Thermoeconomic Analysis & Design of Domestic Refrigeration Systems

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ABSTRACT

Domestic refrigeration consumes a significant percentage of total energy used in both South Africa and the United States. This paper explores and optimizes the thermoeconomics of the refrigeration cycle for domestic refrigerators from an exergy perspective during steady state operation. We find that the Energy Efficiency Rating (*EER*) of the compressor has the most effect on system performance and economics, and, similar to previous studies, we find that the cost of refrigerating is driven by compressor costs. Finally, we note that future efforts to reduce compressor costs should be accompanied by a corresponding effort to improve compressor thermodynamic performance.

1. INTRODUCTION

Electricity usage in South Africa is becoming increasingly widespread as the National Electricity Regulator (NER) works to fulfill the government's promise to provide electricity to the entire country by 2010. As electricity availability has increased, demand for appliances has grown rapidly. One example is domestic refrigerators, which are desired by consumers because they improve quality of life and increase available free time. Accordingly, demand for refrigeration has grown rapidly, as shown in Figure 1.

Over the last two decades, refrigerator technology has improved dramatically, resulting in increased energy efficiency. In 1985, a typical US refrigerator used an average of 800-1000 kWh per year, while a modern US refrigerator uses an average of around 450 kWh per year. Additionally, there is ongoing research to increase the affordability of domestic refrigerators in South Africa [4].

The refrigeration markets in the United States and South Africa are similar, as shown by Figure 2, which is based on advertised prices in July and August 2005. The horizontal axes have different units but identical physical dimensions. The vertical axes show different currencies but are equal in terms of the exchange rate as of 28 July 2005.

Although there is more variety in the size of household refrigerators sold in South Africa, the costs to consumers are approximately equal.

Refrigerator component sources are similar in the two countries, too. Components are manufactured in a mix of both local and foreign countries, with heat exchangers often manufactured near where refrigerators are assembled and compressors typically purchased from international suppliers.

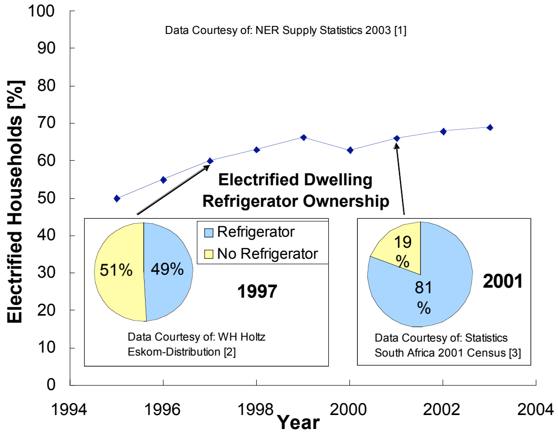
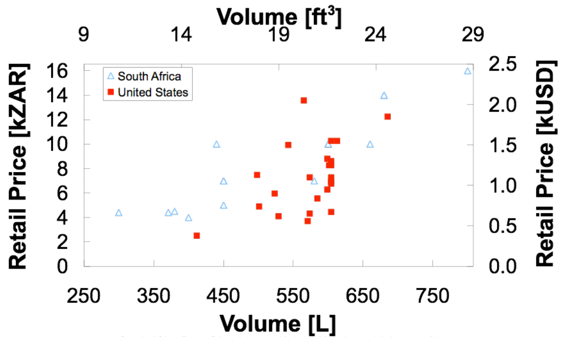


Figure 1: Refrigerator Ownership in Electrified South African Dwellings.



South Africa Data: Dion Adverts 18 July, 28 July, and 3 August, 2005
US Data: Whirlpool, Kenmore, General Electric, Amana, Maytag, KitchenAid, Frigidaire Websites
Currency Rate 28 July, 2005 16:45 GMT: 1 USD = 6.613 ZAR

Figure 2: A Price-Size comparison between US and South African Refrigerators.

The research that follows is based on cost data from the US domestic refrigeration market. The analysis presented here could be extended to the South African context provided that component cost data is available. However, the broad similarities in the US and South African markets indicates that the results presented below are generally applicable in both countries.

As the difference between global electrical power production and rising power demand narrows, it becomes increasingly important that, worldwide, refrigerators use minimum energy resources without sacrificing value to the consumer. Frequently, engineering design optimizations intended to meet such goals are based on the first law of thermodynamics and neglect second-law effects. Both laws can be applied to optimization by exergy analysis.

2. LITERATURE SUMMARY

Exergy (or availability) is a thermodynamic property that represents the maximum work that can be done with a given fluid stream in a reversible process. In recent decades, exergy analysis has become accepted as an alternative to traditional energy analyses for thermal system optimization. Exergy analyses can be used to evaluate the performance of thermodynamic systems. For example, exergy analysis has been used to evaluate the efficiency of ozone-friendly R12 replacements to find which option is most beneficial for a given situation [5]. Exergy analysis has also been used to compare the performance of traditional thermostatic-controlled compressors with load-adjusting, variable speed compressors [6].

The applications of exergy analysis extend to complex applications of refrigeration. One example is an analysis of a multistage cascade refrigeration cycle for production of liquefied natural gas. The analysis calculates exergetic efficiencies for the components and the overall system [7].

In addition to applications evaluating refrigeration cycles, exergy analysis can be applied to heat engines [8] and co-generation systems [9].

2.1 EXERGETIC ANALYSIS

Exergy is the name given to the quantity representing the maximum work that can be done with an energy source in an ideal (reversible) process. Unlike energy, exergy is not conserved: it can be destroyed [9].

Like the thermodynamic state variable enthalpy, exergy is a combination of other thermodynamic properties. It is defined as:

$$e_i = (h_i - h_0) - T_0(s_i - s_0) \qquad (1)$$

$$\dot{E}_i = \dot{m}_i e_i \qquad (2)$$

where e_i is specific exergy at statepoint i, $\dot{E}$ is the exergy rate in watts, $\dot{m}$ is mass flow rate, h is enthalpy, T is temperature, and s is entropy. Note that h_0, T_0, and s_0 are evaluated at the assumed surroundings temperature and pressure, typically 25 °C and 100 kPa, respectively. Exergy balances within a system across each component form the basis for thermoeconomic analyses, also referred to as exergoeconomics [9].

In exergy analyses, costs are associated with every exergy stream in a system. Exergy costing associates a cost with the destruction of exergy, or thermodynamic irreversibility, in each component of a system. The cost of exergy destruction varies depending on the usefulness of the flow stream to which it is assigned [9].

2.2 EXERGY-BASED THERMOECONOMICS

Exergy-based thermoeconomic analyses have many applications. Power cycles, particularly power plants, are frequently analyzed and optimized using exergy-based thermoeconomics [9]. Exergy analyses can be used in examining domestic refrigeration systems, too. Various refrigerants have been examined using techniques of exergy destruction to see which causes the least exergy destruction in specific components of the refrigeration cycle and for the system over all. This approach has been particularly useful for comparing alternative refrigerants to R12. For example, one study examined a refrigerator cycle and a separate freezer cycle and found that the component that destroyed the most exergy in the system was the compressor followed by the evaporator and then the condenser [10].

Refrigeration cycles can also be optimized for a given set of operating conditions to minimize the overall exergy destruction of the system. Considering a table-top size, single compartment R-12 refrigerator, Dingeç and İleri, optimized the thermoeconomics of Turkish refrigerators. They concluded that the optimum condenser area should be larger than that of the evaporator and that the compressor should have an isentropic efficiency of approximately 36%. They also concluded that the cost curve for the compressor has a strong effect on the optimized system design [11].

3. REFRIGERATOR PHYSICAL AND THERMODYNAMIC MODELS

For the present study, we developed physical and thermodynamic models for a domestic refrigerator.

3.1 PHYSICAL MODEL

We analyzed a household refrigerator with an interior volume of 21 cubic feet (approximately 600 L) with a top freezer section and a bottom refrigerator section. The evaporator produces cold air primarily for the freezer. A fraction of the cooled air is diverted from the freezer compartment into the refrigerator compartment to cool it. The total cooling load of the refrigerator is assumed to be 55 W, and the compressor is assumed to run 3999 h/yr (46% duty cycle).

We assume that refrigerator and freezer compartment door openings cause air from the surroundings to mix with the refrigerated air, causing additional thermal load on the refrigeration system. To model this transient effect with a steady-state model, we mix room-temperature air with the cold refrigerator air before it enters the evaporator. The mixing ratio ($f_{open\ door}$) is an input variable to our model. However, for the present study, we set $f_{open\ door}$ at a constant value of 0.1.

R134a is the refrigerant, and thermodynamic properties for air and R134a are provided by Engineering Equation Solver (EES) software [12].

3.2 THERMODYNAMIC MODEL

The model vapor-compression refrigeration cycle is shown in Figure 3.

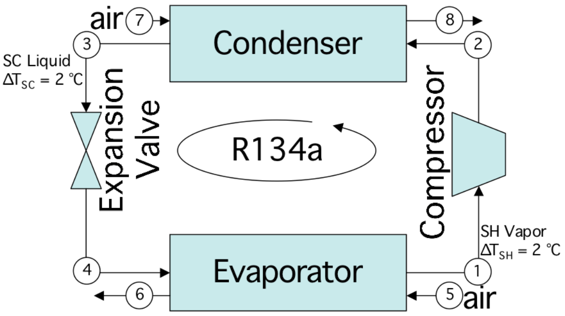


Figure 3: Model Refrigeration Cycle.

For this model, refrigerant and air pressures in both the evaporator and the condenser are assumed constant. We assume superheating (2 °C) and subcooling (2 °C) at the evaporator and condenser outlets, respectively. Because we assume fixed values for refrigerant superheating and subcooling, this model is beneficial for evaluating compressor effects on system behavior. However, it is less helpful for evaluating the effects of heat exchanger designs. The thermal resistance of the refrigerant side of the heat exchangers is assumed to be negligible compared to air-side thermal resistances.

4. COST MODEL

This section describes the cost model for the present study.

4.1 PRIMARY COST VARIABLES

Surface area is the variable upon which we base the overall cost for both condensers and evaporators, because the amount of material in the exchanger dominates the purchase cost of the part for a refrigerator manufacturer.

Energy Efficiency Rating (*EER*) is a common measure for compressor performance and thus a good measure of cost ranges. The American Council for an Energy Efficient Economy, the group responsible for appliance labeling in the US, uses the compressor Energy Efficiency Ratio (*EER*) to determine refrigerator efficiency. *EER* is the ratio of evaporator load to electrical energy consumed by the compressor.

4.2 COMPONENT COST MODELS

The following sections describe the cost models for the primary components of model refrigerators.

4.2.1 Condenser

Pricing for the typical range of condensers runs anywhere from 3 to 8 USD depending on size and manufacturing quantity. (These prices are for large manufacturing runs.) The majority of units are priced between 3 USD and 5 USD. The majority of condensers used in new refrigerators in the United States are known as “dynamic” condensers. Dynamic condensers are smaller and use forced convection compared to larger static condensers that use natural convection. The cost model for dynamic condensers for the present study is given by the following equation

$$C_{cond} = \$4.31\left(\frac{A_{cond}}{0.45\,\mathrm{m}^2}\right)^{2.5} \tag{3}$$

where C_{cond} and A_{cond} are condenser cost and air-side surface area. The compressor cost model used for the present study is much steeper (in terms of cost vs. area) than either the Bejan [9] or Dingeç [11] cost models, because dynamic condensers require additional costs for fans and other mounting hardware compared to static condensers modeled by Bejan and Dingeç.

4.2.2 Evaporator

In previous work, Dingeç [11] used an evaporator cost model whose cost rises much more steeply than the present model. Dingeç examined a small refrigerator with a small cooling load, thus requiring less surface area for the evaporator. The evaporator cost model used for this study was generated using several specific data points from a US manufacturer. The following equation represents the present cost model

$$C_{evap} = 1.25\left[\frac{\$}{\mathrm{m}^4}\right]A_{evap}^2 + \$1.83 \tag{4}$$

where C_{evap} and A_{evap} are evaporator cost and air-side surface area.

4.2.3 Compressor

A cost model for the compressor was generated using a curve fit to publicly-available data from a compressor manufacturer. The information shows that compressors for domestic refrigerators are available with Energy Efficiency Ratings (*EER*s) ranging between 0.60 and 1.8 with cost ranging from 30 USD to 50 USD. The compressor cost model is represented by the following equation

$$C_{comp} = \$45.11\left(\frac{EER}{1.5}\right)^{0.5} \tag{5}$$

where C_{comp} is compressor cost.. For the present study, *EER* is a dimensionless number.

4.2.4 Expansion Valve, Other Costs, and Purchase Price

The expansion valve cost (C_{valve}) has little effect on the system cost, and its cost is specified as a constant (8 USD) for simplicity. Additional costs (C_{other}) include the refrigerator structure, insulation, interior lights, etc. These other costs are modeled as a constant value of 75 USD.

The purchase price (*PP*) for a refrigerator is based on the sum of the component prices as shown below.

$$PP = 7.7 \times \left(C_{comp} + C_{evap} + C_{cond} + C_{valve} + C_{other} \right) \qquad (6)$$

The factor of 7.7 accounts for labor costs and retail markup relative to component costs.

5. EXERGY-BASED THERMOECONOMIC ANALYSIS

Our thermoeconomic analysis evaluated the exergy destruction of each component, and we found, similar to Dingeç [11], that compressor performance has the strongest effect on the economics of the system. Thus, the following sections show model results in terms of compressor *EER*. By doing so, we can evaluate costs due to exergy destruction in each component of the system and identify the cost to produce the cold air stream leaving the evaporator.

5.1 EXERGY ANALYSIS

The exergy for each of the eight state points of the system (four air and four refrigerant) was calculated using equations 1 and 2 as given above. Exergy balances were then constructed for each of the four components in the refrigeration system. Exergy destruction, $\dot{E}_D$, is calculated for each component by the following equation.

$$\dot{E}_{D,component} = \sum \dot{E}_{in} - \sum \dot{E}_{out} \qquad (7)$$

Figure 4 shows the exergy destroyed by each component as the *EER* of the compressor changes and the evaporator and condenser surface area remain constant. As the compressor performance improves, $\dot{E}_{D,total}$ decreases. We also evaluated the exergy destruction for each component as a function of the surface area of the heat exchangers. However, the greatest variation of exergy destruction occurred in the compressor analysis, and the compressor dominates the total exergy destruction by the system for typical designs.

5.2 TRADITIONAL ECONOMICS

Traditional economic analysis seeks to minimize item cost from the manufacturer's point of view. In the case of a domestic refrigerator both purchase cost and cost-to-own (electricity cost over the lifetime of the refrigerator) are important for a consumer. The cost to own the refrigerator changes each year due to inflation and real escalation of electricity rates.

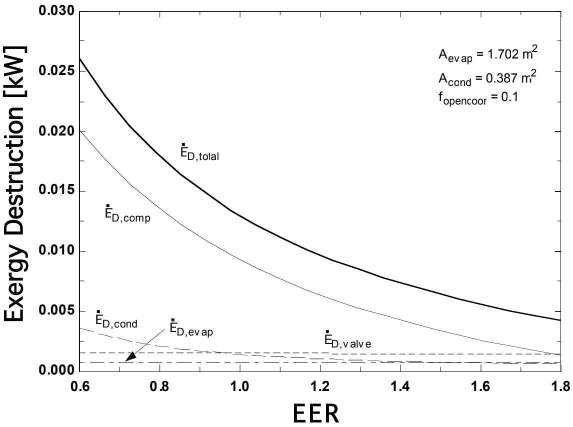


Figure 4: Exergy Destruction of components as a function of compressor *EER*.

We take a "levelization" approach where we consider the time value of money and levelize lifetime costs to a constant annual amount. The levelized purchase price, PP_L, distributes the initial cost of purchasing the refrigerator over the duration of its life. The levelized purchase price accounts for inflation, r_i, and the assumed product lifetime (12 years). The levelized electric cost accounts, additionally, for escalation of electricity costs over the lifetime of the refrigerator.

Although the purchase price is the largest component of the total levelized cost (purchase price plus electricity costs), the cost of electricity is the driving force in making the refrigerator economical from an ownership perspective. The amount of electricity needed for operation is directly related to the efficiency of the compressor. And, the decrease of electricity usage is greater than the increased purchase price of the compressor over time. For this reason, an examination of lifetime costs suggests a compressor with a high *EER* to reduce the lifetime cost of the refrigerator. There is a shallow minimum of levelized cost at about *EER* = 1.4. Figure 5 shows these results.

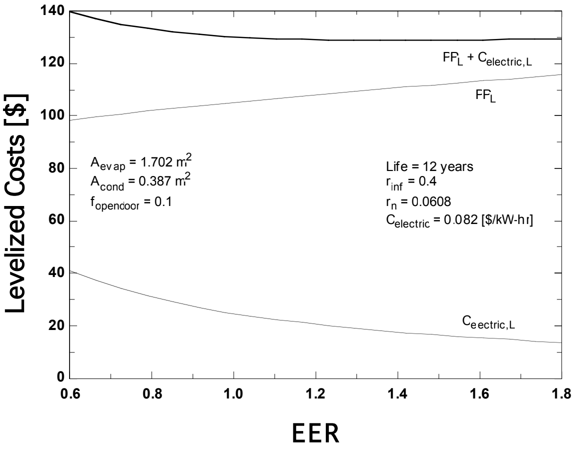


Figure 5: Levelized Costs.

5.3 EXERGY BASED ECONOMICS

We assign exergy-related costs to each stream based on the method of Bejan [9]. There are non-zero costs associated with the cold air exiting the evaporator and the refrigerant statepoints (c_i in units of \$/J). The cost rates ($\dot{C}_i$ in units of \$/s) are the operating cost rates to develop the thermodynamic conditions at any statepoint as the refrigerator is running.

The cost of rates at each state point are related to exergy rates by equations of the form:

$$\dot{C}_i = c_i \dot{E}_i \tag{8}$$

In addition to the exergy costs associated with the eight streams, each component also shares a portion of the initial purchase cost of the system, or the capital investment cost, denoted as $\dot{Z}$ and calculated as follows

$$\dot{Z}_{component} = \frac{PP_L \dfrac{C_{component}}{PEC_{tot}}}{t_{operating\ per\ year}} \tag{9}$$

where $\dot{Z}_{component}$ is the purchased equipment cost rate for a given component, PP_L is the levelized purchase price for a the refrigerator, $C_{component}$ is the cost of the component, PEC_{tot} is the sum of the component costs, and $t_{operating\ per\ year}$ is the total operating time per year. Using the costs of exergy at the state points ($\dot{C}_i$) and the cost rates for each component ($\dot{Z}_{component}$), cost balances can be constructed for each component in the same way that exergy balances are constructed. Specifically:

$$\sum \dot{C}_{in} + \dot{Z}_{component} = \sum \dot{C}_{out} \tag{10}$$

In the cost balance equations, each capital investment cost rate ($\dot{Z}_{component}$) is assigned to the main component to which it belongs. However there are costs manufacture a refrigerator in addition to the four primary components. So, a fifth cost term ($\dot{Z}_{other}$) is included to compensate for items such as insulation, refrigerant, and structure. This capital investment cost rate must also be assigned to an exergy stream. Because the objective of the system is to cool air, these additional costs are assigned to the cold air stream leaving the evaporator. Consequently, the adjusted cost rate for statepoint 6, $\dot{C}'_6$, is calculated using:

$$\dot{C}'_6 = \dot{C}_6 + \dot{Z}_{other} \tag{11}$$

The cost rate $\dot{C}'_6$ represents the cost rate to produce refrigeration.

5.3.1 Cost to Produce Refrigeration

From a consumer point of view, it is desirable to minimize the cost to produce refrigeration. The cost to produce refrigeration is a function of several parameters, including the fraction of time the doors are open and the costs of the primary system components: compressor, condenser, and evaporator.

First, we consider the fraction of time the door is open as shown in Figure 6. Costs increase for higher door opening time, as expected.

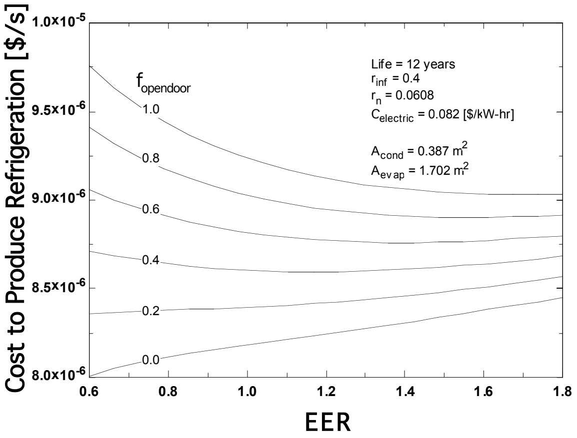


Figure 6: Cost to Produce Refrigeration Related to Door-Open Time.

Figure 7 shows that (for $f_{open\ door} = 0.1$) cold air becomes more expensive to produce as the compressor *EER* increases. It is also clear that the areas of the condenser and evaporator have less effect than the compressor on the cost to produce refrigeration, though the cost to produce refrigeration is least expensive for smaller components. These trends result from component costs driving the total cost of ownership for the refrigerator.

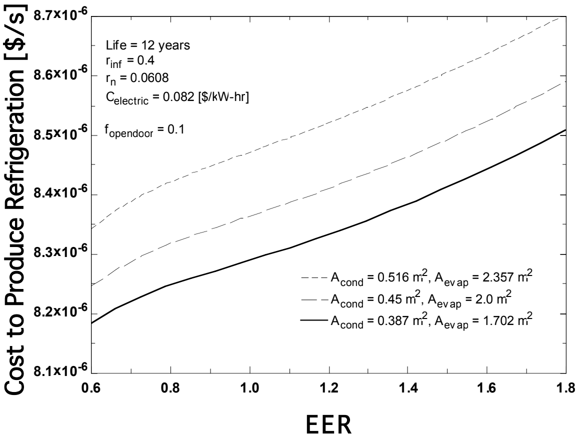


Figure 7: Cost To Produce Refrigeration.

5.3.2 Cost of Exergy Destruction

Each component destroys exergy. The resulting cost rate for exergy destruction by each component ($\dot{C}_{D,component}$) is shown in Figure 8. Because the compressor destroys the most exergy, the costs associated with its exergy destruction are greatest.

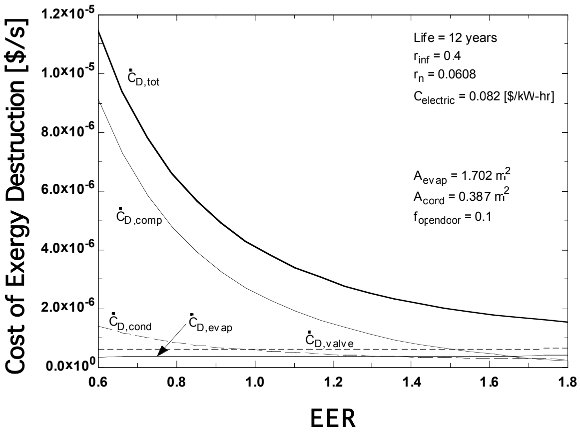


Figure 8: Cost of Exergy Destruction.

5.3.3 Exergoeconomic Factor

One indicator of thermoeconomic performance is the exergoeconomic factor, *f*. The exergoeconomic factor is defined as:

$$f_{component} = \frac{\dot{Z}_{component}}{\dot{Z}_{component} + \dot{C}_{D,component}} \qquad (12)$$

The exergoeconomic factor for a component indicates the ratio between the cost to purchase the component and the cost of exergy destruction by the component. A low value of *f* indicates a component with low initial cost and high exergy destruction cost. More money could be spent on a component with low *f* to improve the overall cost-effectiveness of the system. On the other hand, a component with high *f* has very high component costs and low exergy destruction costs. Less money should be spent up front on a low-*f* component to improve cost-effectiveness of the system. The exergoeconomic factor can be calculated for each of the components in the system.

The exergoeconomic factor for each component is shows as a function of compressor *EER* in Figure 9. High compressor EER results in high f_{comp}: the compressor is too expensive. Low EER results in low f_{comp}: the compressor is too inefficient and therefore too costly due to high exergy destruction costs. This analysis shows that an *EER* of 1.1–1.3 is close to optimal from an exergy point of view.

The evaporator and expansion valve show reasonable exergoeconomic factors. However, f_{cond} is low, and a larger condenser may be warranted.

6. IMPLICATIONS FOR DESIGN

The above analysis indicates that many factors are important for the design of domestic refrigeration systems. And, there are several competing design objectives. (1) On a national basis, very high-efficiency systems that use as little electricity as possible are desirable in an effort to minimize energy usage in the face of a narrowing gap between energy supplies and energy consumption. A refrigerator design that meets this national objective would minimize the levelized electricity cost ($C_{electric,\,L}$). (2) Consumers, on the other hand, may desire minimum cost to purchase and operate a refrigerator. A refrigerator design that meets this consumer objective would minimize the sum of the levelized purchase price and electricity cost (PP_L + $C_{electric,\,L}$). Or, more likely, (3) consumers may desire minimum purchase price. A refrigerator design that meets this consumer objective would minimize the levelized purchase price (PP_L).

We can evaluate the three competing design objectives in terms of optimal refrigerator designs using today's component pricepoints and potential future cost reductions for compressors.

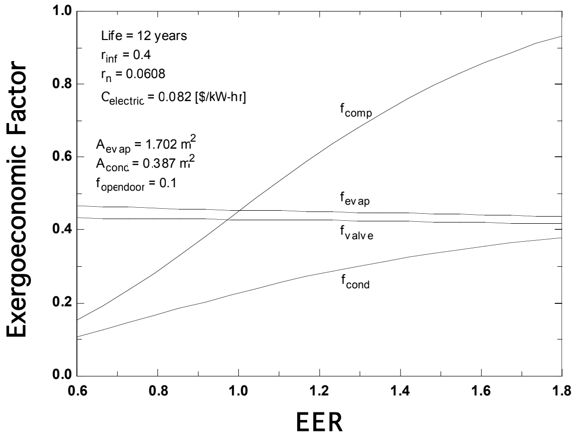


Figure 9: Exergoeconomic Factor.

6.1 EXISTING TECHNOLOGY

Table 1 shows optimal refrigerator designs for the three optimization objectives discussed above. Each row in the table assumes A_{cond} = 0.387 m^2 and A_{evap} = 1.702 m^2.

Table 1: Optimal Designs Using Existing Technology.

Minimization Objective	*EER* [-]	$C_{electric,\,L}$ [$]	PP_L [$]	$C_{electric,\,L} + PP_L$ [$]
$C_{electric,\,L}$	1.8	13.7	115.5	129.2
$PP_L + C_{electric,\,L}$	1.4	17.8	110.6	128.4
PP_L	0.6	41.1	98.4	139.5

6.1.1 Minimum Electricity Usage

The first row of Table 1 shows that a very high-efficiency compressor is required to minimize electricity usage. Doing so increases the purchase price for the consumer (PP_L), but it minimizes the cost to operate the refrigerator ($C_{electric,\,L}$).

6.1.2 Minimum Cost to Own and Operate

The second row of Table 1 shows that a moderate-efficiency compressor is needed to achieve minimum cost to own and operate a refrigerator. An *EER* of 1.4 provides a good balance between up-front initial costs and future electricity usage. If electricity costs increase, a higher *EER* will be more valuable to consumers, and the optimum *EER* will increase beyond 1.4.

6.1.3 Minimum Purchase Price

The third row of Table 1 shows that a low-efficiency compressor provides minimum cost to purchase a refrigerator. This is beneficial to consumers as it reduces the barrier to obtaining refrigeration technology. On the other hand, it significantly increases both lifetime electricity usage and electrical cost to the consumer.

6.2 FUTURE TECHNOLOGY

As research continues [4], technology breakthroughs may affect the thermoeconomics of domestic refrigeration systems. In particular, it may become possible to provide the same level of compressor efficiency for reduced cost. If compressor price reduction can be achieved, both consumers and national utility operators will benefit. Consumers obtain lower purchase prices and lifetime costs for the refrigerator. National utility operators see reduced electricity demand. All three design objectives can be met.

So, we repeat the previous analysis, but we assume a 25% reduction in compressor cost to achieve the same *EER*. Table 2 shows the effect of improved compressor technology. All the costs are lower, but the compressor *EER* that minimizes the cost to own and operate the refrigerator increases significantly as shown in the shaded cells of the two tables.

Table 2: Optimal Designs Using Future Compressor Technology (25 % Compressor Cost Reduction).

Minimization Objective	*EER* [-]	$C_{electric,\,L}$ [$]	PP_L [$]	$C_{electric,\,L} + PP_L$ [$/s]
$C_{electric,\,L}$	1.8	13.7	105.4	119.1
$PP_L + C_{electric,\,L}$	1.7	14.7	104.4	119.1
PP_L	0.6	41.1	92.6	133.7

Figure 10 explores this relationship in detail. The *EER* necessary to achieve minimum cost to own and operate a refrigerator is shown by a dark line. The graph shows that if a compressor technology breakthrough were achieved, the *EER* that minimizes the cost to own and operate a refrigerator will increase. The key is to obtain both compressor cost reductions *and* efficiency improvements to re-optimize household refrigeration systems for any new compressor cost point.

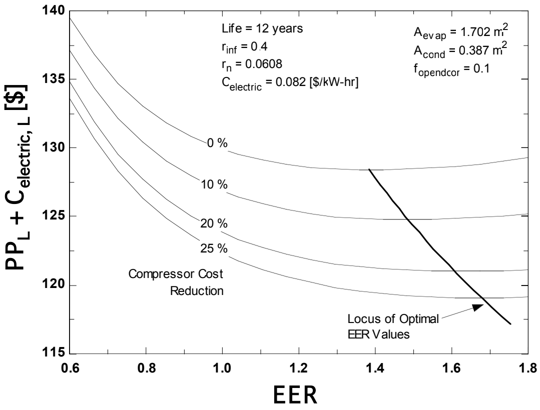


Figure 10: Effect of Reduced Compressor Cost.

7. CONCLUSIONS

Because compressor technology has the greatest effect on the performance and economics of domestic refrigerators, focusing research efforts on reducing the cost to manufacture compressors has a positive effect on the purchase price *and* the cost to own and operate a refrigerator. However, compressor cost decreases must be accompanied by efficiency increases if the greatest impact on the cost to own and operate a refrigerator is to be achieved. If efficiency increases can accompany cost reductions, the purchase price can be reduced, the cost to own and operate a refrigerator declines, and nationwide electricity demand decreases.

8. FUTURE WORK

There are several directions in which this study could be extended in the future.

The present model of the refrigeration system has fixed air velocities across both the condenser and the evaporator, assuming that pressure drop and the power for the fans are negligible. An enhanced model would specify fans and quantify the air-side pressure drop across the heat exchangers to account for the exergy destroyed by pressure drop in the air streams. Including this effect would increase $\dot{E}_D$ in the heat exchangers, but it is not expected to have a significant effect on the economic results presented herein.

Empirical data from heat exchangers could be used to incorporate refrigerant pressure drop through both heat exchangers. In the present model it was assumed that refrigerant-side pressure drop, like air-side pressure drop, was negligible. As with the air-side pressure drop, this pressure drop is not expected to alter the economic results presented herein.

Detailed suction-line heat exchanger thermodynamic and cost models could replace the expansion valve model.

Incorporating two- or three-zone models of the refrigerant flowing through the heat exchangers (according to subcooled, two-phase, or superheated refrigerant states) would improve the accuracy of the heat transfer predictions in the heat exchangers.

Tracking the distribution of the refrigerant mass around the system would enable a more precise model of the heat transfer and relieve the need to specify evaporator superheating and condenser subcooling.

9. ACKNOWLEDGEMENTS

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