Do Heat Pump Clothes Dryers Make Sense for the U.S. Market?

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ABSTRACT

Heat pump clothes dryers (HPCDs) can be as much as 50% more energy-efficient than conventional electric resistance clothes dryers, and therefore have the potential to save substantial amounts of electricity. While not currently available in the U.S., there are manufacturers in Europe and Japan that produce units for those markets. Drawing on analysis conducted for the U.S. Department of Energy's (DOE) current rulemaking on amended standards for clothes dryers, this paper evaluates the cost-effectiveness of HPCDs in American homes, as well as the national impact analysis for different market share scenarios. In order to get an accurate measurement of real energy savings potential, the paper offers a new energy use calculation methodology that takes into account the most current data on clothes washer cycles, clothes dryer usage frequency, remaining moisture content, and load weight per cycle, which is very different from current test procedure values. Using the above methodology along with product cost estimates developed by DOE, the paper presents the results of a life-cycle cost analysis of the adoption of HPCDs in a representative sample of American homes. The results show that HPCDs have positive economic benefits only for households with high clothes dryer usage or for households with high electricity prices and moderately high utilization.

Introduction

Currently, residential electric clothes dryers consume about 71 TWh/year in the U.S. or approximately 4% of total annual residential electricity use (USDOE EIA 2010). Residential electric clothes dryer shipments were 5.6 million in 2008 (AHAM 2008a). 67.2 million U.S. households (or about 60%) have an electric clothes dryer (USDOE EIA 2009a). Residential gas clothes dryers have a significant market share, but are not part of this study.[1]

Heat pump dryers were first developed in Europe by Electrolux in 1997. In 2007, there were at least three European HPCD manufacturers (Electrolux, Arcelik, and Schulthess) along with one Japanese manufacturer (Panasonic). As of 2009, Schulthess has stopped producing its heat pump model, but additional manufacturers (such as Bosch-Siemens, Miele, and Metall Zug AG) now also produce heat pump models (Topten 2010). Currently there are 25 models in the European market.[2] The market share of heat pump clothes dryers in Europe was about 4% in 2009 or about 200,000 shipments per year (out of 4.9 million total clothes dryer sales). The European countries with the largest market share are Switzerland (15.6% market share) and Italy

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[1] Residential gas clothes dryers consume 0.07 Quads of natural gas (or 1.5% of total residential natural gas use). Shipments of gas clothes dryers where 1.3 million in 2008. About 20.2 million (or 18%) households have a gas clothes dryer.

[2] Some of the models appear to be duplicates (e.g. the Siemens and Bosch models are probably the same model as well as the Electrolux and AEG models).

(11% market share). Industry experts in Europe project that HPCDs should continue to gain market share in the next few years. There are no HPCD models currently available in the U.S. market.

Equipment Characteristics

The operation principle of heat pump clothes dryers is illustrated in Figure 1. The heat pump is a mechanical system consisting primarily of a refrigeration loop containing a refrigerant vapor compressor, an evaporator (a type of heat exchanger), a condenser (another heat exchanger) and an expansion device (valve). The clothes dryer heat pump component is shown as "1" on Figure 1.

Figure 1. Heat Pump Clothes Dryer Diagram[3]
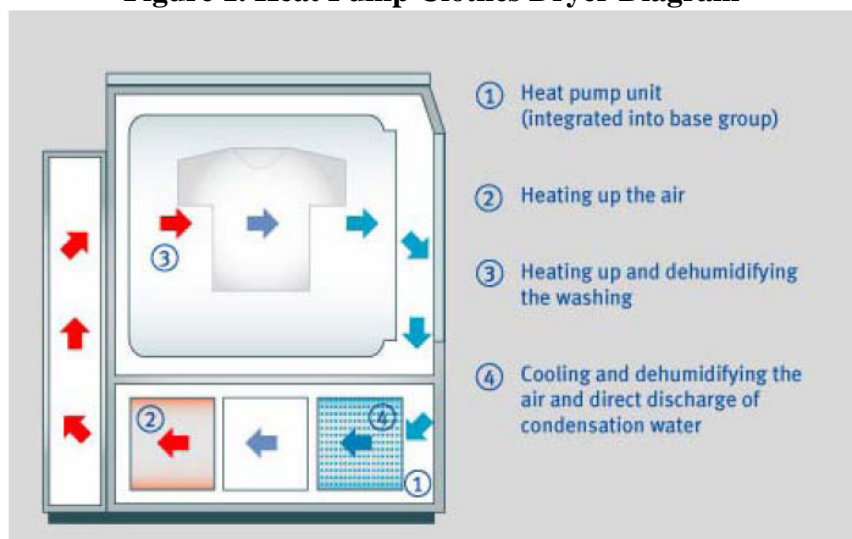
A heat pump delivers heat by extracting energy from the ambient air. The hot dry processed air enters the rear of the drum and interacts with the laundry. Warm moist air exits the drum and proceeds through the lint screen and through the evaporator where a significant portion of the moisture is removed before flowing through the condenser and back into the drum.

Since the evaporator removes the majority of the moisture present in the air exiting the drum, this air can be re-circulated back into the drum. However, in steady state operation the heat pump delivers more heat than cooling so some form of heat rejection is needed. For vented heat pump clothes dryers, the excess heat is vented out.

Heat pump technology can be applied to both vented and ventless (condensing) clothes dryers. All available models in Europe are ventless (Topten 2010). Currently there are no manufactured vented HPCD models, but it is technically feasible to develop such technology based on the development of a prototype by TIAX for Whirlpool (Pescatore 2005).

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[3] http://www.schulthess.ch/en/innovations/heat-pump-dryer.html

Methodology

To assess the economics of HPCDs for U.S. consumers, we conducted an analysis for a representative sample of U.S. homes. We evaluated the economics of HPCDs by calculating the life-cycle cost (LCC) and the payback period (PBP) of purchasing and operating a HPCD compared to a baseline electric clothes dryer. The baseline product represents the most commonly-purchased product today. National economic impacts are evaluated by calculating National energy savings and net present value for differing HPCD market share scenarios,

General Approach for LCC and PBP Analysis

The LCC is the total consumer expense over the life of an appliance, including the total installed price and operating costs (fuel, maintenance, and repair costs). Calculation of LCC discounts future operating costs to the time of purchase, and sums them over the lifetime of the product. The PBP is the amount of time it takes the consumer to recover the estimated higher purchase expense of more energy-efficient products as a result of lower operating costs. Numerically, the PBP is the ratio of the increase in purchase expense from a less energy-efficient design to a more energy-efficient design to the decrease in annual operating expenditures. This "simple" payback period does not take into account changes in operating expense over time or the time value of money.

DOE Energy Information Administration (EIA)'s 2005 Residential Energy Consumption Survey (RECS) is used to develop a nationally-representative sample of households that use clothes dryers (USDOE EIA 2009a). RECS 2005 data shows that there are 67.2 million households that use electric clothes dryers. Our analysis assumed that a HPCD would not replace a gas clothes dryer because the gas clothes dryer is significantly less expensive to operate.

The LCC and PBP analysis is conducted by modeling both the uncertainty and variability of the inputs using Monte Carlo simulations and probability distributions. LCC and PBP spreadsheet models incorporating both Monte Carlo simulation and probability distributions were developed by using Microsoft Excel spreadsheets combined with Crystal Ball (a commercially available add-on to Excel).

Derivation of Inputs

Consumer price. Manufacturer costs were developed in the engineering analysis of DOE's current rulemaking on clothes dryer standards (USDOE EERE 2010). In the engineering analysis, DOE evaluates a range of product efficiency levels and their associated manufacturing costs. DOE typically structures its engineering analysis around one of three methodologies: (1) the design-option approach, which calculates the incremental costs of adding specific design options to a baseline model; (2) the efficiency-level approach, which calculates the relative costs of achieving increases in energy efficiency levels without regard to the particular design options used to achieve such increases; and/or (3) the reverse-engineering or cost-assessment approach, which involves a "bottom-up" manufacturing cost assessment based on a detailed bill of materials derived from tear-downs of the product being analyzed.

DOE determined in the preliminary analysis that the efficiency-level approach was the most appropriate for clothes dryers. The efficiency levels that DOE considered in the engineering analysis are attainable using technologies currently available in residential clothes dryers, or

have been demonstrated in working prototypes. In addition, DOE associated each efficiency level with specific technologies that manufacturers might use. Chapter 5 of the preliminary Technical Support Document (TSD) describes the methodology and results of the efficiency level analysis used to derive the cost-efficiency relationships (USDOE EERE 2010).

By applying estimated manufacturer markups to the manufacturer production costs (MPCs), DOE calculated the manufacturer selling prices (MSPs). After establishing appropriate distribution channels for clothes dryers, we relied on economic data from the U.S. Census Bureau and other sources to define how prices are marked up as the products pass from the manufacturer to the consumer. The overall markup is the value determined by multiplying the manufacturer and other markups and the sales tax together to arrive at a single markup value. The markup methodology assumes lower overall markup for higher efficiency equipment, because some distribution costs do not increase with increased efficiency.

Table 1 shows the estimated consumer cost for the considered clothes dryers. For comparison, the cost of a ventless HPCD in Europe ranges from $1,000 to $3,500 (note that ventless dryers are generally more expensive than vented dryers, however). Since DOE analyzes efficiency levels as candidates for minimum efficiency standards, its analysis of manufacturer costs for HPCDs assumed a high level of production of such products.

Table 1. Clothes Dryers Estimated Average Product Costs

Product	Baseline Integrated Energy Factor (lb/kWh)	Average Manufacturing Production Cost (2008$)	Average Product Cost (2008$)
Vented, Electric, Standard—Baseline	2.96	$222	$433
Vented, Electric, Standard—Heat Pump	4.52	$481	$833

Installation cost. No evidence was found that installation costs would be different between heat pump clothes dryers and baseline electric clothes dryer.

Energy use calculation. We used the approach outlined in the DOE's test procedure (USDOE EERE 1997) to calculate the energy use of the clothes dryer. For each record in the household sample, we determined the annual energy use of the clothes dryer by multiplying the number of cycles per year by the energy use per cycle.

Clothes dryer cycles. We estimated the number of clothes dryer cycles per year for each sample household using data given by RECS on the number of laundry loads washed (clothes washer cycles) per week and the frequency of clothes dryer use. The laundry loads data in RECS fall into one of the bins shown in **Tables 2** and **3**. For the number of loads washed and clothes dryer usage in RECS, DOE assumed a uniform distribution within the boundaries of each bin and randomly assigned a value from within the appropriate range to each sample household.

Table 2. Number of Loads Washed per Week Based on RECS Sample

Bin	Loads per Week	Derived Loads per Year*	
		Min	Max
1	1 load or less	0	78
2	2 to 4 loads	78	234
3	5 to 9 loads	234	494
4	10 to 15 loads	494	806
5	More than 15 loads	806	1118

* The ranges reflect the inclusion of values in between the given bin boundaries. Boundaries are derived by multiplying minimum and maximum values for each bin by 52 weeks. To have a continuous distribution minimum and maximum values are expanded by half a load (e.g. bin #2 goes from 1.5 to 4.5 loads/week).

The resulting average number of clothes washer cycles/year from RECS data in **Table 3** is 301 cycles/year. It differs from the DOE's clothes washer test procedure assumption (392 cycles/year)[4]. It is important to note that the last update of the clothes washer test procedure was in 1990s. Since then RECS data (USDOE EIA 2009c) shows steady decline in the number of clothes washer cycles. Recent Proctor & Gamble survey data (P&G 2008) supports these findings. The changes in clothes washer usage are primarily due to the increase in tub size (from 2.6 cu. ft. in 1990 to 3.2 in 2008 (AHAM 2008b)), as well as a decrease in the number of people per household with a clothes washer (from 2.8 in 1990 to 2.6 in 2005 (USDOE EIA 2009c)).

Table 3. RECS Sample Clothes Dryer Usage

Bin	Description	Fraction of Washer Cycles When Dryer is Used	
		Min	Max
1	Use it every time wash clothes	1	1
2	Use it for some, but not all, loads of wash	0.50	1
3	Use it infrequently	0.00	0.50

The resulting average clothes dryer frequency of usage is 0.95, which represents the fraction of dryer loads to washer loads.

Figure 2 shows the resulting household distribution of clothes dryer cycles/year. The results indicate the average annual number of clothes dryer cycles is 285 cycles/year, and more than 85% of the households use below 500 cycles/year.

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[4] DOE is currently revising its test procedures for both clothes dryers and clothes washers (USDOE EERE 2008).

Figure 2: Distribution of Number of Dryer Cycles per Year
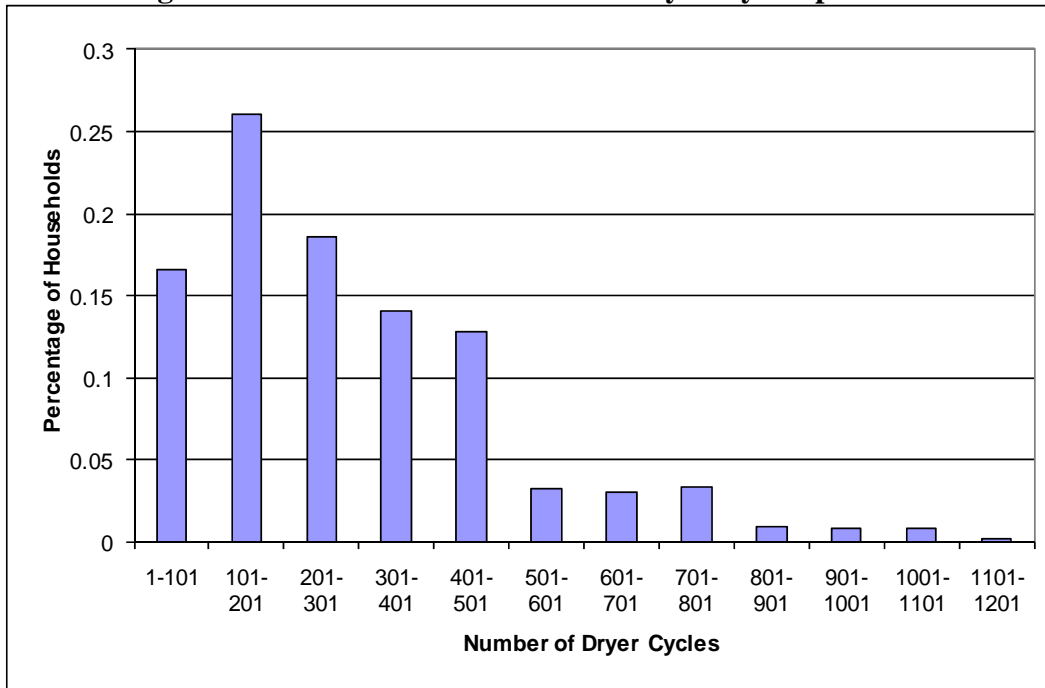
The average number of clothes dryer cycles (285 cycles/year) estimated from RECS data is well below the value used in DOE's test procedure (416 cycles/year). Our estimate represents more current consumer usage of the clothes dryers in the U.S., while DOE's test procedure for clothes dryers has not been updated since the 1980s and reflects the usage at that time.

Energy use per cycle. For the baseline clothes dryer and for HPCD, field energy use was derived by separately estimating the active mode and standby mode energy use and then adding them together. The DOE test procedure calculates active mode energy consumption by dividing the weight of clothes dried per cycle (7 lbs) by the Energy Factor (EF) (lbs/kWh).[5] DOE adjusted the test procedure energy use to reflect field conditions by accounting for clothes dryer load weight and moisture removal factor.

For each household, the field adjustment for clothes dryer energy use during active mode was determined by using the following formula:

$$CD\_EnergyUse_{ActiveMode} =$$

$$\left[\left(\frac{avgLoadWeight_{TP}}{EF} - 0.5kwh\right) * \left(\frac{avgLoadWeight_{Field}}{avgLoadWeight_{TP}}\right) * \left(\frac{RMC_{Field} - 5\%}{RMC_{TP} - 5\%}\right) + 0.5kwh\right] * CD\_Cycles$$

Where:

$avgLoadWeight_{TP} =$ average load weight in the test procedure, lbs,
$avgLoadWeight_{Field} =$ average load weight for each household, lbs,
$0.5kwh =$ average energy use required to heat air and metal regardless of load, kWh

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[5] Energy Factor is the ratio of the weight of clothes washed (lbs) to the energy used in washing them (kWh).

RMC_{TP} = remaining moisture content in the test procedure, %,
RMC_{Field} = remaining moisture content for the household, %,
5% = remaining moisture content at the end dryer cycle,
EF = efficiency of the clothes dryer during active mode, lbs/kWh, and
CD_Cycles = clothes dryer cycles per year.

To assign an average load weight for each household, we developed a distribution of load weights by matching the listed drum sizes for models in the California Energy Commission (CEC) directory (CEC 2008) with the correlations between drum and load weight in the DOE test procedure. The average load weights for standard-size units range from 5.1 lbs to 10 lbs, with a mean value of 8.1 lbs. For comparison, the DOE test procedure uses a weight of 7 lbs for standard-size units.

To assign a remaining moisture content (RMC) value for each household, DOE used a distribution of values based on the number of models in the CEC directory. The RMC values range from 30% to 61%, with an average of 46%. (The RMC in the test procedure is on average 70%.)

Using the above approach, a unique value for the clothes dryer annual energy consumption for each sample household with an electric clothes dryer is calculated using the number of dryer cycles.

For each household, the field-adjusted clothes dryer energy use during standby mode is determined by using the following formula:

$$ClothesDryerEnergyUse_{Standby} = \left[8760 - CD\_Cycles * \left(\frac{CD\_Time}{60} \right) \right] * Standby\_Power$$

Where:

8760 = number of hours in one year, hrs,
CD_Time = clothes dryer time to complete one cycle, min/cycle,
60 = number of minutes in one hour, min/hr,
Standby_Power = standby power, kW, and
CD_Cycles = clothes dryer cycles per year.

To derive the number of standby hours, the clothes dryer is assumed to take on average 60 minutes to complete a cycle (Pescatore 2005; Hekmat 1984; PWC 2008). Standby power is assumed to be 2 W for the baseline unit and 0.08 W for the HPCD.

Estimated energy use. The estimated average annual energy use is 538 kWh for the baseline dryer and 361 kWh for the HPCD. For the baseline, the value is well below the 1,000 kWh consumption estimated by the DOE test procedure (USDOE EERE 1997), AEO 2010 (USDOE EIA 2010), and RECS 2005 (USDOE EIA 2009a). The key reasons for the lower energy use estimated are the reduction in clothes dryer cycles and lower RMC.

Energy costs. Annual energy costs for the considered clothes dryers for each sample household are derived by multiplying the estimated annual energy use by average annual energy prices. Using data from EIA (USDOE EIA 2009b), the average residential electricity prices in 2008 for each of 13 geographic areas (the nine U.S. Census Divisions and four largest States (California,

Florida, New York, and Texas)) is derived separately.[6] Price forecasts from EIA's *Annual Energy Outlook 2010* (*AEO2010*) (USDOE EIA 2010) are then used to estimate future trends in electricity prices. To project future prices, the average prices described above are multiplied by the forecast of annual average price changes in *AEO2010*.

Repair and maintenance costs. The maintenance cost and the repair cost cover all labor and material costs associated with the maintenance or repair. The determination of the repair cost involves determining the cost and the service life of the components that are likely to fail. No evidence was found that repair and maintenance costs would be different for baseline and HPCDs.

Product lifetime. The product lifetime is the age at which the product is retired from service. RECS equipment age, shipments, and electric clothes dryer stock data is used to estimate the distribution of clothes dryer lifetimes in the field.[7] The estimated average lifetime is 16 years; the minimum and maximum lifetimes used in the distribution are 5 and 30 years, respectively.

Discount rates. The approach for deriving discount rates for the LCC analysis involved identifying all possible debt or asset classes that might be used to purchase replacement products, including household assets that might be affected indirectly. The resulting average rate across all types of household debt and equity is 5.1%.

National Impact Analysis

Using the LCC and PBP inputs, we estimated the national level impacts that would result from higher market penetration of HPCDs. The NIA calculates the national energy savings at the site level for different HPCD market share scenarios and then uses conversion factors from AEO 2010 to convert site savings to primary energy savings.[8] The NIA also calculates the net present value for consumers as the difference between the value of operating cost savings and the total incremental installed costs for HPCDs.

Results

Table 4 shows the national results for a HPCD compared to baseline electric dryer. Based on the analysis assumptions, only 12% of households have an LCC benefit. The median payback is 26 years, which exceeds the average lifetime of the HPCD.

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[6] For Census Divisions containing one of these large States, DOE calculated the regional average values leaving out data for the large State—for example, the Pacific division average does not include California.

[7] See chapter 8 of the clothes dryer preliminary TSD (USDOE EERE 2010).

[8] Site energy is the amount of heat and electricity consumed on site by a building as reflected in utility bills. Primary energy is the raw fuel that is burned to create heat and electricity, such as fuel used to generate electricity at a power plant, plus other losses in producing and transporting the fuel and electricity.

Table 4. LCC and PBP Results for Heat Pump Clothes Dryers: National

Product (EF)	Life-Cycle Cost (2009$)			Life-Cycle Cost Savings			Payback Period	
	Average Installed Price	Average Lifetime Operating Cost*	Average LCC	Average Savings (2009$)	Households with		Median (years)	Average (years)
					Net Cost	Net Benefit		
Baseline (3.01)	$552	$638	$1,190	--	--	--	--	--
Heat Pump (4.55)	$953	$428	$1,381	-$191	88%	12%	26	37

* Discounted

The LCC benefits are sensitive to clothes dryer utilization. Average LCC savings become positive with utilization over 700 cycles per year. However, only 6% of the sample households have utilization this high (see **Figure 3**). In addition the LCC benefits are sensitive to electricity prices. For regions with high electricity prices (e.g., the Northeast and California), the LCC savings become positive at about 500 cycles/year.

Figure 3: LCC Savings by Number of Dryer Cycles per Year
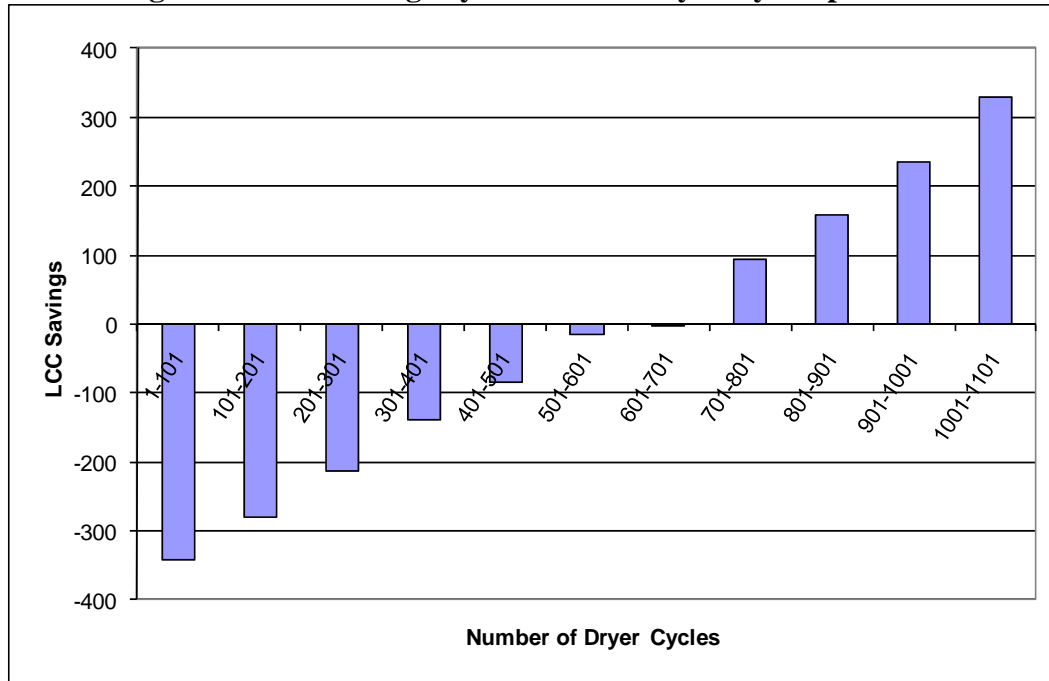
The net energy savings (NES) and consumer net present value (NPV) results for different market share scenarios for HPCDs are shown in **Table 5.** These values represent the national impacts from the substitution of new baseline clothes dryers purchased in 2011-2020 with HPCDs. Total clothes dryer shipments over this period are projected to be 66.2 million. Because HPCDs are most likely to be purchased by consumers for whom they are most cost-effective, we assume that each HPWH market share level is met by the households with the highest LCC savings. For example, the 5% market share level includes households having LCC savings in the 95th percentile and above, while the 20% market share level includes households having LCC savings in the 80th percentile and above.

Table 5. National Impact Analysis Results from 2011-2020

Market Share of HPCD Shipments	National Energy Savings Quads	National Present Value (Billion, 2008$)
5%	0.064	0.41
10%	0.116	0.47
15%	0.162	0.42
20%	0.205	0.31
25%	0.244	0.10
100%	0.544	-9.86

Discussion

The product cost estimates used in our analysis assume a high level of production. Annual production of 1 million units would be roughly 20% of the electric clothes dryer market. Using our analytical framework, it would require a product cost of approximately $740 (11% less than the cost used in our analysis) for HPCDs to be cost-effective for 20% of the sample households. However, the fact that the HPCD is cost-effective in the framework of this analysis does not mean that all of those households will actually purchase the appliance. There is ample evidence that various factors cause households to pass up purchases that appear cost-effective from the analyst's perspective. Therefore, for HPCDs to achieve a 20% market share, the product cost would likely have to be well below $740.

The study did not include a comparison of the economics of HPCDs or baseline electric resistance clothes dryers to gas clothes dryers or other technologies which might be more efficient and cost-effective to some households.

Conclusion

To estimate the cost-effectiveness of HPCDs in U.S. homes, this study utilized recent data on the annual number of clothes dryer cycles and remaining moisture content (RMC) conditions, two key factors that influence clothes dryer energy use. For the annual number of clothes dryer cycles we used 285 cycles/year which is about 30% lower than the number of cycles assumed in the clothes dryer test procedure. This is somewhat compensated by the higher load weight of 8 pounds per load, which is about 15% higher than in the test procedure. For RMC we used on average 42% which is about 40% lower than the RMC value assumed in the clothes washer test procedure (70%). In both cases, these values are significantly lower than the assumptions used in the DOE clothes dryer test procedure, and are a key factor for the lower energy savings for a HPCD.

While HPCDs are much more energy-efficient than conventional electric resistance clothes dryers, the significant increase in product cost is not recouped through reduced operating expenses for most of the households. The national impact of a 25% market penetration rate for HPCDs is 0.244 Quads of source energy savings, which is almost half of the total source energy savings from a 100% market share penetration. Further, market share scenario up to 25% resulted in a positive economic benefit to the United States.

Further, this study found that even with a product cost that assumes a high level of production, HPCDs are cost-effective for only a small share of U.S. households. We estimate

that it would require a product cost of approximately $740 (11% less than the cost used in our analysis) for HPCDs to be cost-effective for 20% of the sample households. However, for HPCDs to achieve a 20% market share would likely require a product cost well below $740. Whether further development of the technology could yield such a cost is uncertain.

In this paper we looked at vented heat pump clothes dryers only. The European models are all ventless. Based on the current DOE study (USDOE EERE 2010), the economics of ventless HPCDs are likely to be less negative than for the vented HPCDs. Although ventless clothes dryers represent less than 1% of the current U.S. market, there is potential for growth in the market share of this product.

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