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An Exploration of Innovation and Energy Efficiency in an Appliance Industry

Prepared by
Margaret Taylor, K. Sydny Fujita, Larry Dale, and
James McMahon

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Abstract

This report provides a starting point for appliance energy efficiency policy to be informed by an understanding of: the baseline rate and direction of technological change of product industries; the factors that underlie the outcomes of innovation in these industries; and the ways the innovation system might respond to any given intervention. The report provides an overview of the dynamics of energy efficiency policy and innovation in the appliance industry, introduces the competitive framework of this industry (which includes an important role for government), defines and discusses the processes and outcomes of innovation in this context, and frames the dilemmas facing energy efficiency policy-makers when considering innovation. The report also provides details of research design and first-order results of a pilot study to empirically and systematically assess the inputs, outputs, and conduct of innovation involved in a case appliance (refrigerators). The results, which have been analyzed at a first-order, speak to the high concentration of the industry, the stability of the market positions of leading firms in the industry, the similarity between the market share and intellectual property positions of the leading firms, the growing importance of R&D in the appliance industry and in refrigerator development (although there is an indication that the industry lags the best practices of comparable industries and firms of similar size), the gradual decline of innovation focus on the energy aspects of refrigerators, and the diversity of the leading firms with respect to their capability to assimilate knowledge. The pilot study itself is novel in attempting to build an initial bridge between long-standing concepts in the innovation literature, such as the resource-based-view of the firm, dynamic capabilities, absorptive capacity, etc., and issues in the energy efficiency policy arena.

Keywords

Innovation, energy efficiency, policy, technological change

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I. Introduction to Innovation and Energy Efficiency Policy

Reducing greenhouse gas emissions to the levels needed to achieve climate stabilization – currently believed to be at least an 80% reduction by 2050 in developed nations – will require many industries to undergo very rapid technological change directed toward sustainability. As fast-paced but sustainable technological change is not an inherent condition of industrial growth for several reasons grounded in economic theory, policy will need to help support it if a stable climate is going to be achievable. Effective policy interventions will need to be informed by an understanding of: the baseline rate and direction of technological change of climate-relevant industries; the factors that underlie the outcomes of innovation in these industries; and the ways the innovation system might respond to any given intervention.

Recent back-casting studies of the technological pathways necessary to reach climate stabilization emphasize that significant gains in energy efficiency are fundamental (e.g., Williams, DeBenedictis et al. 2012). Appliances and buildings are the two industries most closely tied to energy efficiency goals; the appliance industry is the focus of this study.

This report will provide an overview of the dynamics of energy efficiency policy and innovation in the appliance industry. As the innovation process related to energy efficiency in this industry is relatively understudied, particularly when compared to other clean energy domains like renewable energy and advanced vehicles, this report also provides details of research design and first-order results of a pilot study to empirically assess the inputs, outputs, and conduct of innovation in a single appliance ”product.”

The rest of this section introduces the competitive framework of the appliance industry (including the role of government), defines and discusses the processes of innovation and the outcomes of innovation in the context of appliance energy efficiency, and frames the dilemmas facing energy efficiency policy-makers when considering innovation.

The Appliance Industry and Innovation

As mentioned above, the appliance industry is the focus of this study. It should be noted, however, that this industry contains many smaller industries that are focused on specific “products” like refrigerators, air conditioners, etc.

The appliance industry develops in response to traditional competitive forces. Figure 1 illustrates the general forces of competitive rivalry in a model appliance product industry, using a framework that is widely used in business strategy (Porter 1979; Porter 1980). In this framework, the forces of competitive rivalry include: the threat of new entrants; the threat of substitute products; the determinants of supplier power; and the determinants of buyer power. Note that the structural conditions of industry are strongly determined by government actions in this framework. Government actions: can form a barrier to entry or even exit in an industry; can affect the relative positions of an industry’s suppliers and buyers or perform the function of supplier or buyer itself; can affect the relative positions of substitutes vis-à-vis existing firms; and can affect rivalry among existing competitors (see Porter 1980).

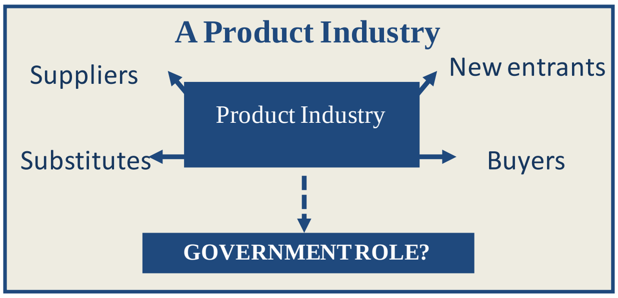

Figure 1: Forces of competitive rivalry in the industry built around a model appliance product

Beyond government's structural effects on the appliance industry, it has a strong effect on the industry's focus on the energy efficiency aspects of product design. Energy efficiency policy instruments that currently affect the global appliance industry include minimum efficiency performance standards (MEPS), top-performer labelling, public procurement, and subsidies (for more detail, see Nadel 2002; Gillingham, Newell et al. 2006). In order to function effectively, the top-performer labelling and MEPS instruments, in particular, require analysis of the overall distribution of products that are currently commercially available in the marketplace, as well as upstream technology developments that have the potential to affect this product mix during the regular updating cycle for these instruments (note that top-performer labelling highlights leading technologies while MEPS cuts off laggard products from the marketplace).

Figure 2 provides an illustration of the importance of the time dynamic for both innovation and policy in the context of energy efficiency. In this figure, a model product remains static regarding its energy efficiency performance while its competitor products and the related MEPS change over time. In each time period, the figure shows a distribution of products with different efficiencies. The sample product, in this case a refrigerator model, is a star-performer in the initial time period t_0, during which standard$_0$ is set for application in the next time period t_1 (the shaded area shows the share of the distribution of products that will be cut-off as laggard energy-performers when the standard comes into effect in the next time period). In time period t_1, the model refrigerator becomes average for the new distribution of products while standard$_1$ is being set for implementation in the next time period t_2. In time period t_2, the model refrigerator becomes a laggard energy-performer that will be cut off when standard$_2$ comes into effect in the next time period t_3 (not shown).

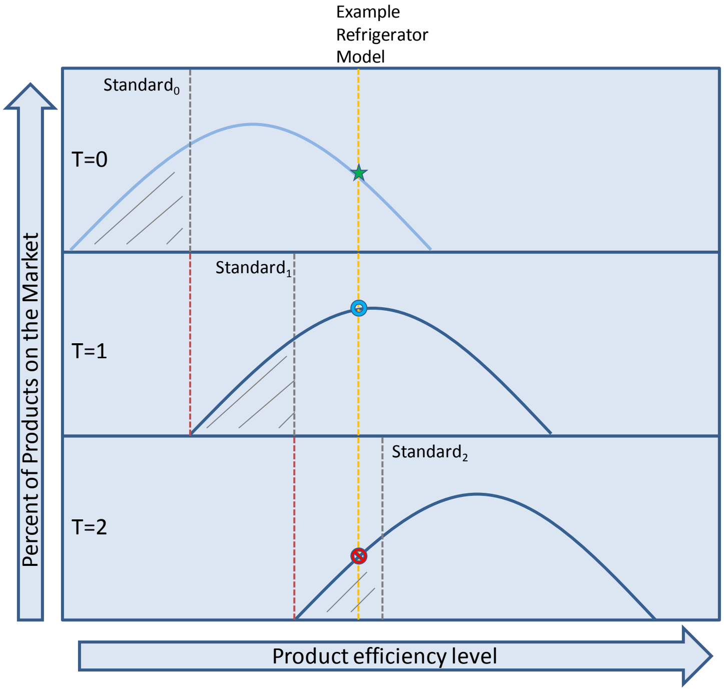

Figure 2: A model product that is locked in place while standards tighten over time.

Processes and Outcomes of Innovation

The factors that would prevent the model product in Figure 2 from remaining static are a set of overlapping innovative activities that are illustrated in the "processes of innovation" in Figure 3. In this figure, the model product industry from Figure 1 is embedded in its competitive framework, with each of its competitive forces a source of innovation for the industry. The firms in the industry have innovative activities defined in published sources (see Schumpeter 1942; Rosenberg 1994; Rogers 1995). In keeping with definitions begun in Schumpeter (1942), “invention,” which is referred to in this paper as “inventive activity,” describes the development of a new technical idea. “An invention is an idea, sketch, or model for a new device, process or system. It might be patented or not, it might lead to innovation or not” (Clarke and Riba 1998). “Innovation,” which is referred to in this paper as “adoption,” in Schumpeter’s rubric refers to the first commercial implementation of a new invention into the marketplace. “Diffusion” refers to the widespread use of a commercial innovation and is often studied by researchers as a communication process through which future users become persuaded to adopt new technologies, in part due to information from previous users (Rogers 1995).

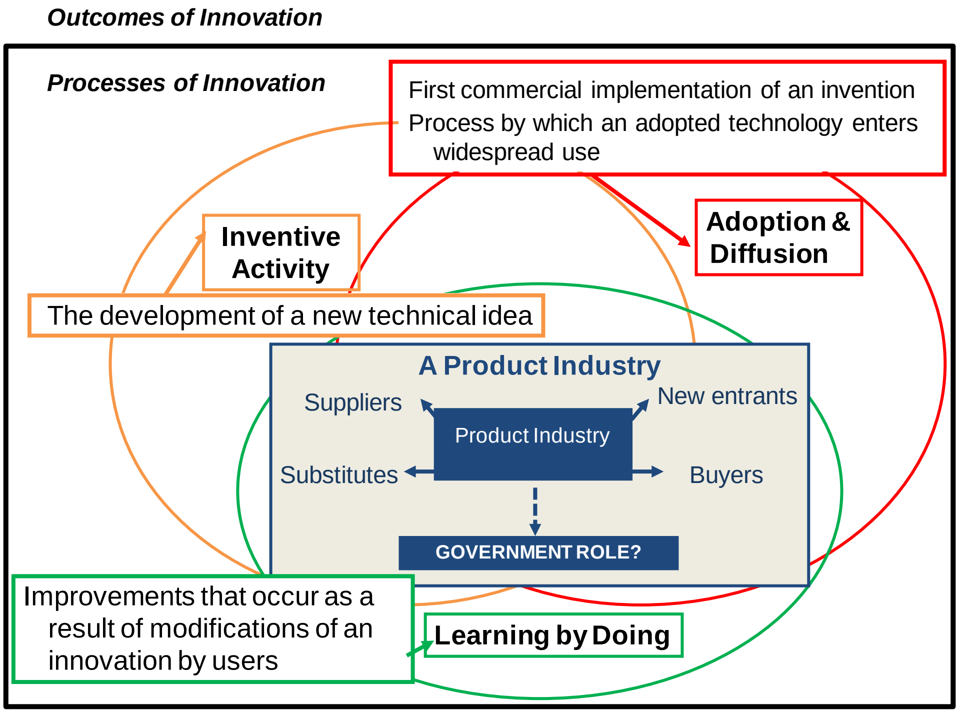

Figure 3: Innovation processes and outcomes in a model product industry

Finally, post-adoption innovative activities that result from knowledge gained from operating experience, such as “learning by using,” “learning by doing,” and “reinvention,” are referred to here as “learning by doing.”[1] Studies have shown that a considerable amount of innovative activity can be traced to these activities (for a discussion, see Cohen and Levin 1989). The basic principle behind learning by doing is that experience creates knowledge that improves productivity (Arrow 1962). An important part of this knowledge, which is acquired through organizational experience, is tacit know-how (see Polanyi 1966; Berry and Broadbent 1984; Nonaka 1991). Technological change attributed to operating experience is often measured through “learning curves,” in which unit costs decrease at a decreasing rate with increasing cumulative output, controlling for time (simlar ratios are also often depicted for performance attributes). As reviewed in (Argote 1999), learning curves have been found in a variety of industries, including those in which discrete products like ships, aircraft, trucks, and semiconductors are produced, as well as in industries in which continuous products like refined petroleum and chemicals are produced.

[1] Learning by doing refers to technological improvements that occur as a result of a user’s modifications of the operations of an adopted innovation in order to correct difficulties or take advantage of opportunities observed during operation (Rosenberg, 1994). Reinvention is “the degree to which an innovation is changed or modified by the user in the process of its adoption and implementation (Rogers, 1995).

The outcomes of the process of innovation (observed to be outside the black box in Figure 3) are reflected in improvements in the attributes of a model product, such as lower costs and improved performance. Note that a recent paper reviewing major appliances in the U.S., Australia, Japan, and Europe shows that the prices of these appliances have been falling while they have been becoming more energy efficient; other than the most expensive appliances, there appears to be little correlation between price and efficiency (Ellis, Jollands et al. 2007). This paper accounts for this fact because of three factors which came out of discussions with appliance manufacturers: (1) the normal product re-design process was able to incorporate new energy efficiency requirements because these requirements were announced with sufficient advance notice (i.e., 3-5 years); (2) manufacturers were innovative with regard to the energy performance of their products; and (3) the costs of some components have come down. This resonates with environmental innovation case studies and theory (e.g., Kemp 1997), which emphasizes things like: the innovative role of outside suppliers; the implementation issues that affect firm behaviour, such as the amount of advance notice given about pending regulation and the speed with which a given policy instrument requires firms to act; and the complicated relationship that exists between regulators and industry (for more on this, see below).

A number of papers in recent years have attempted to quantify the innovative outcomes of appliances subject to energy efficiency policy using an approach that is similar to a true learning curve analysis, in that it charts performance improvements as the dependent variable related to the independent variable of cumulative output (e.g., Weiss, Patel et al. 2010). The distinction is that this method, which is more properly referred to as an "experience curve" approach, considers improvements in new models over time rather than simply the performance improvements that occur through experience with an existing product or production process.

Dilemmas for Energy Efficiency Policy-Makers

In the light of ongoing forces of technological change, energy efficiency policy is less effective if it is based in a static frame. In the case of MEPS, policy-makers invariably face a dilemma with respect to innovation. If standards are set too lax, there will be less incentive for firms to focus a significant portion of their innovation efforts on the energy use – as opposed to other aspects – of their products, particularly in establishing brand differentiation. If standards are set too tight, there will be risks of "crowding out" innovative efforts on other aspects of a product as well as ending sales for certain products, both of which may reduce profits to the extent that overall innovation budgets are cut. Either scenario could result in a slower pace of advance in energy efficient appliances than is societally optimal.

Another dilemma arises from the fact that policy-makers are in a condition of information asymmetry with the appliance industry with regard to firm-specific factors that can have big effects on the outcomes of innovation. Such factors, which the empirical literature has shown can significantly determine the rate and direction of technological change, include: the commitment level of top-level managers to environmental protection (Kagan, Thornton et al. 2003); technological competency (including that both of personnel and of the information management infrastructure within a firm) (del Rio Gonzalez 2009); financial resources (ibid.); export orientation (ibid.); firm size and correlated corporate characteristics such as product diversification (for a review, see Cohen and Levin 1989); market concentration (ibid.); demand structure (ibid.); the conditions that allow firms to appropriate the returns of innovation, including patents, secrecy, and investments in "co-specialized assets" like complementary sales and service efforts (ibid.); and the conditions that allow firms to absorb innovations from outside the firm (Cohen and Levinthal 1990).

One example of how such factors matter to the outcomes of innovation in the energy efficiency context is portrayed in Figure 4, which compiles almost seventy years of refrigerator efficiency testing data. This figure shows that the top performers in this industry have had relatively comparable energy consumption and efficiency profiles for decades, although the distribution of products on the market have had a much wider spread (Deumling 2008). Figure 4 has been interpreted to demonstrate a lack of prioritization by industry regarding energy efficiency, rather than a lack of opportunity for technological advance ("technological opportunity").

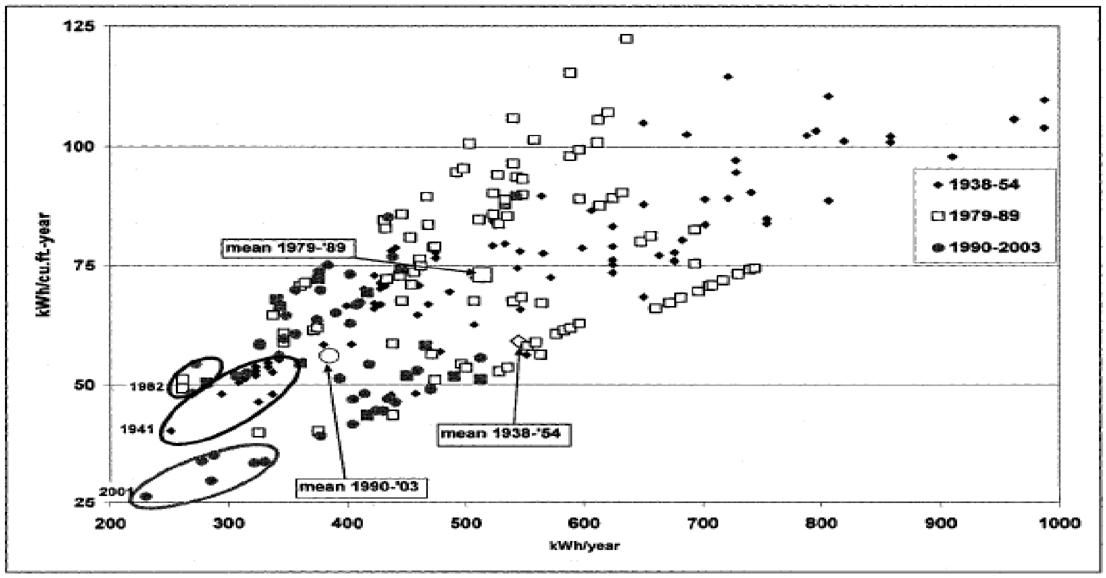

Figure 4: Energy consumption and energy efficiency of 5-10 cubic foot manual defrost refrigerators (most popular in the 1940s and 1950s) for the periods 1938-54, 1979-89, and 1990-2003. Larger symbols represent the mean refrigerators in a series, while ovals denote the best performers from each period. Source: (Deumling 2008)

Efficiency policy typically focuses on gauging technological opportunity when trying to determine the appropriate level of stringency for new MEPS, through the use of tools like engineering assessments and statistical projections. Understanding technological opportunity is helpful in bounding the answers to a major question that arises in the regulatory context: "how likely is it that regulated firms will be able to meet a new standard in a given time period at what could be deemed a 'reasonable' cost?" But the true answer to this question is embedded more deeply in an understanding of the capabilities, resources, strategies, and approaches to innovation management of regulated firms (for a helpful reference that combines the resource-based view of the firm with an understanding of dynamic capabilities that allow certain firms to adapt better than others to changing market conditions, see Eisenhardt and Martin 2000).

Without this knowledge, analysts are left with static snapshots of a given technology's development and often do a poor job predicting its future. For example, they frequently over-estimate the cost of complying with traditional environmental, health, safety, and energy efficiency regulation (Harrington, Morgenstern et al. 2000; Dale, Antinori et al. 2009). In another example, at the outset of cap-and-trade programs, they typically over-estimate allowance prices (Taylor 2012). In addition, they often underestimate the capacity for mature technological platforms to adapt to new non-market requirements (e.g., California determined that internal combustion engines would not be capable of meeting air quality goals, thereby justifying the requirement that manufacturers offer "zero-emission" vehicles for sale). The explanations put forward to account for these errors include: (a) exogenous technological change; (b) lack of firm investment in providing accurate cost estimates for possible future regulation; (c) strategic behavior by firms and/or individuals along the information chain in providing cost estimates for possible future regulation; (d) errors on the part of regulators with incomplete information regarding the business practices of firms (e.g., over-allowance for industry mark-ups, etc.); (e) induced technological change due to increased firm investment in finding least-cost compliance approaches to newly implemented standards; and (f) economies of scale that accompany increased commercialization of standards-compliant technologies (see, for example, Harrington, Morgenstern et al. 2000).

There are not easy answers to address the inaccuracies of these estimates, and in general, the regulatory community has relied on improving its understanding of technological opportunity and the outcomes of innovation, rather than focusing on the processes of innovation in the regulated community. Approaches have included regularly reassessing the state of a technology (e.g., the "biennial review" process in California vehicle emissions regulation, updating appliance efficiency standards, etc.), as well as trying to improve cost-benefit analysis techniques to include changes to future compliance costs that might result from technological innovation. In the U.S., a new federal regulation can only be proposed or adopted if "its benefits justify its costs..." due to Executive Order (EO) 13563 in 2011 (which followed on the previous EO 12866 in 1993). In light of the fact that technologies are constantly developing, the Office of Information and Regulatory Affairs in 2011 explained that the "best-available techniques to quantify anticipated present and future benefits and costs as accurately as possible" include those that identify "changing future compliance costs that might result from technological innovation or anticipated behavioral changes."

In the context of transportation, experience-curve based techniques have been adopted by the Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) as part of regulating greenhouse gases for light-duty and heavy-duty vehicles, as well as establishing new Corporate Average Fuel Economy (CAFE) Standards (see Appendix A). In the context of appliance efficiency standards, in February 2011 the Department of Energy (DOE) proposed an experience curve approach to appliance price forecasting, which has been applied in the following standards, to date: room air conditioning; central air-conditioning; clothes washers; refrigerators and freezers; dishwashers; and furnaces.[2] The Office of Management and Budget, which is an important actor in the U.S. regulatory system of checks and balances has been less willing to allow the technique to become part of the standards for other products.

But even in instances in which an experience curve technique is considered an acceptable part of the regulatory process, the question arises about whether a curve based on current or past data on the outcomes of innovation will continue at the same rate and direction when projected forward over time. To answer that, it is helpful to have a better understanding of what influences a given firm's experience curves, such as firm-specific variables related to the processes of innovation.

[2] In proposing this, the DOE issued a Notice of Data Availability and Request for Comment on the topic of "Equipment Price Forecasting in Energy Conservation Standards Analysis" which included a paper "Using the Experience Curve Approach for Appliance Price Forecasting." This paper compiled appliance price histories for: air-conditioning (room and unitary), electric lighting, electric lamp bulbs and tubes, household refrigerators and freezers, household laundry equipment, household water heaters (electric and non-electric), computers, and compact fluorescent light bulbs (CFLs). The paper estimated cumulative production going into U.S. markets by extrapolating from domestic shipment histories for: clothes washers, household refrigerators and freezers, air conditioning (room and unitary), water heaters (gas and electric), computers, and CFLs. Finally, it detmined experience curves for: water heaters (gas and electic), air conditioning (room and unitary), household refrigerators and freezers, clothes washers, computers, and CFLs (see February 22, 2011 Federal Register (pp. 9696-9700) under 10 CFR Parts 430 and 431 (Docket No. EE-2008-BT-STD-0012).

II. Research Design

This report presents first-order results of a scoping study aimed at improving the regulatory process by making information about firm innovative activities less asymmetric vis-à-vis regulators. It attempts to do this by selecting a few metrics of the innovation process that hold promise based on their: widespread use in the literature; low cost to acquire; and potential for consistent application across a variety of appliance industries over time. It also selects an initial case to test these metrics on: freestanding, standard-size refrigerator-freezers ("refrigerators"), a technology with a well-documented commercial history and publicly available data, as well as an internationally recognized contribution to household energy consumption. Note that most products would be similarly effective test beds for the methods deployed here, although some of their time-series may not go back as far in time. The case of refrigerators is a useful one to explore, both for regulators to understand on its own merits as well as for use as a testing-bed to begin to characterize the inputs, outputs, and conduct of innovation in an appliance industry subject to energy efficiency policy.

This section reviews the major innovation metrics in use in the literature and provides information on the refrigerator case. The refrigerator case material includes the results of data analyzed for this project that provide a window into the outcomes of innovation in this industry as well as the degree of market concentration of the industry (note that this market concentration appears likely to hold in other appliance industries as well).

Innovation Metrics

Scholars have traditionally been interested in measuring three aspects of the innovation process: the inputs organizations invest in it; the outputs organizations derive from it; and the way organizations engage in it.

Inputs into Innovation Processes

The most significant investment a firm makes into its innovation processes generally occurs in its formal R&D operations.[3] Metrics that characterize a firm's R&D operations, either on their own or in relation to a measure of a firm's performance or output, are easily justifiable proxies for a firm's overall inputs into its innovation processes, although a solid theoretical framework that links such metrics with a firm's competiveness or its technological advances is still somewhat lacking (Geisler 2002). The metric of R&D intensity, or the ratio of a firm's R&D investments against its sales, is the most extensively used metric of innovation input in the literature, as well as compiled by governments.

Input metrics are widely used as an indicator of the "best practices" of firms and industries, in large part due to extensive data availability, at least at an aggregate level, at low cost across many firms and industries over time. Standard accounting principles for publicly traded firms make firm financial reports a useful data source, while industry surveys (such as those sponsored by the U.S. National Science Foundation (NSF), the Organization for Economic Cooperation and Development, etc.) can provide more in-depth information. Data consistency is generally good, although there are some noted differences between the definitions of R&D expenditures that some of the major sources employ (studies of these discrepancies date back at least to Cohen and Mowery 1984).

[3] This does not hold true for firms such as start-ups, however, in which a significant amount of the time of the firm's small number of employees is spent in the conduct of R&D. In addition, firms, regardless of size, typically have additional inputs into the innovation process. For example, the knowledge an organization gains from difficulties or opportunities exposed through operating experience is usually an important – albeit unmeasured – input into the innovation process, as is incremental innovation on the shop floor (for a discussion, see Cohen and Levin 1989).

Outputs of Innovation Processes

A number of different metrics of the outputs of a firm's innovation processes have been employed in the literature. Measures of the *quantity* of a firm's innovation outputs include: counts of a firm's patents; counts of publications by a firm's researchers in scientific and technical journals; and various innovation counts such as "new products and processes" (Cohen and Levin 1989; Geisler 2002). The major measures of the *quality* of a firm's innovation outputs include: the citations to a firm's patents by other patents; the citations to a firm's publications by other publications; and expert opinion by peers regarding the firm's research activities (ibid.).[4] Patent counts are the most widely used metric of the outputs of a firm's innovation processes in the literature, and are particularly helpful to consider as a measure of pre-commercial output.

A patent is an exclusive right to exploit an invention, as defined legally in the patent's claims. Patents are required by law to publicly reveal the details of a completed invention that meets thresholds of novelty, usefulness, and non-obviousness; the theory is that publishing the details of inventions advances the pace of innovation in society and justifies the monopoly right. Patents are, by definition, a detailed and publicly available data source; this source is relatively consistent over time, useful in international contexts, and generally linked to both R&D expenditures as well as to commercialization of invention (approximately 40–60% of the innovations detailed in patent applications are eventually used by firms, according to surveys like Scherer and others 1959; Sirilli 1987; Napolitano and Sirilli 1990). The strengths and weaknesses of patent counts as an output indicator are relatively well-understood (for an excellent review, see Griliches 1990).

The Conduct of Innovation

Firms take advantage of physical, human, and organizational resources in order to create value (Eisenhardt and Martin 2000). Dynamic capabilities are "the organizational and structural routines by which managers ... acquire and shed resources, integrate them together, and recombine them" to create value (ibid.). In order to get "inside the black box" of innovation (Rosenberg 1983) and into the processes of innovation as they are conducted by a firm, it is helpful to focus on a firm's dynamic capabilities, as these are what enable firms to adapt to changing market conditions (Zahra and George 2002). Case studies that draw from such qualitative methods as interviews and embedded observation are best suited for this, but they are resource intensive and produce results that policy-makers often find difficult to generalize from, based on the constraints they operate in.

A less ideal, but less intensive approach has been developed in recent years to harness the information provided by a wider mix of innovation data in order to gauge a firm's "absorptive capacity" (ACAP) or its ability to recognize, assimilate, and apply new information to commercial ends. ACAP levels are affected by the size and quality of internal R&D investments (e.g., continuous R&D investments are considered better than sporadic investments due to the cumulative nature of an organization's knowledge in a particular domain; R&D personnel are considered better at reinforcing ACAP if they have diverse backgrounds which help an organization maximize "novel associations and linkages," etc.). ACAP has provided insights into such aspects of innovation management as: (a) new product development (Fiol 1996; Stock, Greis et al. 2001); (b) technological acquisitions and innovation performance (Ahuja and Katila 2001); (c) partner-enabled knowledge creation in

[4] Less prominent quality measures include such heterogeneous assessments of a firm's R&D operations as "return on investment," " return on assets," "cost-savings," "profit per cost of research employee," "goal achievement," "improvements in products and processes," "innovation breakthroughs," "business customer satisfaction," and "contribution to business strategic objectives" (Geisler, 2002).

supply chains (Malhotra, Gosain et al. 2005); (d) the relative roles of internal R&D, R&D cooperation, and contracted-out R&D (Veugelers 1997; Reagans and McEvily 2003); and (e) external knowledge exploitation (i.e., the commercialization of knowledge assets) (Griffith, Redding et al. 2004; Lichtenthaler 2005).

Many empirical studies have shown significant relationships between ACAP and innovative outcomes. Zahra and George (2002), however, usefully break down ACAP into two subsets, potential ACAP (knowledge acquisition and assimilation capabilities) and realized ACAP (knowledge transformation and exploitation). In general, innovative outcomes are reflected in realized ACAP, while Zahra and George (2002) put forth that potential capacity:

> " has received disproportionately less empirical scrutiny when compared with realized capacity … potential capacity provides firms with the strategic flexibility and the degrees of freedom to adapt and evolve in high-velocity environments. By doing so, potential capacity allows firms to sustain a competitive advantage evening a dynamic industry context." (Zahra and George 2002 p. 185)

The four capabilities established in Zahra and George (2002) can be operationalized using many standard data sources. The first potential ACAP capability of knowledge acquisition is typically explored through metrics like the number of years of experience of the R&D department, the amount of R&D investment, etc. The second potential ACAP capability of assimilation is typically explored through metrics like the number of cross-firm patent citations, the number of citations made in a firm's publications to research developed in other firms, etc. The first realized ACAP capability of transformation is typically explored through metrics like the number of new product ideas, the number of new research projects initiated, etc. The second realized ACAP capability of exploitation is typically explored through metrics like the number of patents, the number of new product announcements, the length of the product development cycle, etc.

The Refrigerator Case

Refrigerators have been the subject of many years of efficiency policy, both in the U.S. and in other nations, due to their energy consumption and widespread adoption (for more detail, see Taylor 1995; Deumling 2008; U.S. Department of Energy 2010). We focus on the U.S., which has exhibited a different market pattern than other nations (Bowden and Offer 1994). Table 1 shows major U.S. energy efficiency policy events which affected refrigerators. Note that upstream of commercialization, we are only aware of one major policy effort, which is the super-efficient refrigerator innovation prize competition held in the 1990s (see the Golden Carrot program for refrigerators, as discussed in Taylor 1995).

Table 1: U.S. policy history pertaining to energy efficiency

Year	Event
1975	Energy Policy and Conservation Act (EPCA) signed
1978	DOE publishes test methods for appliances; Voluntary 20% efficiency improvement over '72 levels by 1980 becomes mandatory
1982	DOE publishes 'no-standards standards' which were later overturned
1987	National Appliance Energy Conservation Act (NAECA) signed
1990	First federal refrigerator efficiency standards enacted
1992	Energy Policy Act signed; EPA Energy Star program is created
1993	Federal refrigerator standards are updated; Super-Efficient Refrigerator Program (SERP) Golden Carrot strategy announced.
1997	EPA/DOE Energy Star program expanded to include refrigerators

2001	Federal refrigerator efficiency standards are updated
2007	Energy Independence and Security Act of 2007 (EISA) signed; requires DOE final rule on 2014 refrigerators by end of 2010

Source: (Taylor 1995; Deumling 2008; DOE 2010)

The first residential refrigerator was introduced before World War I, and by 1940, 60% of U.S. households owned the appliance (ibid.). When the energy shocks of the 1970s hit, U.S. policy-makers began to take action about refrigerator energy consumption, as these appliances consumed more energy than any other home appliance (Fischer 2005). Each major component of a refrigerator provides opportunity for energy efficiency innovation (see Figure 5). Compressors and insulation, in particular, have undergone many improvements throughout the history of refrigeration. The technical documents that support U.S. refrigerator MEPS detail current innovations and potential future directions for innovation in processes, technologies, and efficiency-related refrigerator systems (U.S. Department of Energy 1995; U.S. Department of Energy 2005; U.S. Department of Energy 2010).

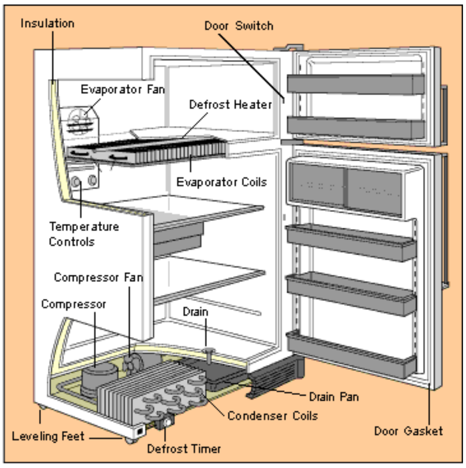

Figure 5: Components of a refrigerator. Source: original source listed as "RemodelGuide.com"

Figure 6 depicts the market average and threshold efficiency level that qualified for the U.S. equivalent of a "top performer" efficiency level at different points in time since 1972. It also depicts the average price of refrigerators on the U.S. market since 1995. Note that the annual value of shipments in the North American Industry Classification System (NAICS) code 335222 for "Household Refrigerator and Home Freezer Manufacturing" was between $U.S. 4.5 and $U.S. 6.2 billion between 1997 and 2008 (International Trade Administration).

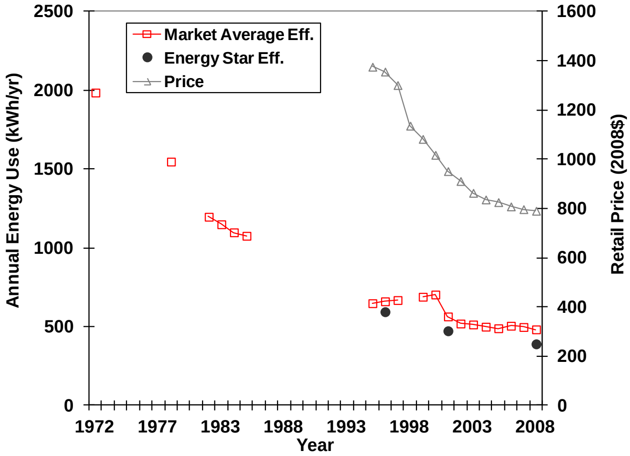

Figure 6: Refrigerator energy use and retail price, 1995 – 2008. Source: Authors' calculation from AHAM Factbooks, Bureau of Labor Statistics, DOE 2010

In another measure of the outcomes of innovation, Figure 7 reproduces experience curves generated elsewhere (Weiss, Patel et al. 2010) for refrigeration products dating back to 1964 on the axes of price and an energy efficiency, versus cumulative global production.

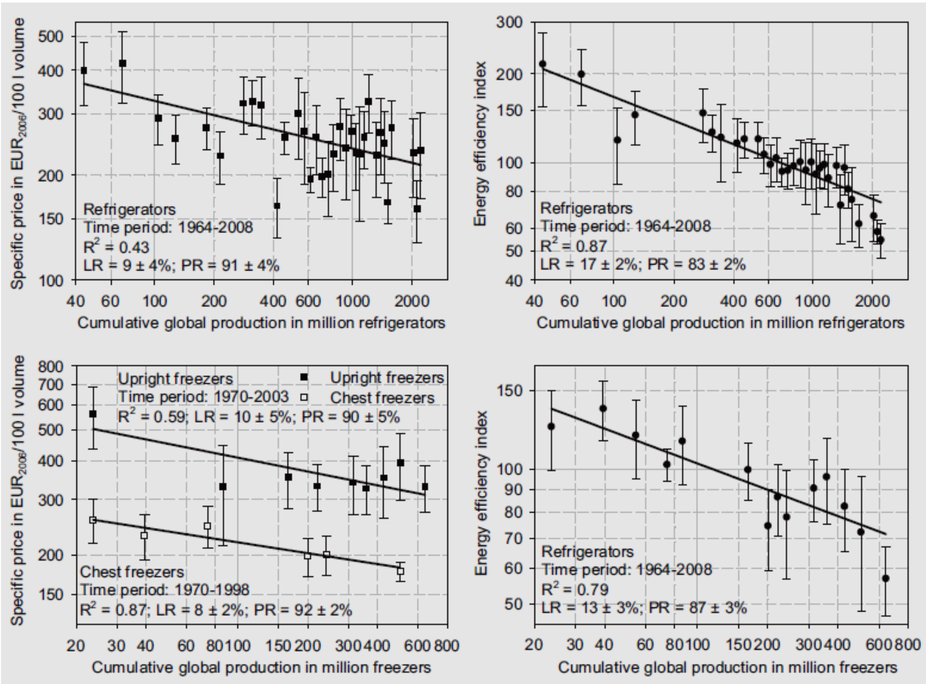

Figure 7: Experience curves in refrigeration products. Source: Weiss, Patel et.al. (2009)

In contrast with the focus on firm internal organization and resources and their relationship to innovation, which was discussed above,[5] the traditional emphasis of business strategy has been on industry structure and strategic positioning within that structure as determinants of competitive advantage (Eisenhardt and Martin 2000). In that model, attributes like firm size and industry concentration are key aspects of firms that are related to innovation. Industry concentration and its relationship to the innovativeness of firms, for example, traces its origins back to Joseph Schumpeter's original hypothesis that a large firm operating in a concentrated industry is more conducive to rapid innovation (Schumpeter 1942).

Applying the Herfindahl-Hirschman Index (HHI) metric used by U.S. anti-trust regulators to this industry reveals that the refrigerator industry in the U.S. is highly concentrated. Figure 8 presents HHI scores for the refrigerator industry; HHI scores above 1,800 indicate high concentration (Fischer 2005).[6] In the ten years represented in this figure, HHI scores always exceeded 1,800, as they did in three additional years reported in (Fischer 2005): 1996 (2,698), 1997 (2,025), and 2001 (2,432). Figure 8 also presents U.S. market share data for four refrigerator manufacturers with greater than 10% of the U.S. market in any given year. The four manufacturers highlighted in Figure 1 – General Electric (GE), Whirlpool, Electrolux, and Maytag – accounted for as much as 98% of the U.S. market (in 2002), and only once accounted for less than 89% of the U.S. market (2008). Note that Whirlpool completed its acquisition of Maytag in 2006, an event that prompted anti-trust concerns. It is

[5] This is known as "the resource-based view of the firm."

[6] The HHI is constructed by summing the squares of the market shares of all the firms in an industry, allowing larger firms to have more weight. HHI scores were constructed for this article from data gathered from the Technical Support Documents for the 1997 and 2010 U.S. refrigerator rulemakings, as well as from *Appliance Manufacturer*, as compiled in Beldock (1988).

also interesting to note that the financial reports of the leading manufacturers generally characterize the refrigerator industry as highly competitive with low profit margins; the HHI scores of the industry would appear to contradict the claim that it is highly competitive.

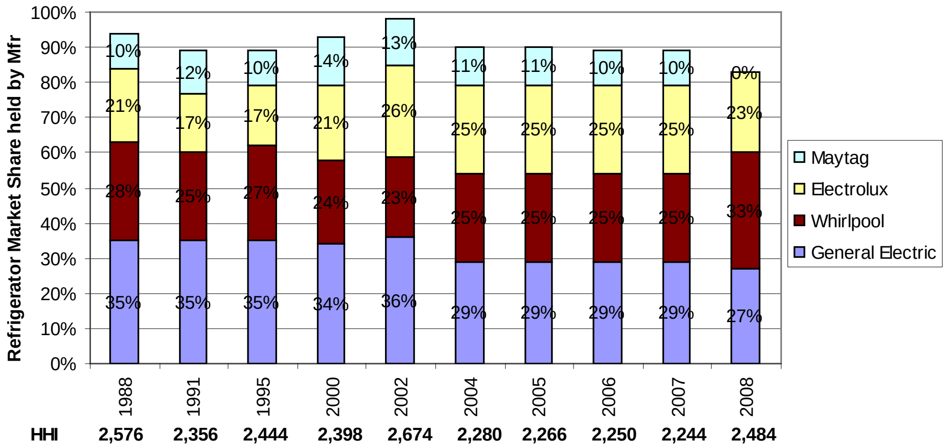

Figure 8: HHI scores, market share in selected years, for leading manufacturers. Source: Authors' calculation from (Beldock 1988; DOE 1995; DOE 2010)

III. Results

This section applies the input metric of R&D intensity, the output metric of patent counts, and the conduct of innovation metric of assimilation capability (one of the operationalizations of ACAP in Zahra and George 2002) to the refrigerator case, with a particular focus on the leading players depicted in 2008 in Figure 8.

Input Metric: R&D Intensity

R&D intensity is the ratio of overall R&D expenditures to net sales, both of which can be determined from the financial reports of publicly traded corporations, at least at an aggregate level. Of the three firms depicted in 2008 in Figure 8, General Electric does not provide useful data for analyzing R&D intensity for purposes of comparison against other industries and firms.[7] Whirlpool[8] and Electrolux[9], however, share a relatively narrow business focus on the manufacture of appliances and related products. Thus, they can be considered "pure plays" (i.e., firms that are devoted to one line of business or whose stock price is highly correlated with the fortunes of a specific investing theme) and their trends can be considered acceptable indicators of trends in the overall industry. Figure 9 presents the R&D intensity of

[7] General Electric, the market leader for many years until it recently lost the title to Whirlpool as a result of the Maytag acquisition, is difficult to study using the R&D intensity metric due to the diversity of the firm's business units and the lack of detail the firm's financial reports provide for each unit. In 2010, General Electric had five major units (revenues in billion $U.S. are provided in parentheses): Energy Infrastructure (37.5), Technology Infrastructure (37.9; this includes Aviation, Healthcare, and Transportation), NBC Universal (16.9), GE Capital (47), and Home & Business Solutions (8.6; this includes "Appliances and Lighting" and "Intelligent Platforms"). The firm only reports R&D expenditures at the aggregate level, rather than at the level of each unit (although General Electric mentioned in its annual filing to the U.S. Securities and Exchange Commission (SEC) that Aviation was the largest focus of its R&D efforts). Revenues and employee numbers are available for each unit, but not at the level of the sub-unit of most interest to refrigerator manufacturing, namely the Appliances and Lighting business. The number of employees in the Appliances and Lighting sub-unit was estimated at 27,000 in 2010, according to General Electric's corporate website. Note that General Electric tried unsuccessfully to sell its appliance business in 2008.

[8] Whirlpool had 2010 net sales of 18.4 billion $U.S., with net sales for refrigerators and freezers of 5.6 billion $U.S., based on author's calculations.

[9] Electrolux had 2010 net sales of 2.7 billion $U.S., with net sales for refrigerators and freezers of 4.7 billion $U.S., based on author's calculations.

Whirlpool and Electrolux.[10] For Whirlpool, R&D intensity has been increasing gradually and has almost doubled since the early 1990s, while for Electrolux, R&D intensity climbed steeply in the early 2000's and has levelled off in the second half of the decade. Note that it is not possible to present the R&D intensity only of refrigerator manufacturing at Whirlpool and Electrolux based on secondary data, however, as the firms do not report R&D expenditures at the level of individual products.

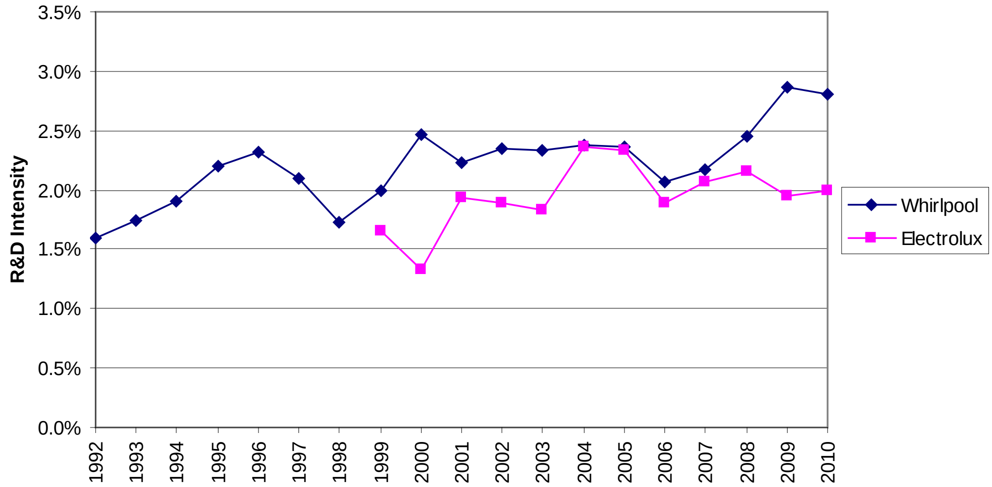

Figure 9: R&D intensity of Whirlpool and Electrolux. Source: Authors' calculations from firm financial reports

Figure 10 places the R&D intensities of Whirlpool and Electrolux between 2003 and 2007 in the context of the average R&D intensity of manufacturing industries, while Figure 11 places these intensities in the context of firms of various sizes in the U.S.; both contextual graphs came from U.S. National Science Foundation (NSF) data. Note that although they have R&D intensity scores that are lower than comparable firms of their size (Whirlpool employed 70,758 in 2010, while Electrolux employed 51,544), their scores are higher than a number of other manufacturing industries. Their scores are, however, a bit lower than average for manufacturers of "electrical equipment, appliances, and components," according to NSF survey data.

[10] The authors were unable to find R&D data on Electrolux before 1999.

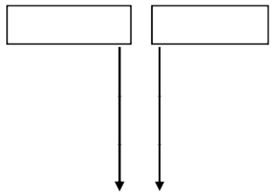

Figure 10: Benchmarked R&D intensity of Whirlpool and Electrolux against the average (between 2003 and 2007) of firms from various manufacturing industries. Source: Authors' calculations from 2008 and 2010 NSF Science & Engineering Indicators reports.

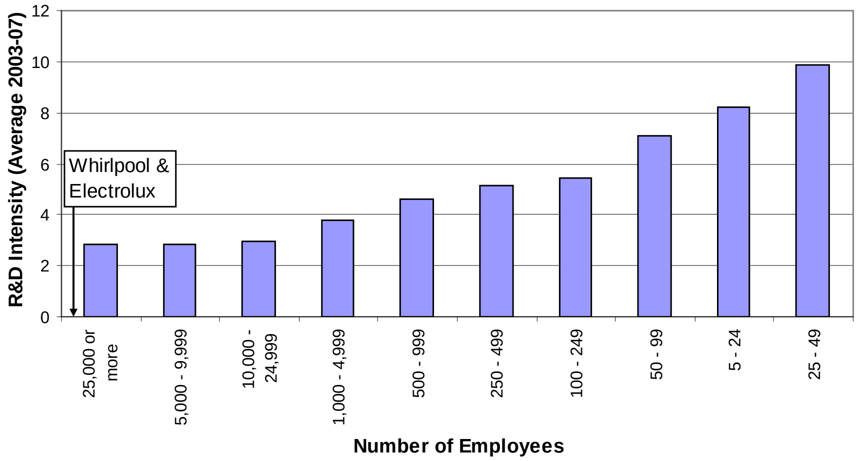

Figure 11: Benchmarked R&D intensity of Whirlpool and Electrolux against the average (between 2003 and 2007) of firms of various sizes, according to their number of employees. Source: Authors' calculations from 2008 and 2010 NSF Science & Engineering Indicators reports.

Output Metric: Patenting Activity

Two datasets were constructed for this paper from United States Patent and Trademark Office (USPTO) data. Dataset construction began with the U.S. Manual of Classification, which groups patents related to "refrigeration" in U.S. Patent Classification (USPC) 62 (for a total of 28,847 patents). The dataset of "refrigerator patents" (1,060 patents) was constructed from patents in USPC 62 that are assigned to (i.e., owned by) the four leading manufacturers, as well as their sub-units, as determined by a consideration of the mergers and acquisitions history included in the TSDs for the 1997 and 2010 refrigerator rulemakings. The dataset of "energy-related refrigerator patents" (64 patents) was constructed through the results of a search of the legal claims of the refrigerator patents for reference to "energy." Patents were issued by the USPTO from 1976 (the earliest date for which full USPTO electronic searching capability is available) until January 17, 2011.

Figure 12 portrays the overall trends in refrigerator patents and energy-related refrigerator patents over the last three decades according to the date that their underlying applications were filed with the USPTO; this is the traditional approach used to back-date patents as close to the initial time of invention as possible. Also in keeping with standard practice, Figure 12 discards the last three years of count data as unreliable due to the potential influence on latter-year counts of pending patents that are currently unobservable. Activity in energy-related refrigerator patents appears to have been relatively flat over time, although activity in refrigerator patents, in general, is increasing. The two series are only loosely correlated (r^2: 0.1614 at a confidence level of 0.0205).

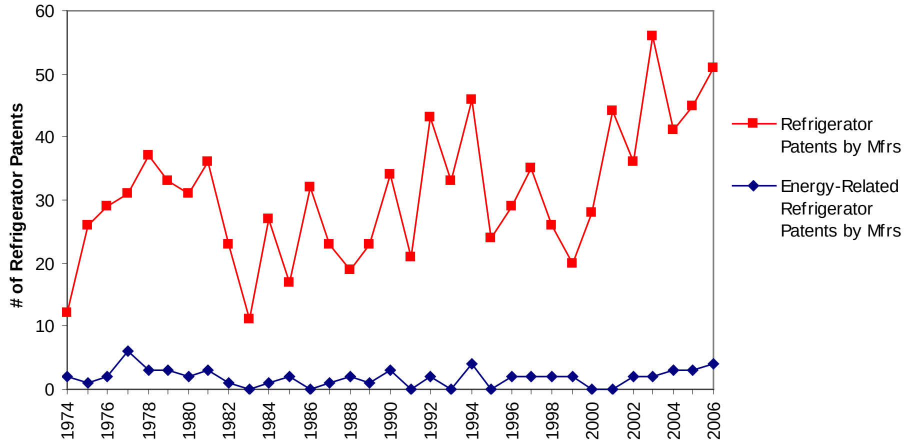

Figure 12: Issued patents by application date for refrigerator patents and energy-related refrigerator patents held by leading manufacturers

Figure 13 breaks down the refrigerator patent dataset by manufacturer. Note that prominence in refrigerator patenting activity is subject to considerable variation, which is not the case with market share, as depicted in Figure 8. Overall rankings in refrigerator patenting over time and market share are consistent, however, with General Electric the leader in both (48% of all refrigerator patents), followed by Whirlpool (31%), Electrolux (12%), and Maytag (8%). Perhaps the most suggestive trend in Figure 13 is the dramatic increase in annual patenting activity by both Whirlpool and Maytag in the 2000's, which may indicate a new approach to innovation management in these firms. Note that of the four leading firms, Electrolux's patent record implies that, over time, it has devoted the most resources on a proportionate basis to the energy aspect of refrigerators (10% of its refrigerator patents are energy-related), followed by General Electric (7%), Maytag (4%), and Whirlpool (3%).

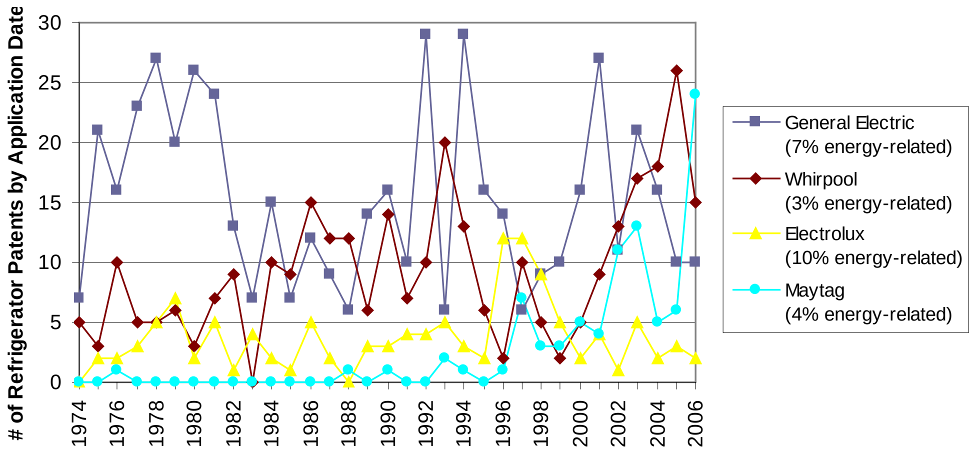

Figure 13: Time-series of refrigerator patents held by the four leading manufacturers. The legend relates the energy-related proportion of each firm's refrigerator patents.

Conduct of Innovation

As discussed above, the four capabilities established in Zahra and George (2002)'s refinement of absorptive capacity (ACAP) can be operationalized using many standard data sources. The R&D intensity data above can be used to gain insight into the potential ACAP of knowledge acquisition, while the number of patents can be used to gain insight into the realized ACAP of exploitation. We hope to perform these tasks in a later analysis.[11] This section, however, presents first-order results regarding the potential ACAP capability of knowledge assimilation, which is typically explored through metrics like the number of cross-firm patent citations, the number of citations made in a firm's publications to research developed in other firms, etc.

We conducted cross-firm patent citation analysis to begin to understand the assimilation capability of the four leading manufacturers. Using the Delphion patent database, we identified the prior art (i.e., previous patents) that the 64 energy-related refrigerator patents cite. In total, 733 patents were identified across a wide variety of nations, industries, and assignees (including firms, individual inventors, etc.). Of the 733 cited patents, Delphion provided details such as the assignee/applicant name for 602.[12] We focused on the patents in the energy-related refrigerator patents that are owned by Electrolux, GE, Maytag, or Whirlpool and cite patents in the 602 that they themselves own or that the other three major manufacturers own (see Table 2).

Table 2: Patent citations of major refrigerator manufacturers

Company	64 Energy-related refrigerator patents	Citations to own patents	Citations to other 3 refrigerator mfrs
Electrolux	13	5	13
GE	37	56	22
Maytag	4	17	140
Whirlpool	9	40	49

The first column of Table 2 shows the breakdown of the original 64 energy-related refrigerator patents by each of the leading manufacturers. The second column shows the number of own patents referenced in each company's energy-related refrigerator patents, while the third column shows the number of patents of other major refrigerator manufacturers referenced in each company's energy-related refrigerator patents. For example, Electrolux's 13 energy-related patents cite 5 Electrolux patents and 13 patents owned by GE, Maytag, and Whirlpool. Not shown in this table, the 64 energy-related patents also cite patents of other appliance manufacturers (Carrier, LG, Philips, etc.), as well as companies from a wide variety of industries, including aerospace (Boeing), electronics (Canon), and energy (Exxon). In total, 197 other firms own the patents cited by the 64 energy-related patents, in addition to the four leading manufacturers and individual inventors.

A first-order analysis shows that Maytag references a proportionately much larger volume of prior art in its patents than do the other leading manufacturers, with Whirlpool a distant

[11] We decided that it would be too time and labor-intensive to gain insight into the realized ACAP capability of transformation, which is typically explored through metrics like the number of new product ideas, the number of new research projects initiated, etc.

[12] The missing patents generally preceded the advent of consistent electronic searching in the USPTO data that Delphion compiles (although a few that occurred during this early time period are captured in the 602).

second and GE and Electrolux far behind. This implies that Maytag's patents draw from a wider set of knowledge than the patents by the other firms, and may be more fundamental. In addition, it is interesting to note that GE and Electrolux take very different approaches to referencing prior art that is within their organizational structure, with GE prominently citing its own patents and Electrolux rarely doing so. This implies that GE draws on less diverse sources of innovation than Electrolux (although this result may be confounded by the wide array of business lines GE covers). More refined analysis of these results is required in order to more fully capture the potential of ACAP for understanding firms' dynamic capability for knowledge assimilation.

IV. Discussion

Policy will need to help support fast-paced but sustainable technological change in many industries if a stable climate is going to be achievable. Effective policy interventions will need to be informed by an understanding of: the baseline rate and direction of technological change of climate-relevant industries; the factors that underlie the outcomes of innovation in these industries; and the ways the innovation system might respond to any given intervention. The goal of this report was to provide a starting point for such efforts in the context of the appliance industry, which is one of the key industries involved in making energy efficiency live up to its promise as a pathway toward climate stabilization.

The report provided an overview of the dynamics of energy efficiency policy and innovation in the appliance industry, introduced the competitive framework of this industry (which includes an important role for government), defined and discussed the processes and outcomes of innovation in this context, and framed the dilemmas facing energy efficiency policy-makers when considering innovation. The report also provided details of research design and first-order results of a pilot study to empirically and systematically assess the inputs, outputs, and conduct of innovation involved in the case appliance of refrigerators.

The pilot study revealed: (1) the high concentration of the industry, which has immediate linkage potential with one of the long-standing threads of innovation scholarship; (2) the stability of the market positions of leading firms over at least a twenty year period, which has linkage potential to scholarship regarding innovation and industry instability; (3) the similarity between the market share and the intellectual property position of the leading firms (although not the energy-relevant aspects of refrigerators), which signals that the propensity to patent is roughly the same across the industry; (4) that R&D appears to be slowly becoming more important to the industry and to refrigerator development (the latter is supported by patent evidence); (5) that R&D intensity does not appear to equal "best practices" for comparable industries and firms of similar size; (6) that the focus of innovation management on the energy aspects of refrigerators appears to be slowly declining over time for the industry as a whole, relative to other aspects of technological change in refrigerators (this is based on the flat trend in energy-related refrigerator patents by the leading firms, in contrast with the increasing trend in overall refrigerator patents); and (7) the leading firms do not have the same knowledge assimilation capabilities, with one manufacturer citing a relatively extensive amount of prior art, another manufacturer engaging in a relatively large amount of self-referential knowledge assimilation, and another engaging in a relatively little amount of self-referential knowledge assimilation.

Although the results of the pilot study are at a first-order of analysis, the pilot study itself represents a novel contribution. The approaches that have been taken in the regulatory context in order to take into account the rate and direction of technological change, as well as the factors underlying this dynamism, are still developing, despite their relevance to several domains of policy, including environmental, energy, health, and safety regulation.[13] Approaches to date tend to focus on engineering assessments of the outcomes of innovation, whether through independent expert review of technological developments or through experience curve analysis. Missing in the regulatory process, however, is a systematic approach to considering long-standing concepts in the innovation literature, such as the resource-based-view of the firm, dynamic capabilities, absorptive capacity, etc. This is somewhat surprising, given the linkage of these concepts to innovative outcomes as well as the potential of these concepts for revealing potential responses to regulatory interventions. Note that the vehicle domain tends to have more focus on these topics, with the regulatory process explicitly considering the ramp-up the automobile industry goes through in order to deliver new model years of vehicles; it might be fruitful to explore the synergies between the regulatory approaches of vehicles and appliances in future work.

Identifying standardized techniques to describe aspects of the innovation process could prove very useful to appliance efficiency policy-makers. For example, identifying a true secondary metric of product cycle times in the process of codifying the absorptive capacity of firms could help policy-makers apply MEPS to products with faster cycle times (like consumer electronics), which they have traditionally been reluctant to do given the pace of the regulatory process. In another example, a clear understanding of product cycle times would assist in designing proper evaluation techniques regarding the effectiveness of MEPS. For an example of the linkage between many of the aspects of innovation management discussed in this article and the policy-relevant factor of product cycle time, see Appendix B.[14]

There are two major priorities we suggest for further study of the dynamics of innovation and appliance efficiency policy. First, we think it is important to extend the refrigerator case studied here to directly establish the linkages between innovation findings regarding appliance efficiency and insights from the broader literature on innovation. Second, we think that the general approach followed in the pilot study should be replicated for other appliances with differing characteristics in order to help bound the innovative capacities of industries with which government appliance efficiency policy-makers interact. For example, refrigerators are a classic residential consumer product with many design goals which compete with efficiency. Many of the same manufacturers studied in the refrigerator case also manufacture products that operate in a similar space (e.g., dishwashers, kitchen ranges, etc.), and insights from refrigerators could be directly relevant to these products. This is not as likely to be true for other products, however, such as commercial systems (e.g., warm air furnaces), commodity products (e.g., motors), and consumer electronics products (e.g., televisions). Note that many of these contrasting products should share the methodological advantages of refrigerators regarding data availability, based on the many products that have been analyzed in the context of experience curves to date (e.g., the recent DOE regulatory work, Weiss, Patel et al. 2010, etc.).

[13] Cases in the context of environmental and energy policy include power plants, vehicles, appliances, and so forth. In the appliance efficiency arena, the regulatory process particularly focuses attention on the maximum performance of commercially-demonstrated technologies (and by extension, the wider distribution of that performance).

[14] Ellis, Jollands et. al. (2007) weighed in on product development cycle times thus: “Appliances are going through a continual design process, either at the ‘platform’ or model level. For white goods the platform will typically be redesigned every 3-5 years while changes to models will occur more frequently. At the platform level, major technical changes are made but cosmetic alterations can be incorporated in model upgrades.”

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Appendix A: Excerpt on Learning in Draft Joint Technical Support Document: Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards (EPA-420-D-11-901)

3.2.3 Cost reduction through manufacturer learning

For this proposal, we have not changed our estimates of learning and how learning will impact costs going forward from what was employed in the analysis for the MYs 2012-2016 light-duty vehicle rule. However, we have updated our terminology in an effort to clarify that we consider there to be one learning effect—learning by doing—which results in cost reductions occurring with every doubling of production.[15] In the past, we have referred to volume-based and time-based learning. Our terms were meant only to denote where on the volume learning curve a certain technology was—"volume-based learning" meant the steep portion of the curve where learning effects are greatest, while "time-based learning" meant the flatter portion of the curve where learning effects are less pronounced. Unfortunately, our terminology led some to believe that we were implementing two completely different types of learning—one based on volume of production and the other based on time in production. Our new terminology—steep portion of the curve and flat portion of curve—is simply meant to make more clear that there is one learning curve and some technologies can be considered to be on the steep portion while others are well into the flatter portion of the curve. These two portions of the volume learning curve are shown in Figure 3-1.

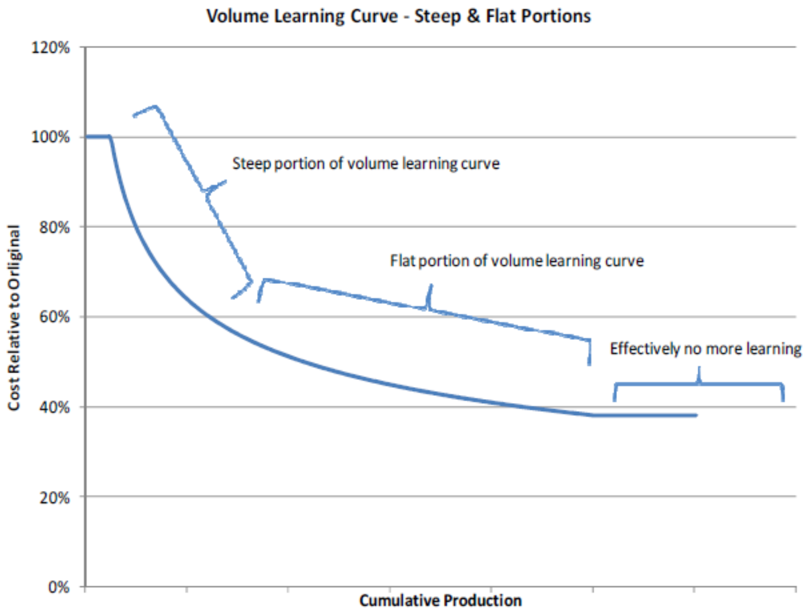

Figure 3-1 Steep & Flat Portions of the Volume Learning Curve

For some of the technologies considered in this analysis, manufacturer learning effects would be expected to play a role in the actual end costs. The "learning curve" or "experience curve" describes the reduction in unit production costs as a function of accumulated production volume. In theory, the cost behavior it describes applies to cumulative production volume measured at the level of an individual manufacturer, although it is often assumed—as both agencies have done in past regulatory analyses—to apply at the industry-wide level, particularly in industries like the light duty vehicle production industry that utilize many

[15] Note that this new terminology was described in the recent heavy-duty GHG final rule (see 76 FR 57320). The learning approach used in this analysis is entirely consistent with that used and described for that analysis.

common technologies and component supply sources. Both agencies believe there are indeed many factors that cause costs to decrease over time. Research in the costs of manufacturing has consistently shown that, as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts. All of these factors allow manufacturers to lower the per-unit cost of production. We refer to this phenomenon as the manufacturing learning curve.

NHTSA and EPA included a detailed description of the learning effect in the MYs 2012-2016 light-duty rule and the more recent heavy-duty rule.19 Most studies of the effect of experience or learning on production costs appear to assume that cost reductions begin only after some initial volume threshold has been reached, but not all of these studies specify this threshold volume. The rate at which costs decline beyond the initial threshold is usually expressed as the percent reduction in average unit cost that results from each successive doubling of cumulative production volume, sometimes referred to as the learning rate. Many estimates of experience curves do not specify a cumulative production volume beyond which cost reductions would no longer occur, instead depending on the asymptotic behavior of the effect for learning rates below 100 percent to establish a floor on costs.

In past rulemaking analyses, as noted above, both agencies have used a learning curve algorithm that applied a learning factor of 20 percent for each doubling of production volume. NHTSA has used this approach in analyses supporting recent CAFE rules. In its analyses, EPA has simplified the approach by using an "every two years" based learning progression rather than a pure production volume progression (i.e., after two years of production it was assumed that production volumes would have doubled and, therefore, costs would be reduced by 20 percent).[16]

In the MYs 2012-2016 light-duty rule and the recent heavy-duty GHG final rule, the agencies employed an additional learning algorithm to reflect the volume-based learning cost reductions that occur further along on the learning curve. This additional learning algorithm was termed "time-based" learning in the 2012-2016 rule simply as a means of distinguishing this algorithm from the volume-based algorithm mentioned above, although both of the algorithms reflect the volume-based learning curve supported in the literature. As described above, we are now referring to this learning algorithm as the "flat portion" of the learning curve. This way, we maintain the clarity that all learning is, in fact, volume-based learning, and that the level of cost reductions depend only on where on the learning curve a technology's learning progression is. We distinguish the flat portion of the curve from the steep portion of the curve to indicate the level of learning taking place in the years following implementation of the technology (see Figure 3-1). The agencies have applied learning effects on the steep portion of the learning curve for those technologies considered to be

[16] To clarify, EPA has simplified the steep portion of the volume learning curve by assuming that production volumes of a given technology will have doubled within two years time. This has been done largely to allow for a presentation of estimated costs during the years of implementation, without the need to conduct a feedback loop that ensures that production volumes have indeed doubled. If we were to attempt such a feedback loop, we would need to estimate first year costs, feed those into OMEGA, review the resultant technology penetration rate and volume increase, calculate the learned costs, feed those into OMEGA (since lower costs would result in higher penetration rates, review the resultant technology penetration rate and volume increase, etc., until an equilibrium was reached. To do this for all of the technologies considered in our analysis is simply not feasible. Instead, we have estimated the effects of learning on costs, fed those costs into OMEGA, and reviewed the resultant penetration rates. The assumption that volumes have doubled after two years is based solely on the assumption that year two sales are of equal or greater number than year one sales and, therefore, have resulted in a doubling of production. This could be done on a daily basis, a monthly basis, or, as we have done, a yearly basis.

newer technologies likely to experience rapid cost reductions through manufacturer learning, and learning effects on the flat portion learning curve for those technologies considered to be more mature technologies likely to experience only minor cost reductions through manufacturer learning. As noted above, the steep portion learning algorithm results in 20 percent lower costs after two full years of implementation (i.e., the MY 2016 costs would be 20 percent lower than the MYs 2014 and 2015 costs). Once two steep portion learning steps have occurred, flat portion learning at 3 percent per year becomes effective for 5 years. Beyond 5 years of learning at 3 percent per year, 5 years of learning at 2 percent per year, then 5 at 1 percent per year become effective.

Learning effects are applied to most but not all technologies because some of the expected technologies are already used rather widely in the industry and we therefore assume that learning impacts have already occurred. The steep portion learning algorithm was applied for only a handful of technologies that are considered to be new or emerging technologies. Most technologies have been considered to be more established given their current use in the fleet and, hence, the lower flat portion learning algorithm has been applied. The learning algorithms applied to each technology and the applicable timeframes are summarized in Table 3-4.

Table 3-4 Learning Effect Algorithms Applied to Technologies Used in this Analysis

Technology	Steep learning	Flat learning	No learning
Engine modifications to accommodate low friction lubes			2012-2025
Engine friction reduction – level 1 & 2			2012-2025
Lower rolling resistance tires – level 1			2012-2025
Low drag brakes			2012-2025
Secondary axle disconnect		2012-2025	
Electric/Plug-in vehicle battery charger installation labor			2012-2025
Variable valve timing		2012-2025	
Variable valve lift		2012-2025	
Cylinder deactivation		2012-2025	
Stoichiometric gasoline direct injection		2012-2025	
Aggressive shift logic – level 1 & 2		2012-2025	
Early torque converter lockup		2012-2025	
5/6/7/8 speed auto transmission		2012-2025	
6/8 speed dual clutch transmission		2012-2025	
High efficiency gearbox		2012-2025	
Improved accessories – level 1 & 2		2012-2025	
Electronic/electro-hydraulic power steering		2012-2025	
Aero improvements – level 1 & 2		2012-2025	
Conversion to DOHC without reducing # of cylinders		2012-2025	
Air conditioner related hardware		2012-20205	
Air conditioner alternative refrigerant	2016-2020	2021-2025	
Cooled EGR		2012-2025	
Conversion to Atkinson cycle		2012-2025	
Turbocharging & downsizing		2012-2025	
Mass reduction		2012-2025	
Advanced diesel		2012-2025	
Hybrid/Electric/Plug-in vehicle non-battery components		2012-2025	
P2 Hybrid vehicle battery-pack components	2012-2016	2017-2025	
Electric/Plug-in vehicle battery-pack components	2012-2025[a]		
Electric/Plug-in vehicle battery charger components	2012-2025[a]		
Stop-start	2012-2015	2016-2025	
Lower rolling resistance tires – level 2	2017-2021	2022-2025	

a Note that the steep learning effects have for EV and PHEV battery packs and charger components have been carried through 5 learning cycles but at a decelerated pace as described in the text.

The learning effects discussed here impact the technology costs in that those technology costs for which learning effects are considered applicable are changing throughout the period of implementation and the period following implementation. For example, some of the technology costs considered in this analysis are taken from the MY 2012-2016 light-duty rule. Many of the costs in the 2012-2016 light-duty rule were considered "applicable" for the 2012 model year. If flat-portion learning were applied to those technologies, the 2013 cost would be 3 percent lower than the 2012 cost, and the 2014 model year cost 3 percent lower than the 2013 cost, etc. As a result, the 2017-2025 costs for a given technology used in this analysis reflect those years of flat learning and would not be identical to the 2012 model year cost for that same technology presented in the 2012-2016 light-duty rule.

Because of the nature of battery pack development (i.e., we are arguably still in the research phase for the types of batteries considered in this proposal, and cost reduction through manufacturer-based learning has only just begun, if it has begun at all), the agencies have carried the learning curve through five steep based learning steps, although at a somewhat slower pace than every two years. This has been done in an effort to maintain the shape of a traditional learning curve. This curve was developed by using the ANL BatPaC model costs as direct manufacturing costs applicable in the 2025 MY. We have then unlearned those costs back to 2012 using the curve shown in Figure 3-2. This is the same curve used in the 2010 TAR (see 2010 TAR at page B-22). This allows the agencies to estimate costs in MYs 2017 through 2025, as well as those costs in each year back to MY 2012, if desired. As noted, this learning curve consists of 5 full learning steps on the steep portion of the learning curve, each of which results in costs being reduced 20 percent relative to the prior step. These learning steps are shown occurring every two years beginning in 2012 until 2020, at which time a 5 year gap is imposed until 2025 when the fifth steep learning step occurs. Beyond 2025, learning on the flat portion of the curve begins at 3 percent per year cost reductions. The smooth line shows a logarithmic curve fit applied to the learning curve as the agencies' cost model would apply learning.

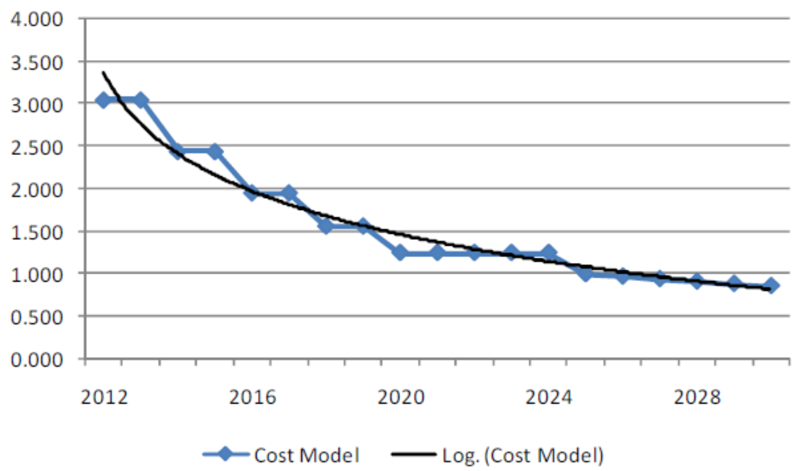

Figure 3-2 Learning Curve used for EV & PHEV Battery-Packs and In-Home Charger Costs

Appendix B: Snapshot into Innovation Process at Appliance Manufacturer, seen through lens of the Industry Trade Press

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Case Study: Product Lifecycle Management

Speeding the Pace of Innovation

Haier uses a product lifecycle management (PLM) system to manage information for 8 product departments and help shrink time-to-market.

Speeding the pace of new product development is one of the main objectives for global manufacturer Haier. Eight of Haier Group's product lines are using product lifecycle management (PLM) technology from Siemens PLM Software, a global division of Siemens Automation and Drives, to support innovation and speed time-to-market. Haier chose the solution based on the software supplier's reputation and the software functionality. PLM implementation was handled by members of Haier's R&D and IT departments along with 60 key users from eight product lines, with support from Siemens PLM.

PLM Reinforces R&D

Haier products include more than 15,100 different specifications and 96 product categories. As this business grows globally, the number of parts and technical documents multiply at a rate up to 40% annually. Before the introduction of PLM solutions, product drawings, documents, and part information were isolated in various systems and existed in different versions. Because the group was unable to standardize information there were consequently problems in quality control, manufacturing, and purchasing. These issues were addressed using Siemens PLM Software's Teamcenter.

The software enabled Haier to establish a centralized part and document library. Today 100% of all technical drawings are in digital format (versus 80% previously) and stored in the Teamcenter vault. Documents have been standardized, and with the PLM system managing the approval/release process and version control, a much-higher level of accuracy and consistency in product information was achieved. This eliminated the inaccurate documentation issues that previously resulted in costs arising from mistakes in ordering and manufacturing.

All parts are also now classified and managed in Teamcenter, which promotes knowledge re-use and has helped Haier reduce the number of parts by 29%. It also helped accelerate the process of part verification and validation by 50%. The company saves money in purchasing because it can buy parts in higher volumes.

Collaboration Shrinks a Refrigerator Design Cycle

Haier is also using the PLM system to improve new product development process efficiency and to support global design collaboration and supply chain operations. Before PLM, too many project delays and inefficiencies arose from a lack of easily referenced product documentation. Now that all new products from the eight product lines are managed using the one PLM system, their status is more visible to management. In addition, the amount of non-value added activities related to collaboration has dropped by 80%, enabling a 15% reduction in time-to-market.

The PLM fosters an environment and an effective means for collaboration among different departments—a must for an effective end product design. During different stages of the actual development process of the refrigerator, the design team engaged people from different departments.

The project team for the refrigerator consisted of members from multiple departments. These included marketing (subdivided into two roles: market and planning), as well as personnel form purchasing, manufacturing (subdivided into module developers and production process developers), standardization, etc.

At the initial stage of development, marketing personnel and product R&D personnel worked together, conducting specific analysis of customer requirements to pin down product specifications and defined a detailed development plan. During some detailed development stages, personnel from purchasing, tooling, production, and other relevant departments participated in the development of the product itself and its parts. At each stage of design, Haier conducted the corresponding review and completed the corresponding approval process—no product design or part design would move ahead to the next stage before it was reviewed and approved. This requirement was implemented from the beginning to the end of the product design.

A product that was recently developed using the PLM system is a multi-door refrigerator. During development, Haier design teams used software products such as as NX (for computer-aided design and analysis) and Teamcenter for product, project, and process management. According to Haier staff who worked on the refrigerator design, PLM-powered development offered significant advantages. Much of the design data for parts was now represented by 3D models, facilitating back-end activities such as die/mould development and digital verification. Because the product development process is more effectively managed, with optimized project management templates, users can more effectively organize various project tasks. Finally, deliverables from product research and development activities are under more control. Design documents and BOMs (bill of materials) are directly managed in the Teamcenter system, and every deliverable has its own approval process. The system notifies every team member who needs to examine and countersign the deliverable. The system also provides markup and browsing tools, so it is easier for personnel to provide comments on the deliverable. During product development, back-end departments are encouraged to engage in the work of front-end departments earlier, thus reducing the number of changes and speeding up the design process.

The Nuts and Bolts of Part Reduction

The PLM system's part library and file library is organized in the form of a classification tree. Each leaf node on the classification tree has its own defined feature attributes; e.g. standard part -> fastener -> bolt -> hexagonal bolt. The feature attributes of a hexagonal bolt include diameter, length, material, etc.

Based on sorting, analysis, and cleanup of historical data, Haier established in Teamcenter a part library architecture that meets its research and development needs and created a library of preferred parts. This library enables designers to quickly position a part by part type, main part parameters, etc. By easily viewing drawings related to a part, designers are able to determine whether or not it will fit the applications.

One of the main reasons the company used a larger number of parts in the past was because designers could not easily search the currently used parts for one that fit the new design. PLM makes accessing currently used parts an easy process, which facilitates the use of the same part in multiple product applications. In addition, Haier established a PLM-based part approval process. At each node of every process a dedicated staffer will evaluate the part to determine if it is already included in the part library and what are the differences between its parameters and the feature values of existing library parts.

The confirmation process for structural parts requiring drawings includes steps for examination, processing, standardization, and approval. Part drawings are being gradually replaced by 3D models. Designers once printed drawing and then shuttled them from one office to another for approval; now the approval process is electronic and handled through Teamcenter. The paper-based markup and browsing tools of the past have been replaced by electronic examination and sign-off steps in the PLM system.

In addition, the "Do you really need to create this part?" examination step is added to the process to promote the reuse of parts.

For parts that do not need drawings, the examination process focuses on their attributes.

Part confirmation and verification ensures that the drawings and attributes of parts pass approval and ensure that the product composed of those parts is able to meet the product specification determined earlier in the process. Structural parts must be normally assembled; electrical parts must be able to meet energy use targets, and so on. In the past such verification required physical prototypes. Now Haier is able to use the PLM system in combination with 3D digital models from NX to conduct virtual assembly analysis, finite element analysis, and other steps to reduce the use of physical prototypes.

Haier's PLM implementation continues to expand. The company's future plans include bringing engineering change and bills of materials under the system, as well as setting up a special process management approach based on Teamcenter to help meet regulatory requirements. The company also plans to extend the PLM system to all divisions and integrate it with with other applications such as ERP, QIS, MES, logistics, and after-sales service to form an enterprise-level business platform covering the entire product lifecycle.

Haier's strength in innovation is evidenced by the company's more than 7,000 patents. Among those, 1234 were awarded for Haier inventions and 589 relate to software intellectual property rights. The company views its PLM implementation as a sound foundation to support innovation and all of its business strategies, including global brand building, diversification and worldwide market penetration.