ex results for a new construction hotel in Spokane, Washington

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$24,000	$24,000	$37,000	$50,000	$73,000
Annual operational cost	$4,500	$8,300	$5,700	$4,200	$4,900
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for conv. hotel)	NA (baseline for all-electric hotel)	5	6	15
Annual energy use (kWh and therms)	2,300 kWh + 2,700 therms	75,000 kWh	45,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	16	7	5	3	3

Results for Detroit, shown in Table 7, reveal a shorter payback period (4 years instead of 5 for Scenario One). With Michigan's current electric generation mix, two heat pump dryers still save GHG (Scenario 2).

Table 7. Cap Ex / Op Ex results for a new construction hotel in Detroit, Michigan

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$24,000	$25,000	$38,000	$51,000	$75,000
Annual operational cost	$4,000	$10,600	$7,100	$5,200	$6,000
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	4	5	11
Annual energy use (kWh and therms)	2,200 kWh + 2,600 therms	71,000 kWh	44,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	16	39	24	15	15

3.3.2. All-Electric Hotel Results

When considering heat pump CTDs in new construction of all-electric hotels, NEEA identified the following key findings:

- **Using a commercial heat pump dryer for 100% cotton hotel towels is cost-effective for all-electric hotels in all seven locations.** The length of the laundry worker shift is extended to enable these energy savings, and the financial payback time varies. Payback is 5 years or less in five of seven locations but lower than the expected dryer lifetime of 12 years in all scenarios. The unadjusted ROI ranges from 13 to 53 percent (payback period of seven years in Houston and two years in San Francisco). Adjusting for three percent inflation yields an ROI of 10 to 50 percent (Pearce et al. 2009). This is Scenario One in the model.
- **More cost-effective energy savings are possible in all seven locations, with a payback of 5 years or less in three.** This assumes that changing hotel bedding and/or a future heat pump dryer design change does not increase costs. The model's unadjusted ROI for Scenario Two ranges from 8 to 36 percent (payback period of nine years in Houston and three years in San Francisco). Adjusting for an inflation of three percent yields an adjusted ROI of 5 to 33 percent (Pearce et al. 2009).

Table 8 shows financial payback for all-electric hotels by location. Appendix C provides summary results.

Table 8. The financial payback period for the three scenarios for all-electric hotel locations

City	Electricity Rate ($/kWh)	Financial Payback Period (years)		
		Scenario One	Scenario Two	Scenario Three
San Francisco, CA	$0.27	2	3	6
Detroit, MI	$0.13	4	5	11
Billings, MT	$0.12	4	5	12
Spokane, WA	$0.10	5	6	15
Portland, OR	$0.10	5	7	16
Phoenix, AZ	$0.12	6	7	17
Houston, TX	$0.09	7	9	23

These results do not include utility incentives for heat pump dryers (which could substantially impact cost-effectiveness) or the synergistic benefits of co-locating dryers with other equipment (e.g., heat pump water heaters).

3.3.3. Conventional Hotel Results

When considering natural gas CTD against a heat pump CTD during new construction of conventional hotels, key results include:

- **Heat pump CTDs are not a cost-effective replacement for natural gas CTDs.** In almost all cases, the heat pump CTD has higher capital and operational costs, which means that the incremental cost of the heat pump CTD is never recovered. Furthermore, in cases where the operational costs of the heat pump CTDs were lower, the payback period is longer than the appliance's lifetime.
- **Heat pump CDTs save CO_2.** Savings of CO_2 emissions relative to the incumbent natural gas CTD occur in all seven locations in the analysis.
- **The cost of saving CO_2 is high.** Avoided CO_2 ranges from $97 per ton to thousands of dollars per ton (US market is ~$30 per ton of CO_2e). The cost per ton of avoided CO_2 would be significantly lower if utility incentives or other financial benefits excluded in this analysis were considered.

3.3.4. Opportunities and Next Steps

Improving the Cap Ex / Op Ex model presents additional research opportunities. In some cases, sources were limited for the model, or additional complexity was omitted. Some opportunities for future updates include:

- **GHG emissions for electrical use.** The current model uses each state's average GHG emissions of electrical generation (EIA 2023a and 2023b). However, electricity is imported and exported across state lines. Unfortunately, the project team could not find a source that captured this, so the values used in this analysis were from electrical generation in each state. A future update could address this and adjust for the time of use carbon intensity, transmission losses, and projected changes to the grid. Gas CO_2 intensities could also vary by state and change with the projected addition of biogas or hydrogen.
- **Additional sources of GHG emissions.** The model could also incorporate GHG implications of refrigerant leaks from heat pump CTDs and natural gas leaks from distribution and wells. Also, the model could incorporate the embodied energy of the dryers and energy production systems.

- **Refinement of HVAC impacts.** The model could better quantify HVAC impacts by considering how the specific climate would influence the number of hours needed for cooling and heating per year. This would enable variation in outdoor air by location to offset the heating from condensing heat pump CTDs.
- **Refinement of duty cycle impacts.** The maintenance and lifetime of the CTDs could be made as a function of the duty cycle (number of cycles per year) rather than a set number of years.

In addition to adjusting some of these inputs, future models could consider other business types, such as laundromats or multifamily laundry facilities.

4. Energy and GHG Savings Model: Methodology and Results

4.1. Overview and Objectives

The energy and GHG savings model aims to examine possible opportunities for the broader adoption of heat pump tumble dryers in the Northwest and across the US.

4.2. Methodology

NEEA used results from the heat pump CTD testing and related investigations to inform the development of an energy and GHG savings model. The model was built for each of the 50 states. Oregon, Washington, Idaho, and Montana are considered the Northwest region. Key model inputs included:

- **CTD efficiency.** Conventional and heat pump dryer efficiency is in the testing protocol detailed in Section 2. The model used an average Energy Factor (EF) of the hotel-specified towels and bedding tests. The EF of the conventional gas dryer was 3.28 lb per kWh, the conventional electric resistance was 3.57 lb per kWh, and the heat pump was 9.16 lb per kWh. Please note that because these dryer tests were performed with a high-water extraction washer, the energy and GHG savings are lower than in actual installation, where various washers with a range of water extraction capabilities exist.
- **CTD stock.** The development of the current stock of CTDs differed between the Northwest and the US. For the Northwest, NEEA used the Commercial Building Stock Assessment (CBSA) estimates of CTDs (2019). The CBSA identified 12,000 electric and 46,000 gas CTDs 7.5 cubic feet and larger and 4,200 gas and 38,000 electric CTDs less than 7.5 cu ft.[3] For the rest of the US, the project team scaled California stock developed in a 2016 report (CA IOUs 2016 p. 18) to the other states using gross domestic product (GDP) (US Department of Commerce 2024).
- **Share of electric and gas dryers.** For CTDs with a capacity of 7.5 cu ft and larger, the model assumes 21 percent are electric in the Northwest (NEEA 2019) and 5 percent are electric in the US (CA IOUs 2016, p. 18).
- **Average outdoor air temperature.** Conventional dryer efficiency is impacted by outdoor air temperature because they intake outdoor air, so the average air temperature for each state was used (Current Results 2024).
- **GHG emissions by state.** The current model uses GHG from electrical generation in each state (EIA 2023a and 2023b). As discussed in Section 3, electricity is imported and exported across state lines. Unfortunately, the project team could not find a source that captures this, so the

[3] The difference in population between the area NEEA represents and the four NEEA states (Oregon, Washington, Idaho, and Montana) is less than one percent and was ignored.

values used in this analysis were from electrical generation in each state. The model employs a national number for natural gas emissions (EPA 2024).

- **Other dryer parameters.** NEEA also used usage patterns (lb textiles dried per year) and a breakdown of each dryer size (from 18 to 200 lb capacity) from CA IOUs (2016).

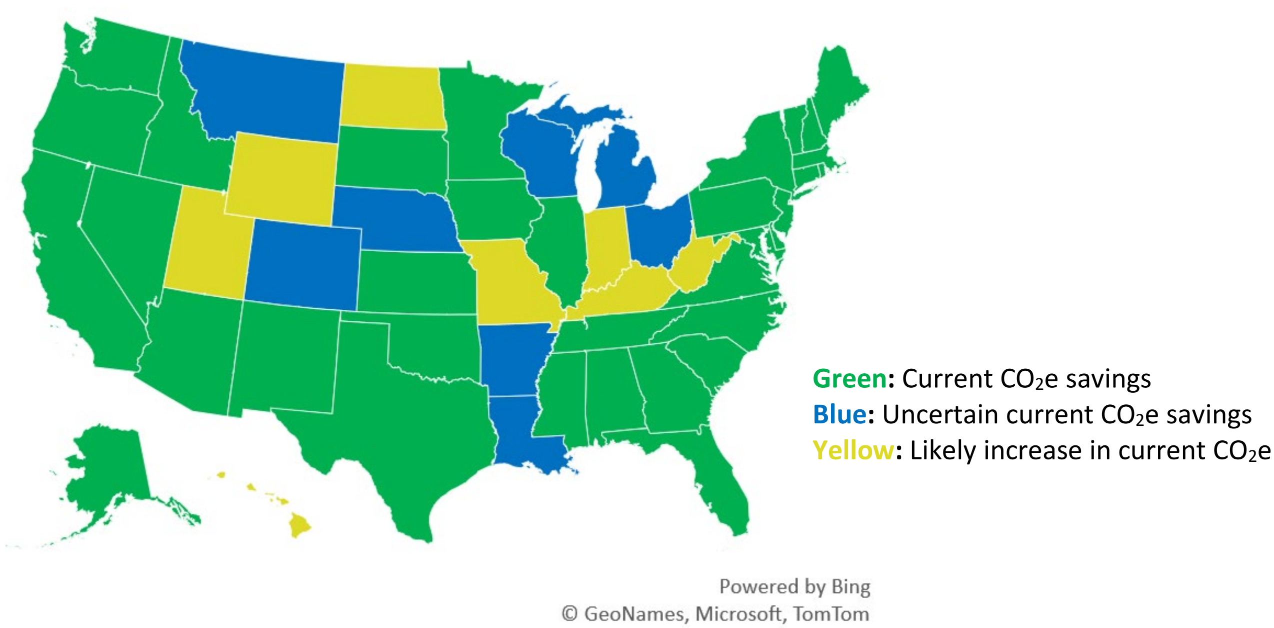
This model replaces the entire stock of electric resistance CTDs with heat pump CTDs, and the energy and GHG savings are tabulated. Replacing natural gas CTDs with heat pump CTDs is considered on a state-by-state basis. The following section discusses the approach to natural gas CTDs and outcomes.

4.3. Results and Discussion

4.3.1. Landscape of Greenhouse Gas Emissions Savings

Because heat pump dryers are more efficient than other CTDs, they always save site energy. However, due to the variation in GHG intensity of each state's electrical grid, a heat pump CTD may or may not currently reduce GHGs relative to natural gas CTDs, which are common in the US.[4] Figure 6 shows the current status of GHG reduction by state for heat pump CTDs. Key findings include:

- For the Northwest, replacing natural gas CTDs with heat pump CTDs saves site energy and will likely reduce GHG emissions for most of the region. The exception is Montana—representing 6 percent of Northwest GDP and 7 percent of the Northwest population—as it has uncertain GHG savings (shown in blue).
- Similarly, for most US states, replacing natural gas CTDs with heat pump CTDs will likely reduce GHG emissions. These 34 states—representing 81 percent of the US GDP and 79 percent of the population—are shaded green in Figure 6.
- In 16 other states, GHG savings are uncertain or expected to increase. Eight states—representing 12 percent of US GDP—have uncertain GHG savings. The remaining eight states—representing 7 percent of US GDP—show that replacing natural gas CTDs will likely increase GHG emissions in the near term (in yellow in Figure 6).



[4] The replacement of conventional electric CTDs with heat pump CTDs always saves GHG emissions.

Figure 6. Current Snapshot of CO_2e savings of heat pump CTDs compared to natural gas CTDs

4.3.2. Regional and National Energy Savings

Regional and national energy savings estimates consider both energy and GHG savings, resulting in energy savings for two cases:

- **Case 1:** Total energy savings for replacing all conventional CTDs with heat pump CTDs.
- **Case 2:** Total energy savings for states where replacing gas CTDs with heat pump CTDs is expected to also decrease GHG emissions during the dryer's lifetime (this includes the 42 blue and green states in Figure 6 where current CO_2e savings are likely or uncertain). In Case 2, conventional electric CTDs in all states are replaced with heat pump CTDs.

Both green and blue states in Figure 6 are expected to have decreased emissions over the dryer's lifetime because conservative forecast scenarios show a 20 percent reduction in electrical grid emissions from 2022 to 2031 (US Congressional Budget Office 2022). This 20 percent reduction scenario is based on current energy sector market dynamics and does not include expected impacts from relevant 2022 legislation. This results in the approaches shown in Table 9: one energy and GHG savings case for the Northwest and two cases for the US (one for all the US and one for the US green and blue states only). For the two US cases, the baseline is the same. In Case 1, CTDs in all states are replaced with heat pump CTDs. In Case 2, gas CTDs in green and blue states are replaced with heat pump CTDs, and conventional electric CTDs in all states are replaced with heat pump CTDs. See Appendix D for energy savings by dryer size.

Table 9. Energy use and savings and GHG production and savings associated with switching CTD stock to heat pump CTDs in the Northwest and the US in two cases

<table>
<tr><th rowspan="2">Region</th><th colspan="6">Energy Savings for switching CTD to Heat Pumps CTD</th></tr>
<tr><th>Baseline Energy Use (site TWh)</th><th>Energy Savings (site TWh)</th><th>% Site Energy Savings</th><th>Baseline GHG Emissions (Millions of tons of CO_2e)</th><th>GHG Savings (Millions of tons of CO_2e)</th><th>% GHG Savings</th></tr>
<tr><td>**Case 1: All NW**</td><td>1.6</td><td>1.0</td><td>64%</td><td>0.29</td><td>0.21</td><td>72%</td></tr>
<tr><td>**Case 1: All US**</td><td rowspan="2">41[b]</td><td>26</td><td>63%</td><td rowspan="2">8.9</td><td>3.0</td><td>34%</td></tr>
<tr><td>**Case 2: US Green & Blue States Only**[a]</td><td>24</td><td>59%</td><td>3.2</td><td>36%</td></tr>
</table>

[a] The energy savings are counted only where GHGs are saved. [b] The baseline for both Case 1 and Case 2 is the same. The difference between the two cases is the number of states where gas CTDs are replaced with heat pump CTDs.

Key observations for Table 9 include:

- **Two-thirds of CTD site energy can be saved.** If heat pump CTDs are used to replace all CTDs (Case 1), approximately two-thirds of site energy is saved. This is because the site efficiency (EF) is approximately three times as high as conventional electric resistance and natural gas CTDs.
- **GHG emissions of the electrical grid have an impact on GHG savings.** The percentage of GHG savings in the Northwest is higher (72 percent) than in the US (34 percent) because of the region's low carbon intensity of electricity.
- **US Case 2 has higher GHG savings.** In Case 1—where heat pump CTDs are installed in every state—the GHG emissions of some states increase. Case 2—where heat pump CTDs only replaced gas CTDs in states where GHG emissions savings are expected over the dryer's lifetime—has higher GHG savings. Because fewer heat pump CTDs are installed, site energy savings are reduced.

Table 10 shows the disaggregated electricity and natural gas consumption and savings for the Northwest and the two US cases.

Table 10. Northwest and US electricity and natural gas use and savings of heat pump CTD stock in the Northwest and in two US cases

Region	Electric			Natural Gas		
	Baseline electric use (GWh/yr)[a]	Increase in electric use (GWh/yr)	% increase	Baseline natural gas use (millions of therms/yr)	Gas savings (millions of therms/yr)	% decrease
Case 1: All NW	410	140	35%	39	39	100%
Case 1: All US	4,200[c]	11,000	260%	1,300	1,300	100%
Case 2: US Green and Blue States Only[b]		10,000	240%		1,200	93%

Notes: [a] The baseline electric use includes electricity of both electric and gas CTDs. [b] The decreases (reduction in gas use) or increases (in electric load) are counted only where GHGs are saved. [c] The baseline for both Case 1 and Case 2 is the same. The difference between the two cases is the number of states where CTDs are replaced with heat pump CTDs.

The key observation from Table 10 is that when all CTDs are replaced with heat pumps, there is an **increase in electricity use and a reduction in natural gas use.** Because electric CTDs are more common in the Northwest, the percentage increase in electricity demand is only 35 percent compared to a more than 200 percent increase in electricity use of CTDs nationally. Natural gas use is reduced because, in the model, all the natural gas CTDs are replaced for the Northwest and in Case 1 of the US. In Case 2, replacing gas CTDs with heat pump CTDs in the green and blue states saves 93 percent of natural gas use.

4.3.3. Opportunities and Next Steps

This model effectively estimates energy and GHG savings associated with heat pump CTDs, but future modeling could be improved as more data become available. Opportunities include:

- **More data on commercial clothes washers and CTD efficiency.** The current model uses dryer efficiencies based on a high-extraction washer. This could be adjusted to represent the washer stock better. Furthermore, the model assumes the same efficiencies at all CTD sizes, which could be refined with more data.
- **Scale the ratio of natural gas to electricity for natural gas CTDs.** The model assumes a constant proportion of site energy for electricity use (2%, based on test data) and could be scaled with CTD size.
- **Customize HVAC impacts of CTDs further to the local climate.**
- **Quantify other sources of GHG emissions**, including fugitive emissions in the energy system and heat pump CTD. Other quantification opportunities include embodied, transport, and end-of-life emissions.
- **Incorporate future projections of GHG intensity of electricity and natural gas by state.** The model only contains a snapshot of current emissions.

Finally, since some states have higher GHG emissions for heat pump CTDs versus natural gas, another opportunity is to investigate emerging technologies in natural gas efficiency, such as modulation, insulation, exhaust heat exchangers, and natural gas heat pumps. Though heat pump CTDs always save

GHGs relative to electric resistance, there are barriers, most notably increased capital costs and drying times.

5. Summary of Project Conclusions, Outcomes, and Future Opportunities

This project represents an important step in better understanding various CTD efficiencies, how heat pump CTD technology may fit into hotel operations, and what energy and GHG savings opportunities heat pump CTDs present in the Northwest and the US. Project conclusions, outcomes, and opportunities are summarized below.

5.1. CTD Lab Investigation: Conclusions and Outcomes

NEEA tested three CTD technology types: two conventional models (one electric resistance, the other natural gas) and one heat pump model, successfully modifying Appendix D2 to measure their energy efficiency and adding hotel-specific loads to evaluate realistic performance. The testing revealed that the modified Appendix D2 approach is effective for CTD testing, and the heat pump CTD saves 60 percent of CTD energy with a 50 to 80 percent longer cycle time. While the heat pump successfully dried 100% cotton towels, it did not effectively process the US hotel-specified bedding load, drying unevenly, wrinkling sheets excessively, and running inconsistently long cycles. These results were incorporated into the hotel Cap Ex / Op Ex model to support the hotel company's decision-making.

Furthermore, NEEA shared the CTD energy savings and drying performance data with the heat pump CTD manufacturer and collaborated with them during the lab testing. This increased NEEA’s understanding of the heat pump CTD technology and enabled the manufacturer to understand better the hotel bedding textiles used in the US market, which differ significantly from other markets where this manufacturer sells similar heat pump CTDs. With this information, the manufacturer plans to update its US market design. This outcome is an excellent example of how NEEA’s Emerging Technology Program can provide early market interventions to support the success of nascent energy-efficient products.

5.2. Hotel Cap Ex / Op Ex Model: Conclusions and Outcomes

The Cap Ex / Op Ex model achieved project objectives to evaluate heat pump CTD as a cost-effective measure for hotel operations, providing essential information to inform decision-making for a low GHG hotel. NEEA also extended the analysis to consider replacing natural gas CTDs used in conventional hotels with heat pump CTDs. Findings for each include:

- **All electric hotels.** Using a heat pump CTD for hotel towels is currently cost-effective in the seven locations evaluated. However, the laundry processing shift length is extended, and the financial payback time varies. More cost-effective energy savings are possible in all seven of the all-electric locations with bedding textiles or heat pump CTD design changes.
- **Conventional hotels.** Heat pump CTDs are not a cost-effective replacement for natural gas CTDs. The heat pump has higher capital and operational costs in almost all cases. Heat pump dryers save CO_2 relative to natural gas CTD in all seven locations in the analysis. Excluding utility incentives yields a high cost of saving CO_2.

"Commercial heat pump dryers provide an excellent opportunity to reduce our hotel's carbon footprint. Heat pump dryers are not a 1:1 replacement for conventional dryers. Still, we would recommend them to other hotel operators that understand the operational changes required."

- *Bruce Becker, Hotel Marcel*

5.3. Energy and GHG Savings Model: Conclusions and Outcomes

When evaluating the energy savings opportunity associated with replacing conventional CTDs with heat pump CTDs, NEEA learned:

- Two-thirds of CTD site energy can be saved.
- GHG emissions of the electrical grid have an impact on GHG savings. The Northwest saves more than 70 percent of GHG emissions, while the US GHG savings is 34 percent.
- Heat pump CTDs increase electricity use while reducing natural gas use.

5.4. Opportunities and Next Steps

This project provided important insights into CTD efficiency and uncovered opportunities for continued research focusing on the hotel industry's specific needs and the broader CTD market. In the immediate future, NEEA aims to continue working with the heat pump CTD manufacturer to support design adjustments that can improve the performance of current models and monitor the market for additional larger capacity CTDs that become available. Some other opportunities for further technical and market research include:

- **Investigate emerging energy efficiency technology for natural gas CTD**. Some CTD use cases may not accommodate the longer cycle time of heat pump CTDs, and the capital cost of heat pump CTDs is high. Furthermore, emissions from natural gas CTDs are lower in some states. Considering these factors, further research could include investigating emerging natural gas CTD efficiency technologies, such as modulation, insulation, exhaust heat exchangers, and natural gas heat pumps.[5]
- **Refine the Cap Ex / Op Ex and energy savings models in various ways**—such as quantifying other sources of GHG emissions or adding a future forecast—which could more effectively support the prioritization of CTD work relative to other Northwest initiatives.
- **Research on vended multifamily laundries and laundromats**. Further technical and market research focused on vended multifamily laundries and laundromats could identify energy savings opportunities and market barriers to adopting smaller-capacity heat pump CTD in vended applications. Research on vended laundries can impact energy affordability for low-income households in the Northwest, who are disproportionately households of color and more likely to experience energy insecurity. Furthermore, some of the challenges with hotel bedding may be less likely in a vended laundry situation where textile loads are expected to be mixed, possibly making vended laundries an opportunity for early adoption of heat pump CTDs.

[5] In a natural gas heat pump, heat from burning natural gas drives a cycle that moves heat, thereby providing more useful heat than burning natural gas alone.

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6.2. Resources from Relevant Experience

Notable efforts by NEEA include seminal research into test procedures (Foster Porter et al. 2020, Dymond 2017, Denkenberger et al. 2012, Dymond et al. 2012), laundry equipment field research published in the Residential Building Stock Assessment (RSBA) Laundry Study (Hannas and Gilman 2014), extensive lab and field study of heat pump clothes dryers (Dymond 2018), investigation of energy use and cycle time of residential laundry washer dryer pairs (Foster Porter 2022), and multiple comment letters to the US Department of Energy (DOE) on test procedures for residential and commercial washers and dryers (NEEA 2020a, 2020b, 2020c, 2019a, 2019b; NEEA et al. 2016). Relevant samples of NEEA work are below.

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Appendix A: Microsoft Excel Lab Test Data

Appendix B: Venting Approaches for Conventional and Heat Pump CTDs

Because of high airflow and the requirement for continuous air supply, conventional commercial tumble dryers (CTDs) larger than 7.5 cu ft (18 lb) are usually installed in a row parallel to an exterior wall (left, Figure B - 1). Between the back of the dryers and the exterior wall is an unconditioned service access (right, Figure B - 1). Open grates in the exterior wall or ceiling of the service access area enable outdoor air to reach the dryer intake. Exhaust air is pushed through a duct that penetrates the wall or the ceiling of the building, usually taking a path through that same service access area (Figure B - 1 right). This means that the intake air temperature of conventional commercial dryers is similar to the outdoor air temperature.

Figure B - 1. Laundromat dryer installation at left: dryers installed parallel to exterior wall; on the right: unconditioned service access area between wall of dryers and exterior wall
Source: CA IOUs (2016) p. 35.

Heat pump commercial dryers available in the US today differ from conventional dryers in two ways:

- The air temperature in the drum is increased using a heat pump instead of an electric resistance element or a gas burner.
- Heat pump dryers have a closed air loop for drying and do not have a conventional exhaust duct. Warm air and moisture are discharged into the room where it operates. This creates an additional load on the building's heating, ventilation, and air conditioning system (HVAC) and an alternate approach to ventilation in the laundry room (not an open-air plenum behind the dryer because the heat comes out of the front of the dryers). See Figure B - 1.

Figure B - 2. Hotel laundry room heat pump CTD installation (image left) and hotel laundry room ventilation solution for heat pump CTD (image right)

Source: Bruce Becker, Hotel Marcel.

The closed loop creates an additional load on the HVAC system of the building compared to conventional CTDs because the heat of condensation is dumped into the room air. The closed loop system of the heat pump dryer also means the heat pump's efficiency is relatively unaffected by outdoor air temperature (whereas conventional dryer efficiency is affected by outdoor air, given that outdoor air is used as intake air). Heat pump clothes dryers can be vented (one now retired residential model did this), increasing efficiency, reducing drying time, and reducing HVAC impacts. HVAC impacts may be reduced further than what is characterized in the Cap Ex / Op Ex model by venting heat outside as shown Figure B - 2 above (right).

Appendix C: Heat Pump CTD Cap Ex / Op Ex Results for Hotel New Construction

Table C- 1. Cap Ex / Op Ex results for a new construction hotel in San Francisco, California

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$25,000	$26,000	$42,000	$58,000	$82,000
Annual operational cost	$4,400	$19,000	$13,000	$9,000	$9,700
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	2	3	6
Annual energy use (kWh and therms)	2,100 kWh + 2,500 therms	68,000 kWh	42,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	15	16	10	7	7

Table C- 2. Cap Ex / Op Ex results for a new construction hotel in Detroit, Michigan

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$24,000	$25,000	$38,000	$51,000	$75,000
Annual operational cost	$4,000	$10,600	$7,100	$5,200	$6,000
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	4	5	11
Annual energy use (kWh and therms)	2,200 kWh + 2,600 therms	71,000 kWh	44,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	16	39	24	15	15

Table C- 3. Cap Ex / Op Ex results for a new construction hotel in Billings, Montana

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$24,000	$24,000	$38,000	$51,000	$74,000
Annual operational cost	$4,000	$10,000	$6,800	$4,900	$5,700
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	4	5	12
Annual energy use (kWh and therms)	2,200 kWh + 2,600 therms	72,000 kWh	44,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	16	40	25	15	15

Table C- 4. Cap Ex / Op Ex results for a new construction hotel in Spokane, Washington

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$24,000	$24,000	$37,000	$50,000	$73,000
Annual operational cost	$4,500	$8,300	$5,700	$4,200	$4,900
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	5	6	15
Annual energy use (kWh and therms)	2,300 kWh + 2,700 therms	75,000 kWh	45,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	16	7	5	3	3

Table C- 5. Cap Ex / Op Ex results for a new construction hotel in Portland, Oregon

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$24,000	$24,000	$37,000	$50,000	$73,000
Annual operational cost	$4,200	$8,100	$5,600	$4,400	$5,100
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	5	7	16
Annual energy use (kWh and therms)	2,100 kWh + 2,500 therms	69,000 kWh	43,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	15	10	6	4	4

Table C- 6. Cap Ex / Op Ex results for a new construction hotel in Phoenix, Arizona

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$23,000	$23,000	$36,000	$49,000	$72,000
Annual operational cost	$3,700	$8,500	$6,100	$4,900	$5,600
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	6	7	17
Annual energy use (kWh and therms)	1,900 kWh + 2,200 therms	62,000 kWh	40,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	14	21	14	9	9

Table C- 7. Cap Ex / Op Ex results for a new construction hotel in Houston, Texas

Attributes	Gas Dryers	Only Electric Resistance Dryers	Heat Pump Dryer Scenarios		
			Scenario One	Scenario Two	Scenario Three
Capital cost ($2023)	$23,000	$23,000	$36,000	$49,000	$71,000
Annual operational cost	$3,200	$7,100	$5,100	$4,200	$4,900
Payback period vs. Baseline Electric Resistance (years)	NA (baseline for regular hotel)	NA (baseline for all-electric hotel)	7	9	23
Annual energy use (kWh and therms)	1,900 kWh + 2,300 therms	64,000 kWh	41,000 kWh	27,000 kWh	27,000 kWh
Tons CO_2e per year	14	29	18	12	12

Appendix D: Energy and GHG Use and Savings of CTD by Size

Table D - 1. Stock energy use and GHG emissions and savings in the Northwest states by CTD size

Dryer Size (in cubic feet of drum volume)	Stock Use and Savings in the Northwest					
	Millions of therms used/ year	Millions of therms saved/ year	GWh used/ year	GWh saved/ year	Thousands of CO_2e tons produced/ year	Thousands of CO_2e tons saved/ year
Gas: < 7.5	0.39	0.39	0.31	-3.8	2.3	1.7
Electric: < 7.5			98	61	14	8.7
Gas: >/= 7.5 and < 13	15	15	12	-140	88	66
Electric >/= 7.5 and < 13			110	68	16	10
Gas: >/= 13 and < 17	0.90	0.90	0.70	-8.8	5.3	4.0
Electric: >/= 13 and < 17			6.5	4.0	0.92	0.57
Gas: >/= 17 and < 21	11	11	8.2	-100	62	47
Electric: >/= 17 and < 21			79	49	11	7.0
Gas: >/= 21 and < 37	9.3	9.3	7.3	-91	55	41
Electric: >/= 21 and < 37			70	43	10	6.2
Gas: >/= 37	3.2	3.2	2.5	-31	19	14
Electric: >/= 37			21	13	3.0	1.9
Total	*39*	*39*	*410*	*-140*	*290*	*210*
Total gas dryers	*39*	*39*	*30*	*-380*	*230*	*170*
Total electric dryers			*380*	*240*	*55*	*34*

Table D - 2. Stock energy use GHG emissions and savings by CTD size in the US if all states switch to heat pump CTDs

Dryer Size (in cubic feet of drum volume)	Stock Use/Savings US All States Heat Pumps					
	Millions of therms used/ year	Millions of therms saved/ year	GWh used/ year	GWh saved/ year	Thousands of CO_2e tons produced/ year	Thousands of CO2e tons saved/ year
Gas: < 7.5	130	130	100	-1,400	810	230
Electric: < 7.5			1,400	840	530	320
Gas: >/= 7.5 and < 13	430	430	330	-4,400	2,600	790
Electric >/= 7.5 and < 13			710	430	260	160
Gas: >/= 13 and < 17	26	26	20	-270	160	48
Electric: >/= 13 and < 17			42	26	15	9.2
Gas: >/= 17 and < 21	310	310	240	-3,100	1,900	560
Electric: >/= 17 and < 21			520	310	190	110
Gas: >/= 21 and < 37	270	270	210	-2,800	1,700	500
Electric: >/= 21 and < 37			460	280	160	99
Gas: >/= 37	93	93	72	-950	570	170
Electric: >/= 37			140	83	50	30
Total	*1,300*	*1,300*	*4,200*	*-11,000*	*8,900*	*3,000*
Total gas dryers	*1,300*	*1,300*	*980*	*-13,000*	*7,700*	*2,300*
Total electric dryers			*3,300*	*2,000*	*1,200*	*730*

Table D - 3. Stock energy use and GHG emissions and savings in the US by CTD size if only green and blue states switch to heat pump CTDs

Dryer Size (in cubic feet of drum volume)	Stock use/savings US Green and Blue States Heat Pumps					
	Millions of therms used/ year	Millions of therms saved/ year	GWh used/ year	GWh saved/ year	Thousands of CO_2e tons produced/ year	Thousands of CO2e tons saved/ year
Gas: < 7.5	130	120	100	-1,300	810	250
Electric: < 7.5			1,400	840	530	320
Gas: >/= 7.5 and < 13	430	400	330	-4,100	2,600	860
Electric >/= 7.5 and < 13			710	430	260	160
Gas: >/= 13 and < 17	26	24	20	-250	160	52
Electric: >/= 13 and < 17			42	26	15	9.2
Gas: >/= 17 and < 21	310	280	240	-2,900	1,900	610
Electric: >/= 17 and < 21			520	310	190	110
Gas: >/= 21 and < 37	270	250	210	-2,600	1,700	540
Electric: >/= 21 and < 37			460	280	160	99
Gas: >/= 37	93	86	72	-880	570	180
Electric: >/= 37			140	83	50	30
Total	*1,300*	*1,200*	*4,200*	*-10,000*	*8,900*	*3,200*
Total gas dryers	*1,300*	*1,200*	*980*	*-12,000*	*7,700*	*2,500*
Total electric dryers			*3,300*	*2,000*	*1,200*	*730*