Field and Market Assessment of Heat Pump Clothes Dryers

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At a Glance

Heat pump clothes dryers—ready for prime time in the U.S.?

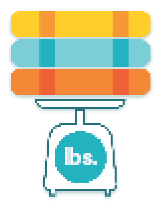
Residential heat pump clothes dryers are more energy efficient than conventional electric dryers and they are ventless, making dryer location more flexible. **So why don't we see more of them in use in Minnesota homes?** To find out, Slipstream conducted a field study in Minnesota to test their performance and household satisfaction with heat pump clothes dryers.

Our study

We provided a free, full-size hybrid heat pump clothes dryer to 11 Minnesota households, and compared its energy performance to the household's existing dryer over a year's time. Households kept a dryer journal, and we interviewed them about their experience with the new dryer and how it compared to their pre-existing conventional dryer. We also bench-tested the full-size heat pump dryer as well as a selection of compact heat pump dryers intended for multifamily applications.

What we learned

SIZE: **In the U.S., we're accustomed to using large clothes dryers (capacities of 6 or more cubic feet).** Currently there is only one option for this size heat pump dryer: Whirlpool manufactures a full-size, hybrid heat pump clothes dryer that uses both heat pump technology and traditional electric resistance to dry clothing. In contrast, there are many options for compact heat pump clothes dryers (4 cubic feet) that are mostly used in multifamily buildings.

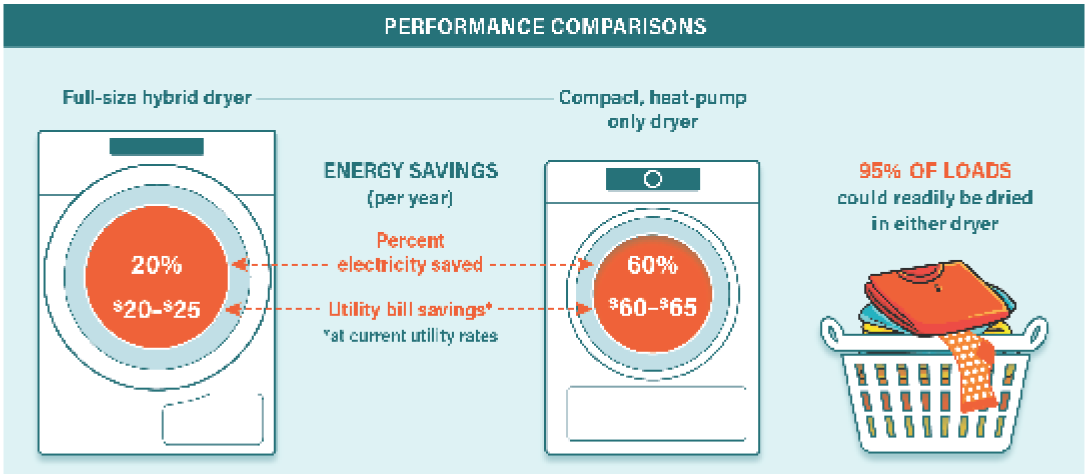


But we found that most loads dried in a full-size dryer would fit in a compact heat pump dryer. Load weights recorded by our study participants indicated that **95 percent of loads** dried in full-size dryers could readily be handled by compact heat pump dryers.

COST: Heat pump dryers cost about $400–$600 more than conventional dryers with similar features, though it's difficult to make direct comparisons. But **cost is likely a big reason why the market share for heat pump dryers is estimated at less than one percent.**

ENERGY SAVINGS: Field-monitoring and bench-testing data—along with field studies by others—suggest average electricity savings of about 20 percent for the full-size Whirlpool hybrid dryer over a conventional dryer, with savings for individual participants in our study ranging from about zero to 40 percent. For a typical Minnesota household in a single-family home, **this would amount to about 200 kWh per year in dryer electricity savings, worth $20 to $25 at current utility rates.**

slipstream



Bench-testing results from four compact, heat-pump only dryers, on the other hand, suggest much higher savings—on the order of **575 kWh per year** in a single-family home, **more than 60 percent savings** over a conventional dryer, and **worth $60 to $65**.

DRYING TIME: Heat pump dryers take substantially longer to dry a load of laundry—from an average of about 75 minutes per load for the pre-existing dryers to 130 minutes with the full size, hybrid heat pump dryer. Drying time, though, was an important issue for only some households in our study, and the monitoring data from the pre-existing dryers showed that back-to-back dryer loads—where longer drying times might be an issue—were uncommon.

SPACE CONDITIONING IMPACTS: Ventless heat pump dryers have a positive impact on space-conditioning costs in Minnesota. The full-size Whirlpool hybrid dryer will typically save 10 to 15 therms of space-heating energy in a single-family home.

Ventless heat pump dryers in new multifamily buildings would also reduce space-conditioning costs slightly. Detailed air-exchange and energy modeling suggests that compact heat pump dryers would reduce space-conditioning costs about $7 per year per housing unit on top of the $45 per unit per year direct savings in dryer electricity.

Making it to prime time

Heat pump clothes dryers are more efficient than conventional electric resistance dryers but are relatively unknown in the Minnesota market. Promoting this appliance could include:

- Incorporating heat pump dryers into utility appliance rebate programs.
- Building consumer awareness of heat pump dryers by tapping into activities promoting heat pump technology for space and water heating.
- Targeting multifamily new construction programs to include incentives for ventless heat pump dryers, which provide energy savings and eliminate the cost of installing dryer venting in every unit.
- Revising the Minnesota Technical Reference Manual to better reflect the savings from both heat pump and non-heat-pump clothes dryers.

This study was funded by Minnesota Department of Commerce, Division of Energy Resources through the Conservation Applied Research and Development (CARD) program.

Executive Summary

Residential heat pump clothes dryers are a potentially significant advancement in clothes drying technology. Not only are they more energy-efficient than conventional electric dryers but they are ventless, which allows for flexibility in dryer location and can provide indirect space-conditioning benefits in heating-dominated climates. This study examined the features, performance, and consumer acceptance of heat pump clothes dryers as a potential addition to Minnesota Conservation Improvement Programs. The study focuses on two clothes dryer markets:

1. replacement of full-size clothes dryers in single-family homes; and
2. dryer selection for multifamily new construction.

Methods

To conduct the study, we provided a free, full-size hybrid heat pump clothes dryer to 11 Minnesota households, and compared its energy performance to the household's existing dryer over the course of about a year. We asked the households to maintain a dryer journal and interviewed participants about their experience with the new dryer and how it compared to their pre-existing conventional dryer.

We also undertook bench-testing of both the full-size heat pump dryer used in the field study as well as a selection of compact heat pump dryers intended for multifamily applications.

Finally, we interviewed developers and others engaged in Minnesota multifamily new-construction markets and modeled how in-unit clothes dryer specification affects space-conditioning energy in new multifamily buildings.

Product Availability and Cost

- ***There are <u>many</u> options for compact heat pump dryers*** — A number of manufacturers offer compact[1] heat-pump-only dryers, which have taken hold in Europe and other parts of the world where what is considered a "compact" dryer in North America is the norm.
- ***But there is currently only <u>one</u> option for a full-size heat pump dryer*** — There is currently only one manufacturer (Whirlpool) offering a full-size heat pump clothes dryer, and that unit is also the only *hybrid* heat pump dryer on the market, meaning that it utilizes both heat pump technology and traditional electric-resistance to dry clothing.
- ***Heat pump dryers carry a significant upgrade cost —*** Heat pump dryers cost about $400-$600 more than conventional dryers with similar features, though direct comparison is difficult owing to the wide range in features, finishes and cost for residential dryers in general. This is no doubt

[1] Compact meaning has a drum capacity of less than about 4.5 ft^3. In contrast, full-size dryers in North America typically have drum capacities of 6 ft^3 and up.

a large driver for why the market share for heat pump dryers is estimated at less than one percent.

Energy Ratings

- ***Federal energy ratings for dryers do not reflect performance under real-world conditions*** —The field-monitoring and bench-testing data from this study support what other studies have shown: that the federal *Combined Energy Factor* (CEF) rating for clothes dryer energy performance significantly underestimates the energy used by clothes dryers under real-world conditions.
- ***Minnesota Technical Reference Manual savings estimates for efficient clothes dryers are too low —*** The above issue with the federal CEF has implications for the Minnesota Technical Reference Manual (TRM), which relies heavily on CEF and other assumptions that this study suggest should be revised. Revising the TRM to reflect more realistic performance and assumptions would substantially increase the estimated savings for both heat pump and conventional efficient dryers.

Heat Pump Clothes Dryers in Single-Family Homes

- ***Consumer response to the full-size Whirlpool hybrid dryer was mixed —*** Offered the choice of keeping a new full-size hybrid heat pump dryer provided by the study (at no charge) or going back to their pre-existing dryer, seven of eleven participants elected to keep the heat pump dryer, and four participants returned it. One of the returned heat pump dryers was later determined to have malfunctioned. People who kept the heat pump dryer tended to perceive it as a higher-end product, appreciated the energy savings, liked the locational flexibility afforded by ventless operation and felt that the lower drying temperature was gentler on their clothing. Those who returned the dryer tended to mention longer drying times and hassle associated with cleaning a secondary lint filter.
- ***Some households resorted to timed-dry operation to achieve satisfactory performance with the hybrid Whirlpool machine*** —Several participants reported that after experimenting with settings, they settled on using timed-dry cycles instead of sensor-based automatic termination for the heat pump dryer to get acceptably-dried clothing. This has significance because timed-dry operation can result in decreased energy performance when the dryer continues to run even if the clothing is already dry.
- ***Energy savings for the full-size Whirlpool hybrid dryer are about 20 percent —*** Field-monitoring and bench-testing data—along with field studies by others—suggest average electricity savings of about 20 percent for the full-size Whirlpool hybrid dryer over a conventional dryer, with savings for individual participants ranging from about zero to 40 percent. For a typical Minnesota household in a single-family home, this would amount to about 195 kWh per year in dryer electricity savings.
- ***Energy savings for compact heat pump dryers are closer to 60 percent*** — Bench-testing results for four compact, heat-pump only dryers, on the other hand, suggest much higher savings: on

the order of 575 kWh per year in a single-family home, which is in excess of 60 percent savings over a conventional dryer.

- ***More than 9 in 10 loads dried in a full*-size dryer would readily fit in a compact heat pump dryer —** Load weights recorded by study participants indicate that 95 percent of loads dried in full-size dryers could readily be handled by compact heat pump dryers. But convincing owners of a full-size dryer to switch to a European-style compact dryer would likely be difficult. A better solution—but one that is in the hands of appliance manufacturers—would be to offer a full-size heat pump dryer with energy performance on par with the current suite of European-style compact heat pump dryers.
- ***Heat pump dryers take substantially longer to dry a load of laundry, but this is not necessarily a deal breaker* for consumers** — As expected, load drying times increased substantially with the full-size hybrid dryer, from an average of 76 minutes per load for the pre-existing dryers to 129 minutes with the heat pump dryer. Bench testing of two of the returned units suggests that the "speed" setting on this dryer provides only a modest reduction in drying time. However, participant interviews indicated that drying time was an important issue for only some households, and the monitoring data for the pre-existing dryers showed that back-to-back dryer loads—where longer drying times might be an issue—were in fact uncommon.
- ***Filter maintenance may affect energy performance more than cycle settings —*** Bench testing by drying the same load under different cycle settings did not show strong variation in energy performance for any of the heat pump dryers but did suggest that the full-size Whirlpool dryer is susceptible to degraded performance if the secondary lint filter is left uncleaned—even within the manufacturer's recommended cleaning interval of every five cycles. The compact heat pump dryers did not seem to be similarly affected by this issue.
- ***Long-term performance of heat pump dryers in unknown, but eventual fouling of coils could be an issue —*** Disassembly of three of the full-size Whirlpool heat pump dryers after field- and bench-testing showed the beginnings of build-up on the heat pump coils. This could be a concern over the long haul because coil cleaning on this particular machine is not easily accomplished without significant disassembly. It also raises some general questions about long-term performance of ventless heat pump dryers if few homeowners are attentive to the need to keep filters and coils clean.
- ***Ventless heat pump dryers have a positive impact on space-conditioning costs in Minnesota —*** Calculations suggest that the full-size Whirlpool hybrid dryer will typically save 10 to 15 therms worth of space-heating energy from reduced infiltration and increased retention of dryer heat inside the home, and these indirect cost savings will outweigh slightly increased air conditioning costs during the summer.

Heat Pump Clothes Dryers in Multifamily New Construction

- ***In-unit laundry is the norm in Minnesota multifamily new construction —*** A review of plans and other documents for a sample of recent multifamily construction projects indicate that the majority of properties are built with provisions for individual, in-unit laundry. Most are built with traditional vented dryers, but a few have been designed for ventless dryers, which can mean either traditional condensing-type dryers or heat pump dryers. Minnesota construction codes do not require the installation of vented dryers.

- ***Multifamily developers have limited awareness of ventless heat pump dryers* —** Interviews with three multifamily housing developers in Minnesota suggest limited awareness of heat pump clothes dryers in this market. Only one developer had installed full-size hybrid heat pump dryers in one of their buildings—as a solution to a perceived make-up air code issue. Another developer was just beginning to research heat pump dryers, and the third was not familiar with them.
- ***Installing compact heat pump dryers in new multifamily properties would avoid the cost of installing dryer venting and would produce significant electricity savings for residents* —** Bench testing of four models of compact heat pump dryers intended for multifamily applications, suggest that compact models use about 1/3 the electricity as a conventional vented electric dryer or a conventional condensing ventless dryer. For a typical household in a new Minnesota multifamily building, this would translate into about 400 kWh per year in electricity savings. Specifying ventless heat pump dryers in multifamily new construction projects would also avoid the cost of installing dryer venting in each unit.
- **Ventless heat pump dryers in new multifamily buildings would also reduce space-conditioning costs slightly —** Detailed air-exchange and energy modeling of the impacts of ventless heat pump dryers on space-heating and cooling energy suggest that compact heat pump dryers would reduce space-conditioning costs about $7 per year per housing unit on top of the $45 per unit per year direct savings in dryer electricity. Similar heating and cooling savings could be obtained using conventional ventless condensing dryers but would not provide the much larger direct savings in dryer electricity.

Recommendations for Minnesota Utilities

- The Minnesota TRM should be revised to better reflect the savings from both heat pump and non-heat-pump clothes dryers. Appendix D to this report provides detailed recommendations in this regard.
- Utilities should consider incorporating heat pump clothes dryers into their appliance rebate programs, along with market-development activities to build consumer awareness and availability of the technology. The awareness building for heat pump dryers could tie into more general efforts to promote heat pump technology for space-heating and water heating.
- Multifamily new construction programs should consider incentives or other encouragement for using ventless heat pump dryers, which provide energy savings and eliminate the cost of installing dryer venting in every unit. In particular, there are opportunities to educate staff at the Minnesota Housing Finance Agency on the benefits of compact heat pump clothes dryers and how they comply with the Green Communities guidelines that developers receiving MHFA financing must follow.

Introduction

Clothes dryers are nearly ubiquitous in Minnesota single-family homes, and about a third of multifamily housing units have in-unit laundry, with electric dryers dominating in both types of housing (Figure 1). However, clothes dryers are largely ignored by energy efficiency programs, because, until recently, the technology had changed little in the last half century. However, heat pump clothes dryers are beginning to appear in the North American market, with the potential to reduce clothes drying electricity consumption by up to 50 percent. And by eliminating the need for external venting, they may also reduce space-heating costs in Minnesota homes.

Slipstream, with project partners the Center for Energy and the Environment (CEE), and Evergreen Economics, investigated the savings and potential market for heat pump clothes dryers by: (1) monitoring a sample of heat pump clothes dryers in single-family Minnesota homes to better assess the real-world energy savings and cost effectiveness of the technology; (2) reviewing laundry journals and interviewing study participants about their experience with currently available models of heat pump clothes dryers; and, (3) exploring the awareness of ventless heat pump clothes dryers for multifamily applications.

Residential Clothes Drying Technology

Electric clothes dryers—including heat pump dryers—can be categorized along three dimensions:

- **Size** – while there is some variation within categories, clothes dryers in general are divided between *standard* (or "full-size") capacity and *compact* dryers. Standard dryers generally have capacities of 6 or more cubic feet, while compact dryers are usually around 4 cubic feet in capacity. In North America, compact dryers are mainly used in multifamily buildings where space is at a premium and households tend to have fewer members. However, in Europe compact clothes dryers are the norm in both single-family and multifamily homes.
- **Venting** – clothes dryers may be designed to be *vented* to the exterior or *unvented*. Vented clothes dryers are the standard in North American single-family homes, but unvented dryers can be found in condominiums, apartments and townhomes that lack facilities for dryer venting. In general, unvented clothes dryers are more expensive and require longer drying times, because they condense and dispose of the moisture from drying rather than heat the clothes and vent the moist air outside.
- **Drying technology** – conventional dryers use electric-resistance coils to heat the air used for drying clothes. Heat pump clothes dryers may use solely heat pump technology for drying (*pure heat pump*) or may allow for a user-selected mix of heat pump and electric resistance drying that trades off energy efficiency and drying time (*hybrid*).

For our study, we monitored full-size hybrid heat-pump dryers in study participants' homes and compared them to their use of their full-size electric resistance dryers. We also bench-tested several compact heat pump dryers and one condensing compact dryer.

Figure 1. Residential clothes dryers in Minnesota.

Heat pump versus conventional electric resistance dryers

A conventional electric resistance dryer heats air that is blown into the drum of the dryer (Figure 2). This warm air absorbs moisture from the clothes and is exhausted out of the house. A conventional condensing dryer instead passes the warm, moist air over a condensing unit to remove the moisture and then recirculates it instead of exhausting it from the home. The condensing unit circulates ambient indoor air to keep the condenser cool enough so that moisture is removed from the air circulating in the dryer. Condensed moisture from the clothing is sent down the drain or collected in a pan in the dryer to be dumped out at the end of the cycle.

Like conventional condensing dryers, heat pump dryers are also a closed-loop system.[2] A heat pump dryer uses two sets of coils to first cool the air from the dryer drum so that moisture condenses out and then reheat the air to return it to the drum (Figure 2 and Figure 3). A hybrid heat pump has the same features but also uses conventional electric-resistance coils to speed drying.

In contrast, a conventional electric dryer would have little more than a blower motor and fan wheel, some ducting and electric coils at the back of the dryer.

[2] For a time, LG offered a full-size vented heat pump clothes dryer, but it has been discontinued.

Figure 2. Types of electric clothes dryers.

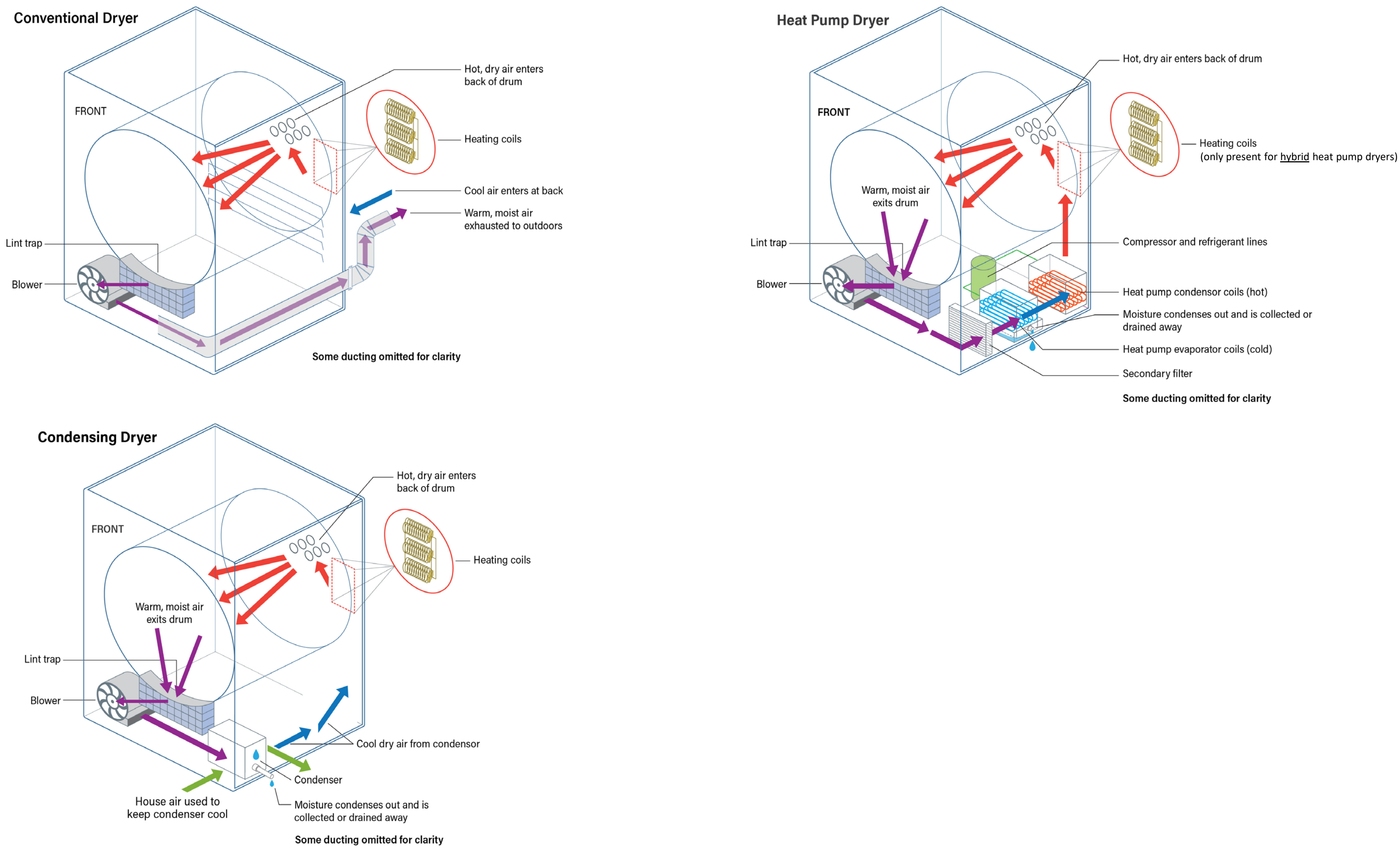
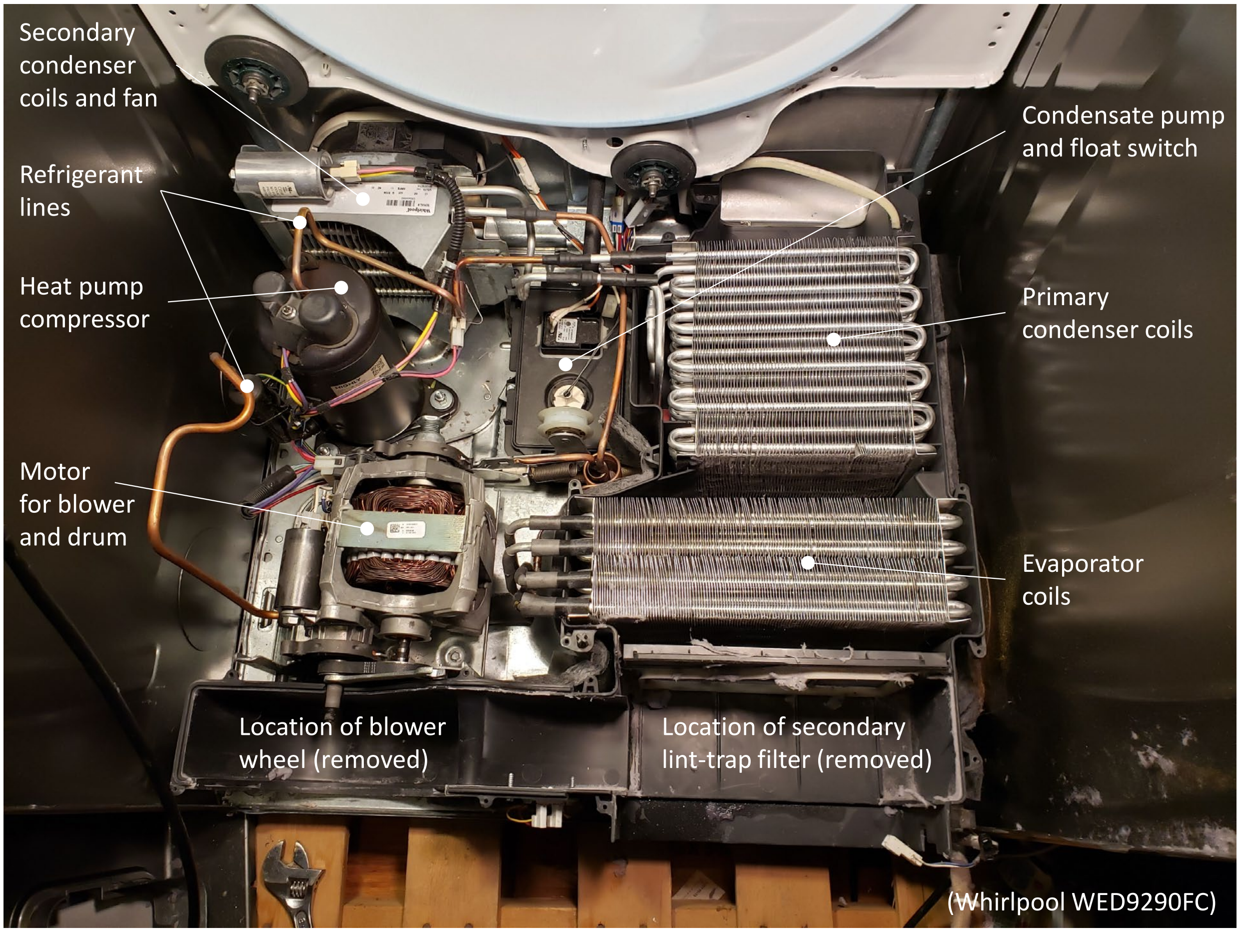


Figure 3. Anatomy of a heat pump clothes dryer (view from above with drum removed).



Conventional clothes dryers dominate the U.S. market. The market share in the U.S. for heat pump clothes dryers is less than one percent (RTF 12/08/2020).

Clothes Dryer Energy Ratings

Clothes dryers are subject to federal minimum efficiency standards that came into effect in 2015. The efficiency standard for clothes dryers is known as the Combined Energy Factor, or CEF, which is expressed in pounds of laundry dried per kWh of electricity consumption.[3] The federal minimum CEF (and the test procedure on which it is based) varies by fuel, size and whether the dryer is vented or unvented (Table 1).[4] For a conventional full-size vented electric dryer, the federal minimum CEF is 3.73 lbs/kWh.

[3] 10 CFR 430.32(h)

[4] In December 2020, DOE also published a final rule exempting dryers with cycle times under 30 minutes from all efficiency requirements, to the consternation of energy efficiency advocates, manufacturers and others (Mauer 2020).

The US Environmental Protection Agency sets minimum qualification criteria for ENERGY STAR qualified clothes dryers. The minimum CEF for ENERGY STAR qualification also varies by fuel, size and dryer venting, but full-size vented electric dryers must have a CEF of 3.93 to gain the ENERGY STAR label, or about 5 percent more efficient than the federal minimum.[5]

It is important to note that the federal ratings and test procedure use 4.4 ft^3 of drum capacity as the dividing line between full-size and compact dryers, and that compact dryers are tested with a much smaller test load (3 lbs) than full-size dryers (8.45 lbs), which, all else being equal tends to result in lower rated performance. Nearly all compact heat pump dryers are in the 4.1 to 4.3 ft^3 size range, which puts them in the compact category for rating purposes, even though (as we will show later) they have sufficient capacity to handle the vast majority of loads that are dried in full-size dryers. For this reason, utilities in the Pacific Northwest instead use 4.0 ft^3 of drum capacity to distinguish between compact and full-size products (RTF 12/08/2020).

Table 1. Federal energy ratings for electric dryers

Size category[a]	**Dryer type**	**Combined Energy Factor (lbs/kWh)**[b]
Full-size	*Federal minimum for a vented dryer*	*3.73*
Full-size	*ENERGY STAR minimum for a vented dryer*[c]	*3.93*
Full-size	Whirlpool ventless hybrid heat pump	5.20
Compact	*Federal minimum for a vented dryer (240V)*	*3.27*
Compact	*ENERGY STAR minimum for a vented dryer (240V)*[c]	*3.45*
Compact	*Federal minimum for an unvented dryer (240V)*	*2.55*
Compact	*ENERGY STAR minimum for an unvented dryer (240V)*[c]	*2.68*
Compact	Typical ventless heat pump	6.00

(a) "Full size" defined as 4.4 ft^3 capacity or higher
(b) as defined in 10CFR 430 Subpart B, Appendix D2
(c) does not include allowable credit for connected dryers

[5] The ENERGY STAR qualification criteria also provide a credit for connected clothes dryers with demand-response capabilities.

Costs

There is a wide range in the cost of conventional dryers (Table 2), some of which owes to extra features (such as steam cycles to prevent wrinkling) and some of which can be attributed to more expensive exterior and drum materials, such as stainless steel.

Table 2. Typical dryer cost

Dryer Type	Typical Cost Range
Full-size, conventional vented	
Low-end	$450-$700
Mid-range	$700-$1,200
High-end	$1,200-$1,800
Full-size, ventless hybrid heat pump	$1,200-$1,400
Compact, conventional vented	$600-$1,200
Compact, ventless condensing	$800-$1,200
Compact, ventless heat pump	$1,000-$1,500

Heat pump dryers involve considerably more hardware (Figure 3) and are invariably more expensive all else being equal. We estimate the cost of upgrading from a conventional ENERGY STAR qualified electric dryer to heat pump dryer with otherwise comparable features to be in the range of $400 to $600. This holds true for both full-size and compact dryers. [6]

Heat pump clothes dryers on the market

At the end of 2016, there were four full-size hybrid dryers on the market (Dymond 2018): LG DLHX4072W, Whirlpool WED99HEDW, Whirlpool WED7990F, and Whirlpool WED9290F. When we began our study in 2018, there was one full-size hybrid heat pump dryer on the market. It was a Whirlpool WED9290FC. By the time we had several households recruited to participate in the study (late

[6] Incremental costs for dryers are hard to determine but in its Measure Updates, the Regional Technical Forum of the Northwest Power and Conservation Council established $406 as the incremental cost for heat pump dryers (relative to non-Energy Star dryers). https://nwcouncil.app.box.com/v/20201208WashersDryers, slide 70.

winter 2018) this model had been discontinued and Whirlpool had not put a comparable model on the market. A new Whirlpool full-size hybrid dryer (WHD560CHW) finally became available in the Minnesota market in the summer of 2019. As of February 2021, Whirlpool lists only two full-size hybrid dryers (WHD560CHW and WHD862CHC), which appear to differ only in terms of exterior finish and drum material. There do not appear to be any other full-size heat pump dryers available in the U.S. at this time.

In contrast to the limited availability of full-size heat pump dryers, several manufacturers offer compact heat pump dryers. These include Asko, Blomberg, Bosch, Miele, Samsung, and Whirlpool.

Literature Review

In preparation for Slipstream's field study of heat pump clothes dryers, we conducted a literature review of studies addressing issues of testing dryer energy use both in situ (household users) and lab (bench) testing. We also reviewed material on heat pump clothes dryers from the Regional Technical Forum (RTF) of the Northwest Power and Conservation Council.[7] A complete list of the studies we reviewed is provided in the reference section of this report.

While energy-efficient ventless dryers (including heat pump dryers) have been in use in Europe for many years, the only innovation in U.S. dryers in the past half-century has been the introduction of automated termination controls using moisture sensors to stop the dryer when the clothes are dry. Even this innovation has had variable results in reducing dryer energy use. In contrast, U.S. clothes washers have become 70 percent more efficient than models sold in the early- to mid-90s (Horowitz 2011).

Energy efficiency advocates began looking at ways to move the U.S. dryer market to more efficient machines. This effort played out in two ways: accurately measuring dryer energy use and identifying lab test procedures that would calibrate with results from real use of dryers by consumers. As a result, there is a reasonable body of literature from about 2010 through 2016 addressing dryer efficiency issues. These studies combine data from field studies and lab testing to provide a more realistic and accurate picture of dryer energy use and efficiency.

Measuring the energy efficiency of dryers is complex. There are many variables in how consumers use their dryer (Dymond 2014). These include:

- variation in the composition of clothing loads (by weight, volume, fiber composition, physical structure, and water content of the clothes coming out of the washer)
- dryer settings (clothing type, tumble options, temperature options, etc.)
- interactions with heating/cooling systems in the home
- consumer behavior (clothing added or removed during a drying cycle, settings used, completed cycles per year, etc.).

[7] The RTF is a technical advisory committee to the Northwest Power and Conservation Council that develops standards to verify and evaluate energy efficiency savings.

The story becomes even more complex when trying to establish a testing protocol that mimics real-world dryer use. Federal test procedures were not effective at differentiating energy use among dryers, making it difficult to rate a dryer's efficiency (with an Energy Star or Energy Guide label). The federal test procedure for determining dryer energy efficiency uses uniform cloths (fifty percent cotton/polyester cloths that are 24 x 36 inches) and has the technician stop the drying cycle when the load reaches 2.5 percent to 5 percent remaining moisture content, which doesn't measure the effectiveness of sensors or control strategies. Nearly all dryers tested under these conditions achieve the same Combined Energy Factor (CEF) (Dymond 2014). An optional test procedure, "Appendix D2" was introduced in 2013 that allows the test to complete the dryer cycle until auto-termination to address the control strategies. Note that energy savings calculations for clothes dryers in the Minnesota Technical Reference Manual (MN Commerce 2020) are tied to these federal CEF ratings.

Tests conducted at Ecova's appliance laboratory in Durango, Colorado using real clothing and a variety of dryer cycle settings and load sizes were more accurate at predicting dryer energy use than the federal test procedures. These tests showed that the federal metric "D2" underestimates dryer energy consumption, on average, by 33 percent. The alternative test methods estimated dryer energy consumption to within five percent on average of real-world use (Dymond 2018).

Another study of dryers (also using Ecova's appliance laboratory) found that tests using real world clothing took approximately 35 percent more energy to dry than did the uniform cloths used in the federal test procedure (Horowitz 2011). The additional energy used is not attributed to higher power use but to longer drying times.

In the Pacific Northwest, these discrepancies led to the development of an alternative measure of dryer efficiency, the Utility Combined Energy Factor, or UCEF (Dymond 2018). The UCEF supplements the federal test procedure with four additional tests of real-world clothing items under prescribed load composition, load weight and cycle settings. The UCEF rating is then calculated as a weighted average of the DOE test results and the results from the four supplemental loads.

Protocols for field studies measuring dryer energy use ranged from collecting metered data on energy use to requiring participants to weigh laundry loads, keep laundry journals, and complete interviews on their experience with the dryer as well as collecting metered data (Dymond 2018, Kongoletos 2015, Martin 2016, McCowan 2015).

Results from several of these studies show that participants do between 311 (Dymond 2018) and 439 (McCowan 2015) loads of laundry annually. The federal test procedure is based on 283 annual loads of laundry; and data from the 2015 Residential Energy Consumption Survey reports 244 annual loads for households in single-family homes.

Several field studies tested hybrid heat pump clothes dryers (Dymond 2018, Martin 2016, Kongoletos 2015)—first collecting data on energy use with pre-existing washers and dryers and then collecting data on the heat pump clothes dryers. Two of these studies, Dymond and Martin, tested a Whirlpool hybrid heat pump clothes dryer (WED99HED)—a precursor to the Whirlpool dryer tested in Slipstream's study. In contrast to our study, however, dryers in these three studies were also paired with new washing machines. In the Dymond and Martin studies, Energy Star-rated front-loading washers (WFW87HEDW and WFW95HED, respectively) were matched with the heat pump clothes dryers. The appliances tested in the third study (Kongoletos 2015) weren't identified.

The Dymond study involved three separate field studies: the Whirlpool hybrid heat pump clothes dryer (WED99HED) was tested in nine homes in the Portland, OR metro area; a Blomberg compact heat pump dryer (DHP24412W) was tested in eight apartments in Renton, WA; and an LG vented hybrid heat pump dryer (DLHX4072) was tested in ten households in Boise, ID. The households recorded washer and dryer settings and clothing weights in a logbook, and data loggers recorded the energy consumption of both the washer and dryer. Data were recorded for at least five loads from the household's pre-existing appliances, and then from ten or more loads from the new efficient washer and dryer.

Of the three dryers tested, the Blomberg compact heat pump dryer was the most efficient. It achieved 65 percent energy savings. The Whirlpool and LG hybrid heat pump dryers achieved 25 percent and 22 percent energy savings, respectively. When the Whirlpool hybrid heat pump dryer was paired with a typical washing machine, it used 717 kWh annually compared to 620 kWh annually when paired with the more efficient clothes washer. For comparison, annual average electric resistance dryer energy use ranges between 800 and more than 1,000 kWh/year (Dymond 2018, Martin 2016, McCowan 2015). Finally, the Whirlpool hybrid heat pump dryer took approximately 20 minutes longer to dry an average load of laundry compared to the pre-existing machine.

The Martin study was conducted in central and south Florida and included eight households. Data on washer and dryer energy use were collected for eight to nine months for both the pre-existing appliances and the Whirlpool appliances. Median energy savings were estimated at 312 kWh annually (34 percent of median baseline consumption). Average annual energy savings were estimated to be 36 percent (346 kWh/year). Households were also asked to weigh their laundry prior to putting it in the dryer and then again when it came out of the dryer (and was dried to their satisfaction). Results confirmed that the new washing machines, with better moisture removal capabilities, contributed to some of the hybrid heat pump dryer savings. The washer and dryer were modeled (comparing the high efficiency washer with a minimum efficiency Energy Star dryer, and the installed Whirlpool hybrid heat pump dryer with a minimum efficiency Energy Star washer) to estimate the relative impact each had on the overall energy savings. The model predicted that 65 percent of the measured energy savings in their study were attributable to the improved efficiency of the dryer itself. Applied to the field-study result of 34 percent overall savings, this would translate into 22 percent dryer electricity savings for the heat pump dryer.

Of particular importance in Florida is the issue of heat released into the surrounding space by heat pump clothes dryers. Most of the heat (95 percent) from electric resistance clothes dryers is vented to the outside of the home. In contrast, all the heat from a heat pump clothes dryer is released to the surrounding space. In one site, the dry bulb temperature of the laundry room rose by more than 10 degrees after the installation of the hybrid heat pump clothes dryer (from about 84 degrees to almost 100 degrees).

The Kongoletos study was conducted in Massachusetts and Rhode Island for National Grid and Eversource and included six households. Metered data were collected for two weeks on pre-existing washers and dryers. The pre-existing appliances were replaced with high efficiency washers and heat pump dryers and data was collected for six weeks. The same brand of washer and dryer were used for all six households in the post-baseline testing. Participants recorded laundry weight and washer and dryer settings for both test periods. Researchers analyzed 102 in situ loads of laundry to establish baseline conditions and 191 loads to understand the technological impacts of the high efficiency washer and heat pump dryer. The weighted average for the pre-existing appliances was 3.84 kWh per load and 1.83 kWh per load for the high efficiency washers and heat pump dryers.

RTF first began assessing heat pump clothes dryers for inclusion as a UES (unit energy savings) measure in 2015 and they are now considered a proven measure with verified energy savings. There is a large body of work that went into establishing heat pump clothes dryers as a UES. Some insights important to our study include:

- RTF determined that the size of compact dryers is less than four cubic feet (making a standard dryer four cubic feet or greater). In contrast, the federal government has determined that compact dryers are slightly larger (4.4 cubic feet or less). This distinction is important because the federal test procedure uses a much smaller load size for compact dryers (three pounds versus 8.45 pounds used for standard dryers) (RTF 12/08/2020).
- RTF corroborates that the Federal energy performance metric (CEF D2) consistently underestimates energy consumption in real world settings. The more complex performance metric developed by the Northwest Energy Efficiency Alliance (Dymond 2018) provides a more accurate estimate of energy consumption (RTF 05/23/2018).
- RTF notes that there are interactions between washers and dryers that affect the energy savings for dryers. Because a high efficiency washer removes more water from the laundry before it goes into the dryer, the high-efficiency dryer uses less energy to dry the less wet clothes. Calculations for energy savings from an efficient washer/dryer combination suggest that the combined savings are overstated by as much as 12 percent for the most efficient washer/dryer combination (RTF 07/18/2017).

Project Objectives

The three primary objectives of this project were:

- to validate direct and indirect energy savings and cost-effectiveness of heat pump clothes dryers in Minnesota homes;
- to better understand consumer clothes drying preferences and gauge Minnesota consumer reactions to heat pump clothes dryers; and,
- to create a road map for incorporating heat pump clothes dryers in Minnesota utility CIPs, with respect to
  - the market for replacement clothes dryers in single-family homes
  - clothes dryer specification in multifamily new construction projects.

Project Methods

The primary component of this project was a field study comparing the energy use of heat pump clothes dryers to newer conventional electric clothes dryers in single-family homes. For the field study we recruited households to participate for 12 months of dryer monitoring during which each participant used a heat pump clothes dryer for half the monitoring period and a conventional dryer for the other half. Participants were also asked to complete dryer journals and a post-participation interview for the consumer research component of the study.

To shed light on the applicability of compact heat pump dryers for the multifamily market, we interviewed a few Minnesota developers, property managers and others involved in multifamily housing, modeled energy savings for prototype multifamily building designs in Minneapolis, and bench-tested four compact heat pump dryers and one compact condensing dryer.

Participant Recruitment

Recruiting study participants proved to be a challenge. Our ideal participant was a household that was shopping for a new electric dryer and willing to pay for a high-end machine, or a household that had recently purchased a high-end electric dryer. To reach these households, we hoped to engage appliance retailers in identifying potential recruits by allowing us to place recruiting brochures in their stores and offering them a $100 incentive for each successful study participant from their store. However, this approach proved unfeasible—it was too time consuming to connect with retailers and convince them to help us.

Though we continued to try and connect with retailers, we pivoted to social media as another means of connecting with potential participants. We purchased targeted social-media (Facebook) ads for the study in the Twin Cities market. The ads directed households to a website where they could learn more about the study and complete a short enrollment application. Participants were offered a free heat pump dryer that they could choose to keep or return at the end of the study. To further encourage participation in our study, we offered participants incentives of $200 to $250 (depending on whether they elected to store their conventional dryer on site while using the heat pump dryer).

Our social media ads resulted in ten potential participants in a period of three months but ultimately only seven elected to participate in our study. Given the slow pace of recruiting participants and a reassessment of the project due to the uncertainty of product availability, we adjusted our expectations on the number of households we were likely to recruit and turned to CEE's contacts for additional participants. Ultimately, we had 11 single-family households in the study. We had originally hoped to recruit 30 households.

Consumer Research

Formal consumer research was limited to study participants, which were initially expected to total 30 households but ultimately involved only the 11 participants we were able to recruit. Each of these participants was asked to complete:

- an intake survey that covered household demographics; specifics about their home, laundry area, and existing laundry equipment; awareness and perceptions of heat pump technology; and information about their purchase of their present dryer;
- dryer journals that tracked use, performance, and satisfaction with their pre-existing dryer and the heat pump dryer over the first eight weeks of each appliance's usage during their study participation;
- a debrief interview that addressed the dryers' performance and participants' satisfaction with each, their preferences between the dryer (including which they were choosing to keep and why), and their likely purchase behavior.

Copies of our intake and exit interview questions and the dryer journal are included in Appendix A.

Field Monitoring

We implemented in-home monitoring of the dryers in our participant households. The monitoring involved collecting data on four variables:

- laundry weight
- electricity consumption
- temperature/humidity
- heating system operation

Onset Hobo loggers and eGuage meters collected data on electricity consumption, temperature/humidity, and heating- and cooling-system operation. Participants were also provided with an internet-connected scale and asked to weigh their laundry before and after drying. This part of the protocol was not as successful as hoped, because some participants were less diligent about weighing laundry loads than others, and it appears that many load weighings were not recorded because the laundry was not left on the scale long enough. Appendix B provides more details about the field monitoring.

Bench Testing

Slipstream and CEE staff bench-tested four compact heat pump dryers and one condensing dryer. The dryers tested were:

- Blomberg DHP24400W—heat pump dryer
- Bosch 300 Series WTG86400UC—condensing dryer
- Miele TWF160WP—heat pump dryer
- Samsung DV22N680*H*—heat pump dryer
- Whirlpool WHD5090GW—heat pump dryer

We also tested two of the full-size Whirlpool units that came back from the field after participants elected not to keep them. One of these was a problematic unit (Site 1) that we determined was malfunctioning when we tested it after removing it from the field.

The testing protocol involved weighing laundry and condensate before and after drying while also monitoring electricity consumption and air temperature in the drum. In addition to drying actual household laundry, we repeatedly dried the same set of clothing under different settings to see how they affected performance, and also conducted tests involving leaving lint traps uncleaned between cycles. Appendix B provides more details and summary results from the bench testing.

Multifamily New Construction Market Research and Energy Modeling

Our exploration of the opportunities available for including compact heat pump clothes dryers in multifamily new construction projects involved:

- conducting interviews with multifamily property developers/managers.
- modeling estimated mechanical ventilation, makeup air and natural infiltration airflows and their impact on energy consumption for prototype low- and mid-rise multifamily building designs in Minneapolis. (Appendix C provides more detail about the airflow and energy modeling effort.)
- bench testing four compact heat pump clothes dryers and one condensing dryer meant for multifamily applications.

Results

Consumer Experience with Heat Pump Dryers

Consumer research embedded into this field study focused on study participants as a window into potential consumer response to heat pump dryers. Heat pump dryers were not available in sufficient numbers in Minnesota appliance retail establishments[8] to gauge shopper perceptions in a meaningful way. For this reason, our study design focused on understanding consumer response from typical Minnesota households that we recruited into the study for their experience with a heat pump dryer. We explored their perceptions, intentions, and experiences during recruitment, during the time they used the heat pump dryer, and upon conclusion of the study. We present results and insights from this component of the study here. This discussion is divided into purchase insights and user satisfaction.

We note that results are qualitative in nature and based on a multidimensional and relatively deep exploration of a *limited number* of consumers. Although the initial plan was for 30 study participants in single-family homes, the study was modified to include only 11 such households. It was later determined the heat pump dryer for one of these participants malfunctioned (see Page 48) shortly after installation; that participant's experience is largely omitted from this section, since the appliance was not functioning as intended.

In many cases, consumer research results are comparative in nature. Conventional electric resistance dryers serve as the frame of reference against which participants assessed the heat pump dryer. In all cases, the heat pump dryer that participants experienced was the same, but the conventional dryer to which participants compared the heat pump appliance differed in brand, model, features, and age.

Dryers Compared

Study participants tried out Whirlpool's full-size heat pump dryer (model WHD560CHW). Whirlpool positions this dryer as a higher-end appliance with a suggested retail price of $1,399.[9] It offers settings and features beyond just the basics, but without some advanced features of other high-end dryers in the same price class, such as steam drying.

The conventional dryers to which participants compared the heat pump appliance varied. While the initial study plan would have limited participants to those who just purchased a brand new dryer, we needed to relax that requirement. Conventional dryers to which participants compared the heat pump model ranged substantially in age, which created somewhat uneven comparisons. Five of the pre-

[8] Further, those heat pump dryers available in appliance stores at the outset of the study were predominately compact dryers with few if any full-size heat pump dryers offered at the retail level in Minnesota. Some stores that were initially shown as carrying full-size heat pump dryers either did not sell them or stopped offering them.

[9] Retrieved from Whirlpool's website on February 12, 2021: https://www.whirlpool.com/laundry/dryers/electric/p.7.4-cu.ft-front-load-heat-pump-dryer-with-intiutitive-touch-controls,-advanced-moisture-sensing.whd560chw.html?. We purchased it for $1,229 from a Minneapolis appliance retailer.

existing dryers were less than a year old and another three were between one and five years old; however, two of the dryers were estimated to be ten or more years old. The pre-existing dryers also varied in where they are positioned in the range from budget to high-end appliances. Most fell in the budget to mid-range part of the spectrum, so the heat pump dryer was an upgrade in terms of general features.[10]

Purchase Insights

Our investigation affirms previously suspected barriers preventing the consideration and acquisition of heat pump dryers by Minnesotans shopping for a new dryer. These include absence of applicable models from retail showroom floors, lack of awareness and familiarity of heat pump technologies and dryers by consumers, and the price differential between mid-range electric resistance dryers and heat pump models.

Retail Placement of Heat Pump Dryers

While not based on a formal study design, we made several observations about the availability, placement, and presentation of heat pump dryers in retail stores during our efforts to recruit appliance stores to help us identify dryer purchasers. Visits to several appliance stores and big box do-it-yourself retailers in the greater Twin Cities Metro area in 2018 revealed that:

- In-store displays of heat pump dryers were mostly limited to compact units that were presented as specialty ventless dryers and placed in inconspicuous locations on the showroom floor.
- Full-size conventional dryers with similar price points as the heat pump models were featured prominently in retail stores; steam drying appeared to be the main feature that placed dryers into the same high-end cost range.
- Full-size heat pump dryers were shown as available on retailer websites, but the models that were available seemed to change during the course of our study.
- A few retailers we approached expressed interest in the heat pump dryer study; however, after repeated follow-ups with all of them, only one followed through to work with our team.

Disposition Toward Heat Pump Technology and Dryers

At study enrollment, we explored perceptions concerning heat pump technology, awareness of heat pump dryers, expectations concerning purchase price, trade-offs between efficiency and drying times with participants. Each of these issues represents a barrier or differentiating factor for heat pump dryers when they compete with conventional dryers.

Pre-study awareness of heat pump dryers or heat pump technology appeared to be low. Only one of the early participants recruited via social media advertisement indicated any awareness or familiarity with

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[10] Pre-existing dryers for which model numbers were readily available are offered for $500 to $800 (manufacturer suggested retail price).

either one. Participants drawn from the general population would not have naturally gravitated toward heat pump models in a dryer purchase for the sake of the technology. Two of the later participants, who were recruited through study team contacts, were familiar with heat pump technology and seemed positive toward it. In fact, one would have actively sought heat pump models in a dryer purchase if available locally. Such positive predisposition toward the technology seems to be the exception rather than a prevailing condition among Minnesotans, however.

Light exploration of expected costs and tolerance for longer drying times in exchange for energy efficiency revealed that study participants:

- Seemed to expect a heat pump dryer to cost a little more than conventional dryers, but only in the range of $100 to $200 above standard dryer prices.
- Generally expressed a willingness to trade off drying time for efficiency, with multiple participants caring little about drying time and some seeing a clear compromise.

These insights should be seen as qualitative and directional in nature, as our study population and response rates on these questions were too low to draw any quantitative insights.

Revealed Preference

At the conclusion of their participation, we gave study participants a choice of dryers. They could keep their pre-existing dryer or the heat pump dryer they tested for us. In all, seven participants kept the heat pump dryer, and three participants kept their pre-existing dryer. [11]

Most likely, study participants' choices were influenced by the combination of the condition and remaining useful life of their pre-existing dryer as well as their comparative satisfaction with the two dryers. Households with relatively new dryers faced the most meaningful choice between appliances because they were both new, while those with older dryers had confounding factors at play that make their selection difficult to interpret. [12]

Among the seven participants with newer dryers (less than five years old when they entered the study), five opted to keep the heat pump dryer over their pre-existing dryer at the conclusion of the study. Rationales provided for their choices were:

- Perceptions of the heat pump dryer as a higher-end, fancier machine. (One participant specifically called out the features and settings included in the HP dryer; another just referred to it as the higher-end appliance among the two choices.) [3 mentions]

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[11] In a few cases, participants asked to keep both because they could make use of a secondary dryer. For these situations, we counted the dryer they chose for their main laundry room as their preferred choice. The study participant with a defective heat pump dryer also opted to keep the pre-existing dryer, but that household is not reflected in these data (or other summaries in this section of the report).

[12] Efforts to recruit only study participants with new conventional electric dryers yielded insufficient participation, so we accepted some participants with older dryers into the study.

- Expectations concerning reduced energy use and costs with the heat pump dryer. [3 mentions]
- Advantages of having a ventless dryer. (All participants had vents for their dryers, but some appreciated the flexibility to locate the dryer where they wished within the laundry room or experienced issues with their existing vent becoming disconnected.) [2 mentions]
- More reliable drying performance from the heat pump dryer than the pre-existing dryer. (These participants were not satisfied with the performance of their pre-existing dryer's temperature sensor and found themselves needing to run multiple cycles to fully dry clothes. Some participants noted similar issues with the heat pump dryer on the settings they tried initially, but were able to identify settings—generally, timed drying—that allowed the heat pump dryer to complete a load on a single cycle.) [2 mentions]
- Softer and less wrinkled clothes when dried in the heat pump dryer than in the pre-existing dryer. [1 mention]
- Quieter performance from the heat pump dryer than the pre-existing dryer. [1 mention]

Those who kept their pre-existing dryers tended to do so because:

- The pre-existing dryer matched their washer (in style, controls, and cycle length). [2 mentions]
- Drying time for the heat pump dryer was noticeably longer than for the pre-existing dryer. (Those who kept the heat pump dryer noticed this too, but the added time was not an issue for them.) [2 mentions]
- Dislike of the second lint filter on the heat pump dryer. [1 mention as a reason for keeping the pre-existing dryer] (Others mentioned the second filter too, citing it as easy to overlook, difficult to use, and seemingly not as well designed as the rest of the heat pump dryer.)

Among the three participants with older dryers, two opted to keep the heat pump dryer while the other participant chose to keep the pre-existing dryer.

Table 3 lists participant dryer choices by the age of their pre-existing dryer.

Table 3. Dryer Selection by Age of Pre-Existing Appliance

Pre-Existing Dryer Age	Chose to Keep heat pump Dryer	Chose to Keep Pre-Existing Dryer	Total Number
Less than 1 year	3	2	5
1-2 years	2	0	2
3-5 years	0	0	0
6-10 years	0	1	1
11+ years	2	0	2
Total	7	3	10

User Satisfaction

Ultimately, user satisfaction is needed for heat pump dryers (or any new technologies) to be sustainable in the marketplace once they have established a foothold. We gauged user satisfaction with the heat pump dryer employed in this study through dryer journals we asked participants to keep and through exit interviews. Aided and unaided inquiries about study participant satisfaction with the heat pump dryer revealed that users were generally satisfied with the heat pump dryer due to its higher end features, the promise of energy savings, or both. Longer drying times were not an issue for many households but proved a deterrent for some.

Overall Satisfaction

The dryer journals offered an opportunity to gather a structured assessment of dryers overall and selected dryer characteristics. When asked to rate the heat pump dryer on a five-point scale, study participants gave it an average score of 3.83 (compared to 3.33 for pre-existing dryers) and a median value of 4 (which is the same median rating as for the pre-existing dryers). These scores are based on dryer journals returned by eight of the study participants.[13]

Open-ended comments about the heat pump dryer show both positive and negative perceptions contributing to users' assessment:

Positive

- Energy efficiency – A couple of participants focused on the energy efficiency of the heat pump dryer above all else. While they did not know just how much energy the dryer saved, they felt very positive knowing that the dryer uses less energy and fits with a general household effort to conserve energy.
- Ventless operation – One participant highly valued the absence of a vent because it allows her to place the dryer anywhere within a tightly packed laundry room without regard to the location of their outside wall or location of the vent opening.
- Quiet operation, settings, features, having clothes finish their drying cycle at a reasonable temperature, and reduced static cling were generally seen as other positives by one or more participants.

Negative

- Time needed to dry—Nearly all participants commented that the dryer does take longer to complete loads. Some wondered whether the moisture sensor functioned properly, as clothes came out of the dryer somewhat moist.

[13] We received dryer journals from eight participants (excluding the one with a defective dryer. Among them, five returned journals for both dryers, two returned one for the HP dryer only, and one returned one for the non-HP dryer only.

- Worsening performance—A few participants thought the dryer's performance decreased.
- Lint filter—Several participants commented that the second lint filter (a unique attribute of the heat pump dryer) was somewhat inconveniently designed and not built as well as they would have expected.

Detailed Assessments

In the dryer journals we also asked participants to assess their heat pump and pre-existing conventional dryers on selected characteristics we expect to be important to consumers. Respondents rated the heat pump dryer at least marginally higher on all categories except time to complete drying, but differences between heat pump and conventional dryers were generally small. The most noticeable difference was on features, which likely reflects the fact that the heat pump dryer provided to participants was a higher-end appliance that distinguished itself from most people's existing dryers on parameters beyond the drying technology it employs. For arguably the most important attribute—effectiveness—participants rated the conventional dryers, on average, between somewhat satisfied and mostly satisfied, while they rated the heat pump dryer just slightly higher at mostly satisfied.

Table 4 shows results quantitatively based on a scale that ranged from not satisfied (a score of 1) to impressed (a score of 5).[14]

Table 4. Participant assessments of heat pump dryer performance (mean score based on a five-point satisfaction scale)

Metric	Conventional dryer average score	Heat pump dryer average score	Difference
Ease of use	3.83	4.33	+0.50
Effectiveness	2.67	3.00	+0.33
Features	2.83	4.50	+1.67
Feel of clothes	3.33	3.50	+0.17
Gentleness on clothes	3.33	3.67	+0.34
Time to dry	3.00	2.67	-0.33

Because drying time is a key difference between heat pump and conventional dryers, we explored the need for speedy drying more thoroughly in the dryer journals with questions about whether specific loads needed to be completed quickly or not. Results were mixed. Four of the eight participants who provided dryer journals reported speed mattered for some (but not all) loads, while the other four did

[14] The full scale was: 1 = not satisfied, 2 = somewhat satisfied, 3 = mostly satisfied, 4 = fully satisfied, 5 = impressed.

not care about time required for drying cycles at all for any loads. Those who expressed a need for quick drying some of the time did so for anywhere from 14 percent to 44 percent of their loads.

The inconvenience of needing to run some cycles a second time were likely of greater concern. Interestingly, some participants abandoned eco mode on the heat pump dryer as a result of incomplete drying, while others experimented with settings. Some of those who liked the heat pump dryer the most reported settling on timed drying, finding that this setting worked best for them.

Energy Consumption and Savings

Field Monitoring of Single-family Dryers

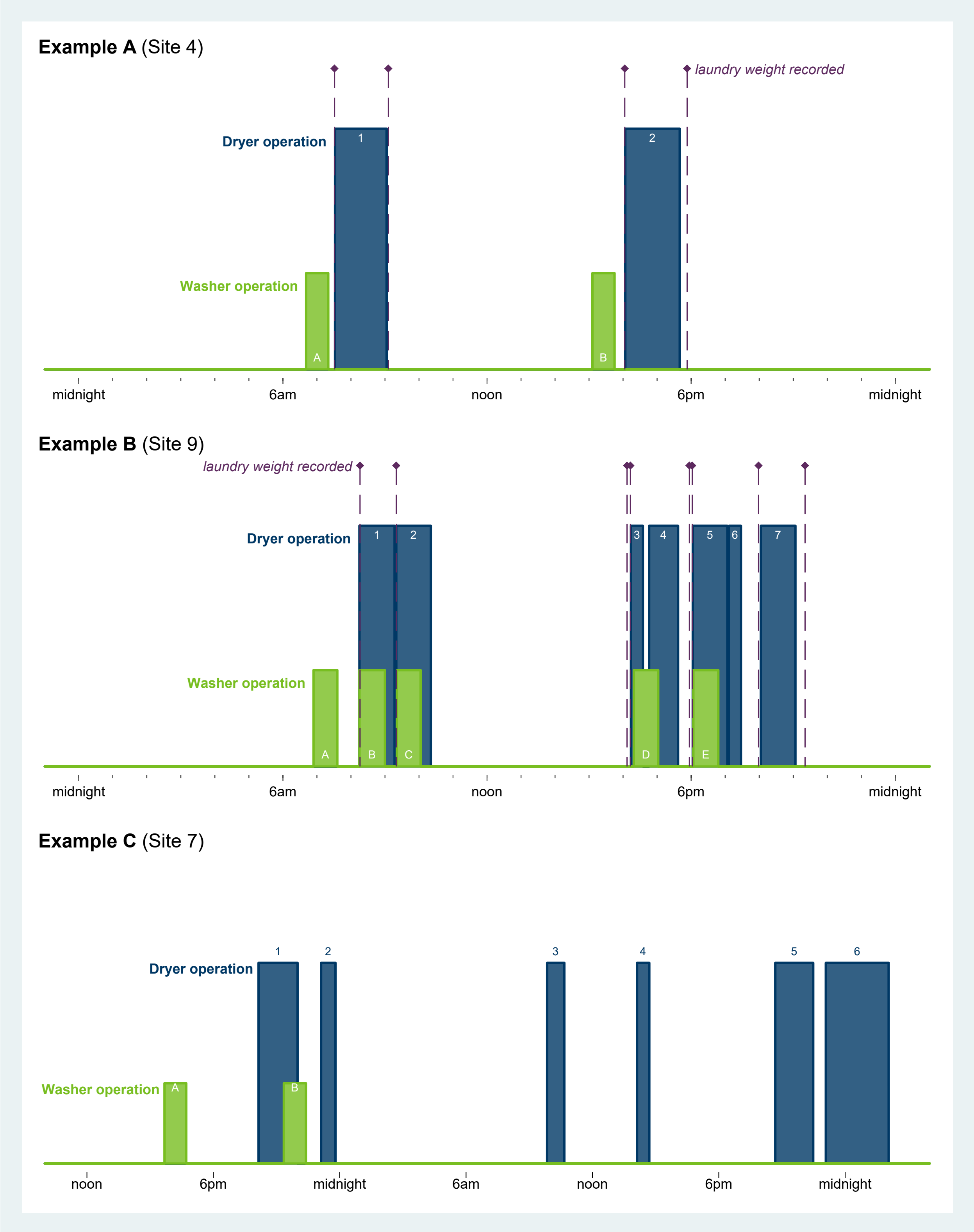
Clothes-drying Behavior

The dryer journals and monitoring data revealed clothes-drying behavior that was far more complex than one might imagine. We found all manner of laundry habits and schedules. In particular, the monitoring data showed a significant incidence of households using more than one dryer cycle per load of laundry. This can occur for several reasons: households may split a wash load into multiple dryer loads using different settings; households might partially dry a load, then remove some items and continue to dry the remaining items; or households may need to run one or more touch-up cycles to fully dry a load that came out unacceptably damp after the first cycle. The last possibility has implications for energy consumption because touch-up cycles are often done using a timed-dry setting that may end up wasting energy by continuing to heat clothing after it has been fully dried (as we demonstrated in our bench testing — see Page 54). Indeed, the monitoring data that we gathered do show an elevated incidence of follow-up cycles that were 10, 20, 40, 60 or 90 minutes in length and thus suggestive of timed-dry operation.

Using the washer and dryer electricity data along with (where available) laundry scale readings, we manually classified every dryer operating cycle according to whether it was a primary or follow-up cycle.[15] These classifications were unambiguous in most cases but required some guesswork in others (Figure 4), particularly when scale readings were absent or, more rarely, when there was dryer activity that was not associated with recent washer operation. Example A in Figure 4 shows two clearly-delineated wash-then-dry loads; example B shows five wash loads and seven dryer cycles, with laundry weight measurements to delineate load changes; and, example C shows an unclear relationship between two wash loads and six dryer cycles in the absence of weight measurements. Dymond et al. (2014) reported similar issues with unambiguously tying individual dryer cycles to wash loads.

[15] There is also a third category of anti-wrinkle operation in which the dryer drum turns over a few times every five minutes following cycle completion until the load is removed. Five sites (Sites 3, 4, 5, 7 and 8) regularly used this feature. We included it in our energy analysis, though it constitutes less than 0.5 percent of aggregate dryer electricity consumption for the sites that used it. We did not count this operation as a distinct drying cycle.

Figure 4. Three examples of wash/dry cycles.



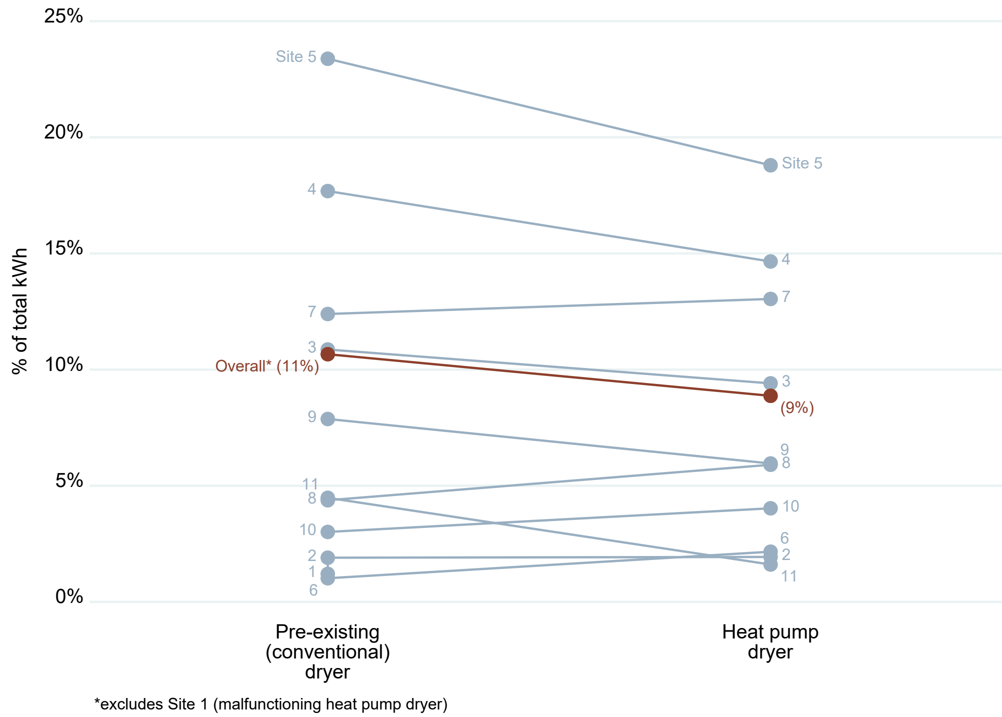
The results of the analysis show that prior to installation of the heat pump dryer, some households used multiple dryer cycles per load for a substantial proportion of their laundry while others only rarely required multiple cycles (Table 5). Following installation of the heat pump dryers, the use of follow-up cycles increased in general, though declined significantly for one site (Figure 5).

Table 5. Prevalence of multiple-cycle dryer loads for pre-existing dryer, by site.

Site	Total dryer loads	Mean dryer cycles per load	% of dryer loads completed in one cycle	% of dryer loads completed in two cycles	% of dryer loads completed in 3+ cycles	% of total dryer kWh used for subsequent cycles beyond the first
1	30	1.03	97%	3%	0%	1%
2	233	1.05	96%	4%	0%	2%
3	389	1.43	68%	23%	9%	11%
4	399	1.78	47%	35%	18%	18%
5	224	1.70	46%	42%	13%	23%
6	136	1.05	95%	5%	0%	1%
7	153	1.29	75%	22%	4%	12%
8	45	1.13	87%	13%	0%	4%
9	105	1.21	80%	19%	1%	8%
10	45	1.07	93%	7%	0%	3%
11	48	1.13	88%	13%	0%	4%

Overall, the data showed that some households were much more likely to use multiple dryer cycles per load than others, both before and after receiving the heat pump dryer. But for most sites, the switch to the heat pump dryer did not dramatically change the fraction of dryer electricity used for additional cycles beyond the first cycle (Figure 5).

Figure 5. Aggregate percent of dryer energy used for subsequent operation cycles beyond the first for the same load.



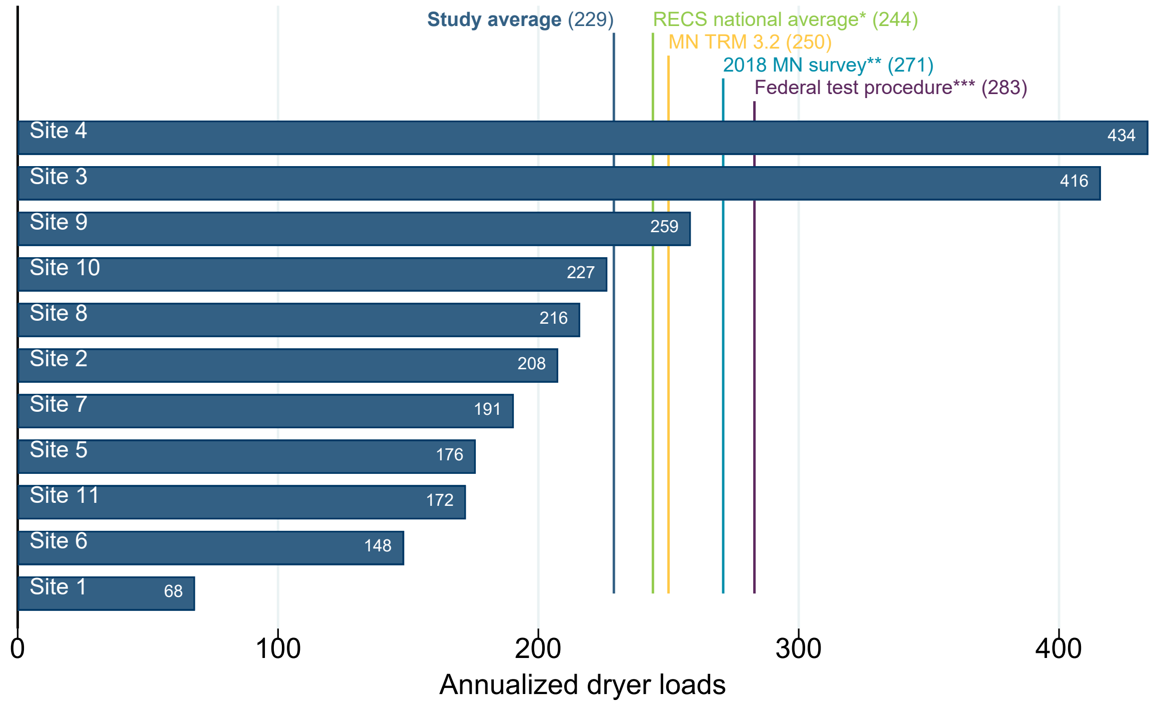
When aggregated into dryer loads over the full monitoring period—regardless of the number of cycles required for a given load or the type of dryer used—the annualized number of loads varied from fewer than 70 to more than 460, with an average of 229 (Figure 6). The study average is somewhat below other estimates of average laundry loads per year.

Because the amount of laundry activity varied over the monitoring period (three households had babies during the study), we normalized dryer electricity consumption for each dryer to the site-level loads-per-year values shown in Figure 6.

Post-drying load weights for the participants in the study ranged from 2 pounds to more than 30 pounds, with an overall median of 9.3 pounds (Figure 7), slightly above the load weight used in the federal test procedure for clothes dryers.

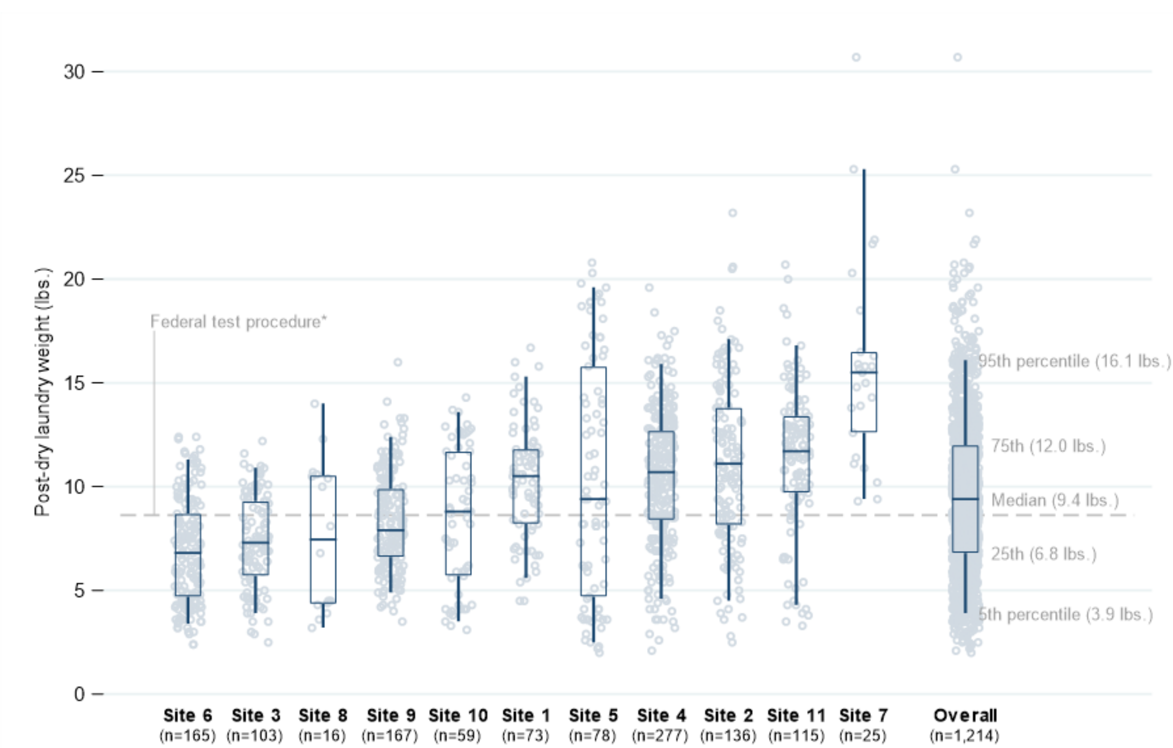
As an aside, we note here that 95 percent of the more than 1,300 loads with weight data would easily fit in a compact clothes dryer, which can generally accommodate loads of 15 to 18 pounds. Even among the three households with five or more household members, only one regularly washed loads that would exceed the limits of a compact dryer.

Figure 6. Annualized dryer loads, by site.



*EIA 2015 Residential Energy Consumption Survey (single-family): "How many times is your clothes dryer used per week?" (n=4,274)
**2018 MN Energy Efficiency Potential Study Residential Survey (single-family): "About how many loads of laundry do you wash per week?" (n=1,435)
***10 CFR 430.23

Figure 7. Distribution of recorded ending load weight, by site and overall.



*8.45 lbs. bone-dry weight (10 CFR 430.23). Adjusted here for assumed 2% remaining moisture content.

Dryer Energy Consumption and Savings

Figure 8 shows power consumption over the course of a typical drying cycle for one of the pre-existing conventional dryers and one of the Whirlpool hybrid dryers. The conventional dryer's 5,000-watt resistance heating elements are on continuously for about the first 25 minutes, then cycle on and off to maintain temperature in the drum. The hybrid heat pump's 1,300-watts of resistance heating is engaged in tandem with the heat pump for the first 10 minutes, then shuts off and the heat pump operates continuously until the end of the cycle.[16]

For both dryer types, most of the electricity is used for heating and drying the clothing (Figure 9).[17] A higher proportion of the heat pump dryer's electricity is devoted to the motor that powers the drum and the air-circulation blower. This is mainly because the overall power draw for the heat pump is much lower, so the drum/blower motor is a higher fraction of the total, but in absolute terms the drum/blower motor drew more power for the heat pump dryers on average (360 watts) than for the pre-existing dryers (260 watts). The resistance elements for the heat pump dryers make up only a small proportion of the overall electricity use.

[16] Under other conditions and settings, the resistance elements may be used at other parts of the cycle.

[17] We did not directly monitor the power draw of individual dryer components, but the drum/blower motor power can be derived from the difference in power across the two legs of the 240V circuit. For the heat pump dryers, we further split non-motor power into heat pump compressor and resistance elements based on the power-draw level.

Figure 8. Typical power-draw and drying-time profiles for a conventional dryer (A) and full-size hybrid heat pump dyer (B). The loads dried in these two examples were nearly identical in weight and moisture content.

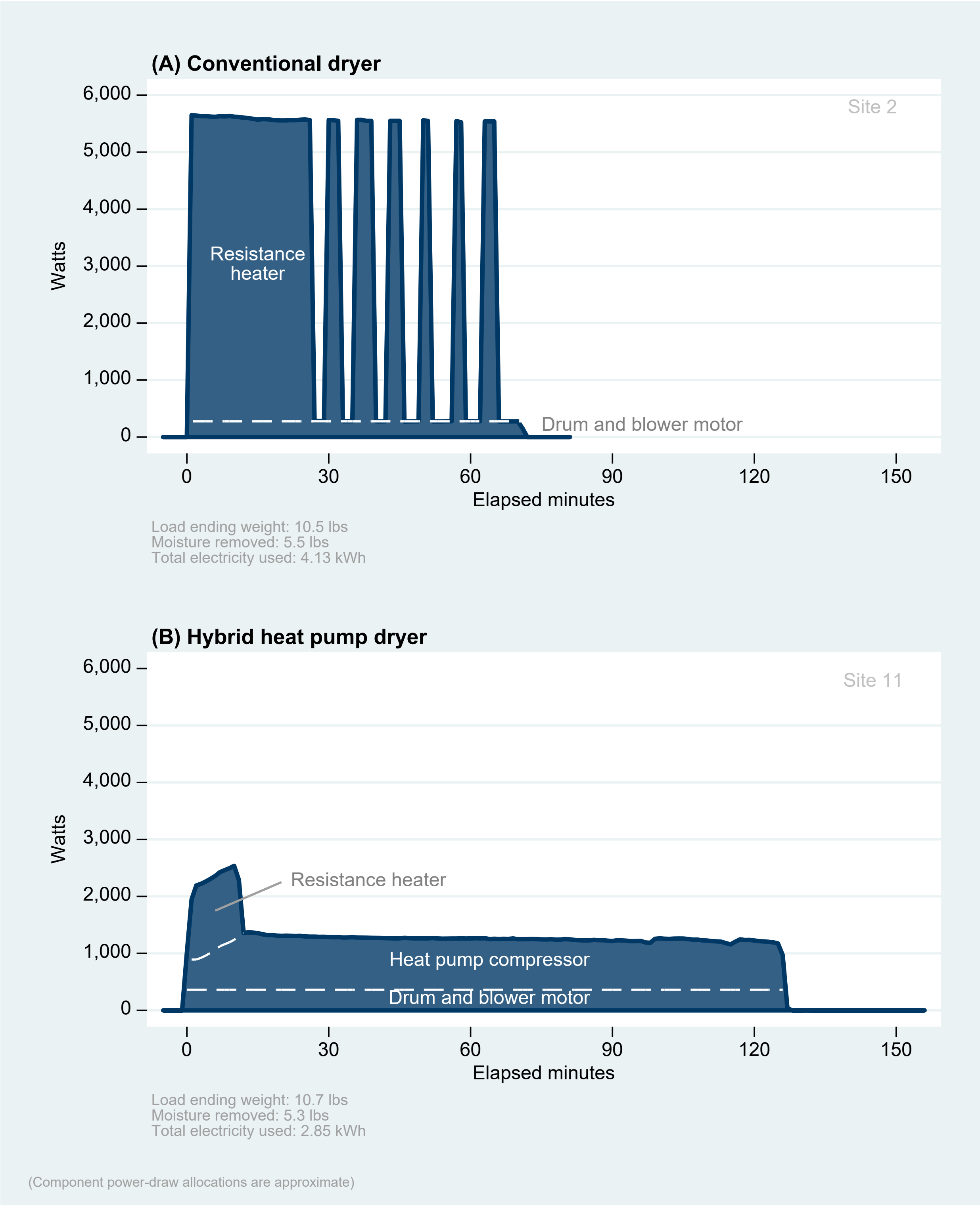
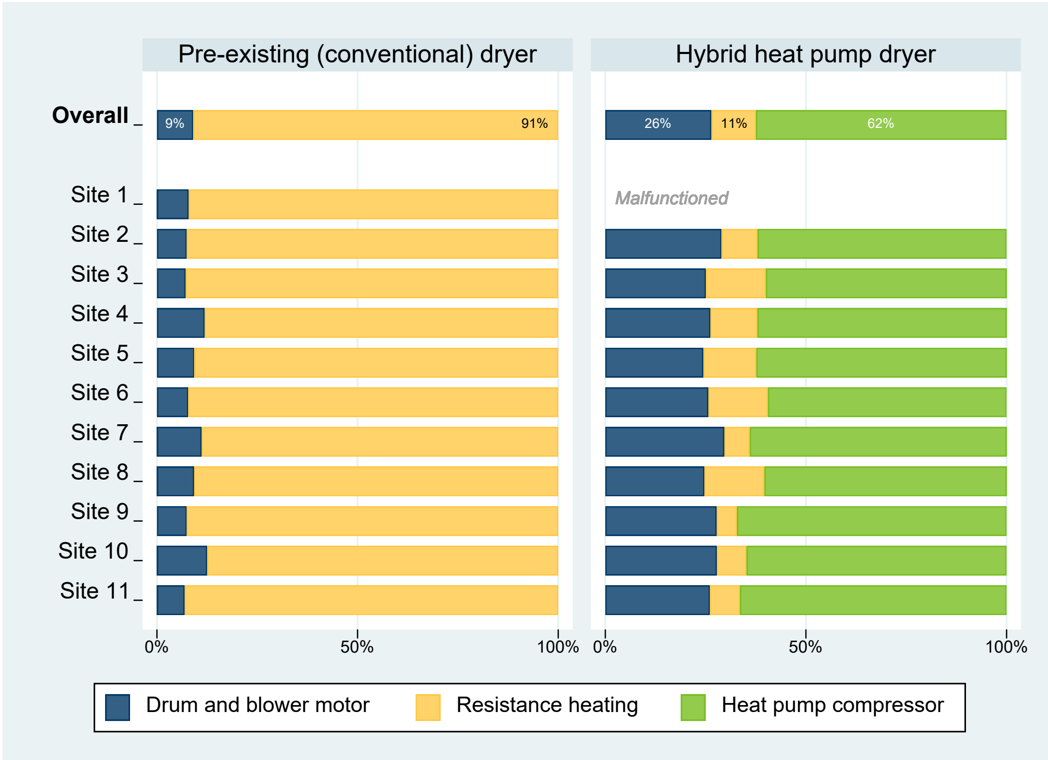


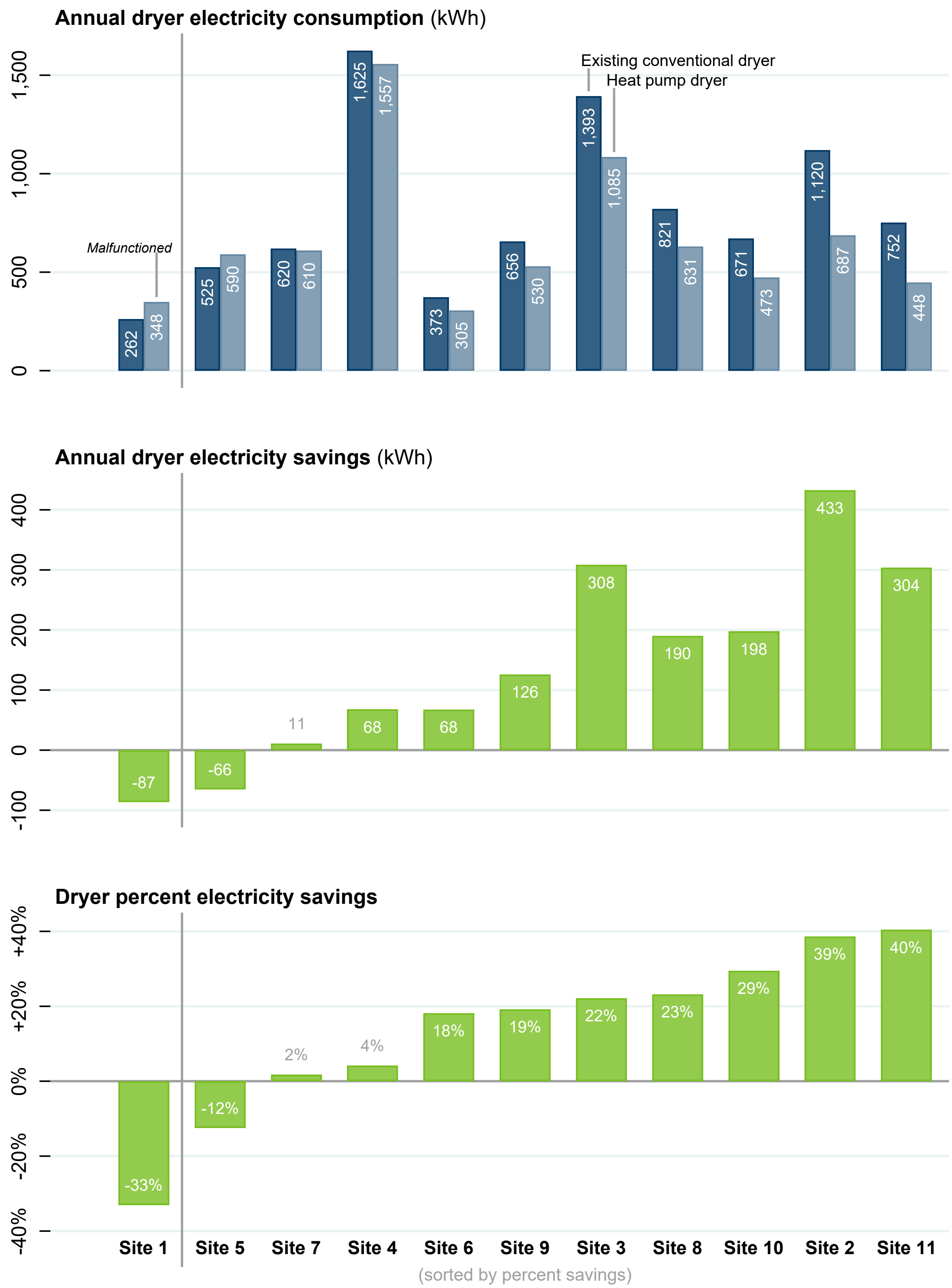
Figure 9. Component allocation of dryer electricity consumption, by site and dryer type.



Commensurate with the wide variation in the amount of laundry dried, there was a wide range in annualized dryer energy consumption across the sites (Figure 10). Electricity savings was substantially negative at Site 1 where the heat pump dryer was later determined to have malfunctioned after the first 20 loads (see Page 48 for more about this). For the remaining sites, savings ranged from -12 percent to +40 percent with a median of 19 percent and an average of about 160 kWh per year. Electricity savings averaged 0.64 kWh per load (Table 6). When this value is applied to our estimate of the number of loads per year dried by the average Minnesota household in a single-family home (285, as detailed in Appendix D), a somewhat higher estimate of about 180 kWh per year is obtained. (Shortly, we will show still higher average savings estimates for an analysis that takes into account the amount of moisture removed.)

The apparent negative savings for Site 5 may be an artifact of how dryer loads are defined, along with the somewhat unusual laundry habits of this household. About half of the loads dried by this household (both before and after installation of the heat pump dryer) involved multiple dryer cycles, and many of these multi-cycle loads began with a very short cycle, typically 11 minutes for the original dryer and 18 minutes for the heat pump dryer—but in some cases as short as just a few minutes. Laundry journal entries suggest that these cases were due to the household separating a wash load and damp-drying some items for a short period before fully drying the rest of the load. It's not entirely clear why this would lead to apparent negative savings on a per-load basis, but it is worth noting here that single-cycle loads for this site showed 18 percent savings in terms of electricity consumption per pound of moisture removed (see Figure 13 on Page 45).

Figure 10. Annualized dryer electricity consumption and savings, by site.



Consumption and savings based on mean kWh per load by dryer type, normalized to the overall average loads per year for each site (see Figure 6).

Table 6. Dryer Electricity Use Per Load

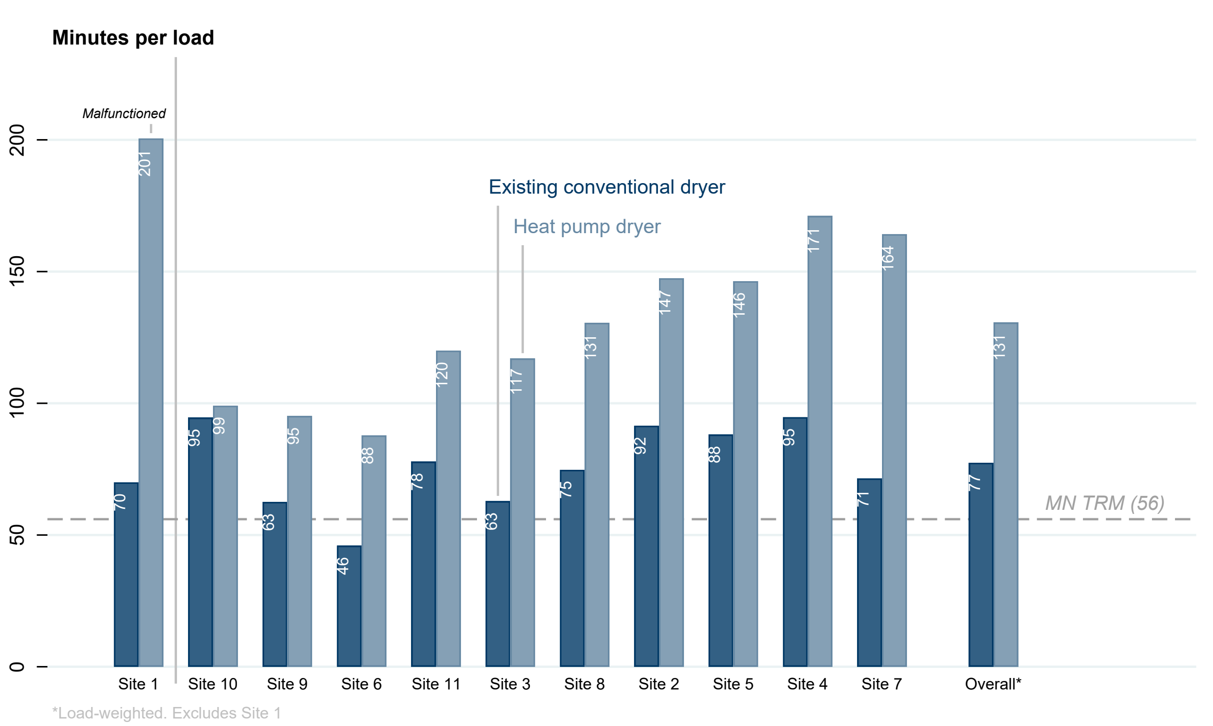
Site	Existing Conventional Dryer (kWh per load)	Heat Pump Dryer (kWh per load)	Savings (kWh per load)	Percent Savings
1	3.84	5.11[a]	-1.27	-33%
2	5.39	3.31	2.08	39%
3	3.35	2.61	0.74	22%
4	3.74	3.58	0.16	4%
5	2.98	3.35	-0.37	-12%
6	2.51	2.06	0.46	18%
7	3.25	3.20	0.06	2%
8	3.80	2.92	0.88	23%
9	2.54	2.05	0.49	19%
10	2.96	2.09	0.87	29%
11	4.37	2.60	1.76	40%
Average[b]	3.50	2.83	0.67	19%

a) Dryer malfunctioned
b) Load-weighted across sites; excludes Site 1

The median savings of 19 percent here is somewhat lower than found for the two other field studies of an earlier generation of the Whirlpool full-size hybrid dryer: Dymond (2018) found 25 percent savings; and Martin (2016) found 22 percent savings.

As expected, drying times increased substantially with the installation of the heat pump dryers.[18] On average, the conventional dryers required 76 minutes per load, while the heat pump dryers required 129 minutes, an increase of 70 percent (Figure 11).

Figure 11. Average time to dry a load, by site and dryer type.

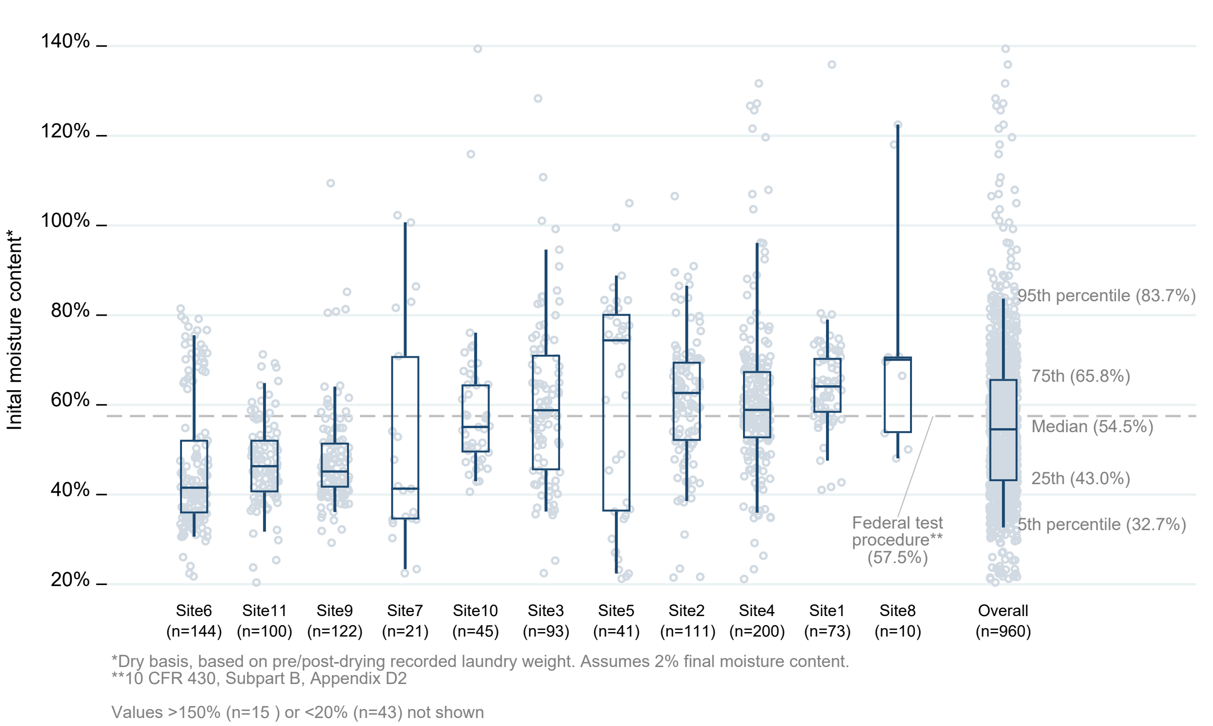


For the subset of dryer loads where we had pre- and post-drying laundry weights, the data show that most loads had a starting moisture content of between 35 and 80 percent (Figure 12).[19] The overall median starting moisture content of 54.5 percent is very close to the value specified in the current federal test procedure for clothes dryers (57.5%).

[18] By "drying time" we refer to the total operating time of the clothes dryer to dry a load, summing across multiple cycles if required for the same load. This is not the same as the load start-to-finish time, which sometimes involved long periods between the end of one cycle and the start of a subsequent touch-up cycle.

[19] Laundry moisture calculations are typically done on a dry basis, meaning weight of moisture in the load expressed as a percent of the bone-dry load weight. Since the field data collection precluded determining bone-dry load weights, we used an assumed 2% final remaining moisture content for our calculations. To guard against cases where a load was damp-dried to a final moisture content significantly above this level—thus rendering our estimated initial moisture content inaccurate—we removed all load cycles that lasted less than 20 minutes, removed less than 2 pounds of moisture or had a calculated initial moisture content of less than 20 percent, all of which are suggestive of a load that is damp-dried to a high final moisture content. We also removed multiple-cycle loads for Site 5 where there was a clear habit of partially damp-drying loads. We also removed a small number of loads (n=15) with very high calculated initial moisture content (>150%) as likely data errors

Figure 12. Initial moisture content for loads with pre/post-drying weights, by site and overall.



Weighing laundry before and after it is dried allows measurement of the amount of moisture removed by the dryer. We examined the overall energy performance of the dryers per pound of removed moisture based on the total electricity consumed and pounds of moisture removed for each dryer across all loads with pre- and post-drying weights. We also calculated the average minutes per pound of removed moisture. Both of these metrics help further normalize dryer performance for differences in load size and moisture content, albeit for a more limited data set of loads with weight measurements.

Although three sites had insufficient data for a savings analysis along these lines, the results for the remaining sites (again omitting Site 1 and its malfunctioning heat pump dryer) indicate savings of 22 percent in electricity used per pound of moisture removed (Figure 13). This is reasonably consistent with the larger analysis based solely on dryer electricity consumption per load, and suggests that the former (load-based) analysis is not unduly confounded by ambiguities in load counts, changes in load size, or differences in load moisture content between the two dryer types.

The sample's overall average performance for the pre-existing dryers (0.67 kWh per pound of moisture) and heat pump dryers (0.52 kWh/lb) are also consistent with field and lab studies in the Pacific Northwest showing 0.6 to 0.7 kWh per pound of moisture for conventional full-size dryers and 0.52 to 0.55 kWh per pound of moisture for an earlier version of the full-size Whirlpool hybrid (Firestone 2018).

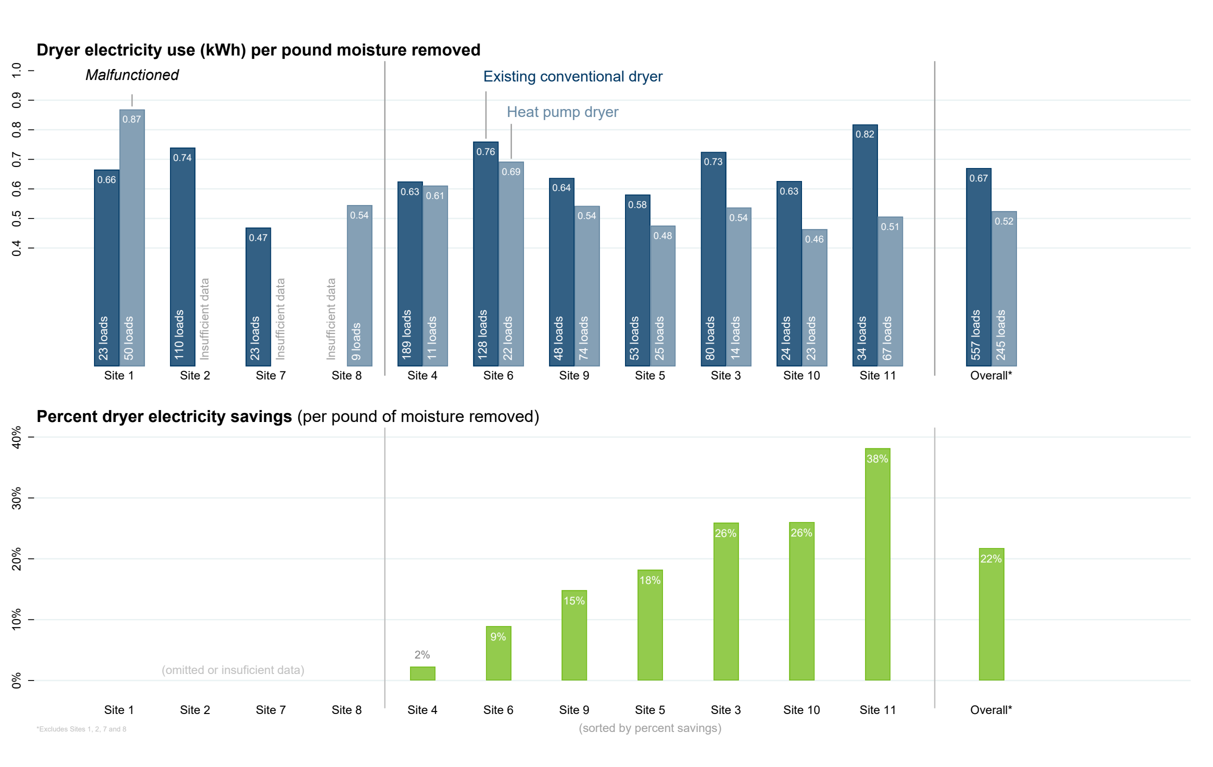
Extrapolated to our estimate of the population-average loads per year for single-family homes (285, per Appendix D) and using the load-weight and moisture content assumptions from the federal test procedure (8.45 lbs, 57.5% initial moisture content and 2% final moisture content), the above results suggest average annual savings of about 195 kWh for the full-size Whirlpool hybrid.

Calculated savings based on energy use per pound of removed moisture are also generally consistent with those calculated based on energy use per load The two exceptions are:

- Site 5, where the kWh-per-load analysis showed -12 percent savings, but the kWh-per-pound-moisture-removed analysis suggests +20 percent savings; and,
- Site 6, where the kWh-per-load analysis showed 18 percent savings, but the kWh-per-pound-moisture-removed analysis indicates only 9 percent savings

As discussed earlier (Page 40), the Site 5 discrepancy is likely due to the household's unusual practice of routinely separating loads at this site, which leads to many loads being omitted in the moisture-based analysis. The Site 6 difference is more difficult to explain but may have something to do with that site being the one with the lowest average load weight and initial moisture content.

Figure 13. Dryer electricity use and savings per pound of moisture removed.



The results here also reinforce what others have found in terms of actual dryer electricity use far exceeding that predicted by the federal test procedure. Table 7 converts the above average measured moisture-removal performance (Column A) to an equivalent field energy factor, expressed in terms of pounds of laundry dried per kWh of dryer energy, and compares that to the federal CEF for the two types of dryers (Column C).[20] The results indicate that the field-study dryers dried about a third less

[20] The federal CEF differs from the field EF calculation in that the former includes standby electricity consumption. The distinction is quite minor since most dryers consume very little electricity when not operating.

clothing per kWh than their federal ratings would suggest, or alternately, they used roughly 50 percent more electricity per pound of dried laundry. This discrepancy is even larger than the 33 to 35 percent more electricity per pound of laundry than found by others (Dymond 2018, Horowitz 2011).

Table 7. Field dryer performance versus federal ratings.

Dryer Type	**Observed moisture-removal efficiency** (kWh per lb. H_2O) *(A)*	**Equivalent field energy factor (EF)*** (dry lb. per kWh) *(B)*	**Federal rated combined energy factor (CEF)** (dry lb. per kWh) *(C)*	**Ratio** *(B/C)*
Conventional	0.670	2.59	3.73**	0.70
Hybrid heat pump***	0.524	3.32	5.20	0.64

*Calculated as 1/(*A**0.575), where 0.575 is the federal-test-procedure specified initial moisture content (dry-basis)
**Typical for conventional vented electric dryers
***Whirlpool WHD560CH

The laundry weight data also suggest that drying times per pound of moisture removed were generally in the range of 10 to 20 minutes per pound for the conventional dryers and 20 to 30 minutes per pound with the heat pump dryers, also confirming the longer drying times per load found in the larger analysis.

We also looked at how electricity consumption per pound of removed moisture compared between loads that required only a single cycle versus those that required multiple cycles, though this was only possible for sites with a sufficient mix of single- and multi-cycle loads and adequate laundry-weight data for both. The results suggest that loads requiring more than one dryer cycle generally used 10 to 20 percent more electricity per pound of removed moisture than did single-cycle loads (Figure 14). While it is possible that the type of laundry being dried plays a role in this difference, the consistency across sites suggests that the dominate factor is more likely that timed-dry settings that tend to be used for follow-up cycles end up wasting some energy by over-drying loads.

Finally, we note that the metrics of energy use and drying time *per pound of removed moisture* are generally higher for very small loads (Figure 15). This is likely at least partly due to the fact the dryer needs a fairly fixed amount of time and energy to come up to temperature after startup regardless of the load size. For small loads, that fixed operating time is spread over fewer pounds of removed moisture thus increasing the energy and time per pound removed.

Figure 14. Electricity use per pound H2O removed for loads with and without multiple cycles.

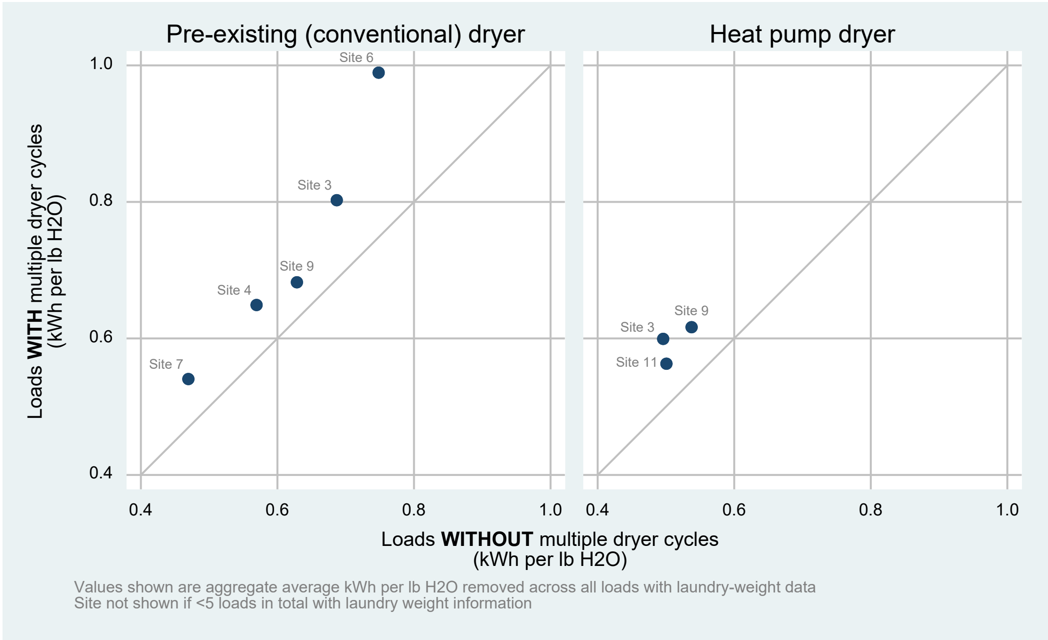
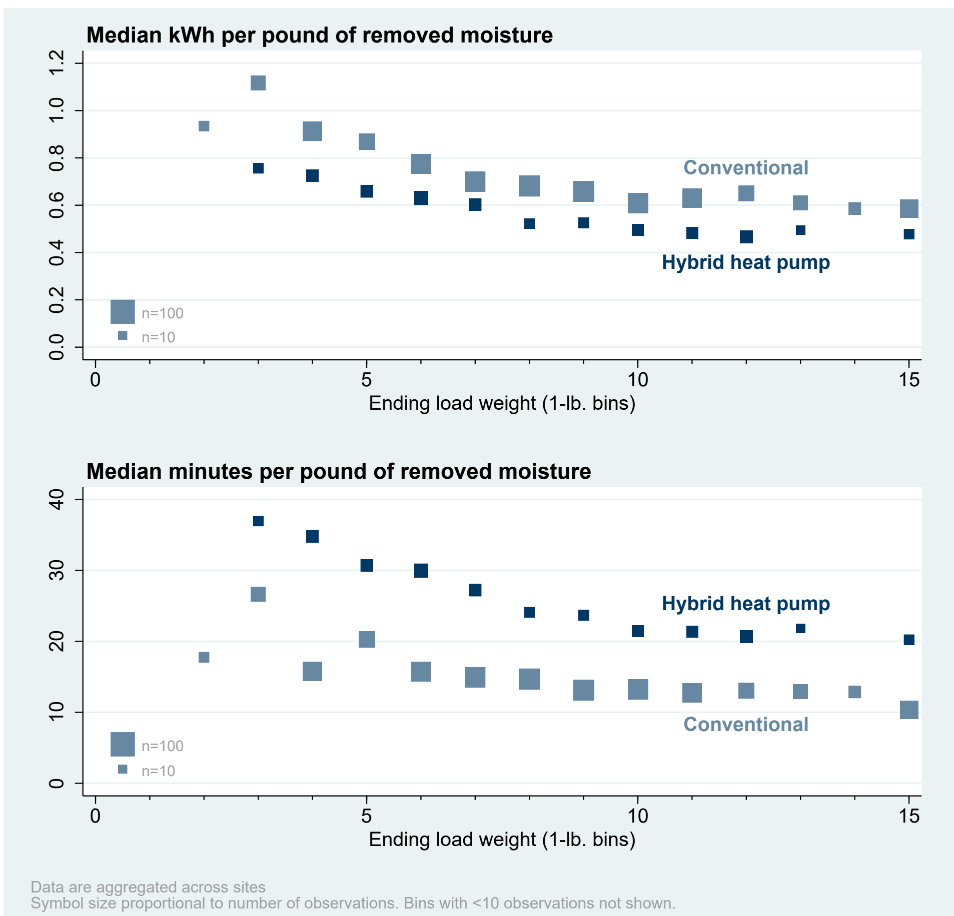


Figure 15. Median kWh and drying time per pound of removed moisture, by ending load weight.



Bench Testing

The bench testing afforded an opportunity to investigate aspects of heat pump clothes dryers that could not easily be accomplished through the field testing. This included:

- investigating the malfunctioning heat pump dryer field tested at Site 1.
- gathering basic performance data for a selection of compact heat pump dryers.
- exploring how energy performance is affected by settings, load size and load type.
- measuring the impact of lint-trap cleaning on energy performance.

Altogether, we ran more than 200 loads through two of the returned full-size Whirlpool dryers, the four compact heat pump dryers and one conventional compact condensing dryer in order to measure energy performance and drying times under different settings, load weights and load compositions. Some of these loads were repeated loads where we washed and dried the same set of items multiple times in order to look at how dryer settings affected performance for the same set of laundry. [21] Other loads were actual household loads that varied in composition and weight.

A Malfunctioning Heat Pump Dryer

As noted above, the heat pump dryer provided to the Site 1 household malfunctioned during the field monitoring period, though this was not apparent at the time. From the ongoing downloads of electricity data and laundry weights, we could see that drying times increased significantly and energy performance declined after the household had dried about 20 loads with the new dryer. We assumed that this was due to a change in dryer settings. However, when the participant returned the dryer to us—after stoically drying nearly 50 loads at an average drying time of almost 4 hours per load—we quickly determined that the dryer was not pumping any condensate out of the unit, indicating some type of malfunction. Indeed, removing the top of the dryer revealed moisture covering most surfaces of the interior (Figure 16). [22]

[21] The testing was done by two of us in different homes, each testing 3 dryers, so there are no "standard" loads that are common to all tested dryers.

[22]The average load of laundry contains more than half a gallon of water to be removed by the dryer.

Figure 16. Moisture covering the interior of the malfunctioning heat pump dryer for Site 1.

Further disassembly of the unit eventually revealed that a float switch used to trigger the operation of the condensate pump was only partially seated (Figure 17). After re-seating the float switch and testing proper operation of the condensate pump, we reassembled the dryer and ran a test load, but this did not solve the problem. The nature of the malfunction remains a mystery.

Figure 17, Partially-seated float switch for the malfunctioning heat pump dryer at Site 1.

Bench-Testing Performance

Figure 18 provides an overview of the performance of the seven functional machines in terms of electricity consumption and drying time per pound of removed moisture, alongside a plot of the same metrics from the field data.

- Although the bench-testing energy performance of the full-size Whirlpool machine appears to be better on average under bench testing (0.41 kWh per pound removed moisture) than seen in the field monitoring data (0.51 kWh/lb), this difference is mostly attributable to differences in average load weight between the bench testing and the field data (Figure 19).
- The performance of the full-size hybrid dryer is not strongly affected by settings. This dryer has overall "eco" and "speed" options and a range of temperature and dryness levels (Figure 20). After running the same load through the dryer repeatedly on different settings, we found modest (15%) increased energy consumption and reduced drying time under the "speed" setting, but little difference for temperature and dryness settings within the general eco/speed selection (Figure 21).
- The energy performance of the four compact heat pump dryers was better than that of the full-size hybrid dryer. On average, the four compact machines dried laundry at an average of 0.24 kWh per pound of moisture, with most loads being between 0.2 and 0.3 kWh/lb. These results are consistent with field- and lab-measured performance of a compact Blomberg machine in earlier testing in the Pacific Northwest (Firestone 2018). The performance of the compact dryers is about 40 percent better than the bench-testing results for the Whirlpool full-size hybrid, as might be expected for machines that dry entirely via heat pump instead of using both heat pump and resistance heat. The compact heat pump dryers also show less sensitivity in energy performance to load size (Figure 19), load composition and dryer settings, though drying times did differ significantly (Figure 18). In particular, dryer settings seem to affect drying time more than overall energy performance. While all of the compact heat pump dryers performed well in energy terms, the Blomberg machine stood out, with an average performance of 0.19 kWh per pound of removed moisture, versus 0.25 kWh/lb for the other machines, though drying times did differ significantly.
- The conventional condensing dryer (Bosch) had energy performance that was on par with the pre-existing conventional dryers in the field study. This machine also showed the highest sensitivity to load size among the bench-tested dryers.

Figure 18. Bench-testing results, with field monitoring results for comparison.

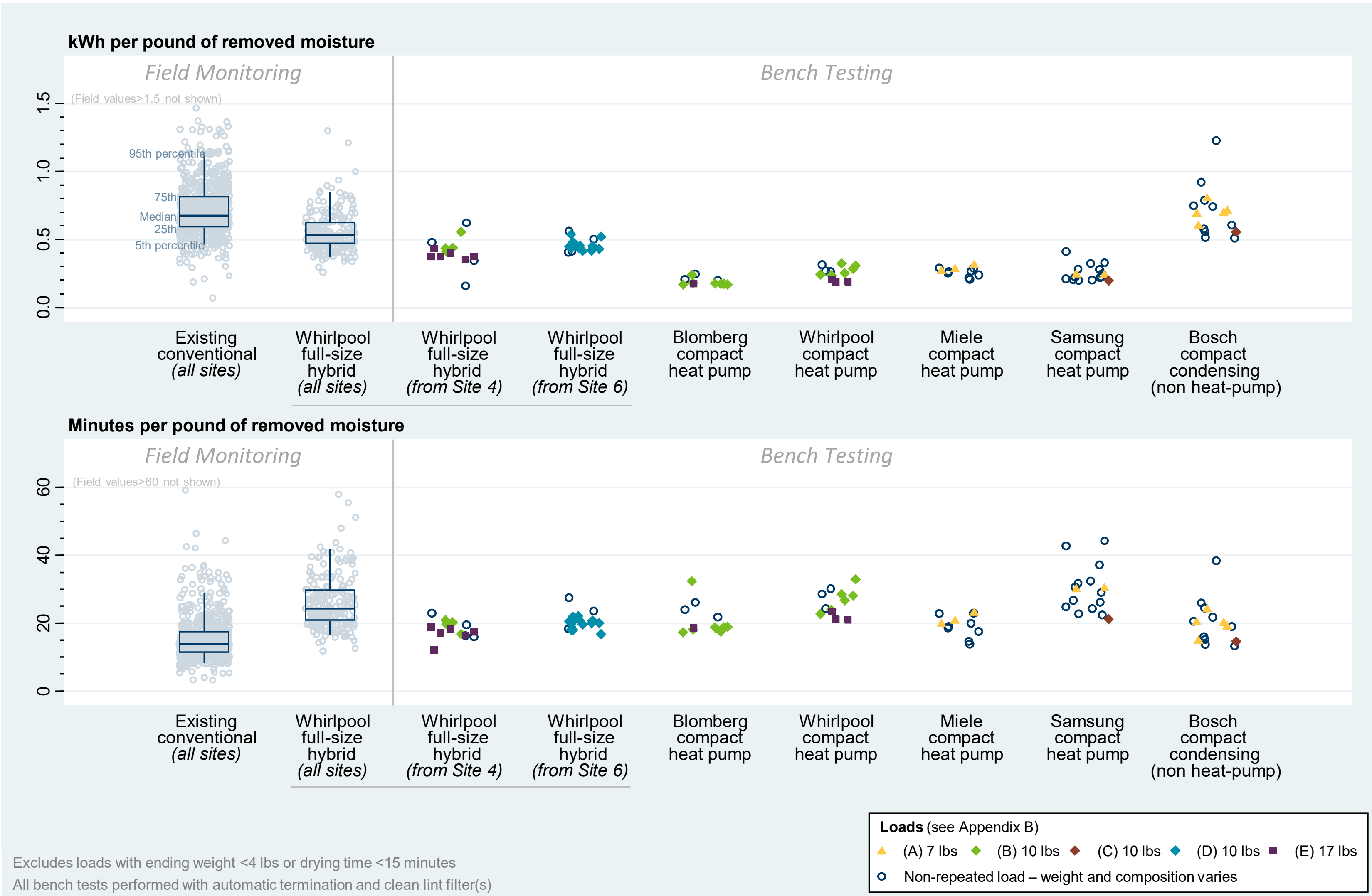


Figure 19. Energy performance versus load weight, comparing bench-testing results and field-monitoring averages.

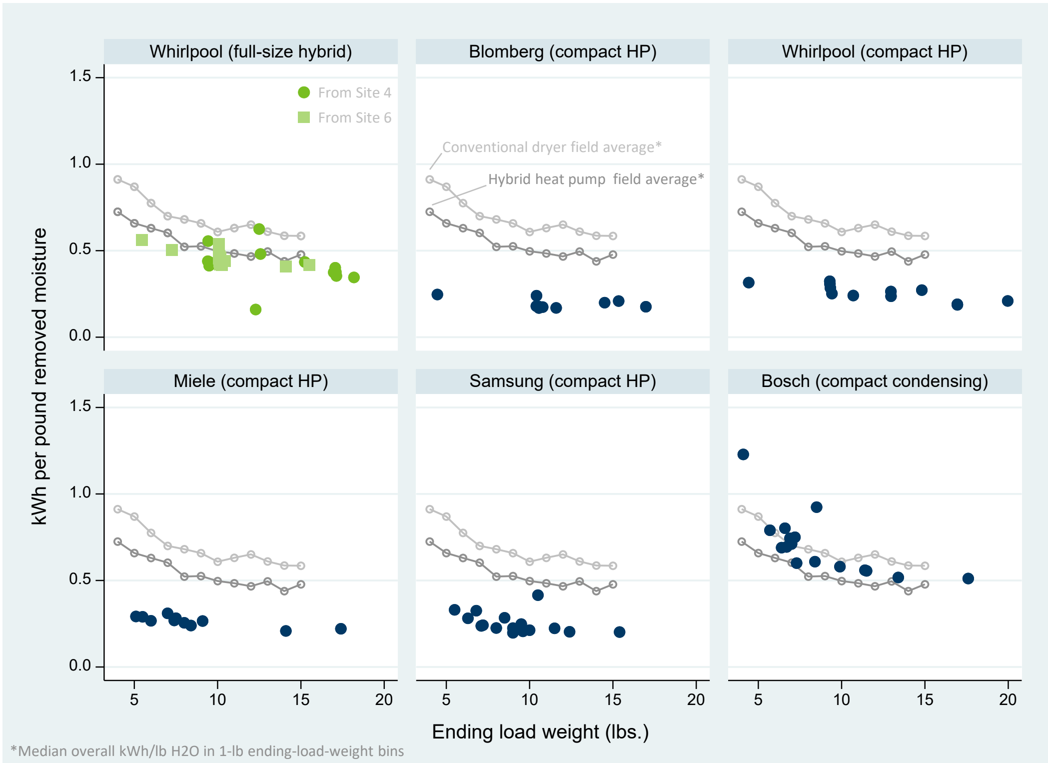
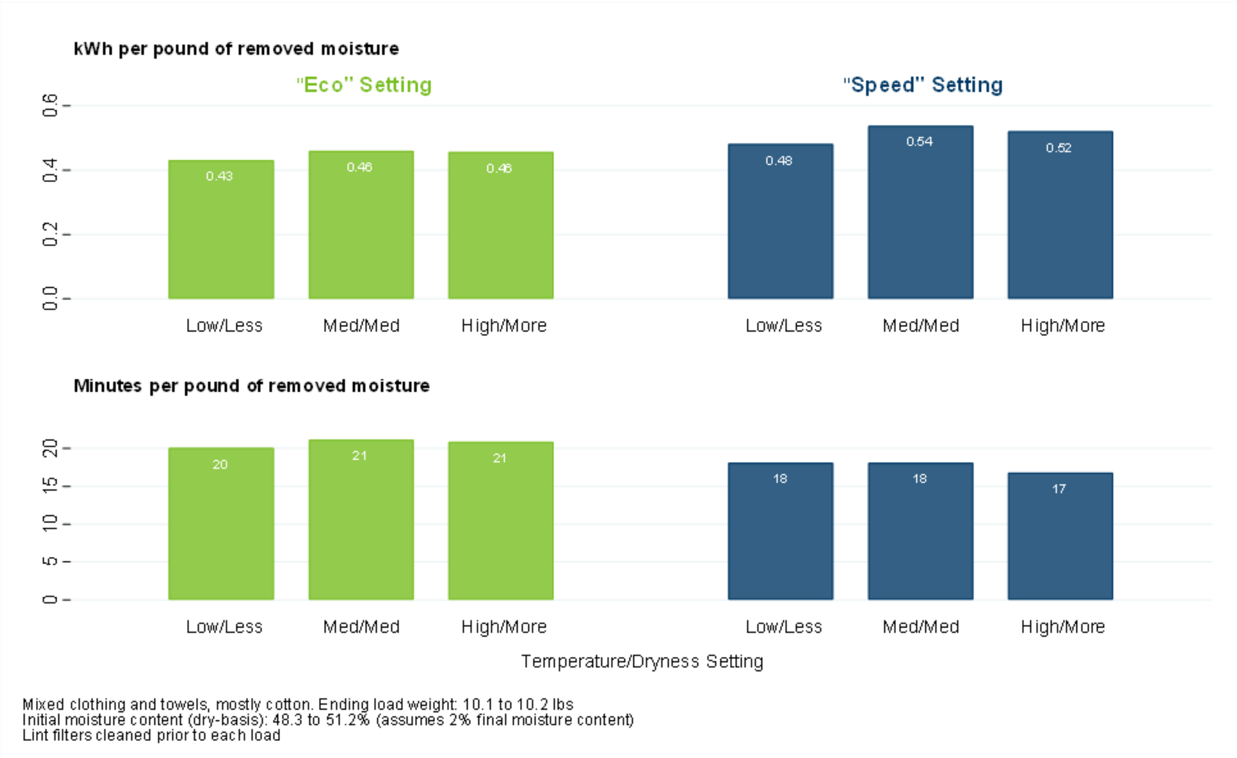


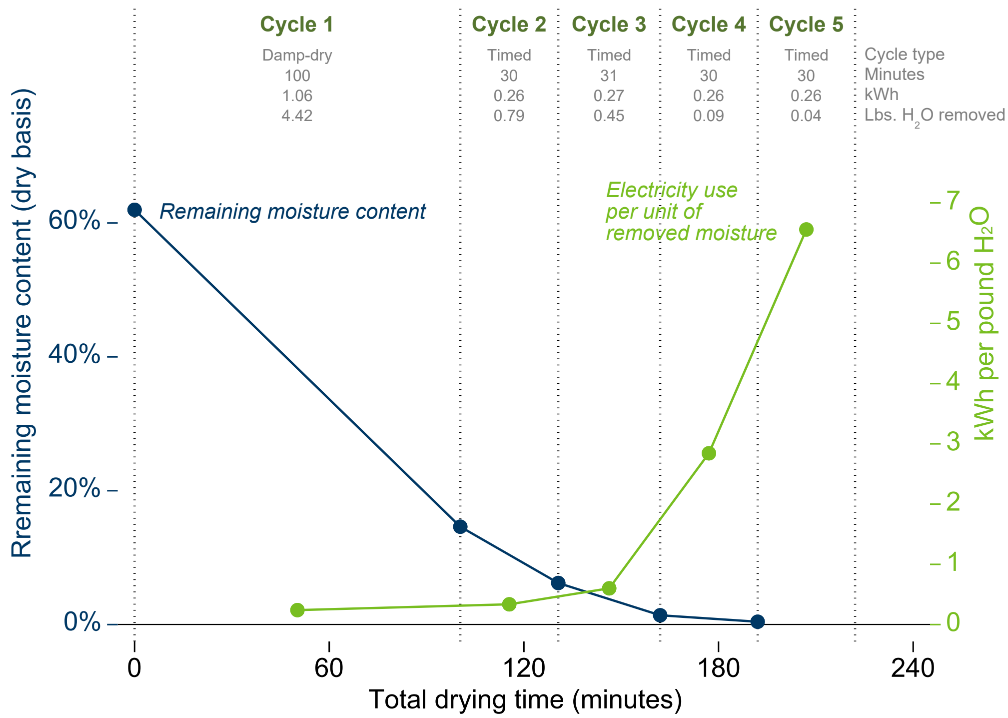
Figure 20. Control settings for the full-size Whirlpool hybrid dryer.

Figure 21. Effect of settings on normalized energy performance and drying time for the Whirlpool hybrid dryer when the same load was dried repeatedly under different automatic-termination settings.



We also used the bench testing to demonstrate the diminishing returns for drying to very low moisture contents. As an experiment, we deliberately under-dried a load of mixed cottons in one of the compact heat pump dryers, then ran four sequential 30-minute, timed-dry cycles to continue to dry the load. As Figure 22 shows, the amount of moisture removed declined with each subsequent touch-up cycle, but the amount of electricity consumed remained constant. This resulted in dramatically higher electricity consumption per pound of removed moisture after the third cycle.

Figure 22. Example of the diminishing returns for touch-up cycles.



Effect of Filter Maintenance on Performance

All but one of the heat pump dryers that we tested has a secondary lint-trap filter in addition to the conventional lint trap found just below the door of the unit.[23] This filter serves to keep the narrow airflow passages through the heat pump coils from becoming clogged with lint. It is important to keep the heat pump coils clean, both for performance purposes and because accessing the coils to clean them requires significant disassembly of some heat pump dryers.

The machines vary in both the design of the secondary lint-trap filter as well as manufacturer's recommendations regarding how often to clean the secondary filter (Table 8).[24]

[23] The exception is the Samsung compact heat pump dryer.

[24] All manufacturers recommend cleaning the primary lint trap after each cycle

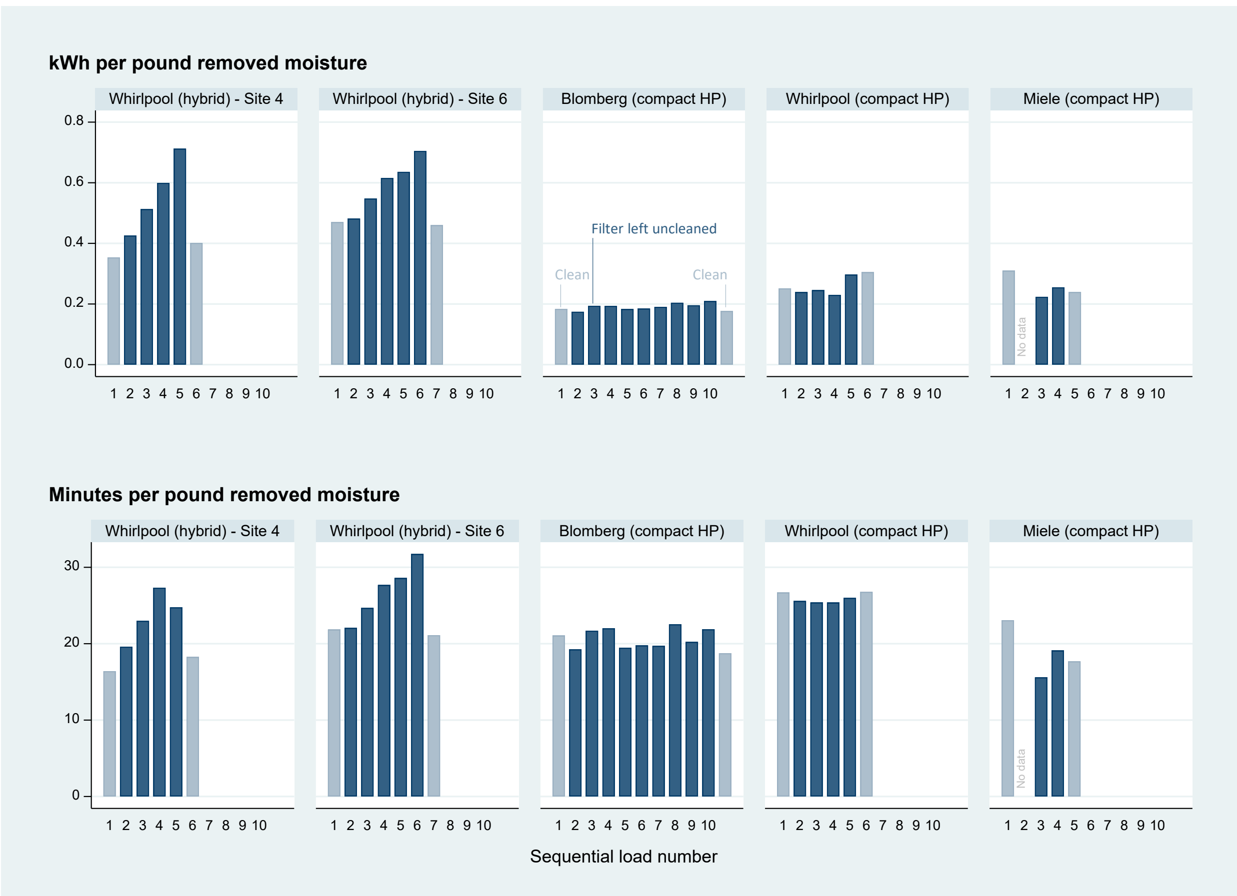
Table 8. Secondary lint-trap filters for tested heat pump dryers.

Machine	Recommended cleaning interval	Filter assembly	Filter
Whirlpool full-size hybrid	Every 5 cycles		
Blomberg compact	Every 3 cycles		
Whirlpool compact	Every 5 cycles		
Miele Compact	Every cycle		

To test the effect of filter maintenance on performance, we ran a series of sequential cycles for each machine, starting and ending with clean filters, but leaving one or both of the filters uncleaned for the middle of the series. We used the same load and washer/dryer settings for each drying cycle.[25] This removes otherwise confounding effects on performance, but also likely somewhat mutes filter-cleaning impacts because repeatedly washing and drying the same load of (unsoiled) laundry probably reduces the amount of lint produced in each cycle.

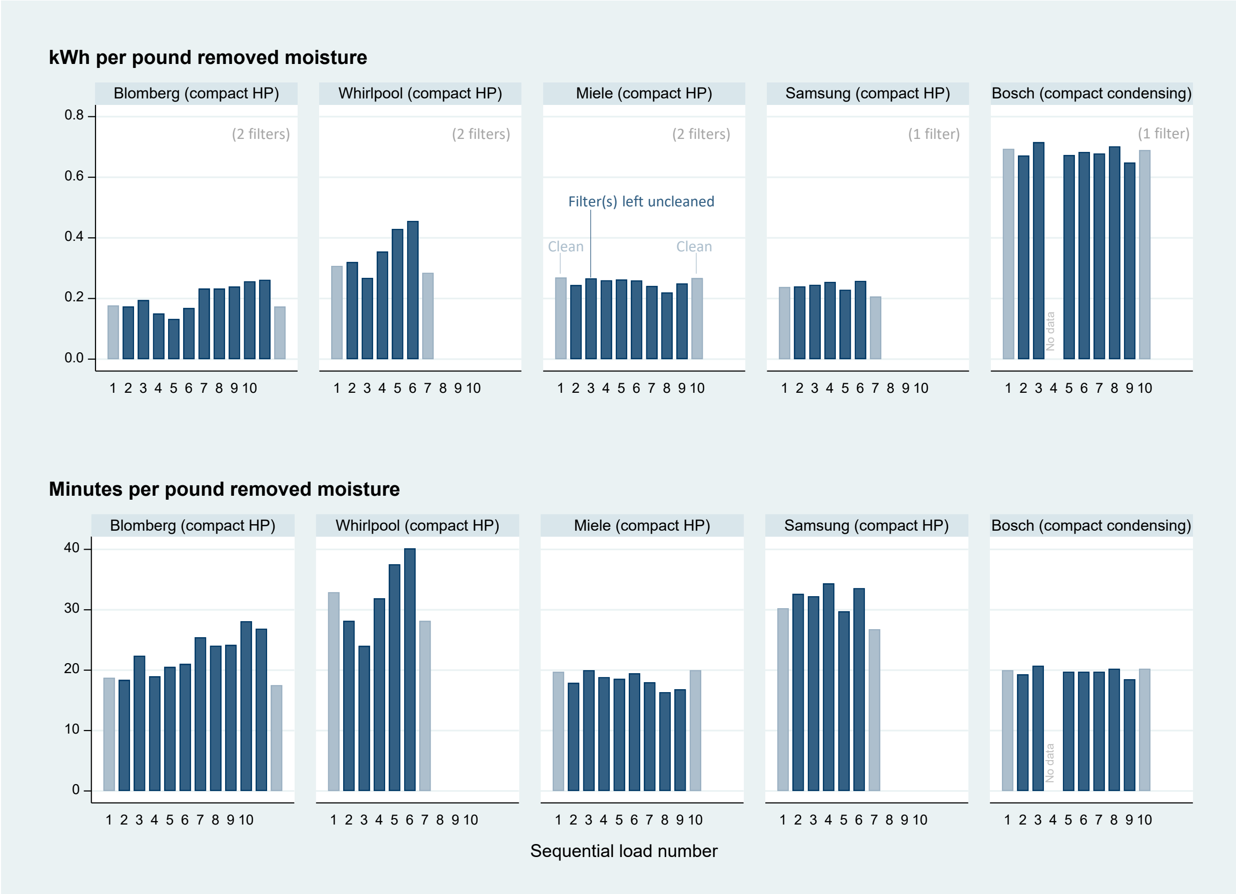
The results of this experiment were mixed (Figure 23 and Figure 24). Some machines showed no effect on either electricity consumption or drying time per pound of removed moisture, while others (e.g., the Whirlpool full-size hybrid machine) showed substantial degradation in both metrics. It may well be that the magnitude of the effect is most strongly dependent on the nature and amount of lint produced by the load being washed, factors that we could not readily control.

Figure 23. Effect of leaving secondary lint-trap filter uncleaned on kWh and minutes per pound removed moisture.



[25] The loads were the same for all cycles for a given machine, but not necessarily the same across machines.

Figure 24. Effect of leaving all lint-trap filters uncleaned on kWh and minutes per pound removed moisture.



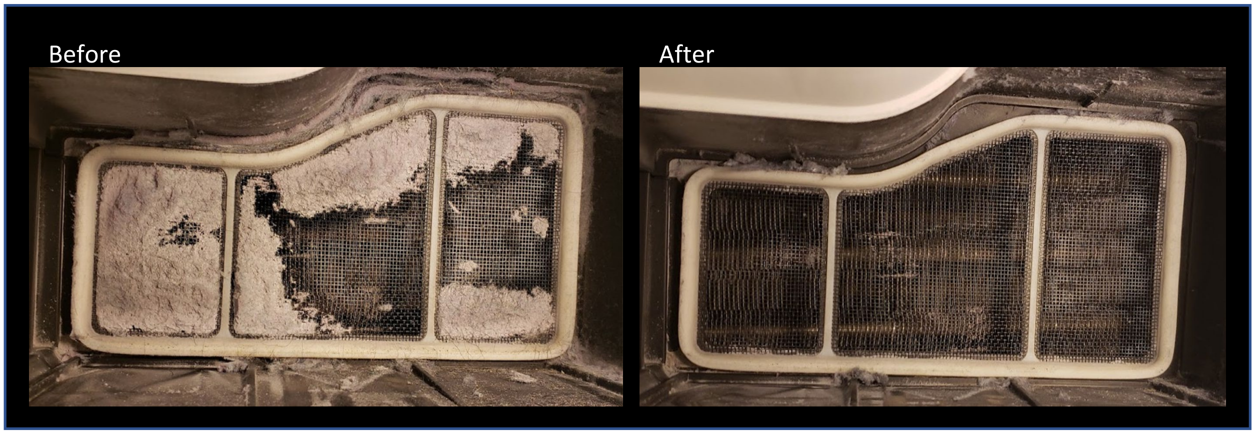
Nonetheless, the experiment suggests that failure to clean filters between loads *can* affect drying performance. Household behavior regarding the secondary lint-trap filter—which is not present for conventional dryers, and for which most manufacturers recommend only periodic cleaning—could thus play a role in the average field performance of heat pump dryers beyond what would be indicated from clean-filter testing.

Heat Pump Coil Inspection

In a related vein, we disassembled three of the returned full-size Whirlpool machines (Sites 1, 4 and 6) to look for evidence of coil fouling beyond the filters. At the time of disassembly, the machine from Site 1 had gone through 47 loads, Site 4 had gone through 275 loads and the Site 6 machine had dried 111 loads.

Prior to disassembly, we observed that a coarse screen located between the secondary lint filter and the heat pump coils was substantially clogged for the Site 6 machine (Figure 25). This was readily solved with a quick vacuum of the screen but could easily go unnoticed by users given that it is at floor level and recessed behind the secondary filter assembly. We re-ran a test load after cleaning the screen but found only a minor (5%) impact on energy performance and drying time (3%) relative to prior runs with the same load and dryer settings.

Figure 25. View of coarse screen located downstream of the secondary lint filter on the Whirlpool full-size heat pump dryer, before and after cleaning (Site 6). The heat pump evaporator coils are visible behind the screen.

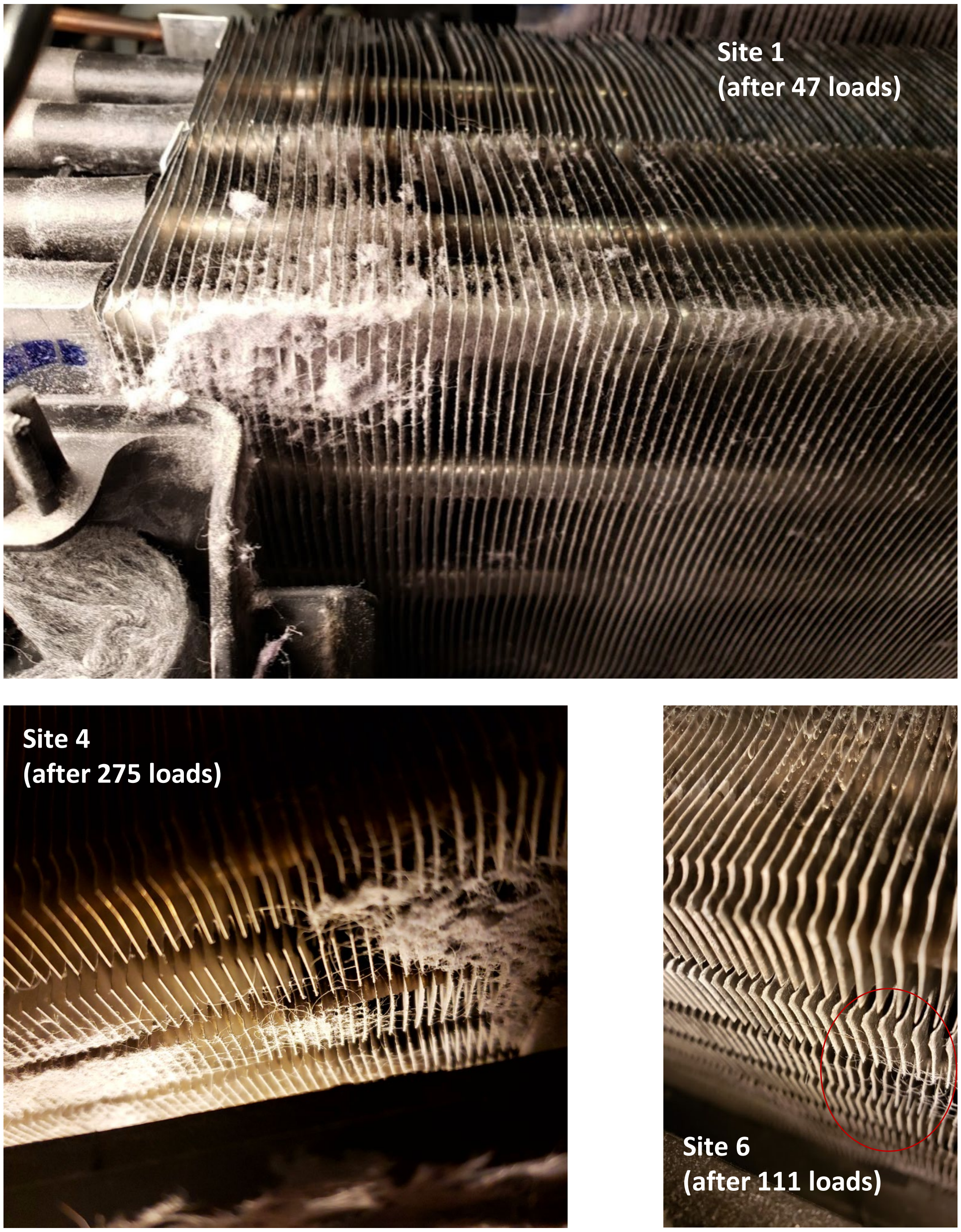


As for the coils themselves, we found minor fouling on the front face of the evaporator coil for two of the three machines and the beginnings of accumulation on the third (Figure 26). The level of fouling that we found is not of concern *per se*, but does raise questions about the potential for long-term fouling and performance degradation given how few cycles the machines had been through when they were inspected. These observations also testify to the difficulty of keeping the working elements of these recirculating machines completely free of lint and other debris.

It is worth noting that accessing the heat pump coils on the Whirlpool hybrid requires substantial disassembly of the machine due to the presence of the screen shown in Figure 25 : we estimate 1.5 to 2 hours of skilled technician labor for disassembly, cleaning and reassembly. It is unlikely that many owners would pay to have such work undertaken, even if they recognized the need for such cleaning.

The other heat pump dryers that we tested provide more direct access to the front face of the evaporator coils behind the secondary lint filter.

Figure 26. Minor coil fouling for three of the full-size Whirlpool hybrid dryers.

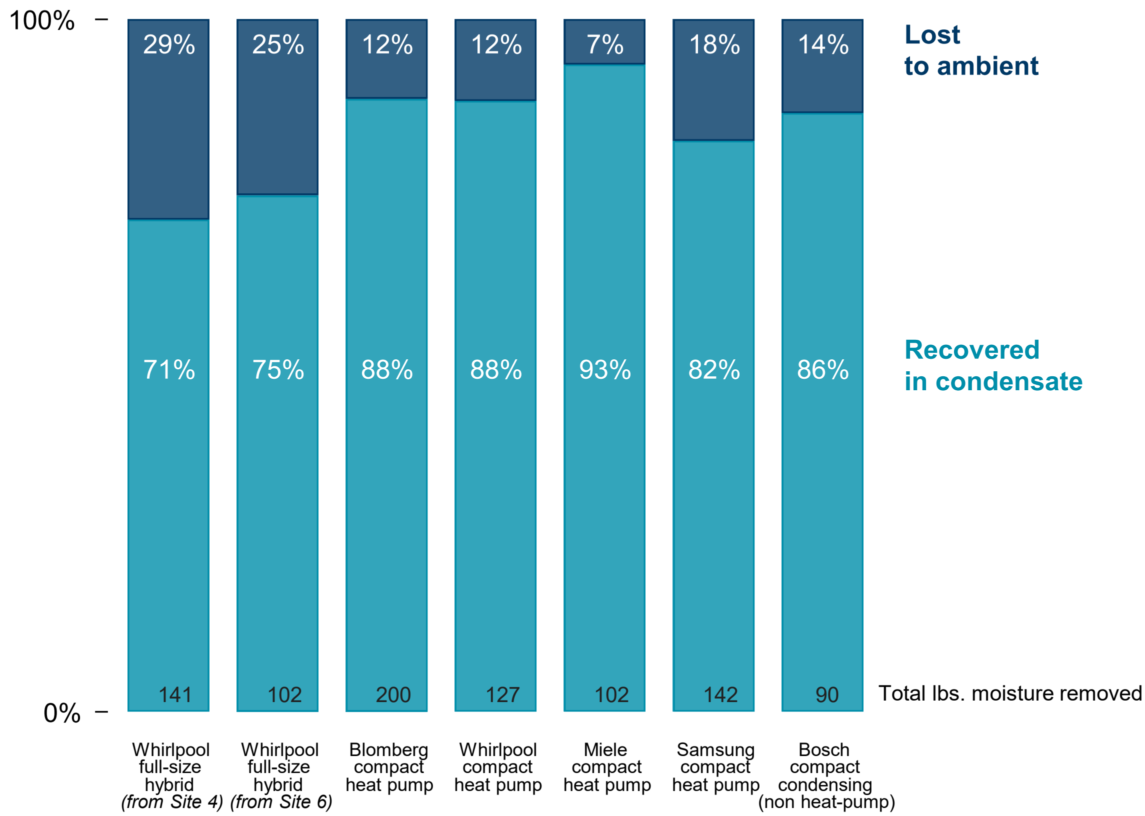


Moisture Recovery

The bench testing also afforded an opportunity to compare the amount of condensate collected from the dryers to the amount of moisture removed (based on pre- and post-drying load weights) and thus measure the amount of moisture lost to the environment during the drying process. For any given load, there is some uncertainty in this calculation owing to the retention of some condensate in the sump area at the end of the cycle, but this effect becomes negligible when the data are aggregated over many loads and expressed as total condensate produced as a fraction of total moisture removed.

The results indicate that the five compact dryers lose 7 to 18 percent of laundry moisture to the environment surrounding the dryer but the full-size Whirlpool hybrid loses 25 to 29 percent (Figure 27). All or most of this difference is likely due to a combination of the fact that the full-size dryer has a larger drum and thus more circumference length for leakage and that the drum for the full-size unit (like most North American dryers) is essentially an open tube that requires felt seals at the front and back of the drum where it rotates against fixed surfaces. In contrast, the drums for the compact dryers are constructed as tubs, with the open end facing the door, and thus do not require seals at the back.

Figure 27. Measured moisture recovery from bench-tested ventless dryers.



Calculated from aggregate condensate and pre/post load-weight measurements across all bench-testing cycles for each unit

For a typical household in a single-family home, these results suggest that laundry moisture escaping to the indoors from the full-size Whirlpool machine could be expected to amount to about 2.5 cups of water per load or bit less than a gallon per week.[26] Many households would benefit from this additional moisture in the middle of a dry Minnesota winter, but additional moisture is not helpful in the summer or if it is concentrated in a laundry room and condenses on cool surfaces such as a basement wall.

[26] Assumptions: 8.45 lbs laundry per load; 57.5% initial moisture content; 27% moisture leakage; 285 loads per year.

Indirect Space-Conditioning Impacts in Single-Family Homes

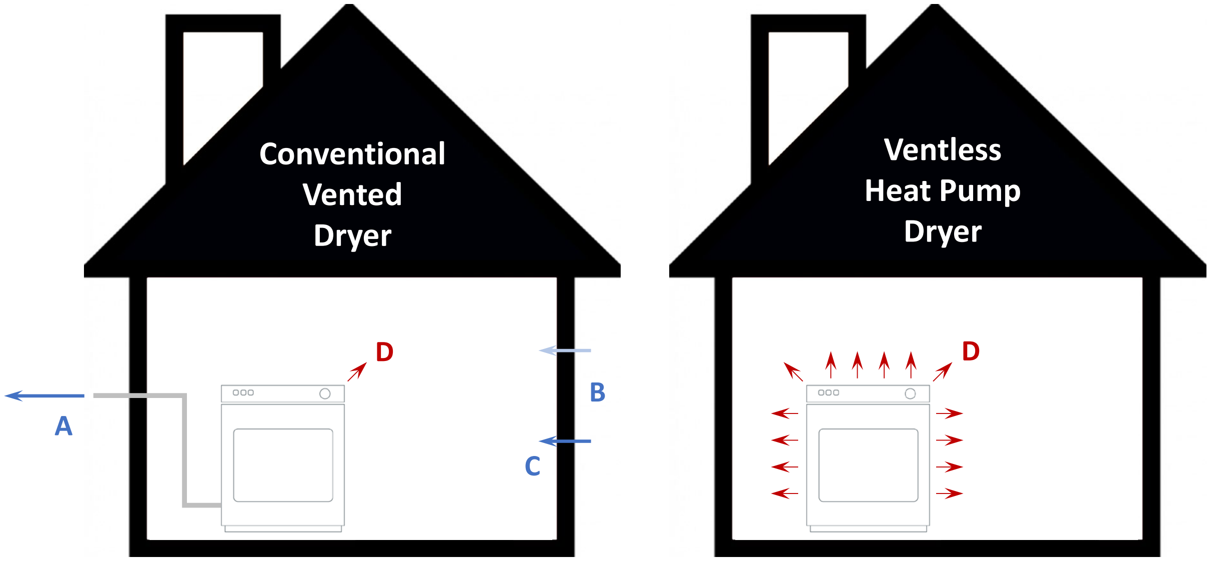
In addition to measuring the direct electricity savings for heat pump dryers, we also estimated their indirect impact on space-heating and cooling. In that regard, the presence or absence of dryer venting is the key difference that affects space-conditioning impacts (Figure 28).[27] A conventional vented dryer acts as an exhaust fan, drawing in outdoor air to make up for what is exhausted by the dryer and thus increasing heating and cooling loads. With a vented dryer, the heat produced by the dryer itself is also largely immediately whisked out of the home by the exhaust.

In contrast, a ventless heat pump dryer imposes no additional infiltration load on the home. But the lack of venting also means that all the heat generated by the dryer remains in the home, offsetting the need for space heating in the winter and increasing the need for space cooling in the summer.

A key element of the assessment is knowing the airflow rate for vented dryers. We were able to do spot measurements for 8 of the 11 sites in the study and found airflows that ranged from 42 to 180 cfm, with an average of 78 cfm. With the exception of the unusually high value of 180 cfm at one site, the distribution compares favorably to similarly-measured dryer airflows from a prior study of new Wisconsin homes, where we found dryer airflow rates that ranged from 21 to 97 cfm in 21 homes, with an average of 52 cfm. Combining the measurements from this study with those from the prior Wisconsin study yields an average of about 60 cfm, which we used for the analysis here.

[27] Note that under most circumstances, the incremental infiltration of outdoor air due to dryer operation is only about half the amount that is exhausted by the dryer, which we assumed here This is due to the somewhat complex way natural infiltration and mechanical ventilation interact.

Figure 28. Assumptions for estimating indirect heating and cooling effects for dryers in single-family homes.



Conventional dryer

- Dryer exhaust (A) must be replaced by infiltration of outdoor air (B).
- Only ½ of the exhaust flow (60 cfm) is replaced by outdoor air (C) that is incremental to what would have occurred by natural means.
- 5% of dryer electricity is retained as heat in the indoor space (D).
- 820 kWh/year dryer electricity consumption

Heat pump dryer

- Ventless, so no infiltration impacts
- 100% of dryer electricity is retained as heat in the indoor space (D).
- 670 kWh/yr dryer electricity consumption

Heating season

- 70F indoor temperature
- 29.5F mid-load outdoor temperature
- 90 AFUE furnace, 0.75 kWh/therm electricity consumption
- 47% of annual dryer operation is coincident with space heating

Cooling season

- 75F/50% indoor temperature/relative humidity (28.5 Btu/lb enthalpy)
- 32.5 Btu/lb mid-load outdoor enthalpy
- 13 SEER central A/C
- 22% of annual dryer operation is coincident with space cooling

Another important aspect is determining how much dryer operation is coincident with space conditioning. Dryer operation in January will certainly have an effect on space heating, but operation on a mild April day will likely have not impact on space conditioning. As part of the monitoring effort, we were able to track the heating and cooling operation of most of the homes. We combined these data with monitoring data on dryer operation to calculate the fraction of annual dryer operation that occurred within 4 hours of the heating- or cooling-system operating. The results suggest that in these

Minnesota homes, about 48 percent of dryer operation was coincident with the need for space heating and 22 percent was coincident with space cooling.

With these inputs and the other assumptions shown in Figure 28, we estimated the typical impact on space heating and cooling from switching to a ventless dryer. The air-exchange impacts for a vented dryer are based on the difference in the heat content of the air exchanged between the indoors and the assumed mid-load outdoor conditions multiplied by the estimated incremental air exchange rate from dryer operation (assumed to be half the dryer flow, as discussed above). Heat gain from the dryer itself assumes that only 5 percent of the dryer electricity remains in the home as heat for a vented dryer, but 100 percent is retained for an unvented dryer.

On balance, the results suggest that a ventless heat pump dryer in a single-family home will typically have a beneficial impact on space conditioning costs, owing mainly to its ability to help heat the home in the winter, which more than offset the additional load imposed on the cooling system in the summer for Minnesota's heating-dominated climate (Table 9). While not large, these indirect impacts boost the energy-cost savings for a heat pump dryer by about a third, from about $17 per year for the direct dryer electricity savings to about $23 per year when the indirect space-conditioning impacts are included.

It should be noted that this analysis is premised on the dryer being located in a fully conditioned part of the home. Many older homes in Minnesota have laundry areas that are in semi-conditioned basements: indirect space-conditioning impacts would likely be attenuated, if not eliminated, in that situation.

Table 9. Estimated dryer incremental impact on space-heating and cooling energy and costs for operating a dryer in conditioned space in a typical single-family Minnesota home, by dryer type.

HVAC category	Conventional Vented Dryer	Ventless Heat Pump Dryer	Difference
Gas for space heating (therms/yr)	+1.3	-11.9	-13.2
Htg season gas-furnace electricity (kWh/yr)	+1	-9	-10
A/C electricity (kWh/yr)	+6	+42	+36
Space conditioning energy costs[a] ($/yr)	+$1.67	-$3.86	-$5.53

[a]At 67 cents/therm for natural gas, 11 cents/kWh for winter electricity and 12.2 cents/kWh for summer electricity.

We examined the heating and cooling monitoring data for direct evidence of HVAC impacts, but did not find anything that was consistent across sites. This is not surprising given both the modest magnitude of the above estimates and the small number of sites.

Ventless Heat Pump Dryers for Multifamily New Construction

Provisions for in-unit laundry appears to be the norm for multifamily new construction in Minnesota. A review of building plans gathered for the recent commercial new construction characterization study showed that 16 of 19 projects were designed for in-unit laundry (LeZaks 2020). Most of these projects were designed for compact laundry equipment with vented dryers, though one project involved full-size laundry appliances and one project specified ventless dryers. These findings largely echo similar data from two other field efforts involving newer Minnesota multifamily buildings (Pigg 2013 and Ecotope 2020).

Clothes Dryers and Minnesota Code

We reviewed current (2020) Minnesota State Building Code requirements for make-up-air requirements and other energy-related provisions for vented and unvented clothes dryers in multifamily buildings. Based on that review—and discussion with a state code official (Rosival 2021)—it appears that for the low- and mid-rise properties that dominate the Minnesota multifamily new construction market, vented clothes dryers will not typically trigger a need for powered make-up air and that code-required make-up air can generally be provided through passive means.

In practice, this appears to be commonly achieved by adding an outdoor-air intake to the return side of in-unit, packaged forced-air heating and cooling systems that are used in many new multifamily buildings. However, this outdoor-air intake also commonly serves the purpose of balancing the exhaust from a continuously operating bath fan that is commonly used to meet the mechanical-ventilation requirements of the code.

The dual role of this intake, combined with different mechanical ventilation and makeup-air requirements for low-rise properties (which are subject to Residential Energy Code) and mid-rise properties (subject to Commercial Energy Code), creates some ambiguity in interpreting code requirements, and leaves open the possibility of different interpretations by officials in different jurisdictions.

Minnesota code does require that when space for a clothes dryer is provided in a new structure, code-compliant dryer venting must also be installed unless unvented dryers are specified and installed prior to occupancy.[28]

Energy and Air Exchange Modeling

To estimate the impact of dryer selection on energy consumption and costs in Minnesota multifamily new construction, we conducted detailed airflow and energy modeling of prototype low- and mid-rise multifamily construction with different types of clothes dryers. Specifically, Specifically, we modeled

[28] 2020 Minnesota Mechanical and Fuel Gas Code, 504.8.6

prototype low- and mid-rise multifamily properties with typical individual-unit HVAC systems. We estimated the energy impacts in these prototype properties for three types of in-unit clothes dryers:

- **Conventional vented dryers** impose heating and cooling loads on buildings due to the effects of venting on air exchange, both when operating and not. However, nearly all of the heat generated by these dryers is immediately exhausted to the outdoors, so internal-heat-gain impacts are minimal.
- **Conventional ventless condensing dryers** avoid the cost and air-exchange implications associated with vented dryers. But, based on the unit that we bench-tested, they are no more efficient at drying clothes than a conventional vented dryer, and all of the heat generated by the dryer stays indoors: this helps offset space-heating loads in the winter but increases cooling loads in the summer.
- **Ventless heat pump dryers** also avoid issues and energy waste associated with dryer venting, and are more efficient at drying clothing. This means less undesirable internal heat gain from drying during the summer**,** but also less offset of space heating during the winter.

Similar to the preceding analysis of HVAC impacts for single-family homes, this multifamily analysis considered the effects of dryer exhaust on building ventilation as well as the contribution that clothes dryers make to the building's internal heat gain. However, the multifamily analysis involved much more detailed airflow modeling to account for the interaction among natural infiltration forces, mechanical ventilation and the air-exchange impacts of vented dryers. The output of the airflow modeling was fed into energy models for the prototype buildings to estimate annual heating and cooling impacts accounting for both air-exchange and internal-heat-gain impacts. The details of the modeling are provided in Appendix C. The results were similar between the two prototype models, so are summarized here in Table 10 for the mid-rise prototype.[29]

The analysis suggests that there are modest indirect HVAC impacts from eliminating clothes dryer venting entirely, but that the more substantial impact comes from specifying unvented compact heat pump dryers instead of conventional vented dryers for in-unit laundry, which our bench-testing suggest would require about two-thirds less electricity for clothes drying.

[29] We also modeled different modes of main air-handler operation, but did not find strong effects from that either. Full results can be found in Appendix C.

Table 10. Estimated clothes-drying and space-conditioning energy and cost difference for alternatives to conventional in-unit vented clothes dryers in a 6-story prototype multifamily building.

Base case: ***conventional vented clothes dryer*** (values are per housing unit per year)	**Alternative:** ***compact unvented condensing dryer***	**Alternative:** ***compact unvented heat pump dryer***
Difference in **dryer electricity** (kWh)	0	-407
Difference in **space heating energy** (therms)	-24	-15
Difference in **space cooling energy** (kWh)	+78	+28
Difference in **air handler electricity** (kWh)	-3	-3
Difference in **dryer operating cost**[a]	0	-$45
Difference in **HVAC operating cost**[a]	-$7	-$7
Difference in **combined operating cost**[a]	-$7	-$52

a) At 67 cents/therm for natural gas, 11 cents/kWh for winter electricity and 12.2 cents/kWh for summer electricity.

Interview Insights

To get insights on the market for compact heat pump clothes dryers in multifamily applications we interviewed three property developers and an architect with the Minnesota Housing Finance Agency (MHFA). The three property developers we interviewed were primarily involved in developing affordable housing. The Minnesota Housing Finance Agency is the state agency involved in financing affordable housing.

Our goal was to learn how familiar multifamily building developers were with heat pump clothes dryers and whether they might consider installing them in buildings with in-unit laundry appliances. Overall, we found little awareness of compact heat pump clothes dryers among the developers we spoke with.

Only one developer has installed heat pump clothes dryers in one of their buildings. The dryers were full size hybrid dryers, not compact heat pump dryers. They installed six Whirlpool full size hybrid dryers (WHD560CHW) as a strategy to meet a make-up air code requirement. This same developer may consider ventless dryers for a larger project that started construction in March 2021. However, they commented that the cost of six ventless dryers versus 40 to 50 for a larger development would be a barrier.

Another developer indicated that they regularly install Energy Star laundry appliances in their developments but would be unlikely to install ventless dryers because they were unknown to them. This developer also mentioned that any buildings they developed using financing from MHFA had to have vented dryers. We interviewed an architect from MFHA to learn more about this requirement.

MHFA requires that buildings they finance follow Green Communities guidelines. Prior to 2020, the guidelines required that clothes dryers be exhausted directly to the outdoors, except for condensing dryers which had to be plumbed to a drain. MFHA appears to have interpreted that guideline as all dryers had to be vented directly outdoors. They have since revisited the guidelines and discovered that this requirement was no longer included in the 2021 version, and they will now allow condensing dryers if there is a floor drain.

Conclusions and Recommendations

Conclusions and recommendations from the study are presented below under the major categories of the market for both full-size and compact heat pump clothes dryers, energy impacts from the technology and recommendations for Minnesota utility programs.

The Market for Heat Pump Clothes Dryers

At a glance, the consumer research component of this study suggests that:

- A subset of Minnesota consumers would be interested in comparably sized heat pump dryers to replace their current conventional electric dryers if they were more widely available and offered at price points that are comparable to mid-range models.
- Current retail market practices are unlikely to prompt many Minnesota consumers—particularly those in single-family homes expecting to buy full-sized dryers—to consider heat pump dryers because awareness about them is low and full-sized models are not widely stocked or displayed on showroom floors in Minnesota.
- Sustainability of heat pump dryer demand once (or if) the technology gains a foothold in the market would depend on both the heat pump technology's performance as well as design and performance characteristics of the models available from manufacturers that are unrelated to the heating technology employed (such as availability of settings, sensor performance, design of lint filters, etc.).
- Multifamily housing developers are unaware of compact heat pump clothes dryers and their benefits for in-unit applications.

Consumer Interest and Product Fit

Study participants in single-family homes appeared to either like or dislike the full-size heat pump dryer they tested. While we cannot quantify the share of Minnesota households that would consider heat pump dryers or find them of interest, we note that seven of ten study participants in the single-family field test opted to keep the heat pump dryer (omitting the participant that returned the dryer after it malfunctioned). Comments about the dryer from those who liked it and those who did not offer insights on features and operational considerations that would make it a good or poor fit for individual households. We have more limited information about potential interest by developers or owners of multifamily homes, where compact units may be more appropriate and ventless options provide an additional benefit.

Potential Market for Heat Pump Dryers (among Single Family Households)

Those who liked the heat pump dryer shared a combination of the following attributes:

Strong appreciation for energy efficiency—While not interested in the details, these participants seemed to trust that the heat pump technology would provide meaningful savings and had only a moderate need to know specifically how much it saves.

Low need for quick drying cycles—Those who liked the heat pump dryer the best expressed little need to have dryer loads complete their cycles quickly or to have them aligned with washer cycle lengths; some indicated that they are never in a hurry to dry their laundry.

Willingness to engage with their new appliance and technology—Most participants experienced a learning curve for the heat pump dryer; those who liked it best seemed more willing to try out different settings and figure out how to make the dryer work best for their needs.

Appreciation for the ventless operation—While mentioned by only one study participant, ventless operation was a big positive attribute for the flexibility it affords in appliance placement even when venting is an option. (The ventless operation is likely to be an even bigger draw for households that do not have or want venting to the outside.)

Unlikely Purchasers of Heat Pump Dryers

Consumers for whom the heat pump dryer likely is a poor fit are those with:

The need to dry clothes quickly—No one in our study needed to dry clothes quickly all of the time, but some had more frequent needs to finish loads at the speed afforded by conventional dryers.

A desire for matching washers and dryers—Matching entails both similarity in controls for convenience and aesthetics as well as alignment of cycle lengths to allow back-to-back loads with ease.

Low interest in experimenting with a new appliance variant—Every new appliance comes with a learning curve, but it seemed that some study participants were quicker to attribute unsatisfactory performance to the dryer while others were more willing to experiment with settings. Several participants suggested that the heat pump dryer was not providing the level of drying they desired early, but those who volunteered that they tried out different settings ultimately found some that provided the expected dryer performance.

Willingness to Pay and Rebates

One key question we were not able to answer in this study is how heat pump dryers would fare in the market among higher-end dryers. This question is important for Conservation Improvement Programs if they choose to promote heat pump dryers. Our study participants tended toward budget and mid-range dryers, and their self-reported willingness to pay more for a heat pump dryer was in the vicinity of a couple hundred dollars, which would imply a purchase cost of $1,000 or less. At an incremental cost of $400 to $600 for a full-size heat pump dryer, utility rebates would need to be substantial if these consumer expectations hold and operational savings cannot make up part of that price gap. One alternative to high rebates would be targeting the luxury market and offering the heat pump dryer as an energy efficiency alternative to high-end dryers. Doing so would minimize the price difference, but we did not investigate how heat pump dryers would be perceived by consumers of luxury appliances.

Retail Practices and Consumer Awareness

Awareness of heat pump dryers and heat pump technology generally were both very low among our study participants, and the typical shopping experience is unlikely to introduce most dryer purchasers to the existence of full-size models or their benefits. (Retailers do stock some compact models for customers looking for ventless options.)

The fact that there is currently only a single manufacturer and model of full-size heat pump dryer in North America is a limitation for consumers currently and a limitation to our consumer research. We found that the availability of full-sized heat pump dryers was very limited and changed during the course of the study. At one point, there seemed to be none easily available while the manufacturer (Whirlpool) changed its offerings. Although numerous options exist for compact heat pump dryers, which are in widespread use in Europe and can be seen and bought in retail stores in Minnesota, it seems unlikely that most owners of a full-size dryer would opt for a compact model—even though our field data suggest that the large majority of laundry loads currently dried in full-size dryers could readily be accommodated by a compact unit. The limited selection and availability of full-size heat pump dryers could pose an initial challenge for consumers with interest in acquiring one. It also limits our study results on consumer experience and satisfaction to a single model with the possibility that participants would have liked alternatives more (or less).

Over time, the introduction of heat pump heating and cooling equipment in the upper Midwest may increase familiarity with the technology generally and result in an association between heat pumps, efficiency, and climate-friendly technology in consumers' minds.

However, retail practices concerning heat pump dryers would need to evolve naturally or be boosted through intentional market interventions to increase consumer awareness. Options for market interventions include:

- Combining early adopter rebates linked with coordinated stocking of heat pump dryers at selected retailers in a pilot program to spur initial demand.
- Using installations of any heat pump appliances in the state as an opportunity to promote heat pump technology generally. For example, efficiency programs that rebate heat pump heating and cooling equipment could inform their participants about the existence of heat pump water heaters and clothes dryers.
- Leveraging utility program relationships with their customers and with retailers to raise awareness of heat pump dryers as an emerging technology in both utility communications and in-store collateral materials.
- Working with early adopters of the technology to gather testimonials and encourage word-of-mouth information sharing.

Any collateral material should offer realistic assessments of who may most benefit from a heat pump dryer to ensure that early adopters are satisfied with their acquisition and help build momentum rather than holding back market growth in any public reviews and word-of-mouth information sharing.

Awareness of heat pump dryers among several multifamily property developers was also low. Of the three developers we interviewed, only one had any experience with heat pump dryers and that was with the full-size hybrid heat pump dryer, not with compact heat pump dryers. We also learned that developers of affordable multifamily housing who received financing from the Minnesota Housing Finance Agency have been precluded from installing ventless dryers in those properties. MHFA requires that buildings they finance follow Green Communities guidelines and prior to our study, interpreted those guidelines as requiring that clothes dryers be exhausted directly to the outdoors.

Energy Savings from Heat Pump Clothes Dryers

The field testing for this study involved a limited number of participants and a single make and model of full-size hybrid heat pump clothes dryer, so broad conclusions are not possible. However, field-study participants saved an average of about 20 percent on dryer electricity by switching to the Whirlpool full-size hybrid heat pump dryer, which translates into 195 kWh per year of savings for the typical Minnesota family in a single-family home. These savings are comparable to what the two other studies (Dymond 2018, Martin 2016) that looked at an earlier generation of this machine found.

Several participants reported that after experimenting, they eventually settled on timed-dry operation instead of moisture-based automatic termination to achieve acceptable results. This suggests that some loss of savings could occur from increased incidence of over-drying with timed-dry operation.

Also, most heat pump dryers have a secondary lint-trap filter that requires periodic cleaning, a chore that is not required for conventional dryers that have only a single easily accessed lint trap. Bench testing for this study with and without cleaning of the secondary lint trap showed susceptibility to degraded performance for the full-size Whirlpool machine when the secondary lint filter is not cleaned—even within the manufacturer's recommended cleaning interval—but the compact heat pump dryers did not seem to be affected in this way. In general, the field- and bench-testing raises some questions about long-term performance of heat pump dryers in the face of poor filter maintenance by consumers or even just eventual buildup on the heat pump coils, which in some cases are quite difficult to access.

The compact heat pump dryers that we bench tested showed about double the energy performance of the full-size hybrid machine that we both bench-tested and deployed in the field study. Since there are no full-size, heat-pump-only machines on the market, it is not possible to fully disentangle how much of this performance difference owes to hybrid versus non-hybrid design and how much is attributable to size or other design differences—however, we suspect that it is mainly the former.

It is also noteworthy that 95 percent of the loads dried in full-size dryers by our field-study participants would have readily fit in a compact dryer. This raises at least the possibility of significant additional electricity savings from encouraging households to purchase a compact heat pump clothes dryer instead of a conventional full-size dryer or even a hybrid heat pump dryer. Overcoming dryer “capacity anxiety” could pose a challenge to this strategy, however.

The study also suggests that there are some indirect space-heating and cooling impacts from ventless heat pump dryers, and that in Minnesota’s heating dominated climate, these work out in favor of additional savings beyond the direct dryer-electricity impacts. For single-family homes, the biggest unknown is dryer location: indirect HVAC impacts will be largest in homes where the laundry area is fully inside the conditioned envelope of the home and will be smallest in homes where the dryer is in a semi-conditioned basement. More detailed modeling for multifamily new construction suggests that there are also modest indirect HVAC benefits from specifying unvented clothes dryers in that setting, but most of the benefit would come from the direct dryer-electricity savings from using unvented compact heat pump dryers that our bench-testing suggest are the most efficient class of clothes dryers available, and that are perfectly suited for multifamily applications.

Overall, the study suggests some significant revisions to the Minnesota TRM algorithms for clothes dryer savings, including both efficiency upgrades for conventional dryers as well as heat pump clothes dryers. Appendix D to this document lays out the details of the recommendations, but the upshot is that the current TRM algorithms appear to substantially undervalue the savings from efficient clothes dryers in general and should be revised upward by roughly 60 to 100 percent. If indirect HVAC impacts are accounted for the savings for efficient clothes dryer would be higher still., a

Recommendations for Utility Programs in Minnesota

- The Minnesota TRM should be revised to better reflect the savings from both heat pump and non-heat-pump clothes dryers. Appendix D to this report provides detailed recommendations in this regard.
- Utilities should consider incorporating heat pump clothes dryers into their appliance rebate programs, along with market-development activities to build consumer awareness and availability of the technology. The awareness building for heat pump dryers could tie into more general efforts to promote heat pump technology for space-heating and water heating.
- Multifamily new construction programs should consider incentives or other encouragement for using ventless heat pump dryers, which provide energy savings and eliminate the cost of installing dryer venting in every unit. In particular, there are opportunities to educate staff at the Minnesota Housing Finance Agency on the benefits of compact heat pump clothes dryers and how they comply with the Green Communities guidelines that developers receiving MHFA financing must follow.

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Appendix A: Field Monitoring Recruitment Materials

Selected Participant Recruitment Materials

Minnesota Clothes Dryer Research Study

LOOKING FOR HOUSEHOLDS WITH A NEW CLOTHES DRYER

A research team funded by a Minnesota Department of Commerce grant is looking for Twin Cities Metro households that have recently purchased or are currently looking to purchase a new electric clothes dryer to participate in a research study of dryer usage and performance.

If you participate…

We will ask you to use your current or newly purchased dryer and a different high end dryer we supply for a few months each. The study team will monitor the dryer performance, ask you to track some aspects of your dryer usage, and get feedback from you. At the end of the study, you keep the dryer you like better.

Study participants will receive up to $250

Please contact the research team for additional details or visit https://www.seventhwave.org/minnesota-heat-pump-dryer-study.

Joe Clark • MinnesotaDryerStudy@EvergreenEcon.com • (800) 551-3923

Intake Interview Questions

- Name
- Address
- Telephone (primary)
- Email address (for study use only)
- Telephone (secondary)
- In what kind of home do you live?
- Do you own or rent your home?
- How long have you lived in your current home?
- Do you have any plans to move in the next two years?
- Where is your laundry equipment located?
- Which of the following are available at or near your laundry equipment?
- When did you purchase your new dryer?
- What is its size?
- What was the size of your prior dryer?
- Is your current washing machine…?
- Is your current washing machine a…?
- Number of adults in your household:
- Number of youth (aged 13-17)
- Number of children (aged 0-12)

- Your age
- Your gender
- Where did you learn of this study?
- Which of the following best describes why you decided to buy a new dryer?
- What were you looking for in a new dryer? Please list the main considerations that caused you to look at some dryers over others.
- Brand name and model number of the dryer you purchased
- Which of the following best describes how familiar you were with **heat pump technology** *before you began looking for your new dryer*?
- Which of the following best describes how familiar you were with **heat pump dryers** *before someone associated with the study mentioned them*?
- What was your perception of heat pump dryers?
- Based on what you know right now, how much do you think you would have been willing to pay for a heat pump based dryer if you had seen one you liked in the store? (Your best guess is fine. Your response does not affect anything about your dryer purchase or study participation.)
- About how much would that have been?
- For electric clothes drying, there is often a trade-off between drying time and energy use. Move the slider accordingly to show which is more important to you and by how much.
    - [Note: When fielded electronically, we showed a slider that the respondent could move within a range that was defined on the left end as “willing to use more energy for faster drying (30 minute cycle; 150% of the energy use)” and on the right end as “willing to take longer drying cycles to save energy (100 minute cycle; 50% of the energy use).” When implemented verbally, we described the question and asked for a response on a 10 point scale.]

Participant Dryer Journal

Note: The dryer journal was formatted as a booklet. We are replicating the individual pages in order here. Each participant received two dryer journals, one for each dryer.

Minnesota Clothes Dryer Study

Information below to be completed by study team

Site #: ________

Dryer #: ________ HP Non-HP

Dear Study Participant,

Please complete this journal as you use the dryer that is currently in your home during the next eight weeks. We ask for load-specific information for the first two weeks (just for the first four loads of each week), weekly information thereafter, and your overall assessment of the dryer after the eight weeks.

If you have any questions, please let us know.

Minnesota Dryer Study
Evergreen Economics
333 SW Taylor Street #200
Portland, OR 97204
(800) 551-3923

Week 1 – Load #1

Date and time loaded into the dryer

Date: ______________________

Time: _____________

Did you weigh the load going into the dryer?
- ☐ Yes
- ☐ No

Which of the following cycles are you using?
- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?
- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?
- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Did you weigh the load coming out of the dryer?
- ☐ Yes
- ☐ No

Week 1 – Load #2

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 1 – Load #3

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 1 – Load #4

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 1 – Loads 5 and beyond

Number of additional loads (beyond the first four)? *Just put a chit mark below for every new load.*

Any delicates cycles? *If you used the delicate or gentle cycle for any of these loads, please check the box below.*

☐

Needed a load finished ASAP? *If you needed any of these loads finished in less than an hour, please check the box below.*

☐

Week 2 – Load #1

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 2 – Load #2

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 2 – Load #3

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 2 – Load #4

Which of the following cycles are you using?

- ☐ Normal / casual / permanent press
- ☐ Heavy duty / bulky / bedding / towels
- ☐ Delicates / gentle
- ☐ Timed dry / quick dry / express
- ☐ Other

Which of the following energy settings are you using?

- ☐ N/A—This dryer doesn't have energy settings
- ☐ Speed
- ☐ Balanced
- ☐ Eco

How soon do you need this load finished?

- ☐ ASAP—I need one of the items right away
- ☐ ASAP—I need the dryer for the next load
- ☐ I could wait an hour or longer

Week 2 – Loads 5 and beyond
Number of additional loads (beyond the first four)? *Just put a chit mark below for every new load.* Any delicates cycles? *If you used the delicate or gentle cycle for any of these loads, please check the box below.* ☐ Needed a load finished ASAP? *If you needed any of these loads finished in less than an hour, please check the box below.* ☐
What do you think of this dryer so far?
Reminder! *Call Joe Clark at (800) 551-3923 if you have any questions or concerns about the dryer study. You can also reach Joe at clark@evergreenecon.com.*

Week 3
Number of loads this week? *Just put a chit mark below for every new load.* Any delicates cycles? ☐ Needed a load finished ASAP? ☐
Week 4
Number of loads this week? *Just put a chit mark below for every new load.* Any delicates cycles? ☐ Needed a load finished ASAP? ☐
Any new comments about the dryer?

Week 5
Number of loads this week? *Just put a chit mark below for every new load.* Any delicates cycles? ☐ Needed a load finished ASAP? ☐
Week 6
Number of loads this week? *Just put a chit mark below for every new load.* Any delicates cycles? ☐ Needed a load finished ASAP? ☐
Any new comments about the dryer?

Week 7
Number of loads this week? *Just put a chit mark below for every new load.* Any delicates cycles? ☐ Needed a load finished ASAP? ☐
Week 8
Number of loads this week? *Just put a chit mark below for every new load.* Any delicates cycles? ☐ Needed a load finished ASAP? ☐
Thank you. This concludes your weekly journal entries for this dryer. Please answer the questions on the next page and return the journal to us.

Dryer Evaluation

How would you rate this dryer?

□ 1 star □ 2 stars □ 3 stars □ 4 stars □ 5 stars

Why did you give this rating? (Continue on back, if needed.)

Please rate your satisfaction with the following attributes of the dryer.

	Impressed	Fully satisfied	Mostly satisfied	Somewhat satisfied	Not Satisfied	Unable to assess
Effectiveness at drying						
Feel of dried items						
Gentleness on fabrics						
Time needed per load						
Ease of operation						
Features and controls						

Could you hear this dryer in your living space?

- □ Not at all
- □ Yes, but it was not bothersome
- □ Yes; it was slightly bothersome
- □ Yes, it was definitely bothersome

(continued on back cover)

Did the laundry room's temperature or humidity feel different when this dryer was in use? If so, how?

During the journaling period, was the length of the dryer cycle ever an inconvenience to you?

- □ Never
- □ Once or twice
- □ A few times
- □ Regularly

If so, how much of an inconvenience?

- □ Slight inconvenience
- □ Moderate inconvenience
- □ Large inconvenience

Do you have any other comments? (Include any additional comments on your dryer rating or notes about weighing here.)

Thank you! Please return this journal to us now in the envelope provided or the address shown on the front.

Exit Interview Questions

- Which dryer do you wish to keep?
- How easy or difficult was the choice?
- What were the top three factors you considered in making your choice?
- If you were to tell your friends about your new dryer on a social media post, what would you say? (Please write a pretend post.)
- What would you suggest to the manufacturer of the dryer you did not choose?
- What did you like, and what should they improve?
- How would you assess their comparative value of the two dryers if you had to buy one new from a retail store? (Your response will not have any effect on the close-out of the study.)
- About how much would you be willing to pay for the heat pump dryer if you were buying one new in a store?
- For electric clothes drying, there is often a trade-off between drying time and energy use. Move the slider accordingly to show which is more important to you and by how much.
    - [Note: When fielded electronically, we showed a slider that the respondent could move within a range that was defined on the left end as “willing to use more energy for faster drying (30 minute cycle; 150% of the energy use)” and on the right end as “willing to take longer drying cycles to save energy (100 minute cycle; 50% of the energy use).” When implemented verbally, we described the question and asked for a response on a 10 point scale.]

Appendix B: Field Monitoring and Bench Testing Details

This appendix provides additional details regarding the field monitoring and bench-testing conducted for the study, including additional detail about the field-monitoring sites and summary results for the bench-testing.

Field Monitoring Site Details

Table 11 and Table 12 provide additional details about the homes, households and laundry equipment in the field-monitoring portion of the study.

Table 11. Field-monitoring site house and household details.

Site #	Number of Adults	Number of children <12 years old	Number of children 13-17 years old	Change in HH size during study
1	1	-	-	-
2	2	1	-	-
3	2	2	1	-
4	2	-	-	-
5	2	3	-	-
6	2	-	-	-
7	2	3	-	+1
8	2	1	-	+1
9	2	1	-	-
10	2	1	-	-
11	2	2	-	+1

Table 12. Field-monitoring site laundry details.

Site #	Existing Dryer	Dryer age (at start of study)	Dyer Airflow (CFM)	Washer	Washer age (at start of study)	Laundry location
1	Inglis IED4300SQ0	3-4 years	42	Inglis ITW4300SQ		Basement (finished) mechanical room near furnace
2	Amana NED4655EW1	1-2 years	73	Amana NTW4516FW0	2 years	Basement (finished) storage area
3	Whirlpool WED7000DW2	<1 year	59	Whirlpool WTW7000DW3		Basement (finished) mechanical room near furnace
4	Kenmore DVMX-ELE-2406026-ELDU	1-2 years	43	Kenmore 110.28132411	1-2 years	Basement (semi-finished) near furnace
5	GE GTD65EBPL0DG	<1 year	52	GE GTW685BPL0DG		First floor laundry closet
6	GE GTD65EBSJ0WS	1-2 years	102	GE GTW680BSJ1WS	5 years	Basement (finished)laundry room
7	Samsung DV40J3000EW/A2	< 1year	180	LG WT7200CW	<1 year	Second floor laundry closet
8	Kenmore DWJR-ELE-2406026-FM54	5 years		Kenmore 110.20022014	5 years	Basement (unfinished) laundry room
9	LG DLE2514W	15-20 years		LG WM1814LW	15-20 years	Second floor laundry hallway/closet
10	GE DDE7110VMLWH	>10 years		Whirlpool LSB6200KQ0	10-15 years	Basement (unfinished) laundry space
11	Kenmore 86870100	>20 years	76	Whirlpool WTW8000NW0	7 years	Basement (unfinished) laundry room

Field Monitoring Details

The foundation of the field monitoring was tracking electricity consumption for the pre-existing and heat pump clothes dryers. This was accomplished by installing eGauge (Model EG4115) electricity meters at the circuit panel with 50-Amp current transformers to track electricity consumption on each leg of the 240V dryer circuit.[30] In addition to monitoring the dryer itself, we also used the eGauge meters to track electricity consumption by the clothes washer, central air conditioner and furnace. The eGauges collected data at one-minute intervals, except for some limited collection of one-second data. Cellular hot spots were used for automated uploading of the electricity data.

Laundry load weights were tracked using internet-connected Nokia (now Withings) Body bathroom scales, which record weights to a tenth of a pound and transmit time-stamped readings to an associated cloud account. Prior to deployment, the accuracy of the scales was verified. Because the scale does not register weights below about 11 pounds, participants were asked to always weigh laundry with a provided basket and 6-lb weight, with a combined tare weight of 9.1 pounds. The idea was that before and after drying a load of laundry, participants would simply place the laundry in the basket containing the 6-lb weight, and then put the basket on the scale, which would then register and time-stamp the reading and transmit it to the associated cloud account. In practice, there was a time lag involved in registering a reading, and because the basket tended to obscure the scale's display indicating whether a reading had been recorded or not, many readings went unregistered by the scale. Participant fatigue with weighing laundry may have also played a role. In addition to the above, we also deployed Hobo data loggers to track temperature and relative humidity in laundry rooms, as well as to track the on/off status of furnace and boiler gas valves for the main heating system.

Bench-testing details

The bench testing used the same eGauge electrical monitoring that was used for the field-monitoring, though with 1-second data resolution. In addition, laundry weights before and after drying were manually recorded (to within 0.1 lbs) and dryer condensate was collected and weighed.

For most loads, we also measured drum-exhaust air temperature by placing a thermocouple connected to an Onset data logger in the exhaust flow. We also ran a few loads with an Onset temperature logger sealed in a plastic bag and placed inside a sock to gauge the relationship between drum-exhaust air temperature and actual load temperature. Finally, for a few loads, we placed pressure sensors at various points in the airflow path to gauge pressure drops and changes in airflow over the course of the cycle.

[30] www.store.egauge.net

Appendix C: Modeling Heating and Cooling Impacts in Multifamily Buildings

In order to explore the impact of unvented dryers on energy use in multifamily buildings, we developed detailed ventilation and energy use models of two buildings, a low-rise 3 story building with 24 apartment units and a mid-rise building with 6 stories and 48 apartment units. We assumed that both prototype buildings are heated and cooled with in-unit, packaged forced-air heating and cooling, as appears to be common practice for multifamily new construction in Minnesota.

We also modeled the common practice of providing an outdoor-air intake to the return side of the packaged system, designed to both passively meet code makeup-air requirements and provide a balanced source of intake air for a continuously operating bath fan to meet the mechanical ventilation requirements of the code. The code requirement for balanced mechanical ventilation would seem to imply that the main air handler would need to be set to operate continuously (or at least on the same schedule as the bath fan), but in practice this may not always happen. We therefore ran the models under two conditions: continuous air-handler operation and auto air handler operation (i.e., only during heating or cooling cycles).

Ventilation Modeling

We used the CONTAM software package to model ventilation, i.e., mechanically and naturally driven air exchange with the outdoor environment. CONTAM is a multi-zone airflow modeling package that allows detailed description of building characteristics and operating conditions related to airflow, including:

- Airflow paths typically modeled as small leaks that follow a power law relationship between pressure difference and airflow. Airflow paths between interior zones and the outdoor environment can be configured to include wind pressure effects.
- Mechanical ventilation equipment, including fans modeled as fixed-flow devices, or fans following a cubic relationship between pressure rise and airflow.
- Schedules describing the operation of mechanical equipment according to a repeating daily or weekly schedule, or a detailed schedule that can vary over each hour of a year for each device.
- Duct elements including backdraft dampers that exhibit different characteristics for forward and reverse flow.
- Weather data including temperature, windspeed and direction, and barometric pressure.
- Other variables not used in our modeling, including variable airflow paths (representing, for example, operable windows and doors), variable zone temperature (which affects air density), and contaminant release or absorption.

We followed Minnesota code requirements for multifamily buildings to guide the mechanical ventilation rates used in modeling:

- MN Mechanical and Fuel Gas Code Chapter 4 (Ventilation) Section 403 includes requirements that apply to multifamily buildings. Per Table 403.3.1.1, mechanical ventilation for living space is required to provide the maximum of 0.35 air changes/hour or 15 cfm/occupant. For the apartment unit we modeled, the 0.35 air changes per hour requirement is the higher value at 47 cfm. This table also calls for the introduction of 0.06 cfm/ft^2 of outdoor air to public corridors.

- MN Mechanical and Fuel Gas Code Chapter 5 (Exhaust Systems) Section 501.4.1 establishes makeup air requirements for dwellings, based on exhaust flow rates for a vented clothes dryer (if present) and 80 percent of the flow of a second exhaust fan, reduced by an allowance of 0.15 cfm/ft^2 for natural infiltration. The resultant makeup air requirement for our models is 72 cfm when vented dryers are present, and zero when unvented dryers are used.
- MN Residential Energy Code section R403.5 applies to apartment buildings up to 3 stories. Section R403.5 requires balanced mechanical ventilation and sets a required continuous ventilation of 0.02 cfm/ft^2 plus 15 cfm/occupant, and allows continuously operating systems to be sized to 50% of the calculated value but not less than 40 cfm.

Field air-leakage measurements for a sample of new multifamily properties included in a recent DOE-funded code-compliance study (Ecotope 2020) were used to develop air leakage estimates used in the modeling. Empirical data collected as part of a recent field study of two 6-unit buildings in Chicago (Slipstream 2021) were used to simulate dryer operation. Actual dryer-operation data for the 10 units in that study with clothes dryers were randomly assigned to units in the model, and randomly varied slightly in time. We modeled the presence of backdraft dampers for outdoor-air inlets and dryer vents, with provisions for a small degree of leakage in the reverse direction.

Table 13 summarizes the modeling inputs. We used a simulation timestep of 3 minutes, with results reported at hourly intervals.

Table 13. Multifamily ventilation modeling inputs for 3- and 6-story buildings

Model component	Values used
Size of each apartment	950 sq ft x 10 ft floor to floor height
Building volume per floor (8 apartment units, stairwell, elevator shaft, and corridor)	85,120 cu ft
Leakage rate: exterior building envelope	0.180 cfm/sq ft @ 50 Pa
Leakage rate: apartments to adjacent apartments (applies to both walls and floors)	0.123 cfm/sq ft @ 50 Pa
Leakage rate: apartments to common areas	0.150 cfm/sq ft @ 50 Pa
Leakage through roof plane	0.090 cfm/sq ft @ 50 Pa
Apartment exhaust airflow (each apartment)	40 cfm continuous (3-story) 47 cfm continuous (6-story)
Apartment makeup air strategy and sizing	Passive inlet to return side of air handler, with backdraft damper. Sized for 72 cfm when air handler operates.
Dryer airflow	60 cfm when operating

Model component	Values used
Dryer operation schedule	Varies by apartment, averaging about 1.4 hours per day, based on empirical field data from a separate study.
Corridor makeup airflow (each floor)	45 cfm continuous
Weather data	Minneapolis TMY3

Figure 29 and Figure 30 show the results of the CONTAM analysis in terms of monthly average air exchange rates for the different dryer-venting and air-handler-operation conditions. These were reduced to annual average rates for input into the energy modeling (see Table 15 under Energy Modeling).

Figure 29. Monthly average CONTAM-modeled air exchange for the low-rise model, by modeled condition and level.

Figure 30. Monthly average CONTAM-modeled air exchange for the mid-rise model, by modeled condition and level.

Energy Modeling

Energy modeling was performed in eQuest using Minneapolis TMY3 weather data, with the general envelope and mechanical-system parameters shown in Table 14. The eQuest models were implemented with one zone per apartment unit (Figure 31). The total infiltration and mechanical ventilation rates were set to the average annual estimate air-change-per-hour (ACH) values from the CONTAM analysis (Table 15), with 0.1 ACH arbitrarily allocated to mechanical ventilation for the purposes of the energy modeling.[31] Internal gain-related inputs for the modeled dryers are shown in Table 16. Dryers were modeled as operating according to the daily schedule shown in Figure 32.

Results for the various modeling runs are provided in Table 17 through Table 20.

[31] eQuest requires some amount of mechanical ventilation to be specified, but since the analysis was concerned only with the overall heating and cooling impacts of air exchange—and the CONTAM-based ACH inputs accounted for both mechanical ventilation and natural infiltration—the split in eQuest between the two is not important.

Figure 31. Prototype floor plan with 8 units per floor used for modeling. The low-rise and mid-rise models varied only in the number of floors.

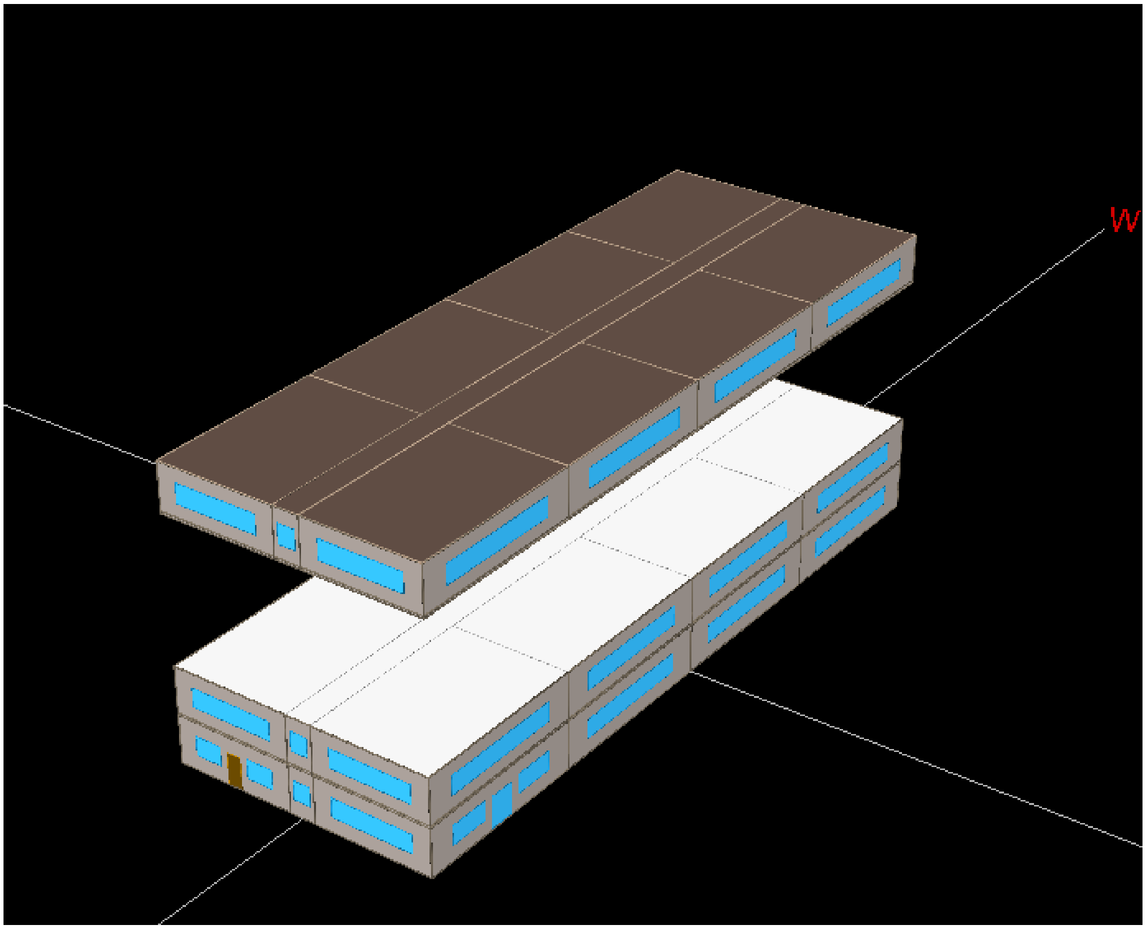


Table 14. Key general modeling inputs

Input assumption	Value
Above-grade wall assembly U-value	0.049
Roof assembly U-value	0.032
Slab-on-grade Foundation insulation R-value	0.010
Window/wall ratio	30%
Window U-value	0.36
Window SHGC	0.4
Heating system efficiency	80%
Cooling system efficiency (EER)	11.2

Table 15. CONTAM-based annual air-change-per-hour (ACH) values used for energy modeling.

Model Prototype	Dryer type	Air-handler mode	Floor	Average annual ACH[a]
3-story	vented	auto	1	0.369
3-story	vented	auto	2	0.224
3-story	vented	auto	3	0.213
3-story	vented	on	1	0.389
3-story	vented	on	2	0.279
3-story	vented	on	3	0.276
3-story	unvented	auto	1	0.348
3-story	unvented	auto	2	0.208
3-story	unvented	auto	3	0.196
3-story	unvented	on	1	0.352
3-story	unvented	on	2	0.262
3-story	unvented	on	3	0.260
6-story	vented	auto	1	0.482
6-story	vented	auto	2	0.310
6-story	vented	auto	3	0.278
6-story	vented	auto	4	0.255
6-story	vented	auto	5	0.239
6-story	vented	auto	6	0.240
6-story	vented	on	1	0.485
6-story	vented	on	2	0.347
6-story	vented	on	3	0.329
6-story	vented	on	4	0.318
6-story	vented	on	5	0.314
6-story	vented	on	6	0.316
6-story	unvented	auto	1	0.460
6-story	unvented	auto	2	0.290
6-story	unvented	auto	3	0.258
6-story	unvented	auto	4	0.236
6-story	unvented	auto	5	0.221
6-story	unvented	auto	6	0.224

Model Prototype	Dryer type	Air-handler mode	Floor	Average annual ACH[a]
6-story	unvented	on	1	0.442
6-story	unvented	on	2	0.324
6-story	unvented	on	3	0.309
6-story	unvented	on	4	0.302
6-story	unvented	on	5	0.301
6-story	unvented	on	6	0.304

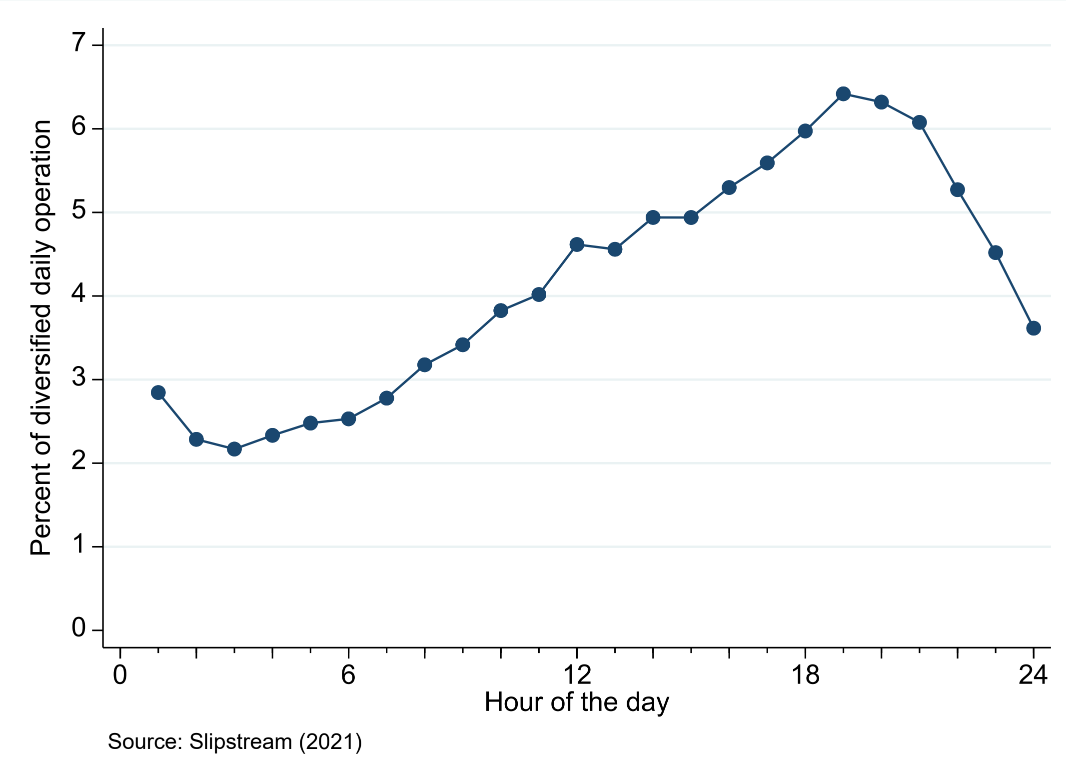
a) Combined effect of mechanical ventilation and natural infiltration

Table 16. Energy modeling assumptions and inputs related to internal gains

Input assumption or *calculated value*	Vented conventional dryer	Unvented compact condensing dryer	Unvented compact heat pump dryer
Dryer loads per year[a]	195	195	195
Average load weight (dry lbs)[a]	8.45	8.45	8.45
Initial moisture content (dry basis)[b]	57.5%	57.5%	57.5%
Dryer kWh per lb removed moisture[b]	0.67	0.67	0.24
Dryer minutes per lb removed moisture[b]	15	20	25
Fraction of dryer heat retained indoors[c]	5%	100%	100%
Minutes per cycle	73	97	121
kWh per cycle	3.255	3.255	1.166
kWh per year	635	635	227
Operating hours per year	237	316	395
Mean dryer operating watts	2,680	2,010	576
Mean dryer operating watts per floor ft^2	2.519	1.889	0.541

a) see Appendix D
b) based on field- and bench-testing results
c) assumed

Figure 32. Diversified daily dryer schedule used for energy modeling.



Results from the various models are provided in Table 17 through Table 20.

Table 17. Modeled energy use and estimated energy costs for low-rise model with auto air-handler operation, by dryer type.

(per year per housing unit)	Vented dryer	Unvented Condensing dryer	Unvented heat pump dryer
Dryer electricity (kWh)	635	635	227
Space heating (therms)	156	139	147
Space cooling (kWh)	1518	1585	1526
Air handler electricity (kWh)	153	151	150
Dryer operating cost	$70.16	$70.16	$25.13
HVAC operating cost	$300.67	$297.44	$295.15
Combined operating cost	$370.83	$367.60	$320.28

Table 18. Modeled energy use and estimated energy costs for low-rise model with continuous air-handler operation, by dryer type.

(per year per housing unit)	**Vented dryer**	**Unvented Condensing dryer**	**Unvented heat pump dryer**
Dryer electricity (kWh)	635	635	227
Space heating (therms)	221	201	209
Space cooling (kWh)	1732	1799	1740
Air handler electricity (kWh)	597	595	595
Dryer operating cost	$70.16	$70.16	$25.13
HVAC operating cost	$418.25	$413.26	$411.62
Combined operating cost	$488.41	$483.42	$436.76

Table 19. Modeled energy use and estimated energy costs for mid-rise model with auto air-handler operation, by dryer type.

(per year per housing unit)	**Vented dryer**	**Unvented Condensing dryer**	**Unvented heat pump dryer**
Dryer electricity (kWh)	635	635	227
Space heating (therms)	166	142	151
Space cooling (kWh)	843	921	871
Air handler electricity (kWh)	111	108	107
Dryer operating cost	$70.16	$70.16	$25.13
HVAC operating cost	$223.18	$216.25	$215.82
Combined operating cost	$293.35	$286.41	$240.95

Table 20. Modeled energy use and estimated energy costs for mid-rise model with continuous air-handler operation, by dryer type.

(per year per housing unit)	**Vented dryer**	**Unvented Condensing dryer**	**Unvented heat pump dryer**
Dryer electricity (kWh)	635	635	227
Space heating (therms)	238	214	223
Space cooling (kWh)	956	1029	982
Air handler electricity (kWh)	580	578	578

(per year per housing unit)	**Vented dryer**	**Unvented Condensing dryer**	**Unvented heat pump dryer**
Dryer operating cost	$70.16	$70.16	$25.13
HVAC operating cost	$336.42	$328.72	$329.04
Combined operating cost	$406.58	$398.88	$354.17

Appendix D: Recommended TRM Adjustments for Clothes Dryers

This appendix provides details on recommended adjustments to the Minnesota Technical Reference Manual regarding savings from efficient clothes dryers, including (but not limited to) heat pump dryers. While the focus here is on electric clothes dryers, some of the proposed adjustments would also affect savings calculations for gas dryers.

Adjustments to the TRM Savings Algorithm

The basic algorithm for clothes dryer electricity use in the most recent version of the Minnesota TRM (3.0) is as follows:

$$\text{Annual kWh} = \text{LOAD} * N_{cycles} / \text{CEF}$$

Where

LOAD is the average load weight (lbs of dry laundry)

N_{cycles} is the average number of dryer cycles per year

CEF is the listed federal energy rating (combined energy factor) for the dryer (lbs of laundry dried per kWh)

Savings are calculated by taking the difference between the calculated energy consumption for a baseline dryer with CEF_{base} and the proposed efficient dryer with CEF_{eff}, while holding *LOAD* and N_{cycles} constant.

The results of this study suggest adjustments to all three of the factors above, which we will discuss in turn, before showing the combined impact on estimated savings in typical use cases.

Combined Energy Factor (CEF)

CEF is at the heart of the savings calculation, as it is the parameter that varies between the assumed base case and the efficient alternative. As with prior studies (Dymond 2018; Horowitz 2011), the field results here indicate that the federal test procedure used to derive CEF ratings for clothes dryers does not do a good job of estimating average real-world energy consumption. In particular, the CEF ratings for standard-size dryers under-estimate energy consumption and the ratings for compact dryers over-estimate consumption. We therefore recommend that an empirical adjustment factor be used in the TRM to account for the bias that is inherent in CEF.

The Dymond and Horowitz studies found actual dryer energy consumption to be 33 to 35 percent higher than indicated by CEF.[32] Because CEF is expressed in terms of pounds of laundry dried per kWh, this

[32] Though both studies tested both full-size and compact dryers, results were not presented separately. The Horowitz study test sample was mostly full-size dryers; the Dymond study looked at pre-existing and three models of heat pump dryers in both full-size and compact configurations.

translates in a CEF adjustment factor of 0.74 to 0.75, which is in reasonable agreement with the 0.70 and 0.64 factors found in this study for full-size conventional and hybrid heat pump dryers, respectively (see Table 7 in the main report). We propose that a 0.70 adjustment factor to CEF be used for full-size dryers.

The bench testing of compact dryers for this study suggests that CEF understates the energy performance of compact dryers, likely because the test procedure uses a laundry load weight of only 3 pounds (more on this later). Compact heat pump dryers typically have a CEF rating of about 6.0 lbs per kWh, but our bench testing suggest a field efficiency of closer to 7.25 (corresponding to a bench-testing average of 0.24 kWh per lb. of removed moisture at an initial moisture content of 57.5%). This suggests a CEF adjustment factor of about 1.2 for compact dryers.

Thus, we propose that the TRM algorithm introduce an empirical adjustment factor, *ADJ*, to be applied to both the baseline- and efficient-model dryer CEF ratings:

$$CEF_{adj\ (base,\ eff)} = CEF_{(base,\ eff)} * ADJ$$

Where

ADJ = 0.70 for full-size dryers

ADJ = 1.2 for compact dryers

All else being equal, this will increase the calculated savings for efficient full-size dryers by 43 percent and decrease the savings for compact dryers by 17 percent.

An alternative approach to the above would be to use the UCEF ratings that are used by utilities in the Pacific Northwest. However, these are only available for a selection of high-efficiency products and for assumed baseline standard-efficiency averages.

Annual Loads (N_{cycles})

The Minnesota TRM uses an assumption of 250 dryer loads per year, based on aggregate reported data from the 2015 Residential Energy Consumption Survey (RECS) published by the Energy Information Agency (EIA). This is somewhat higher than average annual number of loads for the study sample, but lower than other estimates of average number of loads, such as the 283 loads per year used in the federal test procedure calculations (see Figure 6 in the main report).

After reviewing the various estimates as well as the EIA data in some detail, we recommend that a refined estimate derived from the EIA RECS data be employed that accounts for household size for different housing types in Minnesota. To be precise, we recommend that N_{cycles} be based on a RECS-based value of 2.1 loads per week per household member, multiplied by Census-based average household-size estimates for Minnesota households residing in different housing types.

The RECS-based estimate of 2.1 loads per week per household member comes from analysis of the 2015 RECS microdata that allows for direct calculation of this metric for each survey respondent. Nationally, this analysis shows almost no difference in loads per week per person between households in single-family (1.95) and multifamily (2.01) housing, and only moderate variation across the four Census regions (2.03 in the Northeast, 2.10 in the Midwest, 1.97 in the South and 1.76 in the West). We recommend using the Midwest value of 2.10.

Applying the above to Census data on average household size by housing type and vintage yields various estimates of dryer loads per year shown in Table 21.

Table 21. Household size and estimated annual clothes dryer loads.

Housing Type	Average MN Household Size[a]	Dryer Loads per Year (N_{cycles})[b]
Any	2.44	265
Single-family (any)	2.62	285
Single-family (new construction[c])	3.19	350
Multifamily (any)	1.71	185
Multifamily (new construction[c])	1.76	195

a) From 2014-2018 Census ACS PUMS data
b) Based on 2.1 dryer loads per week per person, annualized and rounded to the nearest 5.
c) For Census ACS respondents in homes built in 2010 or later.

We recommend that the single-family based values for N_{cycles} be used for full-size dryers and the Multifamily-based values be used for compact dryers, as the natural market for the two dryer types tends to be split along these lines. As warranted, the new-construction-based values could be used for new-construction programs.

All else being equal, the effect of the recommended adjustments to N_{cycles} is to increase the savings for full-size dryers by 14 to 40 percent and decrease the savings for compact dryers by 22 to 26 percent.

Average Laundry Weight (LOAD)

The Minnesota TRM algorithm uses the load weights specified in the federal test procedure: 8.45 pounds for full-size dryers and 3 pounds for compact dryers.[33] The 8.45 lb value used for full-size dryers closely matches what we observed in our field study, and is comparable to what others have observed, so we do not recommend a change to that value.

[33] Per the federal test procedure, these are bone-dry weights. In practice, most laundry loads come out of the dryer with a small amount of moisture that increases the weight by a percent or two.

However, the 3-lb value used for compact dryers appears to be unrealistic. We recommend instead using 8.45 pounds for compact as well as full-size dryers. In the absence of direct field data on load weights for compact dryers from our study, our rationale for this recommendation is as follows:

- The RECS data show that households with clothes dryers in multifamily housing (where most compact dryers are found) dry the same number of loads per week per person as households in single-family homes. It seems implausible that households in multifamily settings dry the same number of loads per person but only about 1/3 the total laundry weight as households in single-family settings.
- The Dymond (2018) study looked at load weights in 9 units in one apartment building with compact dryers and found an average of 6.7 lbs per load.
- Most compact dryers can easily accommodate 14 to 18 pounds of laundry, so inadequate capacity is not an issue with compact dryers as they are defined by the federal standard. As noted in the main report, 95 percent of the loads dried in the full-size field-study dryers would readily fit in a compact dryer.

All else being equal, the effect of this adjustment would be to increase the savings for compact dryers by a factor of 2.82 (282%). There would be no effect on savings for full-size dryers.

Combined Impact On Savings

Combined, the effect of these adjustments would be to increase the estimated savings for efficient full-size dryers by 63 to 100 percent. The impact on compact clothes dryers would be an increase of 74 to 83 percent. These differences would apply to both non heat-pump and heat-pump dryers.

Interaction Between Clothes Dryers and Clothes Washers

Clothes washers and dryers are often purchased as matched pairs, and there are interaction effects when an efficient washer is purchased with an efficient dryer. Most of the savings from efficient clothes washers actually occurs in the dryer due to the washer's ability to wring more moisture out of the clothing before it goes in the dryer. This makes the savings from an efficient dryer less than would be the case if drying laundry from a standard washer. Conversely, dryer savings predicated on the moisture content in laundry from a standard washer will be overstated if a high-efficiency washer is employed.

However, calculations by researchers in the Pacific Northwest suggest that, at worst, the error in the combined savings would be on the order of 12 percent for failing to account for this interactive effect (RTF 07/18/2017), so it may not be worth introducing the complexity associated with the interaction.

Indirect Space-Conditioning Impacts

As described in the main report, there are space-heating savings and space-cooling penalties associated with replacing conventional vented dryers with ventless models, including heat pump dryers. Our calculations suggest about 15 therms per year of space-heating savings both for single-family homes with a full-size hybrid dryer and compact heat pump dryers in multifamily settings and a net increase of about 25 kWh in electricity associated the space-cooling penalty during the summer less some furnace electricity savings during the winter.

If indirect space-conditioning impacts are deemed worth of inclusion, the values above should be adjusted to reflect the fact that not all dryers in single-family homes are located in fully-conditioned spaces. Dryers for eight of the 11 field-study sites were in basements (see Table 12 on Page 92), but most of those were finished basements and presumably conditioned. In the absence of better data, an adjustment factor of 0.7 to account for 30 percent of dryers being located in spaces that do not yield indirect HVAC impacts would seem reasonable.