SimBuild 2006

Second National IBPSA-USA Conference
Cambridge, MA
August 2-4, 2006

A SCENARIO ANALYSIS OF RETROFIT STRATEGIES FOR REDUCING ENERGY CONSUMPTION IN NORWEGIAN OFFICE BUILDINGS

Lisa A. Engblom[1], Leon R. Glicksman[1,2] and Leslie K. Norford[2]
Building Technology Program
Departments of Mechanical Engineering[1] and Architecture[2]
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

Buildings in Norway account for more than a third of national energy consumption and demand-side management has significant savings potential. Due to the long lifetimes of existing buildings, retrofits rather than efficient new construction are the best way to significantly affect national energy consumption on a short time scale. A steady-state computer model was written to predict annual energy consumption of model buildings that represent typical office buildings in Norway. The program was then used to predict the new energy consumption after applying retrofit strategies. Reductions in energy consumption of up to 45% were possible by simply changing the control settings. Reductions of up to 80% were possible through complete renovation.

INTRODUCTION

Buildings in Norway account for more than one-third of the total national energy consumption, so demand side management has significant potential to decrease national consumption and slow the pace of new construction (Statistics Norway 2006). While it is important to construct energy-efficient buildings, a typical building lasts for 50 to 100 years and it is not unusual for buildings to survive longer. Therefore, the best way to significantly reduce energy consumption in the buildings sector on a short time scale is to retrofit existing buildings.

Within the Norwegian buildings sector, residential and commercial buildings are responsible for roughly equivalent energy consumption. Single family homes are by far the biggest single consumer and have been the focus of most of the past research. Much less information is known about methods for reducing energy consumption in the commercial sector. Total energy consumption is much more evenly distributed among commercial building types. The biggest consumers are retail buildings, industry and storage buildings, office buildings, and schools (Statistics Norway 2006).

The main goal of this study (fully described in Engblom 2006) was to estimate how much retrofitting existing office buildings can realistically reduce their energy consumption. Office buildings were chosen because they have the most uniform characteristics of the commercial building types. This study also identified the most cost effective strategies to achieve reduced energy consumption.

METHODOLOGY

Statistical information was collected about Norwegian office buildings from databases of national statistics, technical studies, and interviews with building researchers and building managers. The data were used to create model buildings that represent typical constructions from different time periods for use in a simulation program. The time periods were defined by the years that new building codes were adopted. Table 1 details the characteristics of the model buildings (Burton 2002, Enova 2004, Lindberg 2005, Mathisen 2005, Statistics Norway 2006, Thyholdt 2005, Wachenfeldt 2004). The assumed geometry, specific fan power, and lighting and office equipment energy consumption did not change over time. Temperature and ventilation set points were similar for all time periods, except that the occupied ventilation rate increased in the newest buildings. U-values became smaller over time, but the portion of the facade covered by windows increased. Heat recovery systems were installed in almost all buildings, but the effectiveness has varied over time. Cooling systems became common in the mid-1980's.

Information was also collected about both standard and low-energy methods for retrofitting buildings, including the investment cost necessary to complete the projects. The costs are from R.S. Means for US buildings (R.S. Means 2005)) because an appropriate source does not exist for Norwegian buildings.

Absolute costs in Norway would be higher, but the relative costs should apply. The standard retrofit projects involved upgrading the buildings to meet the requirements in the most recent building code, which was instituted in 1997. The low-energy retrofits were an estimation of the best-practice options for decreasing the energy consumption of an office building. Figure 1 is a schematic of the current state of the buildings constructed before 1969 and the available retrofit options.

SIMULATION PROGRAM

Description

A highly accurate simulation program was not needed, given available input information. For example, wall properties were characterized solely by estimates of conduction, not materials and construction. Lighting and office-equipment energy were known only by estimates of annual consumption, not by systems or schedules. Further, it was necessary to run the simulation several thousand times for each construction period to analyze retrofit options, which favored rapid execution time. A dynamic simulation program such as EnergyPlus, driven by a script to automatically change inputs, was one option. Instead, we chose to set up a steady-state simulation that appropriately incorporated available inputs. Future work will include a comparison with a dynamic program, to assess the impact of thermal mass.

The simulation program performs a steady-state energy balance using hourly time steps to determine the energy necessary to heat and cool the building. It also determines the energy consumed by the fans based on the ventilation rate and fan efficiency. The energy for lighting, office equipment (computers, printers, etc), and heating water are inputs to the program.

The imbedded temperature and radiation data are for typical conditions in Oslo. Oslo and Bergen have nearly the same heating-degree days (HDD), base 18^{o}C (EnergyPlus 2006) and Norway's heavily populated coastal region has less than 4500 HDD (Skaugen and Tveito 2002). Weather data were generated by METEONORM software, which is based on a 10-year monitoring period (METEONORM 1999).

The simulation program assumes that the heating system is 100% efficient. This assumption is reasonable for current Norwegian office buildings because electricity from hydro plants provides more than 90% of their energy (Statistics Norway 2006). However, if a heating system based on another fuel were installed, the required heating energy would have to be increased by the appropriate change in efficiency.

The program determines overall energy consumption but does not consider peak power consumption. The goal of the project was to determine the potential to reduce energy consumption over one year. Identifying specific situations where the system was under the greatest stress is important but was out of the scope of this project.

The building attributes included in Table 1 are all used in the simulation program, but several additional assumptions were necessary to complete the analysis. These assumptions represent building attributes for which reliable national scale data were not available. The assumptions included:

- The building is a rectangular box with a square profile
- The building has no thermal mass
- The building has four external doors each with an area of 2 m^2
- The air in the building is well-mixed
- Windows are evenly distributed around the building
- The building is occupied from Monday to Friday from 7am to 7pm
- January 1 in the weather data is a Monday
- Heat gain from occupants is 65 Watts / person (AHSRAE 2005)
- Heat gain from lighting is 100% of the annual energy consumption for lighting (Thyholdt 2005)
- Heat gain from office equipment is 100% of annual energy consumption for office equipment (Thyholdt 2005)
- Fans do not contribute to heat gains
- Lights and office equipment are off during unoccupied periods
- Only sensible heat exchange is considered
- The COP of a heat pump is 2 (Francisco et al. 2004)
- The COP of an electric chiller is 3 (NDRC 1996)

Comparison of Results to Statistical Data

Figure 2 shows the predicted annual energy consumption of the model buildings from each time period broken down by end use. Energy for heating is the largest contributor but is not the only important factor. Energy for cooling makes a small contribution to the total energy consumption when it is present.

Energy consumption for lights and equipment were inputs to the total and were not calculated. Their impact on heating and cooling was included in the hourly energy balances. Heating energy was bounded with a degree-day calculation. The program yielded 147 kWh/m^2 for annual heating energy, bracketed by 80 kWh/m^2 for 2000 HDD base 10 ^{o}C and 160 kWh/m^2 for 4000 HDD base 18 ^{o}C. HDD were approximated from EnergyPlus weather data for Oslo (1942 HDD base 10 ^{o}C and 4171 HDD base 18 ^{o}C) (EnergyPlus 2006). The balance-point temperature for the 1980-1986 base-case building, weighted for occupied and unoccupied buildings and accounting for heat gains from occupants, lights and equipment but not solar gains, was about 15 ^{o}C. Fan-energy consumption was hand-checked and found to be accurate.

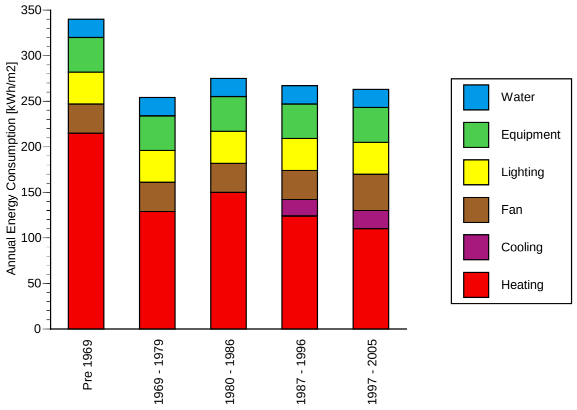

Figure 2 Energy consumption in the model buildings by end use

Simulation results can be compared to data from monitoring projects on the energy consumption of office buildings in Norway. Table 2 compares the average energy consumption over all time periods to the average consumption reported in several publications (Enova 2002, Enova 2004, Statsbygg 2005, Wachenfeldt 2004). The simulation results are similar to the results from these building monitoring projects, but are slightly higher, about 6% above the highest value reported.

Only one study, performed by Enova, has reported the energy consumption in office buildings broken down by age. Table 3 compares Enova's data redistributed to match the time periods used in this study to the simulation results (Enova 2004).

Table 2 Average energy consumption predicted by the simulation program compared to data from monitoring buildings

STUDY	ANNUAL ENERGY CONSUMPTION (kWh/m^2)
Simulation Results	280
Enova	243
Statsbygg	235
Modellbygg	200
Wachenfeldt	262

Table 3 Energy consumption for each construction period from the simulation results and the Enova study.

TIME PERIOD	SIMULATION RESULTS (kWh/m^2)	ENOVA'S MEASUREMENTS (kWh/m^2)
Before 1969	339	228
1969 – 1979	254	226
1980 – 1986	275	226
1987 – 1996	267	246
1997 – 2005	263	303

Enova's data in Table 3 show that the energy consumption of older buildings was fairly consistent, around 230 kWh/m^2. Energy consumption began to increase in the mid-1980's and is up to about 300 kWh/m^2 in the newest buildings. The increase in energy consumption has been attributed to the introduction of cooling systems, increased window areas on the facade, and increased occupant densities within the building.

The simulation program does not show the same trends. The results show that the oldest buildings would have very high energy consumptions, about 340 kWh/m^2. The consumption in buildings built after 1969 varies from about 250 to 275 kWh/m^2, but it is not clearly increasing or decreasing in the simulation results.

The reasons for these discrepancies are not completely clear. Input data for the newest buildings include a modest increase in window area, from 15 to 20% of the building's floor area, which is the maximum area from the most recent building code. It was anecdotally reported that some new office buildings have more glazed area than the code limit, but no studies have quantified the difference (Solem and Amundal 2006). The input data also do not account for increased occupant density because there are no data to describe the change. These factors are probably responsible for the program reporting a lower value than was expected for the buildings constructed after 1986, but the reason for the simulation program's estimating an energy consumption about 90 kWh/m^2 too high for buildings constructed before 1969 is less clear. The high U-values of the facade elements are the primary cause of the high predicted energy consumption for these buildings. It is possible that the buildings have already been retrofitted to a greater degree than was assumed.

However, the Enova study only included 147 office buildings, all of which were involved in government subsidized projects to reduce their energy consumption. It is a self-selected group whose owners are interested in energy conservation, so consumption may be lower than in typical buildings.

While the results of the simulation program do not perfectly match the results from previous building monitoring studies, they are within a reasonable range of known data given the presumed accuracy of the input data. The program was considered to be performing adequately within the restrictions of the available data.

RESULTS

Varying a single parameter

The first step in the retrofit analysis was to look at the effect of altering a single building attribute. Figure 3 shows the percent decrease in energy consumption resulting from changing each building attribute from its original condition to the low-energy retrofit.

The results show that there is a large potential to improve the buildings' performance even by altering a single parameter. Decreases in consumption of 15 to 30% were shown for all of the model buildings. The parameters that were consistently the best performers were introducing a heat pump, lowering the set-point temperature in the winter, improving the building's windows, and lowering the ventilation rate during occupied hours.

Figure 3 also shows that the initial condition of the building is important for determining the best course of action. The attributes are arranged in decreasing order of benefit for the oldest buildings, but this order is different for each construction period. For example, changing the occupied ventilation rate is especially effective for the buildings constructed between 1980 and 1986 because these buildings have a low heat-recovery effectiveness of only 55%.

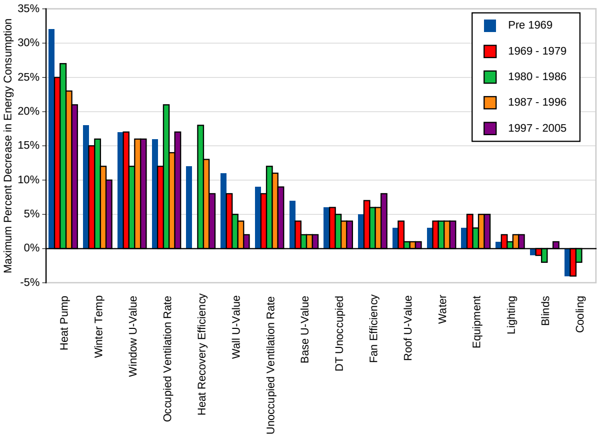

Figure 3 Percent decrease from changing a single attribute from the original condition to the best retrofit for each model building, arranged in order of decreasing importance for the oldest buildings

However, these parameters do not act in isolation and the percent decreases are not simply additive. For example, reducing the required heating energy through other means will decrease the perceived effectiveness of installing a heat pump. It is important to consider how the various attributes influence one other.

Retrofitting individual buildings systems

Recall that the categorization of attributes into systems and the available retrofits are described in Figure 1. A building owner is most likely to consider retrofitting a building with more efficient technologies when the components have to be replaced. It is important to understand what the potential reduction is for each system.

Scenarios were constructed by starting with the building its original condition. Simulations were run for every combination of the original, standard retrofit, and low-energy retrofit condition within each system. Figure 4 shows the scenarios for making changes within each system for the buildings constructed before 1969. Annual energy consumption is shown for each scenario, including the no-retrofit reference scenario.

Changes to the controls and HVAC systems were the most effective and the least expensive methods for reducing energy consumption, but changes to the other systems were still valuable. The controls scenarios have no costs because the buildings already had temperature and ventilation controls. Changing the set points does not require a significant investment in materials or labor.

The results for all of the construction periods were qualitatively the same. Figure 5 shows the scenarios for retrofitting the HVAC system for the buildings from all the construction periods.

The performance of the buildings improves with investment cost at approximately the same rate for all the construction periods. In the buildings constructed before 1969 there was a jump in cost for all the scenarios that include a heat pump. This difference is due to the fact that those buildings have a higher requirement for heating energy and must install a higher capacity, more expensive heat pump.

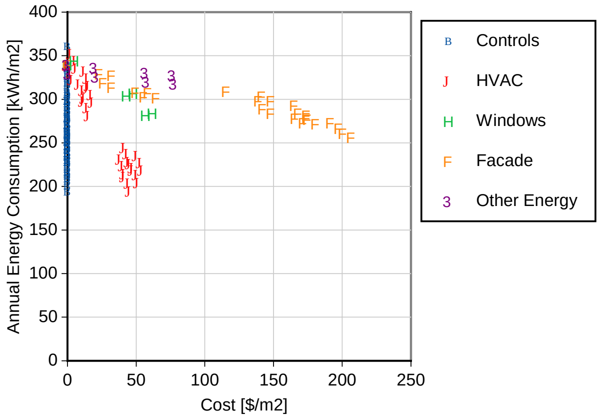

Figure 4 Retrofit scenarios for each building system for the buildings constructed before 1969.

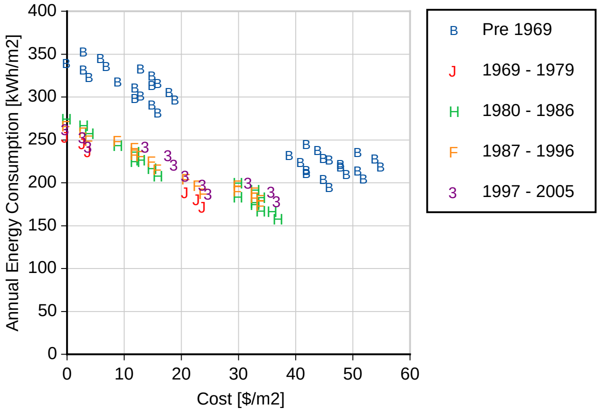

Figure 5 Retrofit scenarios for the HVAC system for all the construction periods

Figure 6 shows the percent decrease in energy consumption from the original condition to the best scenario for each construction period.

Retrofitting the HVAC system and the controls system were consistently the most effective strategy. Within these systems greater decreases in energy consumption were seen in the buildings constructed before 1969 and those constructed from 1980 to 1986 because those construction periods had the lowest heat-recovery effectiveness. Therefore, they benefited the most from lower ventilation rates and more effective heat recovery.

Retrofitting the building facade insulation is significantly less effective for the new buildings in comparison to the older buildings. Building codes required more insulation each time they were rewritten. The newest buildings have U-values close to current best practice.

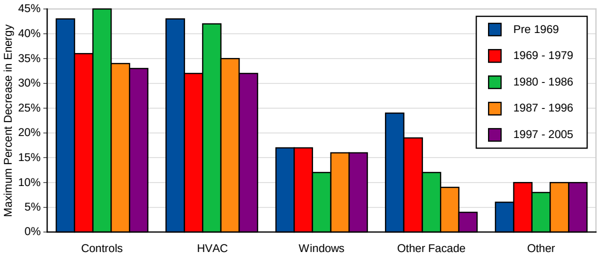

Figure 6 Maximum percent decrease in energy consumption from retrofitting multiple attributes within each building system in each construction period

The windows maintain a potential decrease of about 17% of the total consumption except during the 1980 to 1986 construction period. Retrofitting windows in the oldest buildings is effective because they have windows with high U-values. The buildings built after 1987 have fairly good windows, with U-values of 2 or 2.4 W/m^{2}K, but the buildings have cooling systems and the windows are generally not operable. Therefore, benefits from the more insulative windows are offset by the need to cool the building. Norway has a fairly cool climate, and the cooling requirements could be covered by increased airflow from open windows during much of the summer. Therefore, the primary effect of replacing the windows in new buildings is installing operable windows to reduce the required cooling energy.

Finally, retrofitting the “other energy services” like lights and office equipment becomes slightly more effective in the newer buildings. This result is partly due to the fact that the same decrease in energy is a larger percent of a smaller total energy consumption. In buildings with cooling systems, there is less heat gain to mechanically remove.

Like the changes to the individual attributes, the percent reductions for the various building systems are not additive. The next step was to see how making changes to building attributes within multiple systems changed the energy consumption of the buildings.

Retrofitting multiple buildings systems

To perform this analysis several scenarios were selected from each building system, including the original condition, the lowest energy scenario, and up to three moderate scenarios somewhere between the two. Each of the scenarios for each system was combined with all the scenarios from all the other systems. This approach provided a sample of all the potential conditions without having to consider the millions of potential scenarios from varying each attribute individually.

The scenarios selected for the controls, windows, and other energy consumption were the same for all construction periods. The control system strategies included the original condition, a low ventilation and low temperature case, a moderate temperature and moderate ventilation case, and two cases where the ventilation was reduced but the indoor temperature set point was unchanged. The most extreme controls scenario included a set point temperature of 19°C, which is slightly below comfort conditions (ASHRAE 2004) and provides an upper bound on energy reduction. The windows scenarios included retrofit with the typical and low-energy windows. The other energy services cases included a case where only the water heating unit was replaced and a low-energy case where the water heater, lights, and office equipment were all replaced.

The scenarios chosen for the HVAC and facade systems varied between the different construction periods depending on the results of the systems analysis. In each case, scenarios were chosen that provided the best performance for various investment costs. For the buildings constructed before 1969 four scenarios from the HVAC system were selected: the original condition, installing the low-energy heat recovery system and fan, installing a heat pump, and installing the low-energy heat recovery system, fan, and heat pump. Four scenarios were also chosen for the facade system: the original condition, the low-energy base and standard-retrofit roof, the standard walls and low-energy roof, and the low-energy base, walls, and roof. The selected scenarios for other time periods had different combinations of the original condition, standard retrofit, and low-energy retrofit components.

Figure 7 shows the results for the multi-systems scenarios for buildings constructed before 1969. The results from the other construction periods were qualitatively similar. A complete overhaul of the model buildings led to a total energy consumption of about 70 kWh/m^2. There are many pathways to achieve any goal annual energy consumption between the original consumption and 70 kWh/m^2. There is a set of scenarios that are the best performing configuration for a given investment. By choosing the best control strategy, the building can have a significantly lower energy consumption for the same set of physical attributes. The figures also show that there are diminishing returns. As the building becomes more energy efficient, it takes a greater investment to continue to decrease energy consumption.

Figure 7 shows variations in performance of up to 100 kWh/m^2 for a given cost. This result is primarily due to changes in the control system, which have no associated investment cost. It can also result from cases where several changes to the HVAC system have the same cost as a single facade retrofit but lead to significantly lower consumption.

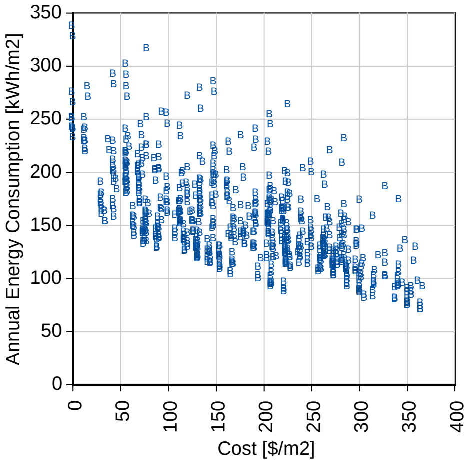

Figure 7 Scenarios for retrofitting attributes from multiple building systems for buildings constructed before 1969

Scenarios that include the HVAC and controls systems were again both the best performers and the least expensive scenarios. The total energy consumption could be reduced by 40 to 55% by making simultaneous changes to the HVAC and controls systems.

CONCLUSION

The best way to reduce the national consumption of energy by buildings in the short term is to retrofit existing buildings. Making changes to the controls and HVAC systems are both the most effective and least expensive strategies for decreasing energy consumption. Changes to the controls system are particularly promising because they do not require additional investment costs. However, the some of the changes must be maintained by the building occupants, which is not always practical. Retrofitting the building facade, windows, or other energy services can lead to significant reductions in energy consumption, but they are unlikely to be cost effective from an energy-reduction standpoint. However, the potential to improve the buildings energy performance should be considered when the building component must be replaced due to damage or fatigue. The economic analysis in Engblom (2006) shows that payback periods for retrofit packages that included the façade were at least 10 years for buildings constructed after 1969.

A total building overhaul, including indoor temperatures slightly below comfort conditions, can reduce the energy consumption of the model office buildings to 70 kWh/m^2, a reduction of 70 to 80%. About 40 to 55% of this total reduction is due to simultaneous changes to the controls and HVAC systems. Many of these scenarios have payback periods less than five years. Reductions of 30 to 45% can be achieved simply by altering the controls system for essentially no cost.

ACKNOWLEDGMENT

This project was undertaken as part of the TRANSES (Alternatives for the Transition to Sustainable Energy Services in Northern Europe) project, which includes researchers from the Norwegian Institute of Technology (NTNU) and its Foundation for Scientific and Industrial Research (SINTEF) in cooperation with the Massachusetts Institute of Technology (MIT), Chalmers University of Technology, and the Institute for Energy Technology (IFE). More information about the project can be found at: http://www.sintef.no/content/page1____9037.aspx.

REFERENCES

ASHRAE. 2004. “Thermal Environmental Conditions for Human Occupancy.” ASHRAE/ANSI Standard 55-2004. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE. 2005. *ASHRAE Handbook of Fundamentals*. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta, GA.

Burton, S. ed. 2002. *Energy Efficient Office Refurbishment* Johnson and Johnson Science Publishers, London, England.

EnergyPlus 2006. EnergyPlus weather data. http://www.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm

Engblom, L.A. 2006. ”Scenarior Analysis of Retrofit Strategies or Reducing Energy Consumption in Norwegian Office Buildings.” M.S. thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology.

Enova. 2002. “Modellbyggprojektet: Måling av Formålsdelt Energibruk in 26 Bygninger.” *Enovas Byggoperatør*, April 2002.

Enova. 2004. “Bygningsnettverkets Energistatistikk 2003” *ENOVA Bygningsnettverk*, ENOVA Rapport 2004:1.

Francisco, P, D. Baylon, B. Davis and L. Palmiter. 2004. “Heat Pump System Performance in Northern Climates” *ASHRAE Transactions* 110(1):442-451.

Lindberg. 2005. Conversations with Kirsten Lindberg of Statsbygg, June 20, 2005.

Mathisen. 2005. Conversations with Hans Martin Mathisen of SINTEF Energy, June 17, 2005.

METEONORM. 1999. METEONORM Software Version 4.0. Copyright METEOTEST, CH-3012 Bern, November 1999.

NRDC. 1996. "NRDC's Washington, D.C. Eco-Office: Tomorrow's Workplace, Today." National Resources Defense Council. http://www.nrdc.org/cities/building/dcofc/dcofcch2.asp.

R.S. Means. 2005. *Assemblies Cost Data*. Barbara Balboni, ed. Kingston, MA.

Skaugen, T.E. and O.E. Tveito. 2002. “Heating Degree Days: Present Conditions and Scenario for the Period 2021-2050.” Norwegian Meteorological Institute report 01/02 Klima.

Solem and Amundal. 2006. Conversations with Hårvard Solem and Jan Peter Amundal of Enova SF, January 30, 2006.

Statistics Norway. 2006. www.ssb.no

Statsbygg. 2005. “Energiforbruk I Statens Bygninger” Statsbygg Eiendomsforvalting, 1996 through 2005 editions.

Thyholdt. 2005. Conversations with Marit Thyholdt of SINTEF Energy, January 2005.

Wachenfeldt, B.W. 2004. "Project Memo: A Spreadsheet Tool for Scenario Analysis of the Energy Consumption in Buildings and Resulting Emissions (Developed within the TRANSES Project)," SINTEF Civil and Environmental Engineering.

Table 1 Description of the model buildings from each time period

	Pre 1969	1969 - 1979	1980 - 1986	1987-1996	1997 - 2005
Building Geometry					
Floor Area (m^2)	1500	1500	1500	1500	1500
Number of Floors	4	4	4	4	4
Floor Height (m)	3	3	3	3	3
HVAC System and Controls					
Indoor Air Temperature (Winter) (°C)	23	23	23	23	23
Indoor Air Temperature (Summer) (°C)	23	23	23	23	23
Temp. Change When Unoccupied (°C)	4	4	4	4	4
Ventilation (Occupied) (L/sm^2)	3.0	3.0	3.0	3.0	4.2
Ventilation (Not Occupied) (L/sm^2)	1.0	1.0	1.0	1.0	1.0
Effectiveness of heat recovery	60%	80%	55%	60%	70%
Fan Power (W/(m^3/s))	2120	2120	2120	2120	2120
Mechanical Cooling?	No	No	No	Yes	Yes
Heat Pump?	No	No	No	No	No
Operable Windows?	Yes	Yes	Yes	No	No
Building Facade					
Infiltration (1/h)	0.3	0.3	0.3	0.25	0.2
Window Area (% of Floor Area)	12.5%	15%	15%	15%	20%
U-Values (W/m^{2}K)					
Walls	0.87	0.58	0.44	0.3	0.22
Roof	0.70	0.58	0.23	0.2	0.15
Base	0.87	0.46	0.3	0.3	0.3
Doors	5.5	3.6	0.45	2	1.6
Windows	5.5	3.6	2.8	2.4	2
SHGC	0.75	0.6	0.5	0.35	0.35
Blind Control?	No	No	No	No	No
Other Energy Consumption					
Lighting Energy (kWh/m^2 annual)	35	35	35	35	35
Equipment Energy (kWh/m^2 annual)	38	38	38	38	38
Hot Water (kWh/m^2 annual)	20	20	20	20	20

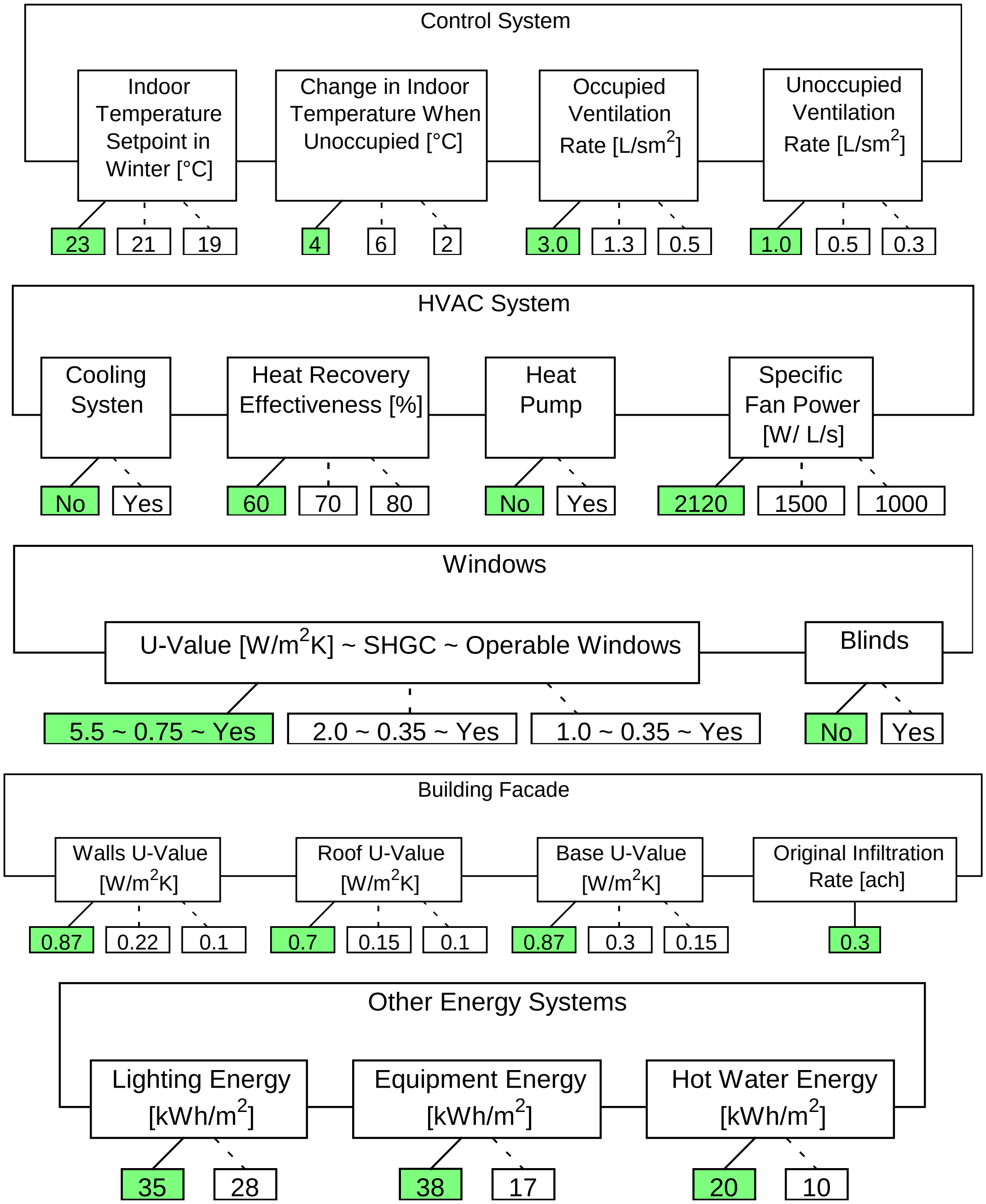

Figure 1 Retrofit options for the buildings constructed before 1969 organized by building system. The highlighted box indicates the original condition of the building. The white boxes describe the potential new conditions after retrofitting.