# Dynamics of energy efficiency in Swedish buildings

**Joel Swisher, Lund University**
**Claes Hedenström, Vattenfall AB**
**Anders Lewald, NUTEK**

## 1. SYNOPSIS

This paper discusses the results of a time-dynamic analysis of the possible effects of energy performance standards for household appliances and utility conservation programs for non-residential lighting in Sweden.

## 2. ABSTRACT

This paper discusses the results of a time-dynamic analysis of the possible effects of energy performance standards for household appliances and utility conservation programs for non-residential lighting in Sweden. We develop dynamic scenarios of household appliance electricity demand and efficiency improvement, based on various levels and timing of energy performance standards. The scenarios account for the dynamics of equipment turnover, existing trends in technology, energy consumption changes over the appliance lifetime, and the distribution of energy efficiency among appliance models on the market. We consider minimum performance standards that remove the least efficient products from the market, as well as public procurement (technology push) to accelerate the high-efficiency appliance market. We focus on refrigerators and freezers[1] but also consider washing machines and other durable appliances. In addition, we examine the dynamics of energy efficiency implementation in the Swedish service sector over the next 15-20 years. The emphasis is on utility programs and on one category of end-use, namely lighting. Efficient technologies include improved lamps, ballasts, luminaires, controls and system designs to better exploit natural daylight and task lighting. We develop dynamic scenarios of electricity demand and efficiency improvement, based on various levels and timing of DSM investment. We examine the achievable rate of energy-efficiency implementation, which over time increases as new energy-saving opportunities appear in new and renovated buildings but is limited by the rate of turnover of existing buildings and equipment. Efficiency measures are further constrained by administrative costs, market penetration limits and the technical and institutional feasibility of some efficiency measures.

## 3. INTRODUCTION

With the exception of strict thermal standards for residential buildings, Sweden presently does not have strong public policies in regard to energy use in buildings. With sufficient hydro and nuclear capacity, Sweden has low electricity prices and marginal costs, at least in the short term. In the future, however, there could be major changes in the electric utility industry, such as reduced use of nuclear power or possible integration into Europe's power market, which would increase the price or at least the *value* of electricity services. The prospect of such changes suggests the need for stronger policies and programs in regard to energy use in buildings. Future policy measures could include increased energy or carbon taxes, energy performance standards, and mandatory utility demand-side management (DSM) programs.

We hope to resolve some of the disagreement in Sweden over the realistic potential for electricity savings through technical efficiency improvements. Some industry groups find less than 10 percent savings potential based on measures that can be implemented immediately under today's economics, while other analyses suggest cost effective technical potential of 50 percent or more, compared to present technology (NUTEK, 1990). In order to study the question of potential energy savings and rates of efficiency improvement, we analyze the dynamics of the possible effects of energy performance standards for household appliances and utility conservation programs for non-residential lighting in Sweden.

## 4. PERFORMANCE STANDARDS FOR HOUSEHOLD APPLIANCES

In this section, we consider the potential impact of introducing energy performance standards for residential appliances, together with the use of public technology procurement and the possible application of higher energy prices. The effect of carbon taxes on electricity use is unlikely to be significant in Sweden, because almost none of the generation capacity is fossil fuel-fired. Increased energy prices or taxes would favour energy-saving investments; however, in the presence of the existing institutional and market barriers to energy efficiency, the impact is likely to be small. We consider the effect of higher electricity prices in one of the scenario cases below. The resulting effect is small, as shown by other studies, and we focus most of our analysis on policy measures that directly influence the technical energy efficiency of the equipment produced and installed.

The impact of utility DSM programs in Sweden is unlikely to resemble that of the regulated North American utilities, as the large Swedish utilities have little direct contact with residential customers, who are served by local distribution authorities. Although some of these distribution utilities have sponsored campaigns for energy-efficient lighting, it is difficult for such short-term programs to influence the choice of durable appliances. Moreover, the planned introduction of competitive forces into the Swedish utility market might encourage utilities to use DSM programs to make their service (kilowatt-hours together with DSM measures) more attractive and economical to the non-residential customer. DSM could thus serve as a tool to defend the utility's market share against new competition, but it is less likely to play a role in the residential sector where the customer is essentially "captive."

For household appliances, energy efficiency standards are an effective way to remove energy-wasting products from the market and capture a large share of the least-expensive energy-saving potential. However, the rate of energy-efficiency implementation is limited by the rate of turnover of existing equipment, and it is subject to constraints on market penetration rates. Also, with standards in place, the remaining savings potential becomes more expensive and difficult to reach with prescriptive measures, further limiting the scope for utility programs.

We develop dynamic scenarios of household appliance electricity demand and efficiency improvement, based on various levels of energy performance standards. The scenarios account for the dynamics of equipment turnover, existing trends in technology, energy consumption changes over the appliance lifetime, and the distribution of energy efficiency among appliance models on the market. We consider minimum performance standards that remove the least efficient products from the market, as well as public procurement (technology push) to accelerate the high-efficiency appliance market. We focus on refrigerators and freezers but also consider laundry-room appliances and dish-washing machines.

### 4.1. Methods and assumptions

The scenarios are based on a simple but detailed vintage model that contains breakdowns of the historical stocks of each type of appliance, which are extrapolated into the future according to a variety of different assumptions, depending on the case. Data on historical appliance energy use came from Sweden's Konsumentverket, the consumer-product certification agency, and NUTEK, the technology and industrial development ministry (Konsumentverket 1992). Year-by-year sales data were provided by the appliance trade association, Elektriska Hushållsapparat Leverantörer, and historical and projected future saturations came from NUTEK and Vattenfall AB, the largest Swedish electric utility and formerly the state power board (IMU 1991).

The fraction of a given year's appliance sales still remaining in service in a later year is a non-linear function of the appliance's age. Few units wear out in the first few years of use, and then the survival rate decreases rapidly as the average lifetime approaches. As an example, the survival rate for a unit with an average lifetime of 15 years would be 80% after 10 years, 50% after 15 years, and 4% after 20 years. The exact lifetimes and decay-exponents used in the analysis are calibrated to agree with observed sales data and estimates of historical appliance saturation levels. The estimated lifetime for the appliances studied ranges form 12 years for dryers to 16 years for freezers. Several appliances such as refrigerators, freezers and clothes-washers have reached a stable level of market saturation, resulting in nearly constant annual sales.

Others, including fridge-freezers and dish-washers, are increasing in sales and saturation, and their future sales are estimated such that they reach saturation levels comparable to the other appliances.

The energy consumption of the appliances in service in a given year is the sum of the energy consumption values for each vintage (age) of models since the time when the appliance was introduced. The consumption for a given vintage is the product of the surviving population of appliances and the average energy use for that vintage. Changes in the consumption of new models, for example the addition of energy-using features or improvements in energy efficiency, are slow to affect the population's average consumption, which is heavily weighted toward the older existing models. For refrigerators and freezers, we assume that new-model energy efficiency declines 2 percent/year over the appliance's life. This factor reflects the deterioration of components and lack of professional maintenance.

The present energy consumption for each appliance type is given in Table 1, together with the average and best available unit consumption, as of 1990. Laundry appliances include both individually-owned units in single-family and multi-family households as well as units in the common laundry rooms of many larger multi-family housing areas. Although the saturation of washers and dryers is increasing in multi-family households, many people still use the common laundry-room equipment for large or special loads (NUTEK 1991).

**Table 1.** ***Appliance energy consumption in Sweden, 1990***

| | 1990 Total Consumption GWh | Typical Size or Daily Load | Consumption (kWh) at Typical Size/ Load | |
|---|---|---|---|---|
| Unit | | | Average | Best |
| Refrigerators | 1200 | 270 liter | 300 | 180 |
| Freezers | 1900 | 180 liter | 490 | 290 |
| Fridge-freezers | 1000 | 200/100 l | 590 | 320 |
| Clothes-washers | 1300 | 2 kg/day | 470 | 350 |
| Tumble dryers | 400 | 2 kg/day | 720 | 480* |
| Dish-washers | 600 | 0,5 load/d | 280 | 200 |

*This value applies to a model available in Denmark
Sources: NUTEK 1992, Konsumentverket 1992, Möller 1992

### 4.2. Scenario projections

For each appliance type, we construct several future scenarios of average new-model energy consumption and efficiency improvement. We use the vintage model to calculate how these trends affect the total energy consumption over time. The total number of new and existing appliances in a given year is assumed to be the same for each scenario. Although we do not consider the possibility of early retirement of older inefficient models as a policy option, this might be an option for future utility programs if they address the residential appliance market.

One scenario we use as a point of reference is to hold the consumption of new units constant at their 1990 levels. This is not a "frozen" efficiency scenario, because the efficiency of new units is generally better than that of older existing units. Thus, even with constant new-model efficiency, the average efficiency of the appliance population will improve gradually over time.

Another scenario is the reference scenario, which is our best estimate of the trend of energy consumption in the absence of major new policy interventions. Although consumer behavior is not highly responsive to energy efficiency opportunities or energy prices, it appears likely that recent trends in efficiency improvement will continue. The average new-model consumption values reach approximately the level of today's best-available unit by the end of our scenarios (2010). This efficiency trend is similar to or somewhat slower than the historical trend for most types of appliances, and it is consistent with the electric industry's recent forecasts, which also do not consider policy changes (Kraftsam 1990).

The first policy intervention we consider is public technology procurement, applied to freezers, fridge-freezers and washing machines. This process, developed in Sweden by NUTEK, combines government incentives with guaranteed orders from organized buying groups (such as apartment managers) in a competitive solicitation for improved energy-efficient products (Nilsson 1992). Manufacturers are invited to enter prototype models with certain features, including a specified minimum energy efficiency, and the entries are judged according to their efficiency and how well they satisfy the other requirements. The winner(s) receive incentive payments and a guaranteed initial order sufficient to begin production of the new model.

This process was successfully completed in 1991 for fridge-freezers, with the winning model's energy use 30 percent below the previous best available and 50 percent below the average in the market.[2] Although the winning model entered the market with a substantial price premium, within one year a competing firm offered a new model with energy use comparable to the winner and a price close to other models on the market (NUTEK 1992). The procurement process has also been applied in Sweden to high-performance windows, high-frequency lighting ballasts, computer displays that turn off automatically, and most recently to washing machines tailored to use in small households.

**Table 2.** ***Appliance energy performance standards, 1996-2005***

| | 1990 | 1990 | 1996 | 1999 | 2002 | 2005 |
|---|---|---|---|---|---|---|
| | Average | Best | Energy Performance Standards | | | |
| | kWh | kWh | | kWh | | |
| Refrigerators(per l/yr) | 1,1 | 0,7 | | 0,7 | 0,5 | 0,35 |
| Freezers(per l/yr) | 2,2 | 1,5 | 2,2 | 1,5 | 1,1 | 0,7 |
| with tech. proc. | | | 2,2 | 1,3 | 1,0 | 0,7 |
| Fridge-freezers (per l/yr) | 1,5 | 1,1 | 1,5 | 1,1 | 0,9 | 0,7 |
| with tech. proc. | | 0,8(1991) | 1,5 | 0,8 | 0,6 | 0,45 |
| Clothes-washers (per kg) | 0,6 | 0,44 | | 0,44 | 0,34 | 0,24 |
| with tech. proc. | | | | 0,34 | 0,28 | 0,22 |
| Tumble dryers (per kg) | 1,0 | 0,7* | | 0,7 | 0,5 | 0,35 |
| Dish-washers (per standard. load) | 1,6 | 1,1 | | 1,1 | 1,05 | 1,0 |

*This value applies to a model available in Denmark
Sources: NUTEK 1992, Konsumentverket 1992, Möller 1992

The effect of technology procurement in the scenarios is to accelerate energy-efficiency gains by raising the efficiency of the best-available model early-on. The introduction of new models at the high-efficiency end of the market pulls the average efficiency upward, and we assume that this efficiency rise causes the average new-model efficiency to reach the level of today's best-available unit by 2010. Even if the long-term level of new-model efficiency is the same as without the procurement process, as might be the case after the application of efficiency standards, total appliance energy use in a given year is still reduced by introduction of higher-efficiency models earlier. The administrative costs of the procurement process are rather low, about ECU 250 000 in the case of the Swedish fridge-freezer procurement (Nilsson 1992).

With both the reference and the technology-procurement scenarios, we consider the introduction of aggressive energy efficiency standards. The progression of standards in our scenarios closely follow those used in an analysis carried out in support of Denmark's Energy 2000 Plan, and the initial levels are consistent with the standards being analyzed for the European Commission (Möller 1992, Lebot et al 1991). We assume that the minimum time necessary to introduce a standard or strengthen the required performance, after the standard has been announced to the industry, is three years (Nordnorm 1992). Thus, we consider possible standards for initial introduction in 1996, with additional steps in 1999, 2002, and 2005.[3]

The 1996 standard is set at approximately the average 1990 new-model consumption, if this level is significantly below that of the reference scenario. (If not, the first standards are applied in 1999.) Placing the standard at the present average eliminates the less efficient half of the present market and allows suppliers time to develop more efficient models without making too many of their existing models immediately obsolete. As shown in table 2, 1996 standards appear appropriate for freezers and fridge-freezers. In addition, stronger standards for these appliances are facilitated by the application of technology procurement. Because some models on the market are already more efficient than required by this standard, we assume that the average new-model efficiency in 1996 will surpass the standard. We use a value midway between the standard and the 1990 best-available model.

Figure 1 shows an example of the efficiency levels we assume for the standards, compared to historical average and best-available values.[4] Note that the best-available fridge-freezer efficiency improves as a result of the technical procurement process, and this new level is used as the basis for the later standards. While minimum performance standards are an effective way to eliminate the least efficient models from the market, they offer little incentive to develop the high-efficiency end of the product line. Technology procurement provides such incentives and creates the possibility of tightening existing standards over time. The two policy measures together give a clear signal to manufacturers that the development of more efficient new models will be rewarded with growing market demand.

The 1999 standard is approximately equal to the best-available model in 1990. This performance level would require significant development work for all suppliers, as today's best model becomes the least efficient model after a few years. Based on present engineering data, this development would increase the manufacturing cost and purchase price of the appliances. However, these energy efficiency levels are similar to those found to yield minimum life-cycle costs for refrigerators and freezers in the Danish analysis (Pedersen 1992). While the consumer may not automatically make the choice to invest in these levels of performance, they are likely to be cost-effective from the societal viewpoint. We assume that the suppliers just reach the required energy performance level in 1999, but then continue to improve thereafter.

The 2002 standard is approximately equal to the highest efficiency level that gave life-cycle costs no higher than the average new model in the Danish analysis of refrigerators and freezers and the highest efficiency level considered in the EC analysis (Pedersen 1992, Lebot et al 1991). This consumption level is generally less than today's best-available model. Thus, this level of efficiency is technically feasible, and its economic penalty is not likely to be large. For the other appliances for which such economic analysis has not yet been done, we use values midway between the 1999 standard and the advanced performance level assumed for the 2005 standard described below. We assume that the suppliers just reach the required energy performance level in 2002, but then continue to improve thereafter.

The 2005 standard is chosen to require the introduction of advanced high-efficiency appliances by that year. The required consumption levels are assumed to be 5-10 percent above those of the most efficient models, based on known technology, reported in the literature (Nørgård 1989). Although this performance level represents a dramatic improvement over the appliances sold today, the average stock energy consumption values, even in the year 2010, are not so greatly reduced because many less efficient models would still be in service at that time. Full realization of these efficiency improvements would take several years longer.

Little detailed economic data are available for this performance level, which exceeds that considered in either the Danish or the EC analyses.[5] Thus, it is difficult to evaluate the economic impact of mandating such efficiency levels, but it is likely that both purchase price and life-cycle cost would increase. Based on present engineering data, it seems that these cost increases would be as large as 50 percent or more in terms of purchase price. However, it is also quite possible that after more than ten years of development, manufacturers would find less expensive ways to produce energy-efficient products than those presently available.

### 4.3. Economics

Another scenario that we consider for refrigerators and freezers is increasing energy prices, without standards, beyond those implied in the reference scenario. Average present residential electricity prices in Sweden are about ECU 0,06/kWh,[6] which we expect to increase at least 30 percent to ECU 0,08/kWh after the year 2000 (Fritz et al 1990). In this scenario, however, we consider an additional 50 percent increase to ECU 0,12/kWh. Thus, a measure that has a 5-year payback at today's prices would have a 4-year payback late in the reference scenario and a 3-year payback in the high-price scenario. Based on data from the Danish analysis and the economic criteria described below, we conclude that only fridge-freezers (not refrigerators or freezers) would be likely to have significant efficiency improvements under this scenario.

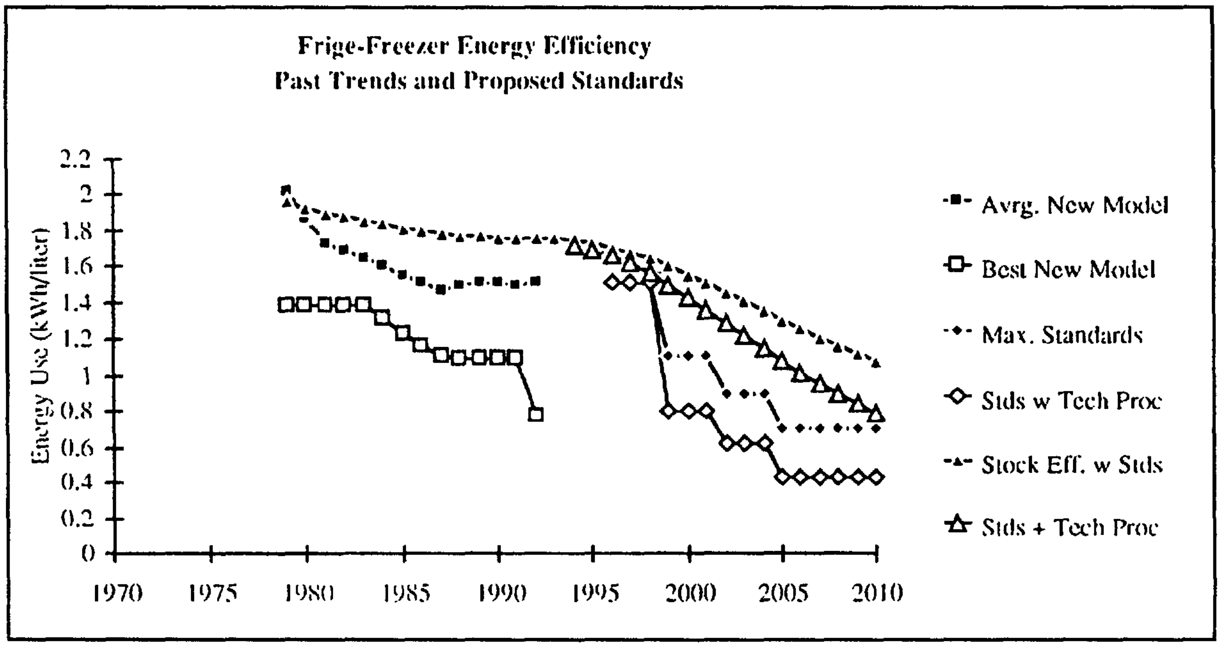

**Figure 1.** ***Historical trends and proposed standards for energy efficency for fridge freezers in Swedish households.***

The economic criteria for the scenarios is based on the Danish analysis and the EC analysis, both of which consider refrigerators and freezers (Möller 1992, Lebot et al 1991). Each study gives several levels of energy efficiency improvement, together with the corresponding costs, for each appliance. The results are generally similar in the two studies. The first significant steps in efficiency improvement have a ECU 0,01-0,02/kWh cost of saved energy and a 2 to 3-year payback at today's Swedish prices (which are about half the Danish prices used). This result suggests a threshold at which consumers are willing to invest in more efficient equipment without additional incentives. Thus, we use a 3-year payback as the minimum economic criterion for consumer acceptance without additional policy measures such as standards.

According to the average and marginal cost data from the two studies, efficiency improvements from today's average new model to the level of today's best-available models would have about a 4-year payback at today's Swedish prices (ECU 0,03/kWh average cost of saved energy or ECU 0,05/kWh marginal cost), or about a 3-year payback with the reference-scenario prices. Thus, we consider these measures likely to be adopted in the future without further incentives. Additional measures have marginal costs of saved energy greater than ECU 0,15/kWh (average cost of saved energy of ECU 0,04/kWh) and thus do not appear cost-effective without new incentives.

The Danish analysis, however, shows additional efficiency improvements for fridge-freezers with a marginal cost of saved energy of ECU 0,09/kWh (average cost of saved energy of ECU 0,03/kWh), which gives a 6-year payback at today's prices or a 3-year payback in the high-price scenario. It appears that only fridge-freezers have additional efficiency improvements that meet our economic criteria, and this efficiency level is reflected in the high-price scenario. The Danish analysis shows costs of additional efficiency improvements for refrigerator units and freezer units that are higher, suggesting that increased energy prices may have little effect for these appliances. Thus, because of the demanding consumer pay-back criteria, it does not appear that increases in energy prices or taxes will have a major effect on energy savings (see figure 2). This result is consistent with detailed studies in both Sweden and Denmark (Nielsen et al 1992, Levin Kruse 1991).

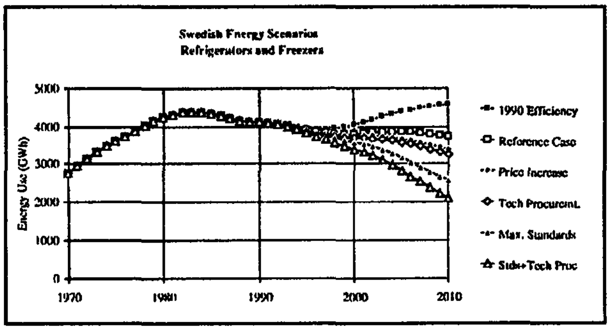

**Figure 2.** *Electricity consumption secnarios for refrigerators and freezers in Swedish households*

### 4.4. Aggregated results of the scenarios

The combined energy consumption totals for the scenarios are shown in figure 2 for refrigerators[7] and freezers, and in figure 3 for laundry-room appliances and dish-washing machines.[8] The scenarios include constant 1990 new-model efficiency, reference cases with and without technical procurement, energy performance standards with and without technical procurement, a delayed-standard case for laundry and dish-washing appliances only, and the high energy-price case described above for refrigerators and freezers only. As mentioned above, technology procurement involves fridge-freezers, freezers and clothes washers. Standards are applied in 1996 for fridge-freezers and freezers, and in 1999, 2002 and 2005 for all the appliances considered.

The reference scenarios, which assume continued technical progress and some price increases, do show significant savings (about 20 percent by 2010) compared to the constant new-model efficiency scenarios. The maximum-standard scenarios show savings of almost 50 percent by 2010, based on new-model consuption savings of almost 70 percent, compared on the same terms (see figures 2 and 3). However, the true policy-driven energy savings should be measured with the reference case as the starting point, rather than the constant new-model or "frozen" efficiency scenarios. This comparison gives savings of about 35 percent for the maximum-standard scenarios.

### 4.5. Conclusions regarding the time dynamics of energy performance standards

The standards assessed in our scenarios are the most aggressive that we consider practical. Time-steps of three years are generally considered the shortest feasible for introducing or strengthening standards (Nordnorm 1992), and the efficiency levels of the standards increase as much as possible without forcing most of the existing models off the market at each step. Moreover, our maximum efficiency levels for the year 2005 are slightly less ambitious than those proposed elsewhere, based on existing technology (Nørgård 1989).

These scenarios show the benefit of moving the high-efficiency end of the market via the public procurement process, which serves to accelerate energy-saving potential earlier in time and is particularly effective in combination with energy performance standards. Although the average new-model efficiency might eventually reach the same levels without the procurement process, earlier introduction of more efficient units can significantly increase total energy savings in a given year. Standards eliminate the least efficient models from the market, but their energy-saving impact is limited by presently available technology because they cannot improve the high-efficiency end of the market. This limitation may be especially strong in regard to laundry and dish-washing appliances, the majority of which are imported into Scandinavia. Without the presence of a large domestic manufacturing base, as is the case with refrigerators and freezers, it may be more difficult to impose strong mandatory standards, without special incentives, on imported products that represent a small fraction of their producers' total market.

One can imagine weaker standards or later introduction, which would yield results in between our standards-scenarios and the reference cases. Even with the aggressive standards, however, it takes a number of years before significant energy savings are achieved. Delaying the introduction of a given level of performance standard would therefore significantly increase the energy use in a given future year. Figure 3 shows a 7 percent increase in 2010 if each step in the laundry and dish-washing appliance standards is delayed by one year. To capture a large share of the existing energy-savings potential, therefore, standards should be progressive over time and should begin early in order to allow sufficient time for the market to respond.

## 5. DYNAMICS OF ENERGY EFFICIENT LIGHTING IN SWEDISH BUILDINGS

This section examines the dynamics of lighting energy efficiency implementation in Swedish non-residential buildings over the next 15-20 years. The emphasis is on utility programs, particularly those that apply to a deregulated utility market, but we also consider the role of government programs and price incentives. Studies in Sweden and other countries have identified large available potential for cost-effective energy savings in commercial and institutional buildings, indicating that electricity customers are not choosing to invest heavily in these measures, despite their economic benefits.

Utility demand-side management (DSM) programs that combine information and incentives, or even direct installation of efficiency measures, can bring the economic evaluation of energy efficiency onto a more equal basis with supply expansion. It is unlikely, however, that the future role of DSM in Sweden will resemble that of the regulated North American utilities, as the entire Swedish utility industry is in the early stages of a restructuring process toward greater competition and less government control. A more likely model is that Swedish utilities will begin using DSM as a tool to defend their market share against new competition by making their non-residential service more efficient and economical (via lower bills, not lower rates).

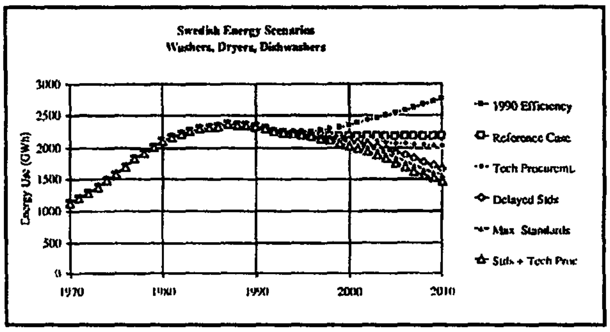

Figure 3. *Electricity consumption scenarios for laundry and dish-washing appliances in Swedish households*

We focus on efficiency measures for one category of end-use, namely non-residential lighting. The focus on lighting allows us to examine in detail the dynamics of energy saving technologies and programs for an end-use that represents more than 10 percent of Sweden's electricity (including residential use), and as much as 20 percent in other countries. In the Swedish service sector, lighting represents 30 percent of the non-heating energy consumption. Efficient technologies include improved lamps, ballasts, luminaires, controls and system designs to better exploit natural daylight and task lighting.

### 5.1. Description of the service sector

Our analysis is based on technical information from the recently completed "Uppdrag 2000," a field study of energy efficiency options by Vattenfall AB, Sweden's largest electric generator and wholesaler and formerly the national power board. This study produced the first detailed statistical picture of energy in the Swedish service sector and evaluated the potential cost and performance of a wide range of energy-saving measures (Hedenström et al 1992). The Uppdrag 2000 results suggest savings potential of about 10-15 percent based on retrofit measures that could be implemented immediately, while other studies have estimated a total savings potential of over 50 percent, compared to present technology, by 2010 (Hedenström 1991, Bodlund et al, 1989).

We examine the achievable potential, which over time increases beyond the retrofit potential, as new energy-saving opportunities appear in new and renovated buildings and equipment that is replaced by newer models. The rate of energy-efficiency implementation is limited, however, by the rate of turnover of existing buildings and equipment, and it is subject to constraints on administrative costs, market penetration rates and the technical and institutional feasibility of some of the common efficiency measures. We develop dynamic scenarios of electricity demand and efficiency improvement, based on various levels and timing of DSM investment.

Table 3 shows the electricity end-use breakdown for Swedish non-residential buildings in 1989, based on information from Vattenfall's Uppdrag 2000 reports. The STIL survey data conducted as part of Uppdrag 2000 covered commercial and public service customers with annual consumption of 20 MWh or more (Hedenström et al 1992). To these results we add end-use estimates for small premises, public works, light industrial buildings, and the non-residential shares of large multi-family housing developments. Our analysis of lighting efficiency measures focuses in detail on the approximately 5 TWh of annual electricity use for lighting in the STIL survey, which is shown in table 4, broken down according to the room-usage type.

### 5.2. Lighting technology analysis

While it is impossible to describe and analyze every building in the country, it is important not to generalize too broadly in an energy analysis of the service sector. The types of customers, buildings, rooms, and technologies vary widely, and we try to strike a balance between the rigor and detail of the analysis and the need for simplicity and transparency. For each of the 14 room-usage types identified above, we chose from a menu of efficient lighting technologies to identify improvements that are likely to be feasible and effective (table 4). We then analyze the cost and performance of the improvements for new buildings, equipment replacements and retrofit applications. Although this approach does not consider the full range of combinations of buildings, occupants, room types and technologies, it does give a reasonable respresentation of the diversity of the sector's lighting applications and their performance.

Much of the technical detail of the efficiency measures is taken from the many case studies that were conducted under Uppdrag 2000. Additional cost and performance data are provided by Wabema, a Swedish lighting consultant. In particular, Uppdrag 2000 focused on retrofit measures that could be carried out immediately, while this study considers longer-term efficiency options, most of which involve new or replacement systems and equipment. The measures shown in table 4 are all based on technology that is commercially available today. Although many of these measures represent considerable efficiency gains

**Table 3.** *1989 Electricity Use in Services and Non-residential Buildings in Sweden (TWh)*

| | Uppdrag 2000 STIL survey | other services | industrial | total |
|---|---|---|---|---|
| Lighting | 5,0 | 2,6 | 3,0 | 10,6 |
| Ventilation | 1,9 | 0,8 | 0,9 | 3,6 |
| Cooling/Kitchen | 3,7 | 0,4 | 0,6 | 4,7 |
| Heating(temp. corrected) | 4,6 | 2,8 | 1,8 | 9,2 |
| Office Equipment | 0,6 | 0,9 | 0,2 | 1,7 |
| Motors/Non-building | 0,9 | 5,0 | * | 5,9 |
| Other | 0,9 | 0,2 | * | 1,1 |
| Total | 17,7 | 12,7 | 6,5 | 36,8 |

*Other non-building end-uses are generally attributed to industrial processes
Sources: Hedenström et al 1992, Kraftsam 1990

compared to present practice, they are by no means the best that can be achieved. Thus, to the extent that even more efficient technology can be introduced during the time horizon of our analysis, our results can be considered somewhat conservative in regard to technical potential.

For each measure in each room-type, we calculate the energy-savings cost and performance. This first step only gives the raw technical-economic potential. We apply several additional factors that limit the potential application of each measure. For example the more efficient technology might already be used, might not be appropriate for some applications, or might have functional or aesthetic limitations, such as CFL's that cannot be used in dimming circuits or rooms with small decorative lighting fixtures.

The many different energy-using technologies and efficiency options must be tracked in detail to account for changes in building and equipment stock, implementation rates and remaining efficiency opportunities. Efficient new and replacement equipment can be installed up to a maximum penetration rate, and all retrofit measures have a similar maximum rate at which they can approach the full penetration level, which must be corrected for the annual turnover in building and equipment stock. These rates depend on the maturity of the market and the level of program activity. In each year during the program, existing equipment remains and new equipment appears. Both provide DSM opportunities, either retrofits or new installations, some of which are captured and some missed. New buildings that do not receive DSM measures become candidates for later retrofits. Some existing equipment turns over and is replaced, offering additional opportunities, while some existing equipment remains into the following year.

The results of the technology analysis are summarized in figure 4 as marginal cost or "supply" curves for saved energy. The cost of saved energy is the sum of the annualized capital cost of the efficiency measure and its increase in operating costs, divided by the annual energy savings. The horizontal axis shows the fraction of lighting energy that can be saved at a given marginal cost, in each of four different years. The reference case for these savings is the consumption resulting when all new and replacement equipment installed after 1990 has the same average efficiency as in 1990. This base consumption value increases with time. At a given marginal cost level, the energy savings include the effects of all the efficiency measures with a cost of saved energy less than that marginal cost level.

The curves are different in each year because of the slow turnover of end-use equipment and the gradual penetration of retrofit measures, assumed to begin in 1994. The maximum energy and savings from efficiency improvements cannot be achieved immediately, rather they gradually increase each year. Some measures, for example lamps with increased lifetimes, have negative costs of saved energy because they save more in maintenance costs than the annualized value of their capital costs. These cost curves show the efficiency potential in a given year at a given cost level, but they do not indicate how much of that potential can be achieved in a real program or would be achieved without the program.

### 5.3. Implementation and market acceptance analysis

We use the Compass computer model from Synergic Resources Corp., modified for Vattenfall and Sweden, to conduct the detailed accounting and market penetration analysis calculations needed in this type of DSM analysis (SRC, 1991). The market adoption of the efficiency measures under different programs and incentives is especially complex. Some measures will be implemented without special programs or policies; i.e. even a "business as usual" reference case includes some energy savings. However, the availability of many cost-effective energy-saving opportunities suggests that customers are not fully investing in these measures, and are not likely to do so in the future.

We assume that the fraction of customers who will adopt a given efficiency measure depends on its economic return, measured by the simple payback time. This formulation can be used to drive the market acceptance analysis in the Compass program, and we use it to explore the different effects of utility-sponsored energy-efficiency incentives or changes in electricity prices. According to the Uppdrag 2000 results, the longest payback that a commercial customer will accept is about 5 years. At the same time, one can identify substantial energy-saving potential that is not being exploited despite a payback of only about 1,5 years. Thus, we use a payback-acceptance function where about 20 percent of customers adopt measures with a 5-year payback, about 50 percent accept 3 years and about 80 percent accept 1,5 years.

The primary implementation mechanism is assumed to be utility-sponsored DSM programs. The utility programs analyzed here employ a shared-savings approach, where the utility or a third-party intermediary pays an incentive for the customer to invest in an energy-efficiency measure, in exchange for a fraction of the energy savings which can be paid via the electricity bill. The relative size of the incentive payment and the shared-savings payments can be tailored to meet each party's economic criteria. For a given shared-savings fraction, e.g. 50 percent, there is a minimum incentive required for the customer's participation, depending on the inherent cost-effectiveness of the measure. As the incentive increases, the measure becomes more attractive to the customer at the expense of the utility's return.

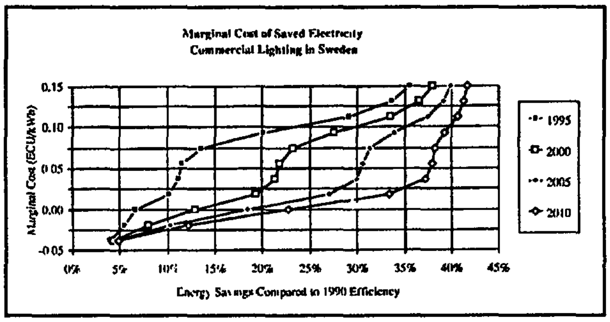

**Figure 4.** ***Energy savings marginal cost curves for lighting efficency measures***

**Table 4.** ***1989 Lighting Energy Breakdown by Room Type, and Efficient Technologies Applied***

| | million sq m | GWh | kWh/m2 | Energy Efficiency Technology |
|---|---|---|---|---|
| Office rooms | 16,5 | 630 | 38 | EFLs, reflectors, HFBs, occ'y |
| Office corridors | 6,6 | 320 | 49 | EFLs, reflectors, HFBs, occ'y |
| School rooms | 11,4 | 350 | 31 | EFLs, reflectors, HFBs, occ'y |
| School corridors | 6,2 | 170 | 28 | EFLs HFBs, CFLs |
| Health care rooms | 3,8 | 100 | 26 | EFLs HFBs, CFLs |
| Treatment rooms | 4,8 | 250 | 50 | EFLs HFBs |
| Health care corridors | 12,7 | 400 | 32 | EFLs, reflectors, HFBs |
| Retail stores | 8,5 | 620 | 73 | EFLs, reflectors, HFBs |
| Food stores | 3,5 | 340 | 97 | EFLs, reflectors, HFBs |
| Hotel/restaurants | 14,6 | 500 | 34 | EFLs HFBs, CFLs |
| Library/meeting rooms | 8,7 | 210 | 24 | EFLs HFBs, CFLs |
| Sport facilities | 5,6 | 270 | 49 | EFLs, HFBs, Hg+HPS |
| Warehouses | 22,1 | 570 | 26 | EFLs, HFBs, occ'y, HPS+MHL |
| Workshops/industrial | 5,5 | 240 | 42 | EFLs, HFBs, HPS+MHL |

Notes: EFLs: Efficient Fluorescent Lights, reflectors: Imaging-reflector luminaires, HFBs: High Frequency Electronic Ballasts, occ'y: Occupancy Sensors, CFLs: Compact Flourescent Lamps (replace incendescents), Hg+HPS: Mercury Vapor Lamps and High Pressure Sodium Lamps (replace flourescents), HPS+MHL: High Pressure Sodium Lamps and Metal Halogen Lamps (replace mercury vapor)

Source: Hedenström et al 1992

We assume an 80 percent incentive, which means that the customer's payback is shortened by 60 percent (20 percent payment for 50 percent savings) and the utility's is increased by 60 percent (80 percent payment for 50 percent savings). For a measure with a customer payback of 1 year, the utility payback is 4 years, in which case both parties are likely to accept the measure. One could arrange similar incentives through a loan program, but experience in other countries has shown that very low numbers of customers are typically willing to take on debt in order to save energy (Nadel et al 1990).

### 5.4. Results of the scenarios

We consider four scenarios: two reference cases with high and low electricity prices and two cases with full implementation of utility-sponsored DSM programs, one with immediate implementation and one with delayed introduction of retrofit programs. In addition we estimate the energy consumption trends with no improvement in efficiency beyond that of the current new equipment. The first reference case has stable prices until after the year 2000, when prices increase by about 25 percent due to supply constraints and/or integration with the European power market. The second case assumes a further 25 percent increase. The market acceptance analysis in Compass can capture the effects of both price changes and DSM incentives.

We use the market acceptance analysis in the Compass program to construct scenarios of energy savings under the different price and program assumptions. The year-by-year energy consumption results from the scenarios are shown in figure 5.[9] We assume that the DSM programs for new and replacement equipment are run from 1994 until 2009, and retrofit programs run from 1994 until the market is saturated (in a separate case we delay the retrofit programs until 2000). We assume that the total luminous flux (lighted area times average illuminance) grows at 2,3 percent per year, consistent with recent electric forecasts for the Swedish service sector (Kraftsam 1990). Thus, the energy consumption with no improvement in new-model efficiency shows substantial growth.

The reference scenario shows significant energy savings, over 10 percent in 2010 compared to the constant-efficiency case (see figure 5). However, total consumption continues to increase despite the assumption of higher electricity prices. Even a 50 percent increase in electricity prices does not have a major impact on reducing consumption growth, as shown by the third scenario in figure 5. This result is consistent with other studies that have reported low customer response to electric price increases, and results from various information and institutional barriers (Nielsen et al 1992, Levin Kruse 1991).

The fact that significant savings would likely be achieved without the DSM program means that there will be customers who take advantage of utility-sponsored incentives, even though they would have invested in efficiency measures without the incentives, i.e. there will be "free riders." Although free riders do not impose additional costs on society (except administration costs), the utility must still pay both the incentives and the program administration cost for the free riders' participation. Evaluations of North American DSM program report free rider fractions from less than 10 percent to more than 50 percent, depending on the type of program, and experience has shown that programs can be designed to avoid excessive free-ridership (Nadel et al 1990). We may overestimate the amount of free riders, because our DSM scenario does not include any specific efforts to avoid free riders through program design, nor do we account for "free drivers," those who invest in energy efficiency without participating in the DSM program.

The full DSM program shown in figure 5 could save enough energy to keep total lighting consumption in 2010 at approximately the 1990 level, rather than increasing by 25 percent as in the reference case. Because this scenario begins with full implementation of both retrofit programs and efficiency measures for new and replacement equipment, the savings increase quickly in the first years. Later, the retrofit measures become nearly saturated and additional savings come mostly from new and replacement opportunities. The total savings by 2010 are about 30 percent of the energy consumption that would occur with constant 1990 efficiency, or about 20 percent compared to the reference case.

Although figure 4 suggests that this level of savings is possible at a <u>marginal</u> cost less than ECU 0,03/kWh, limits to the market penetration of individual measures prevent the full potential from being captured. Thus the scenario includes additional, more expensive measures, increasing the cost of this level of energy savings. The <u>average</u> cost of saved energy in this scenario is about ECU 0,03/kWh, including program administration costs, which vary between 10 and 15 percent of the measure cost. The utility's total cost is about ECU 0,05/kWh, including program administration costs and payments to free riders, which amount to about 30 percent of total participants. Retrofit measures cost the utility about twice as much as new and replacement equipment-measures, on average. Assuming that the utility can recover DSM costs by raising prices by about ECU 0,0001/kWh, their present-value benefit-cost ratio is about 1,5.

### 5.5. Conclusions regarding the time dynamics of utility DSM programs

The retrofit measures considered in the DSM scenario are generally mature technologies that can penetrate the market quickly, although we apply a maximum limit of about 12 percent per year. It could be difficult, however, to implement both a full scale retrofit program and an efficiency program for new and replacement equipment all at the same time. We therefore consider an additional DSM scenario with the retrofit program delayed until 2000. Obviously, this reduces the energy savings in the first years, but by 2010 the total energy savings are nearly equal to those of the full DSM scenario. Moreover, the utility's costs are reduced because there are less free riders and the incentive payments are delayed several years.

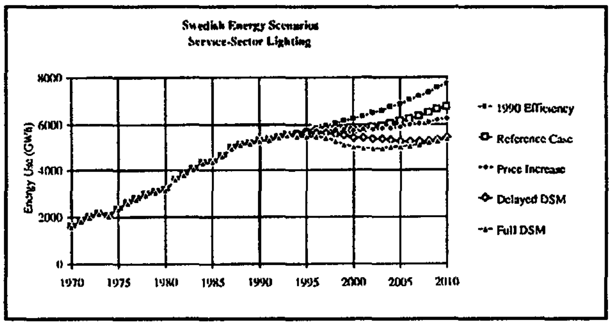

**Figure 5.** ***Electricity consumption scenarios for lighting in the Swedish service-sector.***

This comparison of the two DSM scenarios suggests an important point in regard to flexibility in utility DSM programs. There is some degree of choice as to when retrofit options are exploited, depending on the need for savings and the resources available. This would also apply, in the residential sector, to the lamp replacement programs which have been initiated by some Swedish distribution utilities.

There is no such flexibility, however, for new and replacement equipment, which present one-time opportunities that are lost if they are not exploited when the equipment is first installed. Thus, delaying the new and replacement programs in our DSM scenarios would reduce the total savings under the entire scenario; the lost savings could not be recovered. Capturing this "lost opportunity" DSM resource should therefore be a high priority for DSM program design.

Although these one-time opportunities would seem to reduce the utility's flexibility, they can actual serve as hedge against unexpected load growth. If, for example, the economy grows faster than expected in a given year, driving up energy demand, the number of new buildings and equipment replacements would also increase. With a DSM program in place to capture these energy-efficiency opportunities, the total savings would increase, thus dampening the rate of demand growth. Thus, the DSM programs can make the utility's planning more robust (Hirst 1992).

The strategy of Vattenfall in initiating Uppdrag 2000 was to focus on retrofit measures that could be implemented immediately. This strategy is not presently being carried out, due to the continuing surplus of electric supply in Sweden. Presumably, the efficiency measures identified under Uppdrag 2000 could be implemented later when supply constraints appear, or as a tool to defend the utility's market under the threat of new supply competition.

This strategy suggests that, for the time being, many "lost opportunity" efficiency resources in new and replacement equipment are being missed. Supply constraints will eventually appear, either from reduced use of nuclear power or from additional demand via integration with the European power market. Thus, missing the "lost opportunity" options could prove costly in the future, to society and probably to the utilities as well. Because these efficiency measures are relatively inexpensive, it would appear that they should be a higher priority in utility DSM planning.

One problem with the utility trying to capture low-cost efficiency measures in new and replacement equipment the is high fraction of free riders, which increase the utility's costs. These are the sort of measures that are appropriate for energy performance standards. Although standards are more difficult to define and enforce in the relatively diverse service sector than in households, some states in North America have begun to implement commercial lighting efficiency standards. In this paper, we have not considered the application of performance standards to lighting or other service-sector end-uses, but this issue suggests further research. Even relatively modest standards would help to capture a large share of the low-cost "lost opportunity" efficiency resources, allowing utility DSM planners to concentrate on more elaborate measures where fewer free riders are likely.

## ACKNOWLEDGEMENTS

The analysis work reported here was funded by NUTEK's Department of Energy Efficiency. We thank Hans Nilsson, Lars Nilsson, Thomas B. Johansson, Lee Schipper, Jan Möller and three reviewers for helpful comments and ideas. Leif Wall provided cost and performance data on lighting technologies, and Artur Horowitz provided appliance energy consumption data.

## ENDNOTES

1. The term "refrigerators and freezers" includes all household food storage equipment. For the purposes of the quantitative analysis, we divide these appliances into three categories: fridge-freezers, refrigerator units and freezer units, each of which represents several different types and sizes of appliance by one standard model.

2. These energy savings values are based on laboratory tests by the Konsumentverket. Recent field tests indicate that the winning model uses about 50 percent less electricity than the previous best available model and over 60 percent less than the average in the market (pers. comm. L. Engebeck, Statens Institut för Byggnadsforskning).

3. Typically, standards have the form a+bx, where a and b are constants and x is the unit size. The standards considered here would presumably be implemented using same format. For the purpose of this analysis, we use a simple ratio of energy use to unit size or load, based on the most common units for each appliance type.

4. Energy use is normalized per liter of refrigerator space, with freezer space counted as two liters, as reported by Konsumentverket. Past trends show average new-model and best-available efficiency. The performance standards we consider are first imposed in 1996 and strengthened three times after three-year intervals. A stronger set of standards are made possible by public technology procurement, which accelerates development of the high-efficiency end of the market. Historical average stock efficiency is also shown, and projected into the future based on the two sets of standards. Average stock efficiency lags considerably behind new model efficiency.

5. There is, however, at least one appliance already on the market in Scandinavia that meets this level of performance: a refrigerator sold in Denmark.

6. Including about ECU 0,01/kWh energy tax, but excluding value-added taxes that have recently begun to be applied to electricity sales.

7. The scenarios are: a) all new equipment continues to have the same energy-efficiency as 1990 models; b) reference case, with efficiency improvements implemented according to present trends and consumer payback criteria, 30 percent electric price increase; c) reference case, with 90 percent electric price increase; d) accelerated efficiency improvements in fridge-freezers and freezers through public technology procurement; e) maximum implementation of energy performance standards in 1996, 1999, 2002, 2005; f) maximum standards and technology procurement.

8. The scenarios are: a) all new equipment continues to have the same energy-efficiency as 1990 models; b) reference case, with efficiency improvements implemented according to present trends and consumer payback criteria; c) accelerated efficiency improvements in washing machines through public technology procurement; e) maximum implementation of energy performance standards in 2001, 2005, 2009; e) standards in 1999, 2002, 2005; f) maximum standards and technology procurement for washing machines.

9. The scenarios are: a) all new and replacement equipment continues to have the same energy-

efficiency as 1990 models; b) reference case, with efficiency improvements implemented according to present trends and investment payback criteria, 25 percent electric price increase; c) reference case, with 50 percent electric price increase; d) full implementation of utility-sponsored DSM incentives, with programs for new and replacement equipment beginning in 1994 and retrofit programs delayed until 2000; e) full implementation of DSM incentives, with all programs beginning in 1994.

## REFERENCES

Bodlund, B., et al, 1989. "The Challenge of Choices" in T.B. Johansson,B.Bodlund, R.H.Williams, eds., *Electricity*, Lund University Press.

Fritz, Peter et al, 1990, *Effektivare Elanvändning*, Statens Energiverk, Stockholm, June.

Hedenström, C., Göransson, A., Lindahl, U., Forsman, G., 1992. *Lokalerna och Hushållningen*, STIL-studien, Vattenfall, Vällingby, June.

Hedenström, C., 1991. *Från Krog till Kontor: Slutrapport från Uppdrag 2000-lokaler*, Vattenfall, Vällingby, November.

Hirst, Eric, 1992. *Effects of Utility DSM Programs on Risk*, ORNL/CON-346, Oak Ridge, Tennessee, May.

IMU-Testologen AB, 1991. *Hushållens Elapparatanvändning Elapparatundersökningen*, Sollentuna, December.

Konsumentverket, 1992. *Normer för Maximal Elförbrukning i Hushållsapparater mm*, Stockholm, March.

Kraftsam, 1990. Elprognos för *År 2000*, Stockholm, January.

Lebot,B., Szabo A., Despretz H., 1991. *Study on the Regulation of the Energy Performances of Domestic Electrical Appliances*, Commission of the European Community Directorate General for Energy, October.

Levin Kruse, K., 1991. *Från Mätare till Människa*, Vattenfall, Vällingby, November.

Möller, J., 1992. *Electricity Savings from Implemention of Standards for the Electricity Consumption of Refrigerator/Freezers*, DEFU Teknisk rapport 300UK, Lyngby, April.

Nadel, S., Wolcott, D., Smith, P., Flaim. T., 1990. *A Review of Utility Experience with Conservation and Load Management Programs for Commercial and Industrial Customers*, New York State Energy Research and Developement Authority, Albany, NY, April.

Nielsen L., Jørgensen K., Jordal-Jørgensen,J., 1992. *Elbesparelser i Boliger*, AKF, Copenhagen, August.

Nilsson, H., 1992. "Market Transformation by Technology Procurement and Demonstration," ACEEE Summer Study on Energy Efficiency in Buildings, Monterrey, CA, September.

Nordnorm Kommissionen, 1992. *Principper for Normer for Husholdningsapparaters Elforbrug*, Faelles Nordisk Forslag, January.

NUTEK Kansliet för effektivare energianvändning, 1991. *Undersökning om Hushållens Elapparater och Tvätt*, Stockholm, December.

NUTEK, Kansliet för effektivare energianvändning, 1992. *Eleffektiv Disk-Tvätt-Kyl-Frys*, Stockholm, June.

Nørgård, Jørgen S., 1989. "Low Electricity Appliances-Options for the Future," in T.B.Johansson, B.Bodlund, R.H.Williams, eds., *Electricity*, Lund University Press.

Pedersen, Preben Buhl, 1992. *Engineering Analysis Concerning Energy Efficiency Standards for Refrigerators and Freezers in Denmark*, dk-TEKNIK, ISBN 87-7782-028-2, February.

SRC, 1991. *Compass Users' Manual*, Synergic Resources Corp., Bala Cynwyd, PA.