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

by

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ABSTRACT

Model buildings were created for simulation to describe typical office buildings from different construction periods. A simulation program was written to predict the annual energy consumption of the buildings in their original state and after performing retrofit projects. A scenario analysis was performed to determine the most effective retrofit techniques. This information was used to determine to what degree the national energy consumption of office buildings could be reduced through demand side management.

The results of the analysis showed that it was possible to reduce the annual energy consumption of the office buildings to a minimum of about 70 kWh/m^2. If all buildings in the country were to perform these retrofits, the total energy consumption of office buildings would be reduced by about 75%. The most economical choices of retrofit projects for reducing energy consumption were elements of the controls system and the HVAC system. Retrofits to the windows were also beneficial though more costly. Retrofits to the other facade elements and the other energy services system were shown to produce small changes in annual energy consumption for the required investment cost.

Thesis Supervisor: Leon Glicksman
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Table of Contents

1 List of Figures 6
2 List of Tables 14
3 Introduction 18
4 Background Information on Norway 20
4.1 General Background on Norway 20
4.2 Energy and Buildings Organizations in Norway 21
4.3 Fuel and Power Supply in Norway 23
4.4 Energy Use in Norway 25
5 Previous Buildings Sector Analyses 30
5.1 Lebanon [Chedid 2004] 30
5.2 Scotland [Clarke 2004] 31
5.3 Norway [Myhre 2000] 33
5.4 Lessons Learned 34
6 Energy Consumption in Norwegian Office Buildings 37
6.1 Total Consumption in the Services Sector 37
6.2 Total Consumption by Fuel 38
6.3 Energy Consumption in Office Buildings 39
6.4 Specific Energy Consumption in Office Buildings 40
6.5 Specific Energy Consumption by End Use 43
7 Description of Existing Building Stock 46
7.1 National Level Statistics 46
7.2 Building Characteristics 50
7.3 Summary of Building Characteristics 65
8 Retrofit Costs 66
8.1 Summary of Retrofit Costs 68
8.2 Control System 71
8.3 HVAC System 71
8.4 Building Facade 74
8.5 Other Systems 78
9 Description of Energy Simulation Program 82
9.1 Building Dimensions 83
9.2 Heating and Cooling Energy 84
9.3 Fan Energy 94
9.4 Total Energy of a Single Building 94
9.5 Summary of Program Assumptions 95
9.6 Variable Definitions 96
10 Results and Validation of the Energy Simulation Program 98
10.1 Results of the Simulation Program 98
10.2 Validation of the Results 99
11 Sensitivity of the Energy Simulation Program 104
11.1 Sensitivity Analysis 104
11.2 Effect of Best Practice Assumptions 109
12 Retrofit Analysis 113

12.1 Methodology ... 113
12.2 Retrofitting a Single Attribute ... 121
12.3 Retrofitting Building Systems ... 125
12.4 Retrofitting Multiple Systems ... 134
12.5 Conclusions ... 154
13 Economic Ramifications ... 156
13.1 Payback Period ... 156
13.2 Cost of Conserved Energy ... 167
13.3 Conclusions ... 174
14 Extension to National Consumption ... 175
14.1 Original Consumption ... 175
14.2 Reduction in National Energy Consumption ... 176
15 Conclusions ... 180
16 Appendix A ... 184
16.1 Frost and Ice in Norwegian Heat Exchangers ... 184
16.2 Heat Loss with Heat Recovery ... 185
16.3 Florida Solar Energy Method ... 186
17 Appendix B ... 188
17.1 Pre 1969 Construction Period ... 188
17.2 1969 to 1979 Construction Period ... 194
17.3 1980 to 1986 Construction Period ... 200
17.4 1987 to 1997 Construction Period ... 206
17.5 1997 to 2005 Construction Period ... 212
18 References ... 218

1 List of Figures

Figure 4-1: Map of Norway [CIA 2006] 20

Figure 4-2: Normalized energy and electricity consumption per capita in 1999. Includes the 10 highest per capita energy and electricity consumers [WRI 2004]. 25

Figure 4-3: Percent of primary energy consumption in the buildings sector by energy carrier for Norway in 2001 and the US in 2003 [EIA 2004] [SSB 2006]. 27

Figure 4-4: Domestic final energy consumption except for non-energy purposes and transport. Total by energy source in PJ. 1976-2003 [SSB 2006]. 27

Figure 4-5: Percent of site energy consumption in the building sector by building type in 2002 [Wachenfeldt 2004]. 28

Figure 4-6: Percent of site energy consumption by building type and end use for 2002 [Wachenfeldt 2004]. 28

Figure 6-1: Energy consumption in Norway from 1991 to 2005 in PJ [Bartlett 1993] [SSB 2006]. 38

Figure 6-2: Energy consumption in the services sector by fuel between 1950 and 1991 in PJ [Bartlett 1993]. 38

Figure 6-3: Energy consumption in the services sector by fuel between 1990 and 2003 [SSB 2006]. 39

Figure 6-4: Energy consumption of office buildings managed by Statsbygg. The crosses represent all of the buildings managed, while the dots represent the buildings that were continuously monitored for the full ten years. 41

Figure 6-5: Average specific energy of office buildings from 1976 to 2005 [Bartlett 1993]. 42

Figure 7-1: Floor area of buildings owned by Nordea Bank in m^2 [Haigh 2005]. 52

Figure 10-1: Annual energy consumption by end use predicted by the simulation program for each construction period in $^{kWh}/_{m^2}$. 98

Figure 11-1: Change in annual energy consumption for the six most sensitive parameters in simulations on the buildings constructed before 1969. Values for the winter temperature set point were calculated in °C. 105

Figure 11-2: Change in annual energy consumption for the six most sensitive parameters in simulations on the buildings constructed between 1997 and 2005. 105

Figure 11-3: Sensitivity of building geometry attributes for buildings constructed before 1969. 107

Figure 11-4: Sensitivity of building geometry attributes for buildings constructed between 1997 and 2005. 108

Figure 12-1: Retrofit schematic for the buildings constructed before 1969. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options. 116

Figure 12-2: Retrofit schematic for the buildings constructed between 1969 and 1979. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options. 117

Figure 12-3: Retrofit schematic for the buildings constructed between 1980 and 1986. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options. 118

Figure 12-4: Retrofit schematic for the buildings constructed between 1987 and 1996. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options. 119

Figure 12-5: Retrofit schematic for the buildings constructed between 1997 and 2005. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options. 120

Figure 12-6: Effect of reducing the indoor set point temperature in winter on the annual energy consumption of the buildings constructed before 1969 and those constructed between 1997 and 2005. 121

Figure 12-7: Effect of reducing the ventilation rate during occupied hours on annual energy consumption by end use for buildings constructed before 1969 and those constructed between 1997 and 2005. 122

Figure 12-8: Maximum percent decrease possible from retrofitting each building attribute while leaving the other attributes unchanged. Attributes are organized in decreasing order of benefit for the buildings constructed before 1969. 123

Figure 12-9: Scenarios for retrofitting each building system in buildings constructed before 1969. Note that the controls scenarios fall along the y-axis at 0 cost. 126

Figure 12-10: Scenarios for retrofitting each building system in buildings constructed between 1969 and 1979. Note that the controls scenarios fall along the y-axis at 0 cost. 127

Figure 12-11: Scenarios for retrofitting each building system in buildings constructed between 1980 and 1986. Note that the controls scenarios fall along the y-axis at 0 cost. 127

Figure 12-12: Scenarios for retrofitting each building system in buildings constructed between 1987 and 1996. Note that the controls scenarios fall along the y-axis at 0 cost. 128

Figure 12-13: Scenarios for retrofitting each building system in buildings constructed between 1997 and 2005. Note that the controls scenarios fall along the y-axis at 0 cost. 128

Figure 12-14: Scenarios for retrofitting the HVAC system for each construction period. 129

Figure 12-15: Scenarios for retrofitting the windows of each construction period. 130

Figure 12-16: Scenarios for retrofitting the other facade elements for each construction period. 130

Figure 12-17: Scenarios for retrofitting the other energy services for each construction period. 131

Figure 12-18: Maximum percent decrease in annual energy consumption between the original building condition and the lowest-energy retrofit scenario for each construction period. The systems are organized in decreasing order of benefit for the buildings constructed before 1969. 133

Figure 12-19: Scenarios for retrofitting multiple systems for the buildings constructed before 1969. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below. 141

Figure 12-20: Scenarios for retrofitting multiple systems for the buildings constructed between 1969 and 1979. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below. 142

Figure 12-21: Scenarios for retrofitting multiple systems for the buildings constructed between 1980 and 1986. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below. 143

Figure 12-22: Scenarios for retrofitting multiple systems for the buildings constructed between 1987 and 1996. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below. 144

Figure 12-23: Scenarios for retrofitting multiple systems for the buildings constructed between 1997 and 2005. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below. 145

Figure 12-24: Annual energy consumption by end use for the points highlighted on Figure 12-20 for the multi-systems retrofit analysis of the buildings constructed before 1969. Each of the highlighted points included the low-energy controls scenario. The square point used the Moderate 1 HVAC scenario, but all the other points had the low-energy HVAC scenario. The square and diamond points had no changes to the windows, but the triangle and circle points used the low-energy windows scenario. The square and diamond points included no changes to the facade, but the triangle point used the Moderate 1 scenario, and the circle point included the low-energy scenario. Both the square and diamond points used the Moderate 1 scenario for the other energy services, and both the triangle and circle points included the low-energy scenario. 147

Figure 12-25: Annual energy consumption by end use for the points highlighted on Figure 12-21 for the multi-systems retrofit analysis of the buildings constructed between 1969 and 1979. All of the retrofitted points included the low-energy facade scenario and the low-energy HVAC scenario. The square and triangle points had no changes to the windows. The diamond point used the moderate windows scenario, and the circle used the low-energy windows scenario. Only the circle point included changes to the other facade elements; it included the Moderate 1 scenario. Both the square and diamond point used the Moderate 1 scenario for the other energy services, and both the triangle and circle points included the low-energy scenario. 147

Figure 12-26: Annual energy consumption by end use for the points highlighted on Figure 12-22 for the multi-systems retrofit analysis of the buildings constructed between 1980 and 1986. Each of the highlighted points included the low-energy controls scenario. The square point used the Moderate 1 HVAC scenario, but all the other points had the low-energy HVAC scenario. Only the circle point included changes to the other windows; it used the low-energy scenario. None of the scenarios included changes to the other facade elements. Both the square and diamond points used the Moderate 1 scenario for the other energy services, and both the triangle and circle points included the low-energy scenario. 148

Figure 12-27: Annual energy consumption by end use for the points highlighted on Figure 12-23 for the multi-systems retrofit analysis of the buildings constructed between 1987 and 1996. All of the points used the low-energy controls scenario, except the circle point which used the Moderate 3 scenario. The square point used the Moderate 1 HVAC scenario. Both the diamond and triangle points used the Moderate 2 scenario, and the circle point used the low-energy scenario. The windows were not changed for the square and diamond points. The triangle point used the Moderate 1 windows scenario, and the circle point had the low-energy windows. None of the scenarios included changes to the other facade elements. The square, diamond, and triangle points used the Moderate 1 scenario from the other energy services system; only the circle point used the low-energy scenario. 148

Figure 12-28: Annual energy consumption by end use for the points highlighted on Figure 12-24 for the multi-systems retrofit analysis of the buildings constructed between 1997 and 2005. All of the points used the low-energy controls. The circle point used had every possible low-energy retrofit. The square and diamond points used the Moderate 1 HVAC scenario, but the triangle point used the low-energy scenario. Neither the square, diamond, nor triangle point had any changes to the facade. The square and diamond points used the Moderate 1 other energy services scenario, but the triangle point used the low-energy scenario. 149

Figure 12-29: Annual energy consumption by end use for each controls scenarios for the buildings constructed before 1969 where the fan and heat recovery system have been retrofit (Moderate 1 for the HVAC system). 151

Figure 12-30: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1969 and 1979 where a heat pump has been installed (Moderate 1 for the HVAC system). 151

Figure 12-31: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1980 and 1986 where the fan and heat recovery system have been retrofit (Moderate 1 for the HVAC system). 152

Figure 12-32: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1987 and 1997 where the fan and heat recovery system have been retrofit (Moderate 1 for the HVAC system). 152

Figure 12-33: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1997 and 2005 where the fan has been retrofit and a heat pump installed (Moderate 1 for the HVAC system). 153

Figure 13-1: Nordel Elspot monthly average electricity spot price for January of 2001 through April of 2006 in NOK/MWh with a focus on long term trends. [Nordpool 2006]. 157

Figure 13-2: Nordel Elspot monthly average electricity spot price for January of 2001 through April of 2006 in NOK/MWh with a focus on short term variations. [Nordpool 2006]. 157

Figure 13-3: Scenarios with payback periods of ten years or less by retrofit type for the buildings constructed before 1969. 159

Figure 13-4: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1969 and 1979. 160

Figure 13-5: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1980 and 1986. 161

Figure 13-6: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1987 and 1996. 162

Figure 13-7: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1997 and 2005. 163

Figure 13-8: Scenarios for the buildings constructed before 1969 with payback periods of ten years or less by controls strategy. 164

Figure 13-9: Same scenarios as in Figure 13-7 but with electricity price of 0.0616 $^{\$}/_{kWh}$ instead of 0.0385 $^{\$}/_{kWh}$. 166

Figure 13-10: Same scenarios as in Figure 13-7 but with 30% higher investment cost. 167

Figure 13-11: Cost of conserved energy at a 5% discount rate for scenarios with payback periods of ten years or less for the buildings constructed before 1969. 170

Figure 13-12: Cost of conserved energy at a 10% discount rate for scenarios with payback periods of ten years or less for the buildings constructed before 1969. 170

Figure 13-13: Cost of conserved energy at a 20% discount rate for scenarios with payback periods of ten years or less for the buildings constructed before 1969. 171

Figure 13-14: Cost of conserved energy at a 5% discount rate for scenarios for the buildings constructed between 1997 and 2005. 172

Figure 13-15: Cost of conserved energy at a 10% discount rate for scenarios for the buildings constructed between 1997 and 2005. 173

Figure 13-16: Cost of conserved energy at a 20% discount rate for scenarios for the buildings constructed between 1997 and 2005. 173

Figure 17-1: Retrofit scenarios for the controls system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 188

Figure 17-2: Retrofit scenarios for the HVAC system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 190

Figure 17-3: Retrofit scenarios for the windows of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 191

Figure 17-4: Retrofit scenarios for the non-window facade system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 192

Figure 17-5: Retrofit scenarios for the other energy services system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 193

Figure 17-6: Retrofit scenarios for the controls system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 194

Figure 17-7: Retrofit scenarios for the HVAC system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 196

Figure 17-8: Retrofit scenarios for the windows of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 197

Figure 17-9: Retrofit scenarios for the non-window facade system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 198

Figure 17-10: Retrofit scenarios for the other energy services system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 199

Figure 17-11: Retrofit scenarios for the controls system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 200

Figure 17-12: Retrofit scenarios for the HVAC system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 202

Figure 17-13: Retrofit scenarios for the windows of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 203

Figure 17-14: Retrofit scenarios for the non-window facade system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 204

Figure 17-15: Retrofit scenarios for the other energy servies system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 205

Figure 17-16: Retrofit scenarios for the controls system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 206

Figure 17-17: Retrofit scenarios for the HVAC system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 208

Figure 17-18: Retrofit scenarios for the windows of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 209

Figure 17-19: Retrofit scenarios for the non-window facade system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 210

Figure 17-20: Retrofit scenarios for the other energy services system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 211

Figure 17-21: Retrofit scenarios for the controls system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 212

Figure 17-22: Retrofit scenarios for the HVAC system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 214

Figure 17-23: Retrofit scenarios for the windows of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 215

Figure 17-24: Retrofit scenarios for the non-window facade system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 216

Figure 17-25: Retrofit scenarios for the other energy services system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis. 217

2 List of Tables

Table 4-1: Percent of primary energy consumption by sector in 2003 [SSB 2006] [EIA 2004] [SSS 2004] [SF 2004]. 26

Table 6-1: Total energy consumption from office buildings. The Bartlett report is for both office and retail buildings and should be an upper bound on consumption. 40

Table 6-2: Energy consumption in office buildings by construction year in kWh/m^2 [Enova 2004]. 40

Table 6-3: Enφk Normtall energy consumption simulation results in kWh/m^2 [Enova 2002a]. 43

Table 6-4: Energy consumption broken down by end use for the Modellbyggprojesk in kWh/m^2 [Enova 2002b]. 43

Table 6-5: Energy consumption by end use from the Wachenfeldt report in kWh/m^2 [Wachenfeldt 2004]. 44

Table 6-6: Enφk Normtall results by end use for the southern coastal climate region [Enova 2002a]. 44

Table 7-1: Total number of buildings by construction year from SINTEF [Tokle 1999]. 47

Table 7-2: Total number of office buildings in the GAB register [SSB 2006]. 47

Table 7-3: Calculated number of buildings for each construction period. 48

Table 7-4: Floor area of total building stock in million m^2 [SSB 2006] [Tokle 1999] [Burton 2002] [Enova 2004]. A floor area of 50 million m^2 is projected for the year 2005 with the data from Statistics Norway. 48

Table 7-5: Floor area by construction year from Enova data in m^2 [Enova 2004]. 49

Table 7-6: Total floor area in each construction period in million m^2. 49

Table 7-7: Percent of energy consumed from different energy carriers over time [Bartlett 1993] [SSB 2006]. 50

Table 7-8: Calculated average floor area based on national data in m^2. 51

Table 7-9: Average floor area based on Statistics Norway data [SSB 2006]. 51

Table 7-10: Calculated floor area by construction period in m^2. 52

Table 7-11: Minimum ventilation rates from the 1987 and 1997 code compared to typical practice in $\frac{L}{s\ m^2}$. 54

Table 7-12: Indoor air temperature, ventilation rate, and construction/renovation year for six Danish office buildings [Wargocki 2004]. 54

Table 7-13: Ventilation rates and construction year for three Scandinavian office buildings in $\frac{L}{sm^2}$ [Burton 2002]. 55

Table 7-14: Changes in typical heat exchanger units over time [Mathisen 2005] [Stang 2005]. 57

Table 7-15: U-values for walls, roofs, bases, doors, and windows for each building code in $\frac{W}{m^2K}$ [Codes 2005]. 61

Table 7-16: Solar heat gain coefficients for a selection of window types [ASHRAE 2005]. 63

Table 7-17: Representative Solar Heat Gain Coefficients for each construction period. 63

Table 7-18: Annual energy consumption for lighting equipment and water heating averaged over buildings of all ages in $\frac{kWh}{m^2}$ [Wachenfeldt 2004]. 64

Table 7-19: Annual energy consumption for lighting equipment and water heating for office buildings in the Modellbyggprosjecktet in $\frac{kWh}{m^2}$ [Enova 2002b]. 64

Table 7-20: Summary of characteristics for each representative building. 65

Table 8-1: Demolition and removal costs. [Assemblies 2005] [Mechanical 2006] [Interior 2006] 68

Table 8-2: Typical replacement costs. Costs are the total cost for the retrofit. The capacities of HVAC equipment are per square meter so they can be compared to statistical data and the output from the simulation program. X's indicate information that was not available or not applicable. [Assemblies 2005] [Mechanical 2006] [Interior 2006] 69

Table 8-3: Low-energy replacement costs. Costs for the HVAC system are the typical replacement costs scaled up by 30%. [Assemblies 2005] [Mechanical 2006] [Interior 2006] 70

Table 8-4: Cost of wall components. "t" refers to the thickness of the polystyrene insulation in meters. 75

Table 8-5: R-value of wall components. "t" refers to the thickness of the polystyrene insulation in meters. 76

Table 8-6: Cost of roof components. "t" is the thickness of the insulation in meters. 76

Table 8-7: R-value of roof components. 77

Table 8-8: Cost of base system components. "t" is the thickness of polystyrene insulation in meters. 78

Table 8-9: R-values of base components. "t" is the thickness of polystyrene insulation in meters. 78

Table 9-1: Heat gains from office equipment [ASHRAE 2005]. 87

Table 9-2: Variable definitions. 97

Table 10-1: Annual energy consumption averaged over the entire building stock for the simulation results and several monitoring projects and statistical studies in kWh/m^2 [Enova 2002b] [Enova 2004] [Statsbygg 1995 – 2005] [Wachenfeldt 2004]. 99

Table 10-2: Annual energy consumption for each construction period from the simulation results and enova's statistics in kWh/m^2. Enova's statistics were modified to match the construction periods in this study; See Section 6.4.1. 100

Table 10-3: Annual energy consumption by end use averaged over the entire building stock for the simulation report compared to two studies in kWh/m^2 [Enova 2002b] [Wachenfeldt 2004]. 101

Table 11-1: Change in energy consumption for each model building with and without temperature setback. 110

Table 11-2: Change in energy consumption for each model building with and without ventilation setback. 111

Table 11-3: Change in energy consumption for each model building with and without heat recovery. 111

Table 11-4: Change in energy consumption for each model building with and without a complete glass facade. 112

Table 12-1: Retrofit scenarios selected for the multi-systems analysis for buildings constructed before 1969. 136

Table 12-2: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1969 and 1979. 137

Table 12-3: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1980 and 1986. 138

Table 12-4: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1987 and 1996. 139

Table 12-5: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1997 and 2005. 140

Table 14-1: Specific energy consumption of office buildings based on estimates of total energy consumption and total floor area of office buildings [Enova 2004] [Burton 2002]. 176

Table 14-2: Percent decrease in energy consumption for office buildings for six scenarios based on the scaling factors for the portion of buildings or floor area in each construction period from Enova, the Office Project, and SINTEF. Costs are the initial investment cost in billions of US dollars. 177

Table 14-3: Percent decrease in energy consumption for the entire buildings sector based on the six scenarios of decreasing energy consumption in office buildings and all three scaling methods. Costs are the initial investment cost in billions of US dollars. 178

Table 14-4: Percent decrease in energy consumption for all domestic consumption based on the six scenarios of decreasing energy consumption in office buildings and all three scaling methods. Costs are the initial investment cost in billions of US dollars. 179

3 Introduction

This thesis project is one piece of a much larger project called "Alternatives for the Transition to Sustainable Energy Services in Northern Europe" (TRANSES), 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). The goal of the TRANSES project is to analyze and evaluate potential technology and implementation strategies to create more sustainable energy services in Northern Europe. The total scope of the project includes energy supply, energy demand in the buildings sector, carbon sequestration, and user behavior. It asks the basic question, "Where should we invest in energy infrastructure in order to create a sustainable future for Northern Europe?"

However, the impact of the TRANSES project is not limed to Northern Europe. Northern Europe is serving as a convenient case study for answering that same question on a global scale. The countries under consideration (Norway, Sweden, Finland, and Denmark) include all of the significant sources and consumers of energy that exist in the developed world. They also operate on a single electricity grid that is fairly isolated from the rest of Europe. On a global scale, Northern Europe presents a reasonably contained energy system to study both national energy issues as well as how they are affected by interactions between different countries. There are several ongoing studies looking at various pieces of the entire project and a few trying to tie it all together.

This study examined strategies for decreasing national energy consumption through retrofitting Norwegian office buildings. Residential and commercial buildings consume roughly equal proportions of energy in Norway [SSB 2006]. However, many more previous studies have been performed on residential buildings than on commercial buildings. In terms of meeting the overall goals of the TRANSES project, studying commercial buildings would fill a larger gap in current knowledge. Among commercial buildings the largest consumers are retail buildings, industry and storage buildings, and office buildings [SSB 2006]. Office buildings were chosen for analysis because the most statistical data was available about them and because office buildings were qualitatively the most likely to have fairly uniform characteristics.

The study focused on retrofitting because the turnover in the buildings sector is very low. A typical building can last for 50 to 100 years and it is not unusual for buildings to last longer. Designing and building new energy-efficient buildings is extremely important, but they will not have a significant impact on total national energy consumption for many years. In order to significantly decrease energy consumption in the short-term, changes must be made to the existing infrastructure. This study will begin to estimate how great a decrease is possible and at what cost.

4 Background Information on Norway

Before beginning the actual analysis, it was important to gain an understanding of the context. This chapter describes background information on energy use and buildings in Norway.

4.1 General Background on Norway

Norway is located in Northern Europe, bordering Sweden, the North Sea, and the North Atlantic Ocean, as shown in Figure 4-1. It has total land and water holdings of about 325,000 km^2 and is home to about 4.5 million people. The majority of the population and the three largest cities, Oslo, Bergen, and Trondheim, are located all in southern Norway. Oslo has a population of about 540,000, Bergen about 240,000, and Trondheim 160,000 [SSB 2006].

Figure 4-1: Map of Norway [CIA 2006]

The coastline consists of many islands, long fjords, and indentations. The climate is temperate along the coastlines due to the regulating effects of the North Atlantic Current. The interior is colder and has greater precipitation than the majority of the coastline, but the western coast is rainy throughout the year. The terrain is glaciated, primarily consisting of high plateaus and rugged mountains. However, the valleys between mountains are fertile and there are some small plains. Northern Norway consists primarily of artic tundra [CIA 2006]. The average temperature in Oslo is about 6°C, and it varies from an average temperature of about -5°C in January to about 17°C in July [NMI 2002].

The government is a constitutional monarchy headed by King Harald V, who has been the hereditary chief of state since 1991. The head of the government is Prime Minister Jens Stoltenberg, who has held the position since October of 2005. The legislative branch is a single house of parliament called the Storting. Its members are elected by popular vote and serve four year terms. The prime minister is usually chosen by the monarch to be the head of the majority party in the Storting, but his selection is subject to approval by the Storting. The judicial branch is a supreme court called the Hoyesterett whose members are also chosen by the monarch. [CIA 2006]

The Norwegian economy is based on welfare capitalism and is currently thriving. It has both free market activity and government controls. Norway contains many natural resources of which petroleum, hydropower, fish, forests, and minerals are the most significant. The government runs many of the most prosperous economic areas, including the petroleum sector. Oil and gas production account for a large portion of Norway's economy and typically make up about one third of the country's exports and 18% of the GDP. However, it is predicted that the oil and gas contained in the North Sea will be spent within the next twenty years. In order to prepare for this event, Norway has been saving its budget surpluses in a fund called the Government Petroleum Fund, which was opened in 1990. The fund is internationally invested and is currently valued at more than $150 billion. The GDP is amongst the highest GDP per capita in the world. It had been fairly stagnant but has picked up in the last few years, growing about 1% in 2002, 0.5% in 2003, 3.3% in 2004, and 3.8% in 2005. The currency in Norway is the Norwegian krone (NOK). Between 1999 and 2003, one US dollar was worth between 7 and 9 NOK on average. [CIA 2006] [EIA CAB 2005]

Norway is not a member of the EU, and currently does not have plans to join. The last formal referendum on the issue was in 1994. The primary reason for remaining independent is to retain sole control of Norwegian oil revenues [EIA CAB 2003]. However, Norway is a member of the European Economic Area (EEA). The EEA was formed in May of 2004, uniting all of the EU countries with Norway, Iceland, and Lichtenstein, into a single economic market. The goal is to allow goods, services, capital, and people to move freely through all of the member countries by the same rules in order to create a "homogenous European Economic Area" [EEA 2004].

4.2 Energy and Buildings Organizations in Norway

4.2.1 Statistics Norway (SSB)

Statistics Norway is a government funded organization that collects, processes, and disseminates statistics on economic, social, and industrial issues in Norway. The goal is to create the most accurate picture of Norway possible and ensure that sound economic and social policy decisions can be made. The data is collected by voluntary surveys as well as administrative registers, which are computer databases maintained by the government. Information about all new construction and major renovation projects must be included in the register. The older data is entirely from surveys, but the system is moving towards primarily using the registers. Currently both methods are used for significant portions of the data. Almost all of the collected data are available on the website free of charge. Of particular relevance to this study are the statistics collected on buildings, energy, and the environment. Data from SSB was extensively used in this study to get a picture of how energy is being used in Norway today. [SSB 2006]

4.2.2 Statsbygg

Statsbygg is the state owned organization for building construction and management. Statsbygg currently manages about 2.2 million square meters of floor area including office buildings, schools, and some specialized buildings within Norway. It is also responsible for managing all Norwegian embassies and residencies outside of Norway. Statsbygg is involved with planning and constructing building projects and can serve as a consultant to other construction companies. An internal review of their environmental practices and impact was completed in 2004 and a summary of the results has been published. From this information Statsbygg developed a set of environmental goals that they hope to complete by 2009. The goals focus primarily on waste reduction and an increased consciousness of material choice and recycling as well as energy reduction with a target average consumption of 180 kWh/m^2 across their buildings. [Statsbygg 2006]

4.2.3 Byggsforsk/Norwegian Building Research Institute (NBI)

The Norwegian Building Research Institute studies both technical and social aspects of buildings. The department that specializes in building energy technologies is located in the main office in Oslo. Some of its areas of expertise are energy efficient technologies, building energy requirements, heat transfer and air tightness, and a wide range of indoor environment and ventilation issues. [NBI 2004]

4.2.4 Enova

Enova is a public organization owned by the Royal Norwegian Ministry of Petroleum and Energy and has been in operation since January of 2002. Enova is not directly involved in any research activities. Its objective is to create government policies and financial incentive to promote environmentally responsible energy use and production. In general, Enova's goals are to increase end-use energy efficiency, increase the variety of energy sources within Norway, decrease the use of electricity for heating, and promote the use of renewable energy sources. Its specific goals as of the spring of 2000 are to limit end-use energy consumption, to increase the annual use of hydronic central heating based on renewable energy sources, heat pumps, and waste heat to 4 TWh by 2010, to provide of 3 TWh of electricity from wind resources by 2010, and to increase the use of land-based natural gas. Enova hopes to reduce the energy consumption of commercial buildings with floor areas over 20,000 m^2 by 100 GWh per year. They are also encouraging research into residential buildings to reduce the need for heating systems through decreased heat loss and increased heat recovery. [Enova 2006]

4.3 Fuel and Power Supply in Norway

4.3.1 Oil

Oil was first discovered in the North Sea in the 1960's. There were large increases in oil production in the 1980's and early 1990's, but production has plateaued since then. Starting in the late 1990's Norway began to produce more oil than new finds increased reserves. No new large discoveries have been made recently, and it is thought that there are few significant reservoirs left undiscovered in the North and Norwegian Seas. There is currently hope that there are untapped reservoirs in the Barents Sea, but there are significant cost and environmental barriers to accessing them. Norway is currently one of the largest oil producers and exporters in the world. The average production rate is about 3 million barrels per day, 80% of which is exported. In 2003, Norway was the third largest exporter of oil in the world, behind only Saudi Arabia and Russia. The primary purchasers of Norwegian oil are the UK, the Netherlands, the United States, and Germany. [EIA CAB 2005]

4.3.2 Natural Gas

Norway began producing natural gas in the mid 1970's. In January of 2005, Norway's total natural gas reserves were estimated to be 2 trillion cubic meters. Norway is the eighth largest producer of natural gas, but due to low national consumption it is the third largest exporter behind only Russia and Canada. Like oil, it is thought that all of the major natural gas sources in the North Sea have been found, but more natural gas is still produced each year from incorporating new fields. There is thought to be significantly more natural gas in the Norwegian Sea and the Barents Sea if the cost and environmental barriers can be surpassed to access it. [EIA CAB 2005]

4.3.3 Electricity Production

Hydropower

About 99% of the electricity in Norway is generated from hydroelectric plants. Hydropower is extremely abundant in Norway, but the supply varies with weather conditions. In dry weather, Norway must import electricity from other countries, while in wet weather it can export. A consistent supply of electricity is extremely important in Norway because the majority of heat is supplied by electric resistance heaters or electric boilers. This system can be a problem because the smallest hydropower electricity generation rates usually occur in the winter when the loads are the highest. [EIA CAB 2005]

Another difficulty is that the great majority of useful hydro resources in Norway have already been dammed, and the energy consumption in the country is rising. Since the late 1990's the hydropower plants have not able to generate enough power to cover the national consumption, and Norway has become an importer of electricity. [Nordpool 2006]

Wind Power

The first wind turbines were built in Norway in 1993. As of 2002, there are 11 wind power stations that produced a total of 75 GWh of electricity (0.07% of the national electricity consumption) [SSB 2006]. One of these wind power stations is being expanded, and there are at least two new stations under construction [EIA CAB 2005]. As discussed above, Enova's goal is to create a wind power capacity of 3 TWh by 2010. This production would cover about 9% of the 2002 electricity consumption in Norway.

4.3.4 Electricity Transmission and Distribution

Norway has had an unregulated electricity market since 1991. The original power exchange became Nordpool when it became a common market for both Sweden and Norway. Nordpool now encompasses Norway, Sweden, Finland, and Denmark. There are about 200 power utilities that compete for Norwegian customers in the open market. Consumers can choose their provider without any signup costs [Nordpool 2006]. However, the majority of power companies are still publicly owned. In January of 2002, municipalities and counties owned about 55% of the utilities, the state owned 30%, and private companies owned the remaining 15%. The number of utilities is decreasing as small, regional power companies merge into larger conglomerates [EIA CAB 2003].

The electric grid in Norway is divided into central, regional, and local portions. Statnett, a state owned company, operates the transmission system and owns 80% of the central grid. Statnett is responsible for the construction and maintenance of the entire central grid, ensuring that the total electricity generated will meet the demand in Norway, and for all the connections to grids in other countries. [Statnett 2006]

4.4 Energy Use in Norway

Norway has one of the highest energy consumptions per capita in the world. As shown in Figure 4-2, it had the eighth highest per capita energy consumption and the highest per capita electricity consumption in the world in 1999.

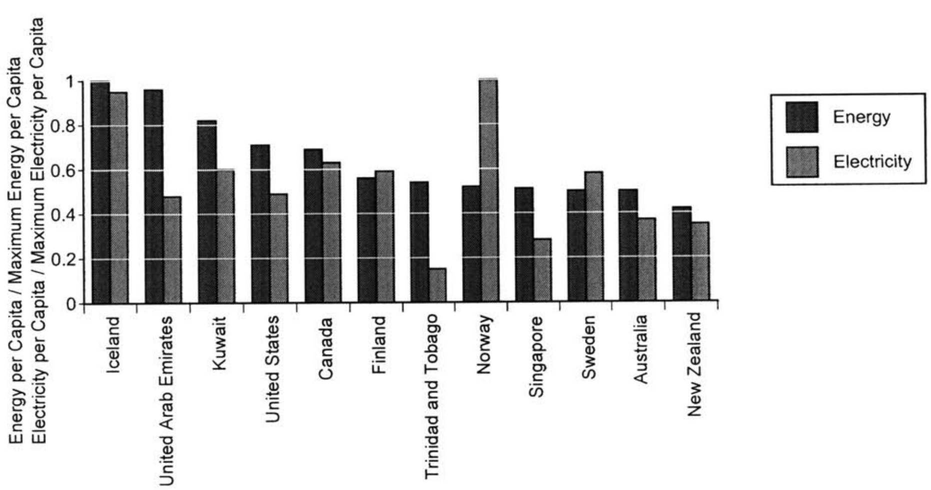

Figure 4-2: Normalized energy and electricity consumption per capita in 1999. Includes the 10 highest per capita energy and electricity consumers [WRI 2004].

Each person in Norway consumed about 250 GJ of primary energy including about 85 GJ of electricity [WRI 2004]. Norway's per capita energy consumption was typical of developed countries in Europe and North America, but its per capita electricity consumption was extremely high. Iceland exhibited similar electricity consumption, but the country with the next highest per capita electricity consumption was Canada, at only 54 GJ per year. Because Norway primarily uses hydroelectricity, such a high electricity consumption was not releasing large amounts of pollutants into the environment in the past. However, since electricity consumption has surpassed the capacity of the hydroelectric plants, pollution is now an issue in finding supplemental power sources. The only way to avoid the need to construct new non-renewable electricity sources is to decrease energy consumption.

Table 4-1 shows the 2003 primary energy consumption in the industrial, transportation, and buildings sectors of Norway, Sweden, Finland, and the United States as a percentage of the total consumption in each country. Each sector was responsible for roughly one third of the consumption in all of the countries shown. The buildings sector in Norway consumed about 38% of the primary energy, a total of about 300 PJ of energy [SSB 2006]. Therefore, improvements in the energy efficiency of buildings have the potential to greatly effect the total national energy consumption.

	Industry	**Transportation**	**Buildings**
Norway	37	25	38
Sweden	45	27	28
Finland	49	16	35
US	37	30	33

Table 4-1: Percent of primary energy consumption by sector in 2003 [SSB 2006] [EIA 2004] [SSS 2004] [SF 2004].

The great majority of energy consumed in the buildings sector in Norway is supplied through electricity. Figure 4-3 shows the percentage of primary energy consumed in the United States and Norway for various fuels. Electricity accounted for 83% and 93% of the primary energy consumed by residential and commercial buildings in Norway in 2001, respectively [SSB 2006]. Electricity is really the only fuel of any significance used in commercial buildings. The balance of fuels used in the residential sector is primarily wood and oil, which are used for supplemental heat. The evolution of residential and commercial primary energy consumption by fuel from 1976 to 2003 is shown in Figure 4-4. As shown on the graph, from 1999 to 2003 energy consumption decreased by about 4%, and the use of petroleum products and district heating increased slightly. These changes are in part due to warmer than average winters, which decreased the electricity demand. However, the seasons were also drier than normal, which decreased the amount of available hydroelectric power, raised electricity prices, and inspired energy conservation efforts [SSB 2006]. While the exact reason for this decrease is not known,

Figure 4-4 does demonstrate that even small changes in the building stock and users' behavior can have a noticeable impact on total energy consumption.

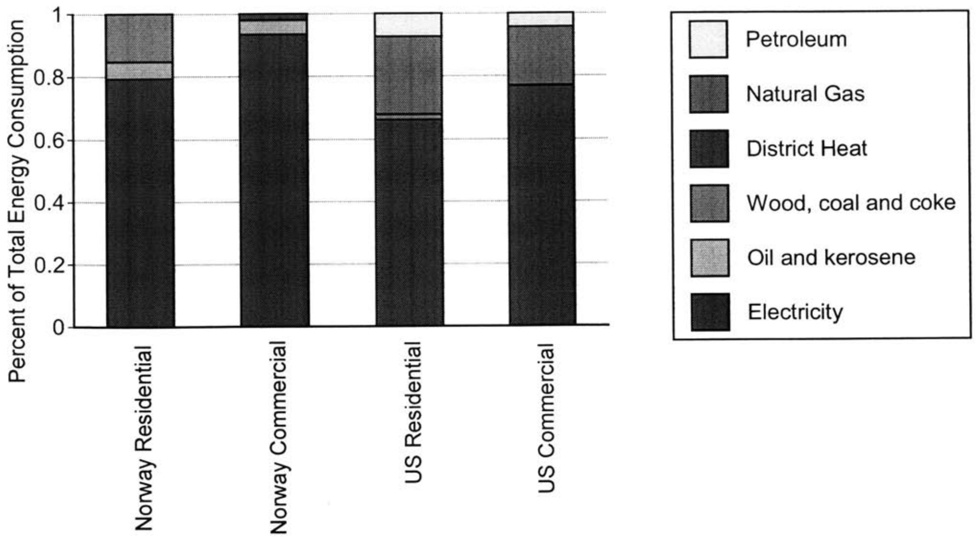

Figure 4-3: Percent of primary energy consumption in the buildings sector by energy carrier for Norway in 2001 and the US in 2003 [EIA 2004] [SSB 2006].

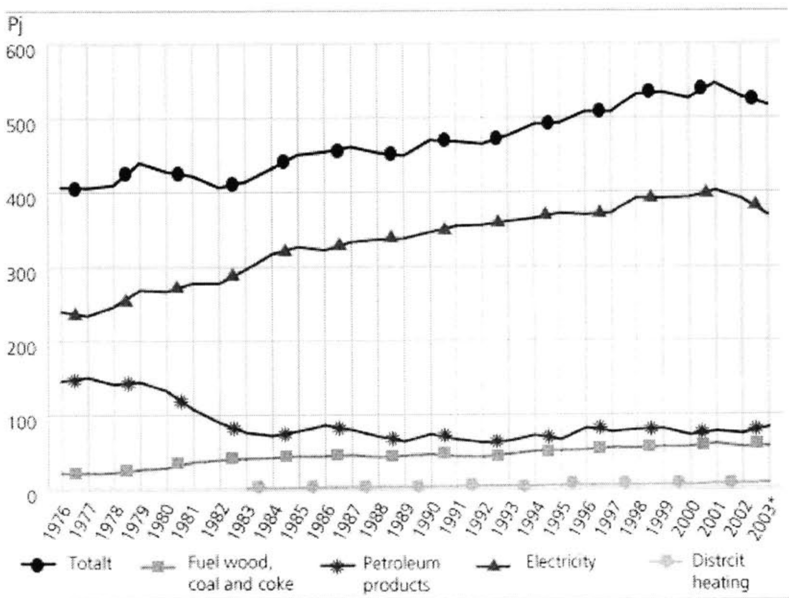

Figure 4-4: Domestic final energy consumption except for non-energy purposes and transport. Total by energy source in PJ. 1976-2003 [SSB 2006].

Within the buildings sector, both residential and commercial buildings make a significant contribution to the total energy consumption. Residential buildings are slightly more important, accounting for about 57% of the total site energy consumption in buildings. Figure 4-5 shows the breakdown of site energy consumption for various building types. Detached houses account for the largest portion of energy by far, at 47%. It also shows that buildings used for retail, industry and storage, and offices are the three largest commercial building consumers. Evaluating one of these three building types would have the greatest impact on commercial building consumption in Norway and would be a more reasonable task than trying to look at all the different types of commercial buildings at once. While some details may differ, the general trends should apply across building types.

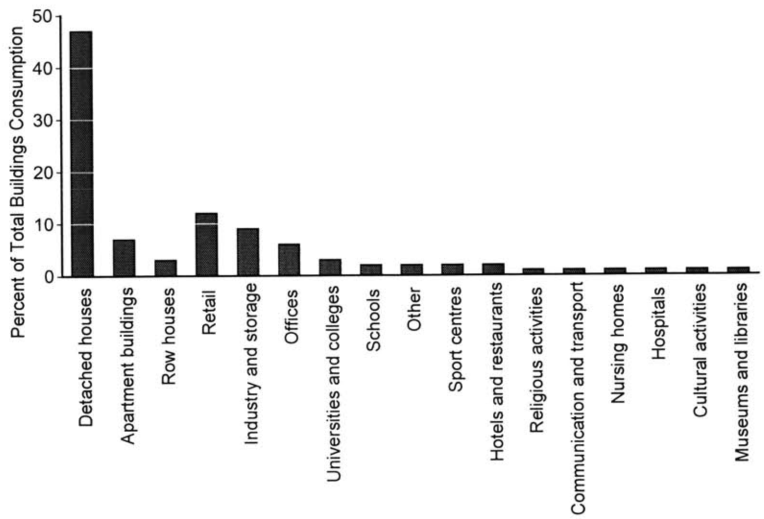

Figure 4-5: Percent of site energy consumption in the building sector by building type in 2002 [Wachenfeldt 2004].

The distribution of site energy consumption by end use in 2002 is shown in Figure 4-6 for residential buildings as well as retail, industry and storage, and office buildings.

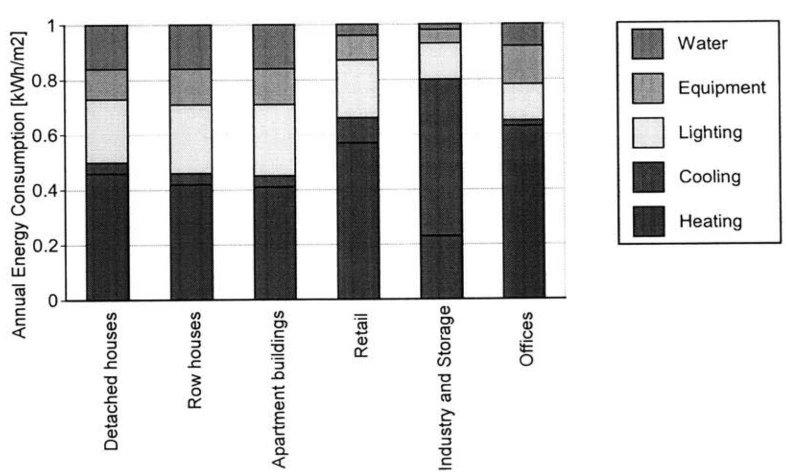

Figure 4-6: Percent of site energy consumption by building type and end use for 2002 [Wachenfeldt 2004].

The distribution of end-use energy is fairly consistent across all the buildings, except for industry and storage where a very large portion of energy was used for cooling, which was likely used for refrigeration. Heat is the largest energy consumer in the other building types, accounting for about 40% of the energy in the residential buildings and 60% of the energy for retail and office buildings. Lighting, water heating, and equipment also accounted for large portions of the energy consumption. In most cases, cooling energy accounted for less than 5% of the total energy consumption.

Each of the end uses makes a significant contribution to the total building energy consumption. Therefore, the energy use of the entire building system must be considered in this analysis. Retrofit techniques and changes in construction methods must apply to the entire building, and whole building simulations will be necessary to predict the effects these changes will have on national energy consumption.

5 Previous Buildings Sector Analyses

Several previous studies have been performed where researchers looked at the large-scale effect of changing building energy efficiency. These studies provided useful guidance on how to setup and implement this analysis. The goals, methodologies, and a brief summary of results for the three projects are described below. The final section of this chapter provides a discussion of the lessons learned from these studies and a description of how their experiences were utilized in this project.

5.1 Lebanon [Chedid 2004]

A study was performed to evaluate the long term effectiveness of a group of energy efficiency options for the Lebanese building sector by researchers at the American University of Beirut and the Lebanese American University. The overall goal of the study was to help stabilize energy consumption in Lebanon to encourage economic development, assist the government in performing economical rehabilitation and development of building infrastructure, and provide basic commodities to people. The researchers chose to use a scenario analysis approach. The primary goals of the study were to develop a baseline scenario that reflects the current state of energy consumption of buildings in Lebanon, propose and evaluate other possible scenarios, and recommend new strategies for increasing the use of energy efficient technologies in Lebanon.

The researchers began by constructing a description of the existing buildings. A building survey performed by the Lebanese Bureau of Statistics (Administration Central de la Statistique) provided information about building function (residential or commercial), climate zones, construction methods, current condition, and number of floors. The researchers chose to categorize all model buildings for the analysis by their construction method and climate zone. Then they estimated U-values for walls, roofs, and windows for each construction method/climate zone pair based on simulations performed in a previous research study. Finally, they estimated the current consumption of electrical equipment in Lebanese buildings using data from previous studies. Once they had a description of the existing buildings, the researchers needed to determine how the building characteristics should be changed in the future. They decided to use the normal values described in the 1982 French building code as the improved building U-values for retrofitted buildings or new construction. The 1982 code was chosen because a previous study had determined the energy savings that would result from upgrading to this standard. They also made certain assumptions for decreasing electricity consumption including use of compact florescent lighting, solar hot water heaters, and energy efficient refrigerators.

The third step was to perform the actual analysis. The researchers chose the use the Long-Range Energy Planning System (LEAP) software to perform the energy analysis. Short term (1994 to 2005) and long term (1994 to 2040) studies were performed to determine what actions should be taken immediately and to identify long term goals. They evaluated several scenarios for both time periods with different assumptions for building construction, renovation, and demolition rates. They also had to make assumptions about electricity, fuel, and equipment prices. Energy consumption in 1994 was about 14 PJ. If no significant improvements are made to the building stock, the energy consumption was predicted to be 38 PJ in 2005 and 88 PJ in 2040. If energy efficient technologies are implemented, the predicted energy consumption is reduced to 36 PJ in 2005 and 69 PJ in 2040, a reduction of 4% and 21%, respectively.

Finally, the researchers used the results to draw conclusions on the actions the Lebanese government should take to reduce energy consumption in the buildings sector. The short term goals included adjusting current electricity prices, establishing an energy efficiency labeling system, giving loans to consumers for energy efficient equipment, training technicians to maintain and repair energy efficient equipment, changing customs policies, and conducting public awareness campaigns. The long term goals included developing a national energy plan, writing building codes and enforcing compliance, encouraging local industry of energy efficient products particularly solar hot water heaters, and including "environmental cost" in economic calculations.

5.2 Scotland [Clarke 2004]

A group of researchers from the University of Strathclyde and analysts from the Scottish Executive, Housing Directive performed an analysis of the residential building sector in Scotland. The overall goal of the project was to develop a method to help policy makers make educated decisions for requiring changes to the residential buildings sector. They used a building simulation program to estimate the energy consumption of model buildings in Scotland,

and used the results to create a decision tool for policy makers. The decision tool on its own is generic and could be used with input from any building sector.

The researchers began by studying the current building stock. They found that information existed to classify buildings by their construction type and age, but that these factors did not predict energy consumption well. The thermal characteristics of the buildings were much more important.

The researchers then chose to create generic "thermodynamic classes" based on five building attributes: window size, insulation level, thermal capacity level, capacity position, and air permeability. Each attribute had two or three possible cases (low/high or low/standard/high) and a thermodynamic class was created for each possible combination of the five attributes. This process created 30 distinct thermodynamic classes. Then an energy simulation program was used to determine the energy consumption of the building described by each thermodynamic class. The results of the energy simulations were used to create regression equations that predict the performance of the building under different weather conditions. The goal of this strategy was to keep the tool relevant in the future when weather conditions and the makeup of the building stock may be different. The user can define the weather and evaluate the change in energy that would result from changing a building from one thermodynamic class to another.

The thermodynamic class system was utilized for two purposes. First, the researchers created a web based tool that policy makers can use to get a qualitative understanding of how changing the thermal characteristics of a building changes the energy consumption. The user chooses a value for each attribute from a drop-down menu and enters the fuel cost and building floor area. The program then provides information about the energy, operation cost, and CO_2 saved in one year that would result from changing the building from its current thermodynamic class to the other possible classes.

The system was also used to examine the potential to decrease energy consumption in existing houses in Scotland. The researchers used statistical data to split up the number of existing houses that belonged to the various thermodynamic classes. They could then simulate the decrease in energy and CO_2 production possible by changing the number of buildings in each thermodynamic class. They found a total potential to reduce energy consumption by 6627 GWh preventing the release of 1.9 million tonnes of CO_2 each year. In 2002 residential buildings is

Scotland consumed approximately 56 TWh of energy [Scot. Executive 2006]. Therefore, the results of this study predict the potential for a 12% reduction in total energy consumption.

5.3 Norway [Myhre 2000]

Lars Myhre of the Norwegian Building Research Institute conducted a scenario analysis on the future energy use of the residential building stock in Norway as an expansion of his PhD work NTNU. The goal of his study was to evaluate how different energy efficiency approaches could help Norway move towards sustainability. Myhre began by categorizing the residential building stock by type (detached house, row house, or apartment) and year of construction and determined the total floor area in each category. He then defined about 20 characteristics to describe the building shape, occupancy, thermal characteristics, and heat sources. To compile this information he used national level statistics as well as results from previous research studies. Myhre also needed to define the rates of building demolition, expansion, and construction in the future. He utilized a previous study that predicted future population growth to define appropriate levels of demolition and new construction.

Myhre programmed his own energy simulation program. The program performed a set of static energy balances to predict the amount of heating energy required by a building in one year based on monthly averaged weather conditions. Cooling energy was not considered. Electrical energy was taken directly from statistics.

Myhre then used his statistical compilation and energy simulation program to run four scenarios to predict national energy consumption in residential buildings from 1990 to 2030. The scenarios included a business as usual case, one with moderate improvements to energy efficiency, one with extreme improvements to energy efficiency, and one that considered installing heat pumps in all new construction and retrofits. He found that it is possible for the total energy consumption of Norwegian residential buildings in 2030 to be less than it was in 1990. The results also showed that heat pumps were especially effective in large buildings, and a qualitative cost analysis suggested that the best method to reduce energy consumption is to make moderate changes to the building energy efficiency and install a heat pump.

5.4 Lessons Learned

All of the studies provided valuable insights into how to construct a useful large scale study of energy use in buildings. Each used some form of a scenario analysis as opposed to an optimization approach. The scenario approach is best because it allows the researchers to see the effects of moderate approaches that may have a lower first cost in comparison to absolute best case. The scenario approach can also reveal strategies that provide very small decreases in total energy consumption or actually increase energy consumption. Finding out what not to do can provide as much useful information as searching for what to do. However, each of these studies used a very small number of scenarios, which leaves the reader with many lingering questions. For example, in the Norwegian study Myhre suggested that completing moderate improvements in energy efficiency and installing a heat pump was the best overall strategy, but he did not actually calculate the total decrease. Also, he lumped together several efficiency improvements without determining if one type of improvement was much more effective than the others. In this study it will be important to use a large number of scenarios to show the total range of possible outcomes and distinguish the most effective retrofit strategies.

The first step in each study was to look at the available statistical data and attempt to categorize the existing buildings in a useful way. This process will also be the best place to start this study. The three previous studies show that all of the necessary information is unlikely to exist in a single source. Various studies and types of data will have to be compiled to form an overall picture of the existing building stock. Existing data will give approximate values for the performance of existing buildings, but studies will likely contradict each other. The previous studies also demonstrate that the best building characteristics for analyzing model buildings are the building's age, climate, and thermal mass. Additional characteristics can be defined for a model building of each category. In terms of total energy consumption, these thermodynamic characteristics are much more important than architectural distinctions. However, none of the studies had enough reliable data to perform a thorough statistical analysis, so the statistical significance of this organization scheme is unknown.

The studies had different approaches to defining the energy consumption of new construction or buildings after retrofit. The Lebanese study used the values defined in the 1982 French building code as their target. The Scottish study created arbitrary thermodynamic classes so that researchers could pick and choose to transfer buildings from one thermodynamic class to another. The Norwegian study defined changes in building characteristics and then calculated the new energy consumption. Each of these approaches is best for different conditions and goals. The Lebanese approach is useful to evaluate a preexisting policy, but it would not give insight into developing new policies. The Scottish approach is good for looking at a small number of possible types of buildings because it significantly reduces the number of times the energy simulation program must be run. However, if a large number of building characteristics is under consideration, there are too many thermodynamic classes, and this approach becomes confusing. The Norwegian approach requires more calculation time, but it is best to examine a large number of building characteristics and still provide insight into building behavior beyond current policy. Since this study will be considering a large number of scenarios Myhre's approach in the Norwegian study is most applicable.

The three studies also used different approaches to actually calculate the annual energy consumption of the buildings. The Lebanese study simply assumed that changes in the facade would decrease the total energy consumption by 25% based on a previous study [Chedid 2004]. The Scottish and Norwegian studies both developed methods to calculate total energy consumption. The Scottish method included thermal mass in the calculation, but the Norwegian study did not. The lesson learned here is that the statistical data the researchers were able to use to describe the existing building determined what type of simulation program could be used. None of these studies were able to simply plug the numbers into a preexisting simulation program. In this study it will be important to determine what statistical data is available before choosing a simulation program. The previous studies suggest that it will be necessary to develop a new program tailored to the available data or use generic building classes as the researchers did in the Scottish study. Since this study will consider a large number of scenarios it is likely that too many "thermodynamic classes" would be created and the Scottish approach would no longer simplify the explanation. Therefore this study will use a simulation program to calculate energy consumption for each building type and potential change.

None of the previous studies included a rigorous cost analysis. While researchers recognize that energy efficiency measures must be cost-effective to be implemented, project costs can be very difficult to estimate under general conditions. Many people assume that there is no way that implementing low energy measures can be economically feasible, but some individual building projects have demonstrated that this is not the case [Glicksman 2006]. This study will include costs so that the results will be considered for both the energy and economical implications.

The next chapters will describe statistical information about energy consumption in Norwegian office buildings and the specific characteristics of the building stock. These previous studies provided a frame to analyze the available data and determine how best to categorize building types and develop the simulation program.

The Bartlett report shows a consumption of about 85 PJ, while the current Statistics Norway data reported that consumption was 119 PJ. The reasons for this discrepancy are unclear.

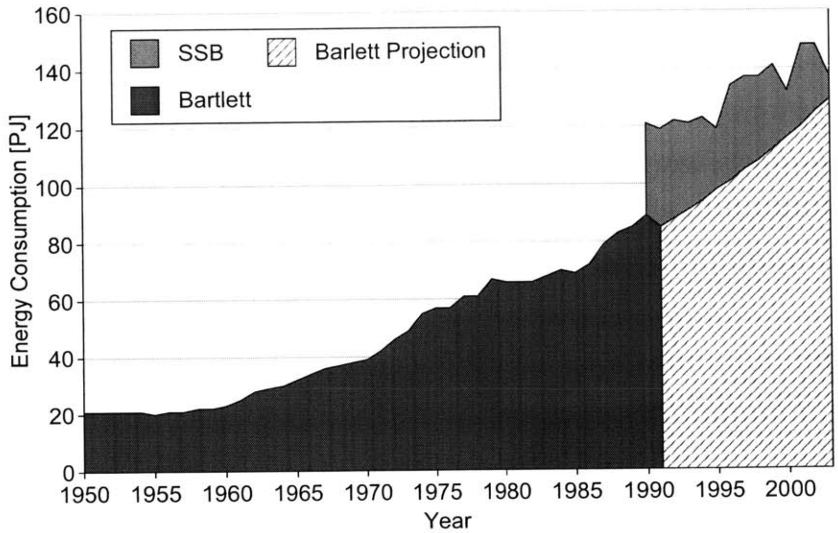

Figure 6-1: Energy consumption in Norway from 1991 to 2005 in PJ [Bartlett 1993] [SSB 2006].

6.2 Total Consumption by Fuel

The Bartlett report also tracked energy consumption in the services sector by fuel source for the period 1950 to 1991 as shown in Figure 6-2.

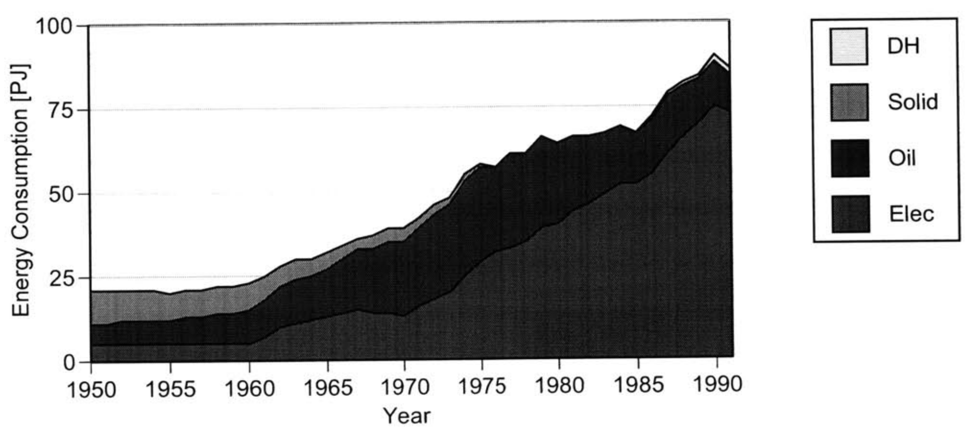

Figure 6-2: Energy consumption in the services sector by fuel between 1950 and 1991 in PJ [Bartlett 1993].

Electricity and oil have been the primary sources of energy since the mid-1960s, and the use of solid fuels was eliminated completely by the mid-1970s. Oil consumption remained fairly constant during the entire time period. Almost all of the growth in energy consumption was due

6 Energy Consumption in Norwegian Office Buildings

Before examining the characteristics of individual office buildings, it is important to get an understanding of the energy consumption of the office buildings on average and as a group. This information will place the performance of individual buildings in the proper perspective and reveal current trends. The sectoral level energy consumption will also be used later to compare results from simulation of the performance of individual buildings and verify that the simulation program is producing reasonable results for the consumption of the current building stock.

6.1 Total Consumption in the Services Sector

Recall from Chapter 4 that Statistics Norway has compiled detailed information about the energy consumption used in industry, transportation, and for other purposes. The "other" category is understood to include residential and commercial buildings. Statistics Norway also compiles data on the energy consumption of residential buildings and calculates the consumption of commercial buildings as the difference between the total consumption of residential and commercial buildings and the consumption of residential buildings alone. As a result, the statistics for the services sector are always accompanied by a warning that some observed fluctuations are due to errors in this calculation [SSB 2006].

In 1993 Statistics Norway published a comprehensive study on energy consumption in Norway between 1950 and 1991 [Bartlett 1993]. Figure 6-1 shows how the energy consumption in the services sector varied over that time period. Energy consumption increased from about 20 PJ in 1950 to about 85 PJ in 1991 with a fairly linear growth rate from 1960 to 1991. The projected energy consumption to 2003 in the figure is based on finding the average growth rate for all the years in the study, 4%, and assuming that consumption grows constantly at that rate. This calculation predicts that commercial buildings in Norway would consume about 130 PJ of energy in 2003.

Statistics Norway also has consumption data available on the internet for the time period 1990 to 2003. This data is also shown on Figure 6-1. In this case the energy consumption in 2003 was about 137 PJ, which is similar to the predicted value from the Bartlett report. However, note that the energy consumption in 1991 differs significantly between the two reports.

to increased use of electricity. District heat was introduced in the mid-1980s and has since accounted for a very small but growing portion of the total energy consumption

The current data on energy consumption in the services sector on the Statistics Norway website can also be broken down by fuel source for the period 1990 to 2003. Again, this value must be calculated as the difference between the total residential and commercial consumption and the reported residential consumption. The results of this calculation are shown in Figure 6-3. Again, electricity and oil accounted for almost all of the energy consumption, and district heat accounts for a small but growing contribution. Total consumption from district heat was about 5 PJ in 2003. Between 1992 and 1999 a few PJ were attributed to consumption of solid fuels or natural gas. It is unclear if this is representative of true data or is simply a calculation error. In either case, no significant contribution of solid fuels or natural gas has been reported since 1999.

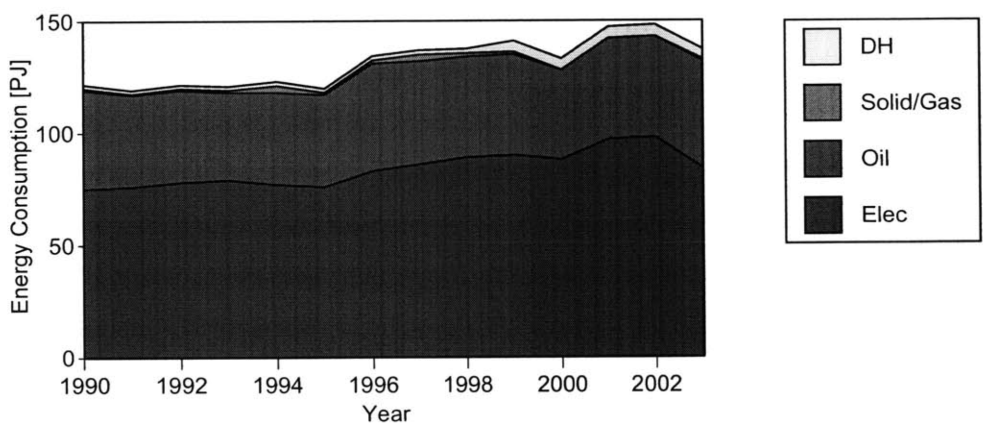

Figure 6-3: Energy consumption in the services sector by fuel between 1990 and 2003 [SSB 2006].

6.3 Energy Consumption in Office Buildings

Energy consumption in the entire services sector is useful in identifying overall trends, but for this study it is necessary to estimate the portion of that energy consumption due to office buildings alone. The Bartlett report listed the percent of total energy consumption in the services sector due to both office and retail buildings for the years 1976 through 1991. Therefore, these figures should provide an overestimate of the total consumption due to office buildings. The portions of total consumption attributed to office and retail buildings varied from 35% to 40% with an average of 37%. Another study, by Bjϕrn Wachenfeldt of SINTEF Energy, reported that office buildings consume only 14% of the total energy in the services sector [Wachenfeldt 2004].

Retail consumed 29%, so the total for office and retail buildings was 43%, which is about 10% higher than the equivalent value in the Bartlett report.

Table 6-1 shows the total energy consumption from office buildings in Norway based on these percentages and the total energy consumption reported by Statistics Norway in 2003, 137 PJ. This data shows that the calculated national energy consumption from the simulation program should be on the order of 19 PJ (5.3×10^9 kWh) but certainly less than 51 PJ (1.4×10^{10} kWh).

	Office %	Energy [PJ]	Energy [kWh]
Bartlett	37	51	1.4e10
Wachenfeldt	14	19	5.3e9

Table 6-1: Total energy consumption from office buildings. The Bartlett report is for both office and retail buildings and should be an upper bound on consumption.

6.4 Specific Energy Consumption in Office Buildings

6.4.1 Measured Data

Enova has two studies that provide information about the energy consumption of office buildings. The Modellbyggprojesk included 8 office buildings whose energy consumption was carefully monitored. The specific energy consumptions of the buildings varied from 161 to 323 kWh/m^2 with an average consumption of 200 kWh/m^2 [Enova 2002b]. Enova also reports statistics on the energy consumption of all buildings involved in their projects. In 2003 this included 196 office buildings with an average consumption of 233 kWh/m^2 [Enova 2004]. Table 6-2 shows how the average specific energy consumption of Enova's buildings varied for buildings constructed in different time periods. Note that the most recent buildings consume the most energy.

	Specific Energy Consumption
Before 1931	214
1931 – 1954	250
1955 – 1970	219
1971 – 1987	226
1988 – 1997	246
After 1997	303

Table 6-2: Energy consumption in office buildings by construction year in kWh/m^2 [Enova 2004].

Statsbygg has published reports of the energy consumption of the buildings it manages each year from 1995 through 2005 [Statsbygg 1995 – 2005]. The reports include data on about 200 buildings, but only about 60 had data for every year in the full 10 year period. Figure 6-4 shows the average energy consumption of buildings managed by Statsbygg each year. One set of data corresponds to all of the buildings, while the other is only for those with complete data for the full ten year time period. The average energy consumption varied between about 200 and 275 $^{kWh}/_{m^2}$. In 2005 the average consumptions were about 215 $^{kWh}/_{m^2}$ and 230 $^{kWh}/_{m^2}$ for all the buildings and the complete data set buildings, respectively. The data for all of the buildings shows a decrease in energy with time. However, the data for the buildings that were monitored for the full ten years, does not show a decrease. Instead, the consumption oscillated around a value of about 240 $^{kWh}/_{m^2}$. In this group of buildings 62% showed a relative increase in consumption from 1995 to 2005. The increases varied between 8 and 304 $^{kWh}/_{m^2}$ with an average increase of about 60 $^{kWh}/_{m^2}$. The remaining 38% showed a relative decrease in consumption from 1995 to 2005. The decrease ranged from 0.4 to 280 $^{kWh}/_{m^2}$ with an average decrease of 70 $^{kWh}/_{m^2}$.

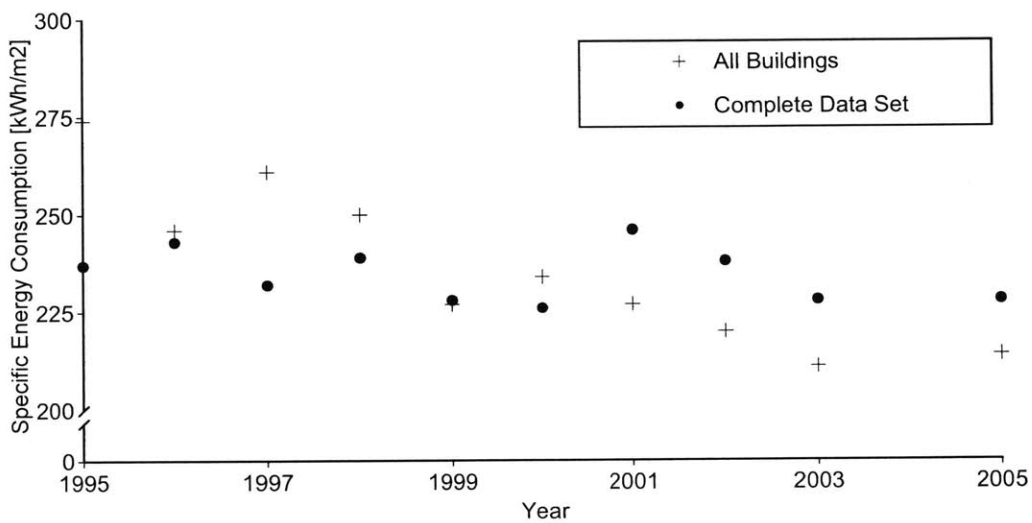

Figure 6-4: Energy consumption of office buildings managed by Statsbygg. The crosses represent all of the buildings managed, while the dots represent the buildings that were continuously monitored for the full ten years.

It is not clear what led to the vastly different behaviors of the continuously monitored buildings. However, the statistics are encouraging because they show that it is possible for office buildings to become more energy efficient with time. Careful study of energy consumption may reveal insights into how to achieve this regularly. Also, since many buildings are using more energy with time rather than less, more information on building energy consumption is necessary to stop and potentially reverse this trend.

6.4.2 Statistics Based Data

Information on the average energy consumption of office buildings can also be estimated with a top-down approach by dividing the total energy consumption of office buildings by the total floor area. The data in the Bartlett report included this information for the time period 1976 through 1991. The data shows a fairly steady decrease in specific energy consumption from close to 400 kWh/m^2 in 1976 to about 300 kWh/m^2 in 1991 as shown in Figure 6-5. The projected specific energy consumption was also calculated by dividing the projected growth of energy consumption by the projected growth of floor area. The average growth rate over the time period 1976 to 2005 was used for both projections. This calculation predicted a specific energy consumption of about 280 kWh/m^2 in 2005.

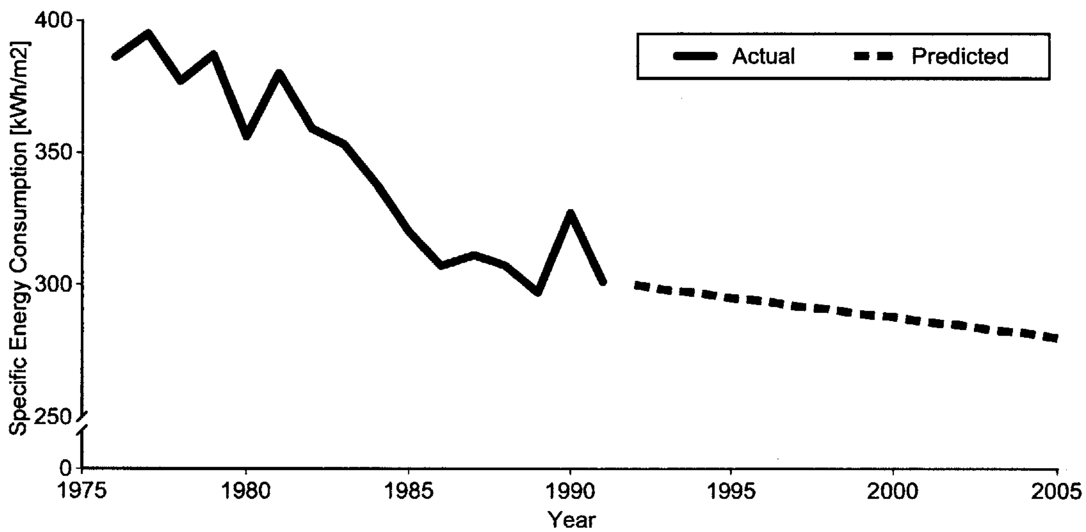

Figure 6-5: Average specific energy of office buildings from 1976 to 2005 [Bartlett 1993].

Wachenfeldt reported an average specific energy consumption of office buildings of 260 kWh/m^2 based on collected statistics. Both Bartlett and Wachenfeldt's data is higher than the average measured data for individual buildings but is within the scatter of performance of specific buildings.

6.4.3 Calculated Data

Enova also has an energy simulation program, Enφk Normtall, which is used to look at the effect of climate on building performance. Enφk Normtall defines three archetype office buildings for construction before 1987, between 1987 and 1996, and after 1997. It uses the same inputs in every simulation, but varies the climate region. Simulation results are shown in Table 6-3. Note that Oslo, which has an average Norwegian climate, is located in the southern coastal climate region [Enova 2002a].

	Before 1987	1987 – 1996	1997 and After
Southern Inland	198	174	135
Southern Coastal	175	157	122
Southern Mountainous	222	194	149
Central Coastal	185	164	128
Central Inland	225	196	151
Northern Coastal	213	186	144
Finnmark Inland	246	213	163

Table 6-3: Enφk Normtall energy consumption simulation results in kWh/m^2 [Enova 2002a].

The Enφk Normtall results match current average consumption results fairly well for the pre-1987 buildings. The predicted average consumption for all buildings constructed after 1987 in all climate regions are significantly lower than the available measured data. Also, the Enφk Normtall results show that new buildings consume significantly less energy than old buildings, which does not agree with measured data from Enova or from Statsbygg.

6.5 Specific Energy Consumption by End Use

A few reports have included information about the total energy consumption broken down by end use. Recall that Enova collected detailed information about the energy consumption of eight office buildings as part of the Modellbyggprojesk. The average energy consumption of these buildings broken down by end use is shown in Table 6-4.

	Average Consumption	Percent
Heating	62	31%
Ventilation	37	18.5%
Water Heating	4.8	2.4%
Fans/Pumps	38	19%
Lighting	27	13.5%
Other	29	14.5%
Cooling	7	3.5%
Total	200	

Table 6-4: Energy consumption broken down by end use for the Modellbyggprojesk in $^{kWh}/_{m^2}$ [Enova 2002b].

The "Other" category in this case would be primarily made up of office equipment. Note that heating is the most important single component, but it by no means dominates the total energy consumption. Ventilation, fans and pumps, lighting, and other all consume roughly equivalent portions of energy in one year. Energy for cooling air and heating water are comparably small but are present.

Wachenfeldt's report also included a breakdown of total energy consumption by end use. His results are shown in Table 6-5. In this case the heating category includes heating and ventilation. Energy consumption for lighting and office equipment are similar but greater than those reported in the Modellbyggprojesk. The most significant difference is that energy for heating water is 20 kWh/m^2, but was reported as only 5 kWh/m^2 in the Modellbyggprojesk.

	Energy Consumption	Percent
Heating	164	62.6%
Equipment	38	14.5%
Lighting	35	13.4%
Water Heating	20	7.6%
Cooling	4	1.5%
Total	262	

Table 6-5: Energy consumption by end use from the Wachenfeldt report in kWh/m^2 [Wachenfeldt 2004].

Finally, the results from Enøk Normtall were also reported by end use. The results for the southern coastal climate region are shown in Table 6-6. In this case the "Other" category primarily includes energy for lighting. Similar to the results for total energy, the Enøk Normtall results for building constructed before 1987 are similar to the average measured and statistical results. However, the simulations for more recent construction have much lower energy consumptions, especially for heating.

	Before 1987		1987 – 1996		1997 and After	
	kWh/m²	Percent	kWh/m²	Percent	kWh/m²	Percent
Heating	61	34.9%	36	22.9%	21	17.2%
Ventilation	26	14.9%	29	18.5%	20	16.4%
Hot Water	10	5.7%	10	6.4%	10	8.2%
Fans & Pumps	17	9.7%	21	13.4%	17	13.9%
Equipment	32	18.3%	32	20.4%	26	21.3%
Other	24	13.7%	24	15.3%	24	19.8%
Cooling	5	2.9%	5	3.2%	4	3.3%
Total	175		157		122	

Table 6-6: Enøk Normtall results by end use for the southern coastal climate region [Enova 2002a].

All three studies show that heating and ventilation consume about half of the total energy used in a building, but the magnitude of the values ranged from 41 kWh/m^2 to 162 kWh/m^2. Reducing energy for heating is clearly going to be an important goal for retrofit strategies. The energy consumed by fans, office equipment, and lighting was fairly consistent between the different studies. Each consumed about 20 to 40 $^{kWh}/_{m^2}$ of energy per year. Reducing energy consumption for these end uses will also be valuable, but the changes will likely have less of an effect than the heating energy. Cooling consumed less than 10 $^{kWh}/_{m^2}$ of energy per year in each report. This result suggests that introducing a cooling system to the building will not change the total energy consumption by more than a few percent. However, it is possible that the cooling requirements could be eliminated completely by taking advantage of increased ventilation from the cool outdoor air.

7 Description of Existing Building Stock

For this study to be successful, it is extremely important to have a detailed, accurate description of the current building stock. This chapter will describe how each characteristic of the representative office buildings was determined. It will also describe the information used to "scale-up" simulation results for the energy consumption of individual buildings to the national consumption.

The representative buildings were divided into five construction periods defined by the years that building codes were put into effect: 1942, 1969, 1980, 1987, and 1997. New codes are currently under development in accordance with EU directive 2002/91/EC on the energy performance of buildings which will be effective in 2006 [Thyholdt 2005].

At the onset of this study, it was hoped that several representative buildings could be defined within each construction period to take effects like thermal mass, floor-plan aspect ratio, building and window orientation, and building location into account. Unfortunately, statistical data was not available to this level of detail. The information presented in this chapter is used to define the characteristics of one representative building in each construction period with no thermal mass. Assumptions for floor-plan aspect ratio, building and window orientation, and building location are described below or in Chapter 9 on the simulation program.

7.1 National Level Statistics

This section describes the total number and floor area of office buildings in Norway and what energy sources they use. The statistics will be used later to transform the energy consumed by individual buildings to a total national energy broken down by energy source.

7.1.1 Number of Buildings

Very little information was available on the number of existing office buildings categorized by construction year. A 1999 study by SINTEF Energy attempted to determine this information, but over 60% of the buildings still had unknown construction years [Tokle 1999]. The results of this study are shown in Table 7-1.

	Number of Buildings
Before 1956	3143
1956 – 1980	1918
1981 – 1997	8002
After 1997	303
Unknown	22951
Total	36317

Table 7-1: Total number of buildings by construction year from SINTEF [Tokle 1999].

Accurate data about the total number of office buildings is available from the Ministry of Environment's Ground Property, Address and Building Register (GAB Register) which began reporting in 2001 [SSB 2006]. The total number of existing office buildings for 2001 to 2005 is shown in Table 7-2.

	Total Office Buildings
2001	36101
2002	37159
2003	37377
2004	37589
2005	37650

Table 7-2: Total number of office buildings in the GAB register [SSB 2006].

In order to determine the total number of existing buildings in the construction periods defined in this study, some manipulation of the data in Table 7-1 and Table 7-2 was necessary. First, the number of office buildings in each construction period was determined from the SINTEF study alone. Within each time period in the SINTEF report, it was assumed that the same number of buildings was built each year. The buildings were then redistributed into the construction periods used in this study. Next, the percent of buildings with known construction years in each construction period was calculated, and those percents were used to find the total number of buildings based buildings with both known and unknown construction years.

However, the SINTEF study only includes buildings constructed up to the year 1999, so the data from the GAB register was used to determine the number of office buildings constructed between 1999 and 2005. The difference between the total number of office buildings in 2005, as reported by the GAB, and the total in 1999, as reported by SINTEF, was calculated. This number was assumed to be the number of new buildings building between 1999 and 2005. All of these new buildings were added the 1997 to 2005 construction period. This method does not try to reconcile the fact that the GAB register reported fewer buildings than the SINTEF report until

2002. The final values for the number of buildings in each construction period category are shown in Table 7-3.

	Calculated Number of Buildings
Before 1969	11660
1969 – 1979	2377
1980 – 1986	8170
1987 – 1996	13256
1997 – 2005	2186

Table 7-3: Calculated number of buildings for each construction period.

7.1.2 Floor Area

Floor Area of Total Building Stock

Several studies have reported the total floor area of existing office buildings. The results, shown in Table 7-4, vary over about a factor of 2. Note that the Statistics Norway study includes floor area for both office and retail spaces. It also reports data every year from 1950 to 1991. The average growth rate over that time period, 4%, projects a total floor area in 2005 of about 50 million m^2. The total for office buildings alone is some unknown fraction of that value.

	Floor Area
Statistics Norway (1991)	30
SINTEF (1999)	58
OFFICE (2002)	30
Enova (2003)	53

Table 7-4: Floor area of total building stock in million m^2 [SSB 2006] [Tokle 1999] [Burton 2002] [Enova 2004]. A floor area of 50 million m^2 is projected for the year 2005 with the data from Statistics Norway.

There is no obvious way to rule out any of these studies or distinguish between them based on methodology. Since the total floor area will be used to scale-up the individual building energy consumption to national level consumption, a range of floor areas must be used to present the range of possible consumption.

Floor Area by Construction Year

The statistics from Enova and the Office Project break down the total floor by construction year. The data from Enova is shown in Table 7-5. This information is only for the 146 office buildings that were involved in projects to decrease their energy consumption subsidized by Enova in 2003. Therefore, the distribution of floor area is not necessarily representative of the distribution of floor area in the estimated total floor area of office buildings in Norway, but it is also the most precise data available.

	Floor Area [m²]
Before 1931	123,000
1931 – 1954	79,000
1955 – 1970	290,000
1971 – 1987	475,000
1988 – 1997	347,000
After 1997	147,000
Total	1,461,000
Total Number of Buildings	196

Table 7-5: Floor area by construction year from Enova data in m² [Enova 2004].

The second set of statistics comes from the Office project. They listed that about 30% of the total floor area is from construction before 1945, another 30% is from the period 1945 to 1980, and the remaining 40% is from after 1980 [Burton 2002]. The exact statistics that lead to these determinations were not described in the text.

As with the total number of buildings, calculations had to be performed to redistribute the data from the time periods used in the referenced studies to the construction periods relevant here. Again, it was assumed that within each time period the same amount of floor area was constructed in each year. The floor area was then redistributed into the construction periods, the percent from each construction period was determined, and then those percents were combined with the total floor area numbers from Table 7-4. The results of these calculations are shown in Table 7-6.

	Enova Floor Area	OFFICE Floor Area
Before 1969	17	15
1969 – 1979	10	3
1980 – 1986	7	4
1987 – 1996	12	6
1997 and After	7	2
Total	53	30

Table 7-6: Total floor area in each construction period in million m².

7.1.3 Energy Carriers

Most office buildings contain both electricity and oil based heating equipment. The building manager will use the system associated with whichever fuel is cheaper [Lindberg 2005].

In some areas district heat systems have been constructed, and all new buildings in those areas must connect to the system. The price of district heat is subsidized by the government to be competitive with the cost of electricity [Thyholdt 2005].

Table 7-7 shows how the distribution of energy carriers used by all commercial buildings in Norway has changed over time based on data from the Bartlett report and current data from Statistics Norway. The increase in electricity use between the 1969 to 1979 and 1980 to 1986 construction periods is characterized by a large increase in the power capacity of the hydro electric power plants in Norway between the mid 1970's and the mid 1980s [SSB 2006]. No statistical information is available that shows the distribution of energy carriers used for office buildings alone. Since most office buildings are constructed with the capacity to use both electricity and oil for heating, it is not necessary to try to estimate different ratios of energy supply for buildings from different construction periods [Lindberg 2005]. Buildings from all construction periods should exhibit the same behavior. Therefore, office buildings as a whole will be assumed to use energy in percentages defined by the most recent data: 90% from electricity, 7% from oil, and 3% from district heat.

	Before 1969	1969-1979	1980-1986	1987-1996	1997-2005
Electricity	30%	36%	71%	81%	90%
Oil	40%	50%	28%	16%	7%
Solid	31%	4%	0%	0%	0%
District Heat	0%	0%	0%	2%	3%

Table 7-7: Percent of energy consumed from different energy carriers over time [Bartlett 1993] [SSB 2006].

7.2 Building Characteristics

7.2.1 Building Geometry

Average Floor Area

Using the statistics in section 7.1, there are several ways to estimate the average floor area of an office building in Norway. Three studies provided data for both floor area and number of buildings, so in these cases a single value for average floor area could be calculated by taking the ratio of the two values. The results are shown in Table 7-8. The ratio is about 1500 m^2 for the data from SINTEF and Statistics Norway, but 7500 m^2 for the data from Enova.

	Average Floor Area
SINTEF	1600
Buildings Involved with Enova Projects	7500
SSB Projected Area / GAB Total Buildings	1300

Table 7-8: Calculated average floor area based on national data in m².

Another way to estimate total floor area is to use Statistics Norway's data on new construction [SSB 2006]. The database has information on the total floor area of office buildings completed in a given year from 1983, but only started documenting the number of buildings in 2001 (see Table 7-2). The number of new buildings was calculated by finding the difference in number of buildings between years. This approach neglects the effect of the number of buildings demolished each year. The average floor area of new construction was then calculated as the ratio between the amount of new floor area and the number of new buildings as shown in Table 7-9. This approach shows a range for the average size of new construction from 700 to 4200 m^2. It is possible that the number of buildings constructed in 2001 is artificially high because 2001 was the first year of the GAB register and they may have missed some buildings in the initial survey. This discrepancy could be responsible for the very low average floor area, 700 m^2, in 2001.

	Number of New Buildings	Total New Floor Area [m^2]	Average New Building Floor Area [m^2]
2001	1058	702,000	700
2002	218	911,000	4200
2003	212	743,000	3500

Table 7-9: Average floor area based on Statistics Norway data [SSB 2006].

Comparing Table 7-8 and Table 7-9 suggests that new buildings are larger than the overall averages, and that building size might have increased over time. To assess this possibility, the ratio between the total floor area by construction period (Table 7-6) and the total number of buildings in each time period (Table 7-3) was determined. The results, shown in Table 7-10, show a decrease in building size for construction between 1980 and 1996 relative to both earlier and later construction. There is no known economic reason for this trend, nor do building researchers qualitatively expect that it is true [Thyholdt 2005]. Since Table 7-10 combines several studies and has multiple layers of assumptions, the assumption is that these results are not valid without some external verification.

	Enova Average Floor Area	OFFICE Average Floor Area
Before 1969	1500	1300
1969 – 1979	4800	1200
1980 – 1986	1000	500
1987 – 1996	1000	400
1997 and After	5600	1000

Table 7-10: Calculated floor area by construction period in m^2.

The final source of information on average building size is a case study of the buildings owned by Nordea Bank [Haigh 2005]. The building floor area by construction year is shown in Figure 7-1. This data verifies that an average building size in the low thousands is reasonable. It does not show a significant increase in floor area over time in the time as suggested by Table 7-9 or a decrease in floor area from 1980 to 1996 as suggested by Table 7-10.

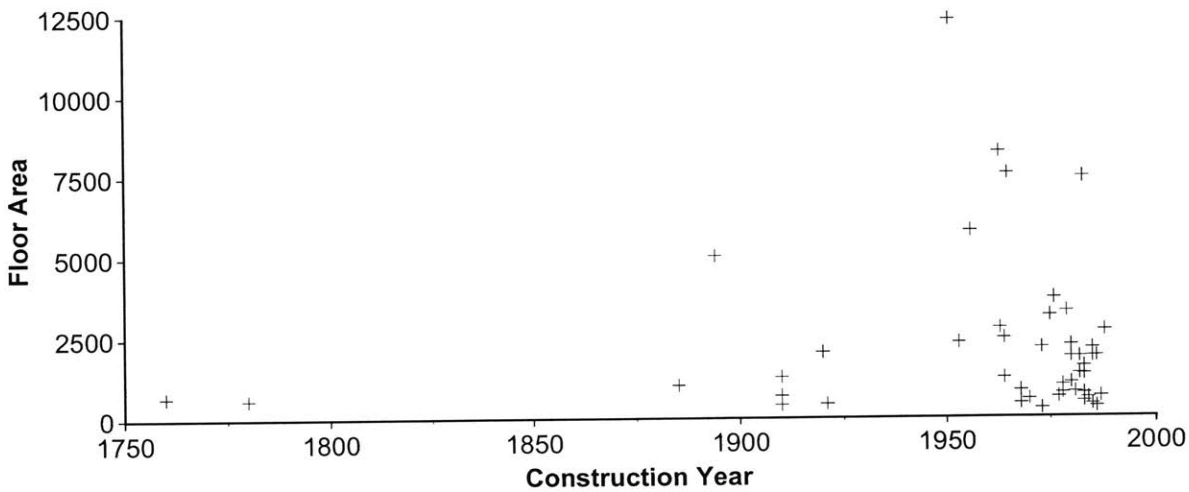

Figure 7-1: Floor area of buildings owned by Nordea Bank in m^2 [Haigh 2005].

From the available statistics, no clear trend for building floor area from different construction periods was revealed. As a result, the representative buildings for each time period will use a single average size. Table 7-8 shows the national average building size for all time periods, but this information still ranges from 1400 to 7600 m^2. The SINTEF and Statistics Norway figures are based on a much larger set of buildings, and they agree with the data from the Nordea Bank case study. Therefore, the Enova number was discounted and a value midway between the SINTEF and Statistics Norway results, 1500 m^2, was chosen to be the representative building size.

Number of Floors

No statistical information was available on the number of floors in office buildings. The value of four floors was chosen for the representative buildings based on personal observation that office buildings were more than 1 or 2 floors, but really tall buildings were pretty unusual, even in cities. Also, in some suburban areas it is mandated that buildings must be four floors or less, so that they are not visible from a distance [Sirevåg 2005].

Floor Height

Office rooms in Norway are typically between 2.6 and 3m tall [Thyholdt 2005]. A floor height of 3m was chosen for each of the representative buildings.

Aspect Ratio

No statistical information was available on the aspect ratio of buildings either. All representative buildings are assumed to have a square profile.

Number of Occupants

There is also no statistical information available on the number of occupants in office buildings. Assumptions for occupant density were developed based on lighting estimates as part of the 1997 building code. They used 15 m^2 / occupant within office areas (neglects hallways, stairwells, etc) and 25 m^2 / occupant of total building size [Thyholdt 2005]. Since the statistical information on floor area is for the total floor area of the building, 25 m^2 / occupant was chosen as the occupant density.

Building researchers qualitatively feel that new construction have higher occupant densities, but no quantitative information is available on this change [Solem 2006].

7.2.2 HVAC System and Controls

Ventilation Rates

Ventilation Rate during Occupied Hours

Norwegian buildings typically use 100% outdoor air. Minimum ventilation rates were first regulated to guarantee good indoor air quality in the 1987 building code. Regulators specified 5 cubic meters of air per square meter of floor area per hour ($\frac{m^3}{h\ m^2}$) in the 1987 code. The 1997 code changed the requirements to 7 liters per second per person ($\frac{L}{s\ person}$) plus a function to deal with emissions from materials. Additional ventilation of 0.7, 1, or 2 liters per second per square meters of floor area ($L/_{s\,m^2}$) were required for low emitting materials, typical materials, and undocumented materials, respectively. However, most buildings use much higher ventilation rates in practice. A typical rate within working areas of new buildings is 15 $m^3/_{h\,m^2}$, but older buildings typically use a lower rate [Mathisen 2005]. Table 7-11 shows these values converted to $L/_{s\,m^2}$ assuming that a building contains 1500 m^2 of floor area, there are 25 m^2 of floor area per occupant, and typical materials are used. Note that the value for typical practice in recent construction is more than 3 times greater than the minimum value specified in the 1997 code.

	Ventilation Rate
1987 Code	1.4
1997 Code	1.3
Typical Practice for Recent Construction	4.2

Table 7-11: Minimum ventilation rates from the 1987 and 1997 code compared to typical practice in $L/_{s\,m^2}$.

Several case studies have also reported information about ventilation rates in Scandinavian buildings. An indoor air quality study was performed on six office buildings in Denmark in which detailed results of the ventilation rate, construction year, and time of last renovation was reported. The ventilation rates were measured over six days in October and November of 2001; the results of which are shown in Table 7-12. The average ventilation rate for all six buildings was 2.3 $L/_{s\,m^2}$. No relationship between the ventilation rate and the construction year or the last renovation is evident in these buildings.

Building	**Indoor Air Temp [°C]**	**Ventilation Rate [$L/_{s\,m^2}$]**	**Construction Year**	**Last Renovation**
1	21.6	2.85	1972	2002
2	23.9	1.71	1964	N/A
3	21.9	1.43	1974	1999
4	23	2.44	1904	1999
5	22.7	3.14	1993	N/A
6	23.3	2.24	1963	N/A
Average	23	2.3		

Table 7-12: Indoor air temperature, ventilation rate, and construction/renovation year for six Danish office buildings [Wargocki 2004].

Ventilation rates were also reported for several Scandinavian office buildings as part of the Office Project. The results are shown in Table 7-13. The Norwegian office building was built in 1961, and operates with an overall ventilation rate less than that of either the 1997 or 1986 Norwegian building code. The Danish office building in this study also operates with a ventilation rate significantly below the values reported in Table 7-12.

Building	Supply Flow Rate	Return Flow Rate	Construction Year
Danfoss Headquarters, Denmark	0.75 – 0.89	0.4 – 1.1	1991
Sentralbygg 1, NTNU, Norway	1.2	0.78	1961
Krokslatt 149, Gothenburg, Sweden	1.1	1.1	1961

Table 7-13: Ventilation rates and construction year for three Scandinavian office buildings in $L/_{sm^2}$ [Burton 2002].

The literature on ventilation rate during occupied hours has not revealed a consensus on a typical or appropriate value. Much of the discrepancy has to do with the fact that ventilation air is not only used to guarantee good indoor air quality. It can also be used to condition the space. The ventilation rate varies in different buildings depending on the function it serves.

Interviews with building researchers and building managers confirm that most office buildings operate with ventilation rates much higher than the code values [Mathisen 2005] [Lindberg 2005] [Nes 2005]. Therefore, the representative buildings will use high values from the range of data revealed in the literature. This approach may overestimate the energy necessary for heating and ventilating buildings. However, it will also call a lot of attention to ventilation rate as an issue. If building managers are setting high ventilation rates simply to control air quality, it may inspire them to reevaluate this practice.

The ventilation rates during occupied hours for buildings constructed after 1997 will be the 4.2 $L/_{s\,m^2}$. A value on the high side of the range of ventilation rates in the Danish study, 3 $L/_{s\,m^2}$, will for used for all the representative buildings built before 1997.

Ventilation Rate during Unoccupied Hours

One common method for reducing energy consumption in office buildings is to set back the ventilation rate during unoccupied hours. It is common practice to use an automated control system for this purpose rather than require building managers to do it manually. Most office buildings were either constructed with a control system for the ventilation rate or have been retrofitted with one [Lindberg 2005].

There are two typical setback strategies. The first strategy is to turn the ventilation system completely off when the building is not operated and turn it back on two hours before people are scheduled to arrive in the morning. The other method is to leave the system running at all times, but turn it down to the code value for preventing problems from emissions from materials when the building is not occupied. The second strategy is more typical, but both are used [Mathisen 2005].

The reference buildings will have a control strategy where the ventilation rate is decreased to 1 $\frac{L}{s\,m^2}$, the code value for preventing air quality problems from typical materials, during unoccupied hours.

Specific Fan Power

A typical metric for modeling the power required for ventilation system fans is 1 watt per cubic foot per minute or 2.1 watts per liter per second of ventilation air ($W/\frac{L}{s}$) [Mathisen 2005]. Several case studies and standards were evaluated to verify this assumption. The first study evaluated the energy performance of a Swedish office building constructed in the 1960s before and after converting the ventilation system from a constant volume system to a variable system. The specific fan power before and after the conversion was 2.5 and 1.2 $W/\frac{L}{s}$, respectively [Maripuu 2005]. Another study compared common practice and current building codes for buildings in the US, the UK, and Sweden for a number of characteristics, including specific fan power. In Sweden there are different ratings for different classes of buildings with specific fan powers ranging from 4 $W/\frac{L}{s}$ to 1 $W/\frac{L}{s}$. In the UK 2 $W/\frac{L}{s}$ is considered good practice, and 3 $W/\frac{L}{s}$ is a typical power rating. Finally, ASHRAE 90.1-1999 listed specific fan powers that vary from 2.7 to 1.7 $W/\frac{L}{s}$ for different types of ventilation systems [Field 2005].

None of these sources provide statistics for how specific fan power has changed with time, and all are in the general range of 2.1 $W/\frac{L}{s}$. Therefore, the standard approximation of 2.1 $W/\frac{L}{s}$ will be used in all the representative buildings.

Heat Recovery

Heat recovery has been used in new construction since about 1970 [Mathisen 2005]. Installing heat recovery is an extremely common retrofit for existing buildings as well. Since most office buildings in Norway undergo a major refurbishment of the ventilation system every

15 years, most office buildings built before 1970 now have heat recovery systems as well [Sirevåg 2005] [Lindberg 2005] [Nes 2005].

Three main types of air to air heat exchangers have been used in office building heat recovery systems: rotary, plate, and runaround. A rotary heat exchanger or rotary enthalpy wheel has a revolving cylinder made out of a desiccant material that allows air to flow through it, contacting a large amount of surface area within a compact volume. The supply and exhaust air streams are separate, but heat and moisture pass directly through the desiccant heat exchanger material in a counterflow pattern. A plate heat exchanger separates the supply and exhaust air with fixed plates. The plates can be made of many different types of materials with various surface treatments to increase the heat transfer across the plates. A plate heat exchanger can be design to transfer moisture, but many do not. They can also be set-up in parallel, counterflow, or cross-flow configurations, depending on the effectiveness and space restrictions. Lastly, a runaround heat exchanger or coil energy recovery loop uses an intermediate heat transfer path instead of direct exchange between the supply and exhaust air. Finned surfaces in both the supply and exhaust streams transfer heat to each other through a loop of water or antifreeze [ASHRAE 2004].

No statistical information about the type of heat recovery unit and corresponding efficiency is available. Interviews with building researchers have revealed conflicting recollections of the type and efficiency of heat exchanger most often used in practice. The type of heat exchanger unit and heat recovery effectiveness most commonly used in practice in the opinion of two building researchers are shown in Table 7-14. Note that the high effectiveness rotary units in the 1970s were taken out of service because the heat transfer surfaces contained asbestos.

	Mathisen		**Stang**	
Time Period	**Exchanger Type**	**Effectiveness**	**Exchanger Type**	**Effectiveness**
Retrofits to Pre-1970	Don't Know			
1970s	Rotary	80%	Recirculation Air	
1980s	Runaround or Unmixed Plate	50% 60%	Rotary	70%
1990s	Runaround or Unmixed Plate	50% 60%		
Current Practice	Rotary	80%		

Table 7-14: Changes in typical heat exchanger units over time [Mathisen 2005] [Stang 2005].

Mathisen's estimates will be used because the information provided is more complete. Since the ventilation systems are retrofit about every 15 years, heat recovery systems would have been installed throughout the 1970s and 1980s. Therefore, the representative buildings the pre1969 construction period will have an effectiveness of 60%, the median effectiveness for these two decades. The period 1969 to 1979 will assume an effectiveness of 80%. Buildings in the period 1980 to 1986 will have an effectiveness of 55%, which assumes half of the buildings use runaround heat exchangers and half use unmixed plate heat exchangers. The representative buildings for the time period 1987 to 1996 will have an effectiveness of 60%, assuming that more buildings would use the more efficient system by this time. Finally, the 1997 to 2005 buildings will have an assumed effectiveness of 70%, indicating that some plate heat exchangers were still used, but some more efficient rotary heat exchangers were used as well.

Indoor Air Temperature

Indoor Air Temperature during Occupied Hours

Building energy simulation programs typically assume that the indoor air temperature is 21°C during occupied hours [Mathisen 2005] [Enova 2002a]. However, buildings in practice usually have somewhat warmer temperatures. The report on Danish office buildings also included measurements on average indoor air temperature as shown in Table 7-12. The average temperature for all six buildings during occupied hours was 23°C. There is no evident relationship between construction year or last renovation and the indoor air temperature.

The results from the Office Project showed temperature measurements for a typical summer day and a typical winter day for the three Scandinavian buildings. The average indoor air temperatures were 24°C and 23°C for the summer and winter days, respectively [Burton 2002].

A Finnish study examined the effect of indoor air temperature on productivity [Niemela 2002]. Researchers measured the temperature in two "call-centers" in one building from July through October. The first call center had two zones, one on the north side of the building and the other on the south side. The average temperatures in the northern and southern zones were 23.6°C and 25.2°C, respectively. The second call center had the same area and number of occupants as the first. The call center initially had no cooling system, but cooling was installed in August. They found that the average temperatures were 22.6°C and 25.1°C with and without cooling, respectively.

The average indoor temperature during occupied hours will be taken to be 23°C for the representative buildings in all time periods.

Indoor Air Temperature during Unoccupied Hours

Like the ventilation system, most Norwegian office buildings have a control system to change the indoor temperature when the building is not occupied [Lindberg 2005]. A typical temperature for nighttime setback during winter is 19°C [Mathisen 2005].

All of the representative buildings will be assumed to have a control system to change the indoor air temperature during unoccupied hours. The buildings will be assumed to have an indoor temperature of 19°C during the winter and 27°C in the summer when the building is not occupied. The summer setpoint is only relevant if the building also has a cooling system.

Cooling System

Cooling systems have been increasingly installed in Norwegian office buildings as the occupants have begun to expect more consistent comfort conditions. Most new construction will now include a cooling system, and it has been common for the last 15 to 20 years [Thyholdt 2005] [Sirevåg 2005] [Lindberg 2005]. Therefore, the representative buildings from the construction periods 1987 to 1996 and 1997 to 2005 will be assumed to have a cooling system. Buildings from all the other construction periods will not.

Heat Pump

Heat pumps have been installed occasionally in new construction, but they are not widely used [Sirevåg 2005]. None of the representative buildings will be assumed to operate heat pumps.

7.2.3 Building Facade

Infiltration Rate

Infiltration rates are officially limited by building codes to be less than 1.5 air changes per hour at 50 Pa. Office buildings must maintain this tightness for five years, which is the warrantee for most building materials. The infiltration rate is not measured after construction unless there is a thermal comfort problem, and the building owner is taking some legal action to have the problem fixed [Grimnes 2005].

However, even if detailed measurements were available for all new buildings, they would be of limited use. An office building is typically pressurized to about 3 or 4 Pa, and there is no rule of thumb to extrapolate data from infiltration rates at 50 Pa to true infiltration rates. An extrapolation can be made based on wind speed, surrounding conditions, and leakage area if the relationship between infiltration rate and pressure is characterized for high pressures [Emmerich 1998].

Also, most buildings become more leaky over time [Grimnes 2005]. Performing a calculation to estimate the infiltration rate of new buildings would provide limited information on the infiltration rate of older buildings.

The only available data for infiltration rate are the assumed values used as inputs in an energy simulation program used by Enova, Enøk Normtall. The values are 0.3, 0.25, and 0.2 air changes per hour for office buildings constructed before 1987, between 1987 and 1996, and after 1996, respectively based on measurements in a small sample of buildings [Enova 2002a]. These values have been qualitatively confirmed with Norwegian building researchers [Mathisen 2005] [Solem 2006].

Since no other statistical information is available, the Enøk Normtall infiltration rates will be used in the representative buildings in this study.

Window Area

The glazed portion of the facade was determined from the building codes. The codes began to list the maximum window area as a percent of floor area in 1980. For the 1980, 1987, and 1997 codes, the maximum percentages are 15%, 15%, and 20%, respectively [Codes 2005]. These percentages will serve as the glazed area for the corresponding construction periods. In the 1949 code, there was a requirement for additional insulation if the window area exceeded 12.5% of the floor area [Codes 2005]. This value will be used for the glazed area in the pre-1969 construction period. The 1970 code had no requirement for window area [Codes 2005]. It is assumed that 15% of the floor area is glass area on the facade for this time period, in accordance with the next building code.

No statistical information was available on how the windows were distributed around the building. Therefore, it is assumed that there is an equal portion on each wall.

Norwegian building managers and building researchers qualitatively feel that more windows are used in practice particularly in new construction [Thyholdt 2005] [Lindberg 2005] [Solem 2006]. However, no one can quantify a glazed area that would better represent real buildings. The building codes do have a loophole that if more windows are used, the insulation must be increased to compensate to get an equivalent performance. Therefore, assuming code values for window area and U-values is a good assumption for energy performance, but there may be discrepancies in identifying the best retrofit technologies.

U-Values

Minimum U-values for insulation and windows are specified in every code. These values define the as-built condition and are not necessarily representative of the current state of the buildings. However, conversations with building managers have revealed that they feel that changing windows or insulation is not a cost effective retrofit. This type of project would only be considered if the original facade had been damaged for some reason [Sirevåg 2005] [Lindberg 2005]. Therefore the U-values specified in the code are a reasonable estimation of the current state of the facade. Table 7-15 contains a summary of the minimum U-values for each facade component and building code.

	1949 Code	1969 Code	1980 Code	1987 Code	1997 Code
Walls	0.87	0.58	0.44	0.3	0.22
Roof	0.7	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

Table 7-15: U-values for walls, roofs, bases, doors, and windows for each building code in W/m^2K [Codes 2005].

Certain assumptions and simplifications were made to get a single representative value for each code. The 1949 and 1969 codes specify different requirements based on climate zones. The values selected correspond to the climate zone containing Oslo, because Oslo's climate has been demonstrated to serve as an average climate for all of Norway weighted by the number of dwellings in each climate zone [Myhre 1995].

No specific minimum U-value is listed for windows in the 1949 code. The code does require that if more than 12.5% of the facade area is glazed, double paned windows must be used. This suggests that single paned windows were most common at the time. The U-value of

5.5 $W/_{m^2K}$ is a typical U-value for a typical single paned window with a wooden frame [ASHRAE 2005].

In the 1969 code the minimum U-value for wall insulation is dependant on the thermal mass of the walls. Since the simulation program does not take thermal mass into effect, the low thermal mass value is used. Different U-values for different conditions are also specified for the windows in this code. Recall from the section on window areas, that the 1969 code did not specify a maximum window area for the facade. A value of 15% of the floor area was chosen to be consistent with the other codes. Therefore, the U-value for buildings with glazed areas less that 30% of the floor area was selected for the representative value.

The 1980 code specified an average U-value for the facade, including both windows and walls, of 0.45 $W/_{m^2K}$. It was necessary to split the average U-value into separate values for the windows and walls to determine their relative importance in the retrofit analysis. However, given the geometry of the model buildings, it was not possible to achieve an average U-value of 0.45 $W/_{m^2K}$ with reasonable approximations of U-values for the windows and walls. If the U-value of the windows was 2 $W/_{m^2K}$, the value in the 1987 code, the average U-value for the walls and windows would be more than 0.45 $W/_{m^2K}$ even if no heat was transferred through the walls at all. Therefore, the U-values chosen are halfway between the values in the 1969 code and the 1987 code.

Solar Heat Gain Coefficient

The solar heat gain coefficient (SHGC) is a parameter that approximates the portion of radiation incident on a window that is translated into a heat gain in the space. It is defined as the sum of the radiation that is transmitted into the space and the portion of the radiation absorbed into the window panes that is reemitted into the space. It can be approximated as:

$$SHGC = \tau + N\alpha \qquad \textbf{7-1}$$

where τ is the solar transmittance of the glass, α is the solar absorptance, and N is the inward-flowing fraction of the absorbed radiation [ASHRAE 2005]. The inward flowing fraction of absorbed radiation decreases with each pane of glass in the window because more radiation is reflected away from the building's interior. Therefore, windows with lower U-values also have lower solar heat gain coefficients. This effect can be magnified by adding a reflective coating to the glass panes rather than relying on the standard glass properties alone. The solar heat gain coefficient can be calculated for both direct and diffuse radiation. Table 7-16 gives an overview of the range of SHGCs exhibited by windows with various characteristics.

	Direct Normal Radiation	Diffuse Radiation
1/8" Clear Glass Panes		
Single Pane, Uncoated	0.86	0.78
Double Paned, Uncoated	0.76	0.66
Double Paned, $\varepsilon = 0.2$	0.65	0.57
Double Paned, $\varepsilon = 0.05$	0.41	0.36
1/4" Clear Glass Panes		
Single Pane, Uncoated	0.81	0.73
Double Paned, Uncoated	0.7	0.6
Double Paned, $\varepsilon = 0.2$	0.6	0.53
Double Paned, $\varepsilon = 0.05$	0.37	0.32

Table 7-16: Solar heat gain coefficients for a selection of window types [ASHRAE 2005].

Approximate SHGCs were selected for each construction period to represent the increasing quality of windows over time. The radiation data used in the simulation program is a single value that includes both direct and diffuse radiation. Therefore, one representative SHGC was selected rather than separate values for direct and diffuse radiation. Since the two values generally differ by only about 5%, this is not an unreasonable simplification. The final selections for each construction period are listed in Table 7-17.

	SHGC
Before 1969	0.75
1969 – 1979	0.65
1980 – 1986	0.6
1987 – 1996	0.35
1997 to 2005	0.35

Table 7-17: Representative Solar Heat Gain Coefficients for each construction period.

Blind Control

Blinds are a good way to improve comfort conditions in an office building by decreasing glare and decreasing solar gains during the summer. None of the representative buildings are currently assumed to have a control system for blinds.

7.2.4 Energy Consumption from Lighting and Office Equipment and Water Heating

No statistics were found that allowed an estimate of the energy used for lighting, office equipment, and water heating based on the type and distribution of equipment. However, studies have measured the amount of energy used in buildings in one year distributed by end use. The distribution of energy shown in Table 7-18 is a compilation of a number of studies performed by Enova and SINTEF Energy averaged over buildings from all construction periods.

	Energy Consumption
Office Equipment	38
Lighting	35
Water Heating	20

Table 7-18: Annual energy consumption for lighting equipment and water heating averaged over buildings of all ages in kWh/m^2 [Wachenfeldt 2004].

One of the studies used to create Table 7-18 is the Modellbyggprosjecktet by Enova. Enova carefully monitored the energy consumption for eight office buildings and reported the total consumption by end use. The results, listed in Table 7-19, are useful to get a better idea of the variability of energy consumption between different buildings. However, they do not provide useful information about how end use consumption changes in buildings from different time periods. Note that all of the buildings studied in the Modellbyggprosjecktet use significantly less energy for heating water than the value in Table 7-18.

Building	1	2	3	4	5	6	7	8	Average
Office Equipment	40.0	2.0	21.1	39.8	21.0	37.1	48.8	21.7	**29**
Lighting	20.0	17.0	33.5	47.4	28.0	25.8	17.6	23.9	**27**
Water Heating	14.0	6.0	5.5	1.2	3.0	1.0	4.4	2.9	**4.8**

Table 7-19: Annual energy consumption for lighting equipment and water heating for office buildings in the Modellbyggprosjecktet in kWh/m^2 [Enova 2002b].

Since no studies have tracked how the end use energy consumption from existing buildings constructed at different times, the averages over all time periods shown in Table 7-18 will be used for all the representative buildings.

7.3 Summary of Building Characteristics

Table 7-20 shows a summary of all the characteristics for each construction period.

	Pre 1969	**1969 - 1979**	**1980 - 1986**	**1987- 1996**	**1997 - 2005**
Building Geometry[1]					
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[2]					
Indoor Air Temperature (Winter)	23	23	23	23	23
Indoor Air Temperature (Summer)	23	23	23	23	23
ΔT for Not Occupied	4	4	4	4	4
Ventilation (Occupied) [L/sm2]	3.0	3.0	3.0	3.0	4.2
Ventilation (Not Occupied) [L/sm2]	1.0	1.0	1.0	1.0	1.0
Effectiveness of heat recovery	60%	80%	55%	60%	70%
Fan Power [W/(m3/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[3]					
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/m2K]					
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[4]					
Lighting Energy [kWh/m2 annual]	35	35	35	35	35
Equipment Energy [kWh/m2 annual]	38	38	38	38	38
Hot Water [kWh/m2 annual]	20	20	20	20	20

Table 7-20: Summary of characteristics for each representative building.

[1] See section 7.2.1
[2] See section 7.2.2
[3] See section 7.2.3
[4] See section 7.2.4

8 Retrofit Costs

This chapter describes the methodology for estimating the first cost to complete energy-related building retrofit projects. For a more detailed description of the reasons for choosing these projects for consideration see Chapter 12. The costs are in US dollars rather than Norwegian kroner because a comprehensive public database is published for the average costs of building projects in the US by RS Means [Mechanical 2006] [Interior 2006] [Assemblies 2005]. At this time there is no equivalent public source of information on the cost of building projects in Norway. Cost information from an internal database at Statsbygg provided cost comparisons for some of the retrofit projects considered in this study. Statsbygg's costs were typically between a factor of 1.2 and 1.7 greater than the US Means costs [Hellberg 2006]. However, there was no universal difference, and individual projects varied out of that range. The RS Means costs will be used for consistency. It is likely that costs in Norway would be significantly greater, but the order of magnitude difference in price between different components or processes should apply in both countries.

Each total cost includes the cost of materials, labor, and heavy-duty equipment necessary to complete the installation. RS Means collects data from companies on the cost to complete building projects, including additional time or materials necessary if the project does not go to plan. However, much of the information is for new construction. Retrofit projects are more likely to incur additional, unexpected costs when existing components are in poor condition or do not match the original plans.

The cost for demolition and removal of the existing system as well as the cost of a typical system and a low-energy system were compiled for each retrofit project under consideration. The total cost of the retrofit includes the demolition and removal cost only if there is an existing system that must be replaced. The cost information does not include any estimates for how completing a retrofit project will affect the cost of operating or maintaining the building. Some of the possible retrofits may require different types and frequencies of maintenance than the original equipment.

RS Means does not estimate the cost of renting or operating the specialized equipment necessary to complete the projects. A typical rule of thumb is that equipment costs will be about 5 to 10% of the total cost of the project [Fernandez 2006]. RS Means does supply the material and labor costs as well as the total cost with and without operations and profit (O&P). The percent O&P can be calculated by comparing the two values. When required, equipment costs were estimated as 10% of the total material and labor costs. The total cost of the project was then the sum of materials, labor, and equipment increased by the percent O&P.

A summary of all of the relevant costs is provided in the first section of this chapter. The subsequent pages describe how each cost was determined and potential additional costs that were not included.

8.1 Summary of Retrofit Costs

Retrofit	Description	Materials Cost ($)	Labor Cost ($)	Equipment Cost ($)	Total ($)	Operations and Profit	Total with O&P ($)
HVAC System							
Air Source Heat Pump	<140 kW	0	480	48	528	50%	787
Rooftop Chiller	< 10 tons	0	595	60	655	50%	990
Heat Exchanger	Plate Type	0	1600	160	1760	50%	2668
Fan	< 9 m^3/s	0	115	12	127	50%	194
Building Facade							
Windows	Aluminum Sliding	0	9.7 / m^2	0	9.7 / m^2	60%	15 / m^2
Wall Insulation	< 1% of Construction	X	X	X	X	X	X
Roof Insulation	< 1% of Construction	X	X	X	X	X	X
Base Insulation	< 1% of Construction	X	X	X	X	X	X
Other							
Lighting	10 fluorescent fixtures per square meter	0	1.3 / m^2	0	1.3 / m^2	60%	2 / m^2
Hot Water Heater	< 150 L	0	57	0	57	0.7	86

Table 8-1: Demolition and removal costs. [Assemblies 2005] [Mechanical 2006] [Interior 2006]

Retrofit	Description	Materials Cost ($)	Labor Cost ($)	Equipment Cost ($)	Total ($)	Operations and Profit	Total with O&P ($)
HVAC System							
Air Source Heat Pump	140 kWh/m^2year, COP = 2	18,800	4825	2363	25,988	20%	30,800
Air Source Heat Pump	100 kWh/m^2year, COP = 2	15,600	4825	2043	22,468	20%	26,950
Air Source Heat Pump	60 kWh/m^2year, COP = 2	8375	2550	1093	12,018	20%	14,410
Rooftop Chiller	3 tons	2900	705	361	3966	20%	4675
Enthalpy Wheel	4 L/sm^2, $\eta = 70\%$	9800	1050	1085	11,935	20%	13,640
Enthalpy Wheel	3 L/sm^2, $\eta = 70\%$	8200	945	915	10,060	20%	11,550
Enthalpy Wheel	1.6 L/sm^2, $\eta = 70\%$	6350	760	711	7821	20%	8965
Fan	4 L/sm^2, 1600 W/(L/s)	2200	1200	340	3740	30%	4675
Fan	3 L/sm^2, 1600 W/(L/s)	1800	1100	290	3190	30%	4070
Fan	1.4 L/sm^2, 1600 W/(L/s)	1400	970	237	2607	30%	3328
Building Facade							
Windows	Aluminum Sliding, 2 W/m^2K	~66%	~33%	X	X	X	345 / m^2
Wall Insulation	Block Face Cavity, 0.22 W/m^2K	~33%	~66%	X	X	X	237 / m^2
Roof Insulation	0.15 W/m^2K	~50%	~50%	X	X	X	94 / m^2
Base Insulation	0.3 W/m^2K	~50%	~50%	X	X	X	106 / m^2
Other							
Lighting	9 W/m^2	7.6 / m^2	10 / m^2	X	X	X	18 / m^2
Office Equipment	1 computer per person, 1 printer, copier, and fax per 10 people	X	X	X	85500	X	X
Hot Water Heater	300 L	1175	38	X	1213	10%	1325
Blinds	Stock Horizontal	26 / m^2	4 / m^2	X	30 / m^2	20%	36 / m^2

Table 8-2: Typical replacement costs. Costs are the total cost for the retrofit. The capacities of HVAC equipment are per square meter so they can be compared to statistical data and the output from the simulation program. X's indicate information that was not available or not applicable. [Assemblies 2005] [Mechanical 2006] [Interior 2006]

Retrofit	Description	Materials Cost ($)	Labor Cost ($)	Equipment Cost ($)	Total ($)	Operations and Profit	Total with O&P ($)
HVAC System							
Enthalpy Wheel	4 L/sm^2, η = 80%	X	X	X	X	X	18,140
Enthalpy Wheel	3 L/sm^2, η = 80%	X	X	X	X	X	15,360
Enthalpy Wheel	1.6 L/sm^2, η = 80%	X	X	X	X	X	11,920
Fan	4 L/sm^2, 1000 W/(L/s)	X	X	X	X	X	6220
Fan	3 L/sm^2, 1000 W/(L/s)	X	X	X	X	X	5413
Fan	1.4 L/sm^2, 1000 W/(L/s)	X	X	X	X	X	4430
Building Facade							
Windows	Triple Pane, Argon Filled, Vinyl Frame, 1 W/m^{2}K	~66%	~33%	X	X	X	456 / m^2
Wall Insulation	Block Face Cavity, 0.1 W/m^{2}K	~33%	~66%	X	X	X	290 / m^2
Roof Insulation	0.1 W/m^{2}K	~50%	~50%	X	X	X	130 / m^2
Base Insulation	0.15 W/m^{2}K	~50%	~50%	X	X	X	130 / m^2

Table 8-3: Low-energy replacement costs. Costs for the HVAC system are the typical replacement costs scaled up by 30%. [Assemblies 2005] [Mechanical 2006] [Interior 2006]

8.2 Control System

In this study the control system refers to the temperature and ventilation setpoints in the building. It is assumed that the buildings already have an automated control system or that the building managers are responsible for changing the temperature and ventilation setpoints when the building is unoccupied. Therefore, changes to the control system are not associated with any cost. In some buildings reprogramming the existing control systems may incur additional labor costs, and some system components may need to be upgraded or replaced.

8.3 HVAC System

8.3.1 Air Source Heat Pump

The cost information is for a split system air-to-air heat pump. A split system heat pump is most likely to be used in a retrofit situation because the indoor and outdoor sections are installed separately, which makes it easier to find suitable locations in comparison to a single package heat pump. An air source model is also preferable to a ground source heat pump because not all building sites have space to drill the connections into the ground and the cost of drilling varies dramatically depending on the soil conditions around the building. It was assumed that the heat from the heat pump can be included in the existing heat distribution system in the building. No costs were included for installing additional distribution equipment.

Demolition and Removal

The demolition and removal cost is the mean cost for removing any existing split system air-to-air heat pump with a capacity less than 140 kW. A summary of the relevant costs is provided in Table 8-1.

Typical Replacement

The cost of replacement was determined for heat pumps with three different heating capacities 119 MBH, 85 MBH, and 50 MBH. These units can supply approximately 140 $^{kWh}/_{m^2 year}$, 100 $^{kWh}/_{m^2 year}$, and 60 $^{kWh}/_{m^2 year}$ for the buildings in the study, which all have a floor area of 1500 m^2. All three heat pumps are assumed to have a COP of 2, which is typical for air-to-air heat pumps under cold weather conditions [Fransisco 2004]. A summary of the relevant costs is provided in Table 8-2.

Low Energy Replacement

No low energy heat pumps are included in the analysis. While some companies advertise higher efficiency heat pumps, it has been demonstrated that they still perform with a COP of about 2 in real buildings in cold climates [Fransisco 2004].

8.3.2 Cooling System

The cost information for installing a cooling system is for a rooftop electric chiller. It was assumed that cool air from the chiller could be distributed through the existing distribution systems in the building. No costs were included for installing additional distribution equipment.

Demolition and Removal

The demolition and removal costs are for any rooftop chiller that provides less than 10 tons of cooling, or roughly 140 $^{kWh}/_{m^2 year}$ for the model buildings in the study. A summary of the relevant costs is provided in Table 8-1.

Typical Replacement

The chiller included in a typical replacement has a 3 ton cooling capacity, or roughly 40 $^{kWh}/_{m^2 year}$ for the model buildings. A summary of the relevant costs is provided in Table 8-2.

Low Energy Replacement

No low energy replacement chiller was considered.

8.3.3 Heat Exchanger

The heat exchanger is an air-to-air unit used for ventilation air in the heat recovery system. It was assumed that the new heat exchanger could be incorporated into the existing heat recovery system. No costs were included for altering or adding distribution equipment.

Demolition and Removal

The demolition and removal costs are for a plate type heat exchanger. These heat exchangers have the lowest efficiency of the heat exchangers that were commonly used in

Norway and are therefore the most likely to be replaced. A summary of the relevant costs is provided in Table 8-1.

Typical Replacement

The typical replacement heat exchanger for the heat recovery system is an enthalpy wheel. These heat exchangers can have very high efficiencies by transferring both heat and moisture. Three different enthalpy wheels were considered with capacities of 4000, 8000, and 10,000 CFM or roughly 4, 3, and 1.6 $L/_{sm^2}$ for the model buildings. All three enthalpy wheels were assumed to have an effectiveness of 70%. A summary of the relevant costs is provided in Table 8-2.

Low Energy Replacement

The low energy enthalpy wheels are assumed to have an effectiveness of 80%. The cost of this component was estimated as the cost as the 70% effective version increased by a factor of one third [Fernandez 2006]. A summary of the relevant costs is provided in Table 8-3.

8.3.4 Fan

This section refers to the fan in the ventilation system, and assumes that all of the ventilation air is driven by a single large fan. No costs are included for replacing or altering the distribution system. It was assumed that the new fan could be used with the existing equipment.

Demolition and Removal

The demolition and removal costs are for any fan with a capacity less than 9 $m^3/_s$ or roughly 6 $L/_{sm^2}$ for the model buildings. A summary of the relevant costs is provided in Table 8-1.

Typical Replacement

The three fans considered for the typical replacement have capacities of 10,000, 7500, and 3480 CFM, or roughly 4, 3, and 1.4 $L/_{sm^2}$ for the model buildings. Each was assumed to have a specific fan power of 1600 $W/L/_s$. A summary of the relevant costs is provided in Table 8-2.

Low Energy Replacement

The specific fan power of the low energy fans was assumed to be 1000 $W/\frac{L}{s}$. The cost was assumed to be the cost of the typical efficiency fan increased by a factor of one third [Fernandez 2006]. A summary of the relevant costs is provided in Table 8-3.

8.4 Building Facade

8.4.1 Windows

Depending on the size of a window and the specific conditions of a building, installing windows can require specialized equipment. For example, if the windows are too large to be installed from within the building, cranes must be on site to lift them to the proper location. All of the window prices assume that additional specialized equipment is not necessary and no additional equipment cost was calculated.

Demolition and Removal

The demolition and removal costs vary by the size of the window and the type of frame. The costs considered are for windows with an aluminum frame. RS Means lists the cost for removing windows up to approximately 1, 2.3, or 4.6 m^2. The averaged cost of all three sizes is included in Table 8-1, assuming the window had the largest possible area for its range.

Typical Replacement

The typical replacement windows are sliding double paned windows with aluminum frames. They are assumed to have a U-value of $2\frac{W}{m^2K}$. RS Means lists the price for windows with specific dimensions, not on a general cost per area basis. The cost per square meter of the windows varied from 244 to 551 $\frac{\$}{m^2}$. The values summarized in Table 8-2 are the average values for all the possible sizes.

Low Energy Replacement

The low energy replacement cost was more difficult to estimate. It was assumed that the only difference between installing a typical window and a low energy window was the additional material cost. The labor costs would be the same. RS Means provided the price of installing triple paned, argon filled, low-e, vinyl framed glazing but not as part of a window system. Therefore, it was necessary to estimate the additional cost of an operable window frame. It was assumed that the frame cost would be similar to the frame for the double paned, aluminum window. This cost is approximately the difference in material cost for the operable double paned window and the material cost for double paned glazing alone. The calculated frame cost was added to the cost of the triple paned, argon filled, low-e, vinyl framed glazing to estimate the material cost of an operable, low energy window system. The total cost is the sum of this material cost and the labor costs for installing a window. A summary of the final cost is provided in Table 8-3.

8.4.2 Wall Insulation

Installing insulation in a wall requires very different methodologies depending on the structure of the wall. It was assumed that it was not possible to install insulative material into an existing air space without disturbing the facade in the model buildings. Instead, the outer facade material and existing insulation must be removed and replaced. This analysis assumed that the wall had a block face cavity structure, modeled as several components in series, each with a distinct cost and R-value. The cost and R-Values of the wall components are listed in Table 8-4 and Table 8-5. The cost of interior furnishings like wall board and paint are neglected from the cost of replacing the facade, but they are necessary for calculating the overall U-value of the wall.

	Cost [$\$/m^2$]
Fluted Block Patition (4" thick)	98
Concrete Block Wall Backup (4" thick)	60
Horizontal Joint Reinforcing	3
Polystyrene Insulation	300t
Flashing Aluminum	4
Shelf Angle	16
Control Joint	1
Backer Rod	1
Sealent	3
Total	186 + 300t

Table 8-4: Cost of wall components. "t" refers to the thickness of the polystyrene insulation in meters.

	R-Value [m^2K/W]
Outside Surface	0.03
Two 4" Lightweight Concrete Blocks	0.60
Polystyrene Insulation	31.2t
Gypsum Board (1/2" thick)	0.08
Inside Surface	0.12
Total	0.83 + 31.2t

Table 8-5: R-value of wall components. "t" refers to the thickness of the polystyrene insulation in meters.

Demolition and Removal

The demolition and removal cost of the facade is typically less than one percent of the total retrofit cost [Fernandez 2006]. No costs were included for demolition and removal.

Typical Replacement

The cost and R-Value information in Table 8-4 and Table 8-5 was used to determine the thickness of polystyrene insulation necessary for the retrofit. The goal U-Value for a typical replacement was 0.22 W/m^2K, which required a thickness of 0.12 m of polystyrene insulation. The total cost of the wall retrofit is summarized in Table 8-2.

Low Energy Replacement

The same methodology was used to find the total cost for the low energy case. In this case the goal U-Value was 0.1 W/m^2K, which required 0.3 m of polystyrene insulation. The total cost of the retrofit is summarized in Table 8-3.

8.4.3 Roof Insulation

A similar methodology to the wall insulation retrofit was followed for the roof insulation retrofit. It was assumed that additional insulation could not be installed to the existing structure. All of the roof components had to be removed and replaced. The cost and R-value of each roof component is listed in Table 8-6 and Table 8-7.

	Cost
Roof Covering	0.2 $\$/m^2$
Roof Edging	5.3 $\$/m$
Fiberglass Insulation	270t $\$/m^2$

Table 8-6: Cost of roof components. "t" is the thickness of the insulation in meters.

	R-Value [m^2K/W]
Outside Surface	0.03
Built up Roofing (0.375")	0.06
Fiberglass Roof Insulation	20.4t
Foam Board (0.5" thick)	0.08
Air-Space	0.20
Gypsum Board	0.10
Inside Surface	0.11
Total	0.58 + 20.4t

Table 8-7: R-value of roof components.

Demolition and Removal

The demolition and removal cost of the facade is typically less than one percent of the total retrofit cost [Fernandez 2006]. No costs were included for demolition and removal.

Typical Replacement

The goal U-value for a typical roof retrofit was 0.15 W/m^2K, which required 0.3 m of fiberglass insulation. The total cost of the retrofit is summarized in Table 8-2.

Low Energy Replacement

The low energy replacement required 0.5 m of fiberglass insulation to meet a goal U-value of 0.1 W/m^2K. The total costs of the project are summarized in Table 8-3.

8.4.4 Base Insulation

The base insulation refers to the insulation between the ground and the building. Like the walls and the roof both the cost and the U-values come from multiple components. The costs and R-Values of the base system components are summarized in Table 8-8 and Table 8-9.

	Cost [$\$/m^2$]
Prestressed Concrete Floor Slabs (4" thick)	75
Edge Forms (6" thick)	4
Welded Wire Fabric	6
Concrete Ready Mix, Regular Weight	6
Place and Vibrate Concrete	2
Finishing Floor (Steel Trowel)	7
Curing	1
Polystyrene Insulation	300t
Total	101 + 300t

Table 8-8: Cost of base system components. "t" is the thickness of polystyrene insulation in meters.

	R-Value [m^2K/W]
One 4" Lightweight Concrete Block	0.30
One 6" Lightweight Concrete Block	0.32
Polystyrene Insulation	31.2t
Inside Surface	0.11
Total	0.73 + 31.2t

Table 8-9: R-values of base components. "t" is the thickness of polystyrene insulation in meters.

Demolition and Removal

The demolition and removal cost of the base is typically less than one percent of the total retrofit cost [Fernandez 2006]. No costs were included for demolition and removal.

Typical Replacement

The goal U-Value for the base retrofit was 0.3 W/m^2K, which required 0.08 m of insulation. The total cost of the retrofit project is summarized in Table 8-2.

Low Energy Replacement

The low energy replacement required 0.2m of fiberglass insulation to meet a goal U-value of 0.1 W/m^2K. The total costs of the project are summarized in Table 8-3.

8.5 Other Systems

8.5.1 Lighting Energy

The installed lighting capacity after retrofitting is about 9 W/m^2, or about 28 kWh/m^2 of energy consumption in one year. It was assumed that the lights are always on during occupied hours, and the lights will have a steady state power requirement. In a real building the lights are turned off at some times, so the peak power requirement may be higher and require additional lighting fixtures.

Demolition and Removal

The information for the cost of demolition and removal in RS Means is based upon the number of lighting fixtures. 10 fixtures per 100 m^2 provide about 9 W/m^2 of lighting energy. The total cost is summarized in Table 8-1.

Typical Replacement

The cost to install new lighting equipment is supplied by RS Means in power per area for incandescent fixtures. The cost to achieve 9 W/m^2 of lighting energy is summarized in Table 8-2.

8.5.2 Office Equipment

In this study office equipment refers to the computers, printers, copiers, and other electrical equipment used in the office building. It was assumed that all of the retrofits will take place at the same time, so the building occupants must replace all their equipment at the same time. In a real building the costs for replacing office equipment are likely to be spread over time when occupants replace outdated equipment.

Demolition and Removal

No costs are included for demolition and removal of office equipment. It was assumed that the occupants of the building can dispose of the current equipment.

Typical Replacement

The amount of office equipment in the building is based on the assumption that each model building has about 60 occupants. It was assumed that each occupant had a desktop computer with a monitor and that there was one fax machine, copier, and laser printer for each group of 10 occupants. Therefore, 60 computers, 60 monitors, 6 fax machines, 6 copiers, and 6 laser printers must be acquired to completely retrofit the building with energy efficient office equipment. A survey of the listed prices on manufacturers' internet sites was used to estimate the cost of purchasing the equipment. It is likely that lower prices could be negotiated with the companies if the equipment was purchased in bulk.

The Energy Star webpage was consulted to find energy efficient desktop computer models. The manufacturers whose internet sites listed the relevant cost information were Acer, Dell, Hewlett Packard, IBM, Lanix, MPC, and Sony. The prices varied from $269 to $1749 with an average cost of about $850. Therefore, the total cost of replacing the desktop computers is $51,000.

The same methodology was followed to determine the cost of purchasing new LCD computer monitors. In this case models from Acer, BenQ, Dell, Gateway, Hewlett Packard, IBM, LG, NEC, Phillips, Sony, and View Sonic were considered. The prices ranged from $180 to $6329. The most expensive monitors were extremely large and not typical of the monitors used in an office environment. A typical price for a monitor used for business computing was about $300. Therefore, the total cost of replacing the computer monitors is $18,000.

Next, the price of replacing fax machines, copy machines, and laser printers with energy efficient versions was considered. Again, the Energy Star web page provided the information on the energy efficient models. The website www.staples.com was the source of cost information. The prices of fax machines varied from $200 to about $1000. $250 was the typical price of a standard machine for business purposes, so the total cost of replacing fax machines was $1500. The prices of copy machines varied from $749 to $1500. The $1500 machine was typical of the type of machine used for business purposes. The less expensive machines would be more appropriate in a home office. Therefore, the total cost of replacing copy machines was $9000. Finally, the cost of laser printers varied from $300 to $6300 with an average cost of about $1000, and the total cost of replacing the laser printers is $6000.

The total cost for replacing all of the office equipment in the building is summarized in Table 8-2.

8.5.3 Hot Water

The equipment for heating water for the building is highly dependent on the intended use of the water. For example, an office building that includes a cafeteria or restaurant will use much more hot water than one without. It was assumed that there were no special needs for hot water in the office buildings in this study. A single hot water heater provides water to sinks for occupants to wash their hands or for use in small kitchenettes.

Demolition and Removal

The demolition and removal cost is for any water heater smaller than 150 L. A 150 L tank would provide 2.5 L of hot water a day for each occupant on a single fill of the tank. This volume is adequate for an office environment. A summary of the costs to remove the existing tank is provided in Table 8-1.

Typical Replacement

The smallest water heater listed in RS Means has a 300 L capacity. The cost is summarized in Table 8-2.

8.5.4 Blinds

The cost information for installing blinds is for horizontal, interior blinds. The blinds are assumed to be solid color, stock blinds made from aluminum. The costs are summarized in Table 8-2.

9 Description of Energy Simulation Program

An energy simulation program is necessary to calculate the annual energy consumption of the reference buildings in their current condition as well as to predict the change in consumption due to each retrofit option. The program must be accurate, and its input parameters must be adaptable to use the available statistical information to accurately represent the current building stock. The program must also execute calculations quickly in order to be useful for a large scenario analysis. While many existing building energy simulation programs can supply the required accuracy, none of them provide the combination of simplicity and flexibility required by this project[5]. Therefore, a new program was developed.

This program uses the available statistical information, is repeatedly executable without user intervention, and could easily be adapted for use with other sets of buildings in other countries. The energy simulation program was written in Visual Basic through Microsoft Excel in order to facilitate ease of use in other situations. The 24 building characteristics listed in Table 7-20 are the input parameters used in the program to predict the annual energy consumption of a building.

Each section below describes the algorithms and assumptions used in the program. First, the building geometry is determined. This information is then used to calculate the energy for heating and cooling the building through a static energy balance with hourly time steps. Next, the energy consumption by the fans in the ventilation system is calculated based on the ventilation rate and specific fan energy. Finally, the program determines the total energy consumption in the building by adding the heating, cooling, and fan energy to the energy consumption by lights, office equipment, and water heaters which were inputs to the program. These steps are described in detail in the remainder of this chapter. A summary of all of the program assumptions is provided in Section 9.5. An index of all of the variables used in formulas and their definitions is provided in Table 9-2.

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[5] For a list of free and commercial building energy simulation programs recommended by the US Department of Energy see http://www.eere.energy.gov/buildings/tools_directory/

9.1 Building Dimensions

Statistical data and other references provided information about the total floor area of the buildings, the approximate height of one floor, the total number of floors, and the window area of the facade as a percent of floor area. These three input variables are not sufficient to define the entire geometry of the buildings. Therefore, the simulation program makes several additional assumptions: the building is a rectangular box with a square profile, it has four external doors, and the area of a single external door is two square meters.

With this available information the simulation program can calculate the roof and floor areas, the area of the windows, the total area of external doors, the insulated portion of the external wall area, and the total building volume for use in later calculations. The first step is to calculate the area of the base and the roof as:

$$A_B = A_R = \frac{A_F}{N_F} \tag{9-1}$$

where A_B is the area of the base in m^2, A_R is the area of the roof in m^2, A_F is the total building floor area in m^2, and N_F is the total number of floors. The total window area can also be simply calculated as:

$$A_G = w \cdot A_F \tag{9-2}$$

where A_G is the window area in m^2 and w is the window area as a percent of total floor area. Next, the area of all the external doors is:

$$A_D = d \cdot N_d \tag{9-3}$$

where A_D is the total area of external doors in m^2, d is the area of a single door in m^2, and N_d is the total number of external doors. Finding the insulated portion of the external walls is a two-step process. First, the length and height of a single wall of the box are determined as:

$$L = \sqrt{A_B} \tag{9-4}$$

and

$$h = f \cdot N_F \tag{9-5}$$

where L is the length of the square base in m, h is the total building height in m, and f is the height of a single floor in m. Then the insulated portion of the external walls, A_W, is calculated in m^2 as the total area of all four walls less the window and door areas:

$$A_W = 4 \cdot h \cdot L - A_G - A_D \qquad \textbf{9-6}$$

Finally, the total building volume in m^3, V, is calculated as:

$$V = h \cdot A_B \qquad \textbf{9-7}$$

9.2 Heating and Cooling Energy

The second set of calculations in the simulation program determines the amount of energy used to heat and cool a building in one year. The calculations neglect any thermal mass in the building. The program performs a simple, static energy balance with hourly time steps. All of the characteristics provided in Table 7-20 to describe the representative buildings are directly used in this calculation except those that define the building geometry, the specific fan power, and the energy to heat hot water. Weather data is also imbedded within the program to represent the outdoor conditions. Even with this fairly large set of input data several assumptions still had to be made. These assumptions will be described throughout this section, and will be summarized at the end of the chapter.

The calculation of heating and cooling energy is performed in two main steps. First, a set of calculations is performed to define basic terms that are used in both the heating and cooling algorithms and are constant at all times. Then, the static energy balance is performed assuming that the air in the building is well-mixed and at a constant temperature. In one hour increments, the program determines if and how much heating and cooling is required and keeps running totals of both the heating and cooling energy. These calculations are described in detail in Section 9.2.2, but first it is necessary to understand the origins of the hourly weather data.

9.2.1 Weather Data

In order to perform the energy balance data the program must know the outdoor temperature conditions and incident radiation every hour of the year. Ideally, weather data from multiple climate zones would be used along with data on how the structure and makeup of office buildings and the number of buildings or total floor area varies in the different climate zones. However, statistical information was not available to describe the buildings to this level of detail, so a single set of average weather data was needed for all of Norway. Previous research has identified that the climate in Oslo best represents the average Norwegian climate when weighted by the number of existing buildings [Myhre 1995]. Therefore, statistical information on typical outdoor temperatures and solar radiation in Oslo serves as the weather conditions for all of the representative buildings in the simulation program.

The temperature and radiation data imbedded in the program were generated by METEONORM Software Version 4.0. METEONORM was developed for use in solar engineering projects and includes databases of typical temperature and radiation values based on 10-year measurement periods. The software can also perform calculations to determine the incident radiation on inclined planes. These calculations tend to underestimate the incident radiation in comparison to measured values by about 2% per year [Meteonorm 1999]. Given the approximations necessary to construct the representative buildings, 2% error in the radiation data was considered acceptable for the simulation program.

Therefore, METEONORM was used to generate the hourly data for dry-bulb outdoor temperature and solar radiation incident on vertical surfaces facing North, South, East, and West in Oslo. The outdoor temperature data was imbedded in the program in its original form. Since the distribution of windows around the building is not known, the program assumes that the windows are evenly distributed. Therefore, the hourly values for incident radiation on the building surfaces are the average of the data for the North, South, East, and West facing planes.

9.2.2 Heating and Cooling Energy Calculations

Define Constants

Before the hourly energy balance is performed, several variables can be defined that will not change from hour to hour.

Internal Gains from Lighting

The heat gain from lighting can be estimated from the energy consumption of lighting in the building. In the US it is typical to assume that 70 to 80% of the electrical energy used in lighting enters the building as heat [Energy Star 2004]. However, Norwegian building researchers usually assume that all of the electrical energy is converted to heat [Thyholdt 2005]. This discrepancy reveals that US energy researchers assume that the return air in the ventilation system has been designed to pick up some of the heat from the lighting, while Norwegian researchers assume that it all enters the room. Allowing all the heat from lighting to enter the room was historically not a problem in Norway because it would simply offset some of the heating requirements in the room. Since heat was typically supplied by electric boilers or electric resistance heaters, there was no significant difference in efficiency between using the boiler or the lights and equipment to heat the room.

In the US typical office buildings and new office buildings consume 22 W/m^2 and 11 W/m^2 of energy for lighting, respectively [Energy Star 2004]. Assuming that buildings are occupied for 12 hours a day and five days a week, the buildings would consume 68 and 34 kWh/m^2 in one year. Since average Norwegian office buildings use 35 kWh/m^2 of energy each year, most buildings must already be using efficient lighting technologies.

The simulation program assumes that the heat gain from lighting is 100% of the electrical energy. This approach is appropriate because it is typical practice in Norway and because energy efficient lights are already being used. If the lighting were consuming much more electric energy, the difference between 70% and 100% would be more significant.

Two more assumptions must be made to convert the electrical energy to heat gain in a single hour. The simulation program assumes that the building is occupied from Monday to Friday from 7am to 7pm and that the lights are off during unoccupied times. Therefore, the annual energy consumption from lighting can be split up into hourly portions of the total heat gain. The simulation program calculates the heat gain from lighting during a single, occupied hour as:

$$G_Z = \frac{Q_Z \cdot A_F}{3120} \qquad \textbf{9-8}$$

where G_Z is the heat gain from lighting in one hour in kWh, Q_Z is the annual electricity consumption from lighting in kWh/m^2, and 3120 is the number of occupied hours in one year. This approach neglects the fact that in a real building a small but unknown portion of the lights remain on at all times.

Internal Gains from Office Equipment

It is also standard practice in Norway to assume that 100% of the electrical energy for office equipment is converted to heat in the building [Thyholdt 2005]. Table 9-1 shows typical heat gains from different densities of office equipment in a room. The density changes represent varying numbers of computers, computer monitors, laser printers, and fax machines [ASHRAE 2005]. In converting the heat gains from power to energy, it was assumed that the office equipment was in operation for 12 hours a day and five days a week. Norwegian office buildings consume about 38 $^{kWh}/_{m^2}$ of energy for office equipment in a year, which is about the annual heat gain associated with medium density office equipment as shown in Table 9-1 [Wachenfeldt 2004].

Density of Equipment	Heat Gain [$^{W}/_{m^2}$]	Annual Heat Gain [$^{kWh}/_{m^2}$]
Light	5.6	17
Medium	11.1	35
Medium – Heavy	16.7	52
Heavy	22.2	69

Table 9-1: Heat gains from office equipment [ASHRAE 2005].

The energy simulation program assumes that 100% of the supplied electricity for office equipment enters the building as heat. This assumption is appropriate because it is standard practice in Norway and because it corresponds to a reasonable assumption for equipment density. Therefore, with the additional assumption that office equipment is turned off during unoccupied hours, the heat gain from office equipment in a single, occupied hour is:

$$G_E = \frac{Q_E \cdot A_F}{3120} \qquad \textbf{9-9}$$

where G_E is the heat gain from office equipment in one hour in kWh, Q_E is the annual electricity consumption from office equipment in $^{kWh}/_{m^2}$, and 3120 is the number of occupied hours in one year.

Internal Gains from Occupants

An adult man and woman give off approximately 75 and 55 W of sensible heat, respectively, while performing office work [ASHRAE 2005]. Assuming that the office employs equal portions of men and women, the average heat gain from the building occupants is 65 W/person. Therefore, the internal gains from occupants in one hour can be calculated as:

$$G_P = \frac{65 A_F \Delta t}{OA} \qquad \textbf{9-10}$$

where G_P is the internal gain from occupants in Wh, OA is the average floor area in m^2 per occupant, and 65 is the value for Watts per occupant, and Δt is the time period of the heat gain in hours (1 hour in the simulation program).

Latent heat is neglected for both heating and cooling loads. It would introduce an additional 55 W of heat gain accounting for only 4% of the total internal loads [ASHRAE 2005].

Transmission U-Value

The program also calculates the overall U-value for transmission of heat to air through the building roof, walls, windows, and doors as:

$$sumUA = U_R \cdot A_R + U_W \cdot A_W + U_G \cdot A_G + U_D \cdot A_D \qquad \textbf{9-11}$$

where sumUA is the overall U-value for transmission in W/K, U_R is the U-value of the insulation in the roof in W/m^2K, U_W is the U-value of the insulation in the walls in W/m^2K, U_G is the U-value of the windows in W/m^2K, and U_D is the U-value of the doors in W/m^2K.

Ground Temperature

The final constant value is the temperature of the ground. The ground temperature can be approximated as a constant value equal to the average air temperature during the coldest month of the year [ASHRAE 2005]. Using the METEONORM weather data February is the coldest month with an average air temperature of -2.8°C.

Calculations Performed Every Hour

The rest of the calculations are performed every hour to calculate running totals of the heating and cooling energy necessary in the building in order to maintain the desired indoor temperature. The calculations assume that the air in the building is well-mixed and at a constant temperature. The program tracks the day of the week and assumes that the building is occupied from Monday to Friday from 7am to 7pm. January 1st in the temperature and radiation data is assumed to be a Monday.

Frost and Ice Formation in Heat Exchangers

During very cold weather, frost and ice can form inside the heat exchanger in the heat recovery system, reducing the heat exchanger effectiveness. The cold supply air causes the heat exchanger surfaces to become very cold and can reduce the temperature of the warm exhaust air below its dew point. Water vapor condenses out of the air and forms ice when it contacts the heat exchanger surfaces, or water vapor can directly sublimate into frost. The effectiveness is reduced because the frost and ice layer causes additional resistance on the heat transfer surfaces and because the cross-sectional area that air can flow through is reduced, which increases the pressure drop across the heat exchanger [ASHRAE 2004].

While formation of frost and ice can be a serious problem, the types of heat exchangers used in Norwegian office buildings should not have a problem with frost and ice if they are well constructed and maintained. The majority of heat recovery units in Norwegian office buildings include plate heat exchangers with low efficiencies or rotary heat exchangers. In both cases frost and ice are unlikely to be problems. Therefore, the simulation program does not calculate a reduced efficiency due to frost or ice formation. More details about frost and ice formation in Norwegian heat exchangers are included in Appendix A.

Heat Gains

The simulation program calculates the heat gains in the building from solar radiation as well as heat given off by occupants, lighting, and office equipment. One of the input variables defines whether or not the building has automated blinds. If no blind control system is present, the window shading coefficient is assumed to be 1 at all times. This assumption means that none of the radiation that is incident on the window is blocked. If a blind control system is present, the shading coefficient is decreased to 0.5 when the solar gains are above 73 W/m^2. The 73 W/m^2 limit corresponds to the level of radiation where the glare from sunlight becomes uncomfortable for occupants [Design Advisor]. The shading coefficient of 0.5 corresponds to approximately one minus the reflectivity of Venetian blinds [ASHRAE 2005].

Solar gains are calculated every hour of the year, even when the building is not occupied. The formula used by the simulation program is:

$$Q_S = I \cdot SHGC \cdot a \cdot A_G \qquad \textbf{9-12}$$

where Q_S is the solar heat gain in Wh, I is the incident radiation in W/m^2, SHGC is the solar heat gain coefficient, and a is the portion of the solar gains blocked by blinds.

In addition to solar gains, the building will also experience internal gains. The total internal gain is the sum of the gains due to occupants, lighting, and equipment:

$$Q_I = G_P + G_Z + G_E \qquad \textbf{9-13}$$

where Q_I is the total internal gain in kWh. The internal gain is only calculated during occupied hours, and is assumed to be zero at all other times.

The total heat gain is the sum of the solar gains and the internal gains, calculated as:

$$Q_G = Q_S + Q_I \qquad \textbf{9-14}$$

where Q_G is the total heat gain in one hour in kWh.

Air U-Value

The next calculation determines the overall U-value for infiltration and ventilation. The simulation program calculates this value as:

$$U_{air} = \rho \cdot c_p \left[n_v^* (1 - \varepsilon \cdot phr) + n_i \right] \qquad \textbf{9-15}$$

where U is the overall heat transfer rate for ventilation and infiltration in W/K, ρ is the density of air in kg/m^3, c_p is the specific heat of air in J/kgK, n_v^* is the appropriate ventilation rate depending on the hour in the day and the day in the week in m^3/s, n_i is the infiltration rate in air in m^3/s, phr is the percent of ventilation air that goes through the heat recovery system, and ε is effectiveness of the heat recovery system. Appendix A provides more detail on how the ventilation portion of this formula was constructed.

Indoor Air Temperature

The indoor air temperature in the building depends on the occupancy schedule and the outdoor air temperature. During occupied hours the indoor air temperature is the constant temperature defined in the input data. If the building is unoccupied the indoor temperature is defined as:

$$T_i = T_i OC - DTNOC \qquad \textbf{9-16}$$

during the heating season or:

$$T_i = T_i OC + DTNOC \qquad \textbf{9-17}$$

during the cooling season where T_i is the indoor air temperature in °C, TiOC is the defined indoor air temperature for occupied hours °C, and DTNOC is the temperature change during unoccupied hours °C. The exception to this rule is if the building is unoccupied and the outdoor temperature is between these two values. In this case the air does not have to be conditioned and the indoor temperature is assumed to be equal to the outdoor temperature.

Maximum Open Window Heat Transfer

The program also determines the maximum amount of air that could be transferred to the building through open windows to help offset required cooling energy. Q_{window} in kWh is calculated in Wh as:

$$Q_{window} = \left(0.0625 \rho c_p A_G - 0.5 A_G U_G\right)\left(T_i - T_{out}\right)\Delta t \qquad \textbf{9-18}$$

where T_{out} is the outdoor air temperature in °C. The factor of 0.0625 represents the ventilation rate from open windows found using the Florida Solar Energy Method for estimating wind-driven buoyancy flows. Additional detail about the origin of this equation is included in Appendix A.

Heat Transfer During One Hour

The next step is to calculate the heat transfer during one hour including ventilation, infiltration, transmission to the air, and transmission to the ground. This calculation is performed in two different ways depending on the presence of radiation from the sun. Solar radiation can locally heat the air around a building surface causing a different heat source or sink than the ambient conditions. The sol-air temperature is the air temperature that in the absence of radiation would cause the same amount of heat transfer as the true conditions including radiation exchange. The sol-air temperature is defined as:

$$T_{s-a} = T_{out} + \frac{\alpha I}{h_o} - \frac{e \Delta R}{h_o} \qquad \textbf{9-19}$$

where T_{s-a} is the sol-air temperature in °C, α is the absorptance of the surface, h_o is the heat transfer coefficient of the surface W/m^2K, e is the hemispherical emittance of the surface, and ΔR is the difference between long wave radiation incident on the surface and radiation emitted by a black body at ambient conditions in W/m^2K. ΔR is approximately 114 W/m^2K for a horizontal surface and 0 W/m^2K for a vertical surface. For building materials, α/h_o can be approximated as 0.3 m^2K/W, ε can be approximated as 0.9, and h_o can be approximated as 20 W/m^2K [ASHRAE 2005]. The values deviate slightly from the default ASHRAE values to correspond to brick or concrete facades. Therefore, the sol-air temperature is:

$$T_{s-a} = T_{out} + 0.3I - 5 \qquad \textbf{9-20}$$

for the building roof, and:

$$T_{s-a} = T_{out} + 0.3I \qquad \textbf{9-21}$$

for building walls exposed to solar radiation.

When solar radiation is present, the simulation program assumes that the building roof and wall area equivalent to one of the four walls is exposed to solar radiation. Therefore, the simulation program calculates the total heat exchange as:

$$\begin{aligned} Q_{temp} = & \left[U_{air} + \tfrac{3}{4}(U_W A_W + U_G A_G + U_D A_D)\right](T_i - T_{out})\Delta t \\ & + \tfrac{1}{4}(U_W A_W + U_G A_G + U_D A_D)\left[T_i - (T_{out} + 0.3I)\right]\Delta t \\ & + U_R A_R\left[T_i - (T_{out} + 0.3I - 5)\right]\Delta t \\ & + U_B A_B\left[T_i - T_{ground}\right]\Delta t \end{aligned} \qquad \textbf{9-22}$$

where Q_{temp} is the heat transferred through ventilation, infiltration, transmission to air, and transmission to the ground in one hour in Wh, U_B is the U-value of the base in $W/_{m^2K}$, and T_{ground} is the temperature of the ground in °C. However, if solar radiation is not present, the sol-air temperature is not taken into consideration. This approach neglects a small amount of heat lost by radiation from the roof at night. Neglecting this heat loss at night changes the predicted annual energy consumption of the model buildings by less than one percent. Therefore, the simulation program calculates the total heat exchange at night as:

$$Q_{temp} = \left[(U_{air} + SumUA)(T_i - T_{out}) + U_B A_B (T_i - T_{ground})\right]\Delta t \qquad \textbf{9-23}$$

Heating and Cooling Energy

Next, the program must determine whether heating or cooling is necessary in this hour and add the necessary energy to the running totals of heating and cooling energy. If Q_{temp} is a negative value, cooling is necessary to maintain the desired indoor temperature. If the building does not have operable windows, the total amount of cooling necessary during this hour is simply:

$$Q_C = \frac{|Q_{temp}| + Q_G}{3} \qquad \textbf{9-24}$$

where Q_C is the cooling energy required in one hour in Wh and the cooling system is assumed to have a COP of 3. Electric chillers used in office buildings typically have coefficients of performance between about 3 and 5, so 3 is a conservative assumption [NRDC 1996]. However, if the windows are operable, the cooling required is compared to the total additional cooling that could be supplied by open windows. If Q_{window} is greater, no cooling energy is added to the total. This means that the program assumes that the occupants open the windows just enough to maintain the ideal indoor temperature. If open windows cannot maintain the desired indoor temperature, the windows must be closed and the chiller cools the building according to Equation 9-24.

Another possible case is that Q_{temp} is a positive value, which would indicate that heating is required, but difference between the heat exchange during the hour and the internal gains in that hour is negative. In this case the building is losing heat to the outside environment, but not enough to offset the gains in the building and maintain the desired indoor temperature. In this case, if the windows are not operable, the required cooling energy is only to eliminate the excess heat gains:

$$Q_C = \frac{Q_{temp} - Q_G}{3} \qquad \textbf{9-25}$$

Again, if operable windows are an option, the required cooling energy is compared to the maximum amount of additional cooling that could be supplied by opening the windows. If open windows do not cover the entire cooling requirement, the windows are closed and the chiller cools the building according to Equation 9-25. If cooling is necessary the appropriate value is added to the running total of cooling energy, Q_{CE}.

Equations 9-24 and 9-25 for calculating cooling energy neglect latent heat exchange in the chiller. Latent heat loss should be a fairly minor contribution to the total cooling energy in the Norwegian climate. According to the METEONORM weather data, the relative humidity on the hottest hours of the year is typically between 40% and 60% with an average of 51%. The ideal relative humidity for human comfort and the prevention of disease transmission is 30% to 60% [ASHRAE 2004]. The maximum temperature reported for any hour in the year was 27°C. Assuming the outdoor conditions are 27°C with a relative humidity of 50% and the indoor conditions are 23°C with a relative humidity of 50%, the change in latent heat to cool the air, including the 55W of latent heat from occupants, is only 8% of the heat exchange. The outdoor temperature is only above 23°C for about 40 hours a year. Therefore, neglecting latent heat exchange should not significantly affect the calculated total cooling energy.

The final possible case is when both Q_{temp} and Q_{temp}-Q_G are positive values. In this case the building is losing more heat to the outside environment than the internal gains can provide and additional heating energy is required. In this case, the required heating energy in one hour is calculated as:

$$Q_H = Q_{temp} - Q_G \qquad \textbf{9-26}$$

and this value is added to the running total. This approach assumes that the heating system is 100% efficient. One of the possible retrofit options is to install a heat pump to provide energy for the heating system. In this case the formula for the required heating energy is changed to:

$$Q_H = \frac{Q_{temp} - Q_G}{2} \qquad \textbf{9-27}$$

where the factor of two is the assumed COP. A COP of 2 is typical of actual heat pump performance in cold climates [Fransisco 2004]. If heating is required, the total for this hour is added to the running total of heating energy, Q_{HE}.

9.3 Fan Energy

The calculation of the energy required by the fans for the ventilation system is simply based on the ventilation rate and the specific fan power. Since the ventilation rate changes when the building is unoccupied, a weighted average ventilation rate must be used based on the occupancy schedule. The formula used in the simulation program is:

$$Q_F = 8.76\left(n_v OC \cdot \frac{3120}{8760} + n_v NOC \cdot \frac{5640}{8760}\right) FanPower \qquad \textbf{9-28}$$

where Q_F is the annual energy consumption of the fans in kWh and FanPower is the specific fan power in $W/_{m^3}$, and 3120 is the number of occupied hours in one year. The program assumes that the fans are not in the occupied areas of the building and therefore do not contribute to the internal heat gains.

9.4 Total Energy of a Single Building

At this point the simulation program has calculated annual energy consumption for heating, cooling, and fans. In order to determine the total energy consumption in the building, the only step remaining is to add these values to the energy consumptions for lighting, office equipment, and water heating which were inputs to the program. First, the input values must be converted to kWh, the units used by the simulation program in all of its calculations. This step is simply accomplished by multiplying by the total floor area of the building:

$$Q^*[kWh] = Q^*[{}^{kWh}/_{m^2}] \cdot A_F \qquad \textbf{9-29}$$

where Q* is the annual energy consumption of lighting, office equipment, or water heating in kWh. Then the total energy consumption is found by summing each component:

$$Q = Q_{HE} + Q_{CE} + Q_F + Q_Z + Q_E + Q_W \qquad \textbf{9-30}$$

where Q is the total energy consumption by a single building in one year in kWh, and Q_W is the energy consumed to heat water. Lastly, the specific energy consumption can be determined by dividing by the total floor area of the building:

$$Q'' = \frac{Q}{A_F} \qquad \textbf{9-31}$$

Where Q'' is the specific energy consumption in ${}^{kWh}/_{m^2}$.

9.5 Summary of Program Assumptions

The building characteristics are well defined by the characteristics listed in Table 7-20. However, the simulation program still had to include a number of assumptions to perform the necessary calculations. These assumptions are summarized below.

- The building is a rectangular box with a square profile
- The building has no thermal mass
- The building has 4 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 per person
- Heat gain from lighting is 100% of the annual energy consumption for lighting
- Heat gain from office equipment is 100% of annual energy consumption for office equipment
- Fans do not contribute to heat gains
- Lights and equipment are off during unoccupied periods
- Only sensible heat exchange is considered
- The COP of a heat pump is 2
- The COP of an electric chiller is 3

9.6 Variable Definitions

Variable	Units	Definition
a		Portion of Solar Radiation Blocked by Blinds
A_B	m^2	Base Area
A_D	m2	Door Area
A_f	m^2	Floor Area
A_G	m^2	Window (Glass) Area
α		Solar Absorptance
A_R	m^2	Roof Area
A_W	m^2	Insulated Wall Area
c_p	$J/_{kg\ K}$	Specific Heat of Air (1000)
d	m^2	Area of 1 Door (2)
ΔR	$W/_{m^2 K}$	Difference Between Long Wave Radiation Incident on a Surface and Radiation Emitted by a Black Body at Ambient Conditions
Δt	h	Time Step in the Simulation Program (1)
DTNOC	°C	Change in Internal Temperature During Unoccupied Hours
e		Hemispherical Emittance
ε		Effectiveness of Heat Recovery System (Heat Exchanger Effectiveness)
f	m	Floor Height
FanPower	$W/_{m^3/s}$	Fan Power Required for Ventilation System
G_E	kWh	Internal Gains from Equipment in One Occupied Hour
G_P	Wh	Internal Gains from People in One Occupied Hour
G_Z	kWh	Internal Gains from Lighting in One Occupied Hour
h	m	Building Height
h_o	$W/_{m^2 \cdot K}$	Heat Transfer Coefficient of Building Surfaces
I	$W/_{m^2}$	Hourly Solar Radiation – Average of Values for North, South, East, and West Facing Vertical Planes
L	m	Building Length/Width
N_d		Number of Doors (4)
N_f		Number of Floors
n_i	$m^3/_s$	Infiltration Rate
n_v^*	$m^3/_s$	Placeholder for Occupied or Unoccupied Ventilation Rate
$n_v NOC$	$m^3/_s$	Ventilation Rate During Unoccupied Hours
$n_v OC$	$m^3/_s$	Ventilation Rate During Occupied Hours
OA	$m^2/_{person}$	Occupant Area (25)
phr		Percent of Ventilated Air with Heat Recovery
Q	kWh	Total Energy for One Building
Q*	kWh	Placeholder for Lighting, Office Equipment, or Water Heating Energy

Variable	Units	Definition
Q''	kWh/m^2	Total Specific Energy
Q_C	Wh	Cooling Requirements for Transmission, Ventilation, and Infiltration
Q_{CE}	kWh	Total Cooling Energy Required
Q_E	kWh/m^2	Annual Energy Consumed by Office Equipment
Q_F	kWh	Total Fan Energy
Q_G	kWh	Total Heat Gain
Q_H	Wh	Heating Energy Required for One Hour
Q_{HE}	kWh	Total Heating Energy Required
Q_I	kWh	Internal Gains
Q_L	kWh	Total Heat Loss
Q_S	Wh	Solar Radiation Gain
Q_{temp}	Wh	Heat Transfer in One Hour
Q_W	kWh/m^2	Annual Energy Consumed by Heating Water
Q_{window}	Wh	Maximum Energy Possible to Supply Through Open Windows
Q_Z	kWh/m^2	Annual Energy Consumed by Lighting
ρ	kg/m^3	Density of Air (1.2)
SHGC		Solar Heat Gain Coefficient
sumUA	W/K	Sum of U Value times Area for Each Transmission Element
T_{ground}	°C	Ground Temperature
T_i	°C	Internal Air Temperature
T_iOC	°C	Internal Temperature During Occupied Hours
T_{out}	°C	Hourly Outdoor Temperature
T_{s-a}	°C	Sol-Air Temperature
U_{air}	$W/m^2 \cdot K$	Overall U Value for Ventilation and Infiltration
U_B	$W/m^2 \cdot K$	Base U Value
U_D	$W/m^2 \cdot K$	Door U Value
U_G	$W/m^2 \cdot K$	Windows (Glass) U Value
U_R	$W/m^2 \cdot K$	Roof U Value
U_W	$W/m^2 \cdot K$	Walls U Value
V	m^3	Building Volume
w		Window Area as % of Floor Area

Table 9-2: Variable definitions.

10 Results and Validation of the Energy Simulation Program

This chapter describes the results of the energy simulation program for each of the model buildings and compares those results to previous building monitoring projects and statistical studies. For more information on the previous studies, refer to Chapter 6.

10.1 Results of the Simulation Program

Figure 10-1 shows the results of the simulation program using the inputs described for the model buildings. The total annual energy consumption varied from 255 kWh/m^2 for the buildings constructed between 1969 and 1979 to 341 kWh/m^2 for the buildings constructed before 1969. The total consumption was between 255 kWh/m^2 and about 275 kWh/m^2 for the other construction periods. Energy used for heating was the largest consumer of energy for all the construction periods, accounting for roughly half of the total energy. Energy for the ventilation fan, lighting, and office equipment were approximately equal in importance; each consumed from 30 to 40 kWh/m^2 of energy in one year. Energy for cooling the building was a small portion of the total energy consumption for those buildings with a cooling system. Cooling energy and energy for heating water both consumed about 20 kWh/m^2 in a year.

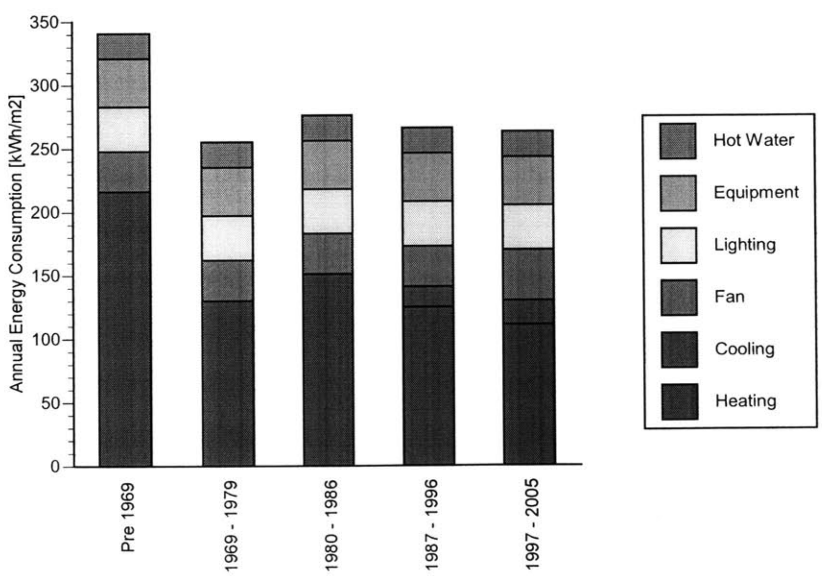


Figure 10-1: Annual energy consumption by end use predicted by the simulation program for each construction period in kWh/m^2.

10.2 Validation of the Results

The results in Figure 10-1 were compared to published information from building monitoring projects and statistical studies in order to determine if the simulation program and input data were valid.

10.2.1 Overall Average

Table 10-1 compares the results of the simulation program averaged over all of the model buildings to results from several other studies. Recall from Chapter 6 that the Enova data was the average energy consumption of all the office buildings involved in projects aimed at reducing energy consumption subsidized by Enova. The Modellbygg project was a detailed monitoring project, which involved eight office buildings, to determine segregated consumption data by end use. The Statsbygg data was the average energy consumption of all the buildings managed by Statsbygg, and Wachenfeldt's data was an estimate of the average consumption of office buildings in Norway.

	Annual Energy Consumption
Simulation Results	280
Enova	243
Modellbygg	200
Statsbygg	235
Wachenfeldt	265

Table 10-1: Annual energy consumption averaged over the entire building stock for the simulation results and several monitoring projects and statistical studies in kWh/m^2 [Enova 2002b] [Enova 2004] [Statsbygg 1995 – 2005] [Wachenfeldt 2004].

The annual energy consumption reported in the previous studies varied from 200 kWh/m^2 for the Modellbygg project to 265 kWh/m^2 in Wachenfeldt's study. The average results from the simulation program were 280 kWh/m^2, which is about 6% higher than Wachenfeldt's results. The annual energy consumption predicted for all of the construction periods was on the high side of the range of results from these studies, but it was the very high consumption predicted for the oldest buildings that pushed the average over all construction periods above the range.

10.2.2 Results by Construction Period

The next comparison looked at the trends in consumption over time. Only one study by Enova included segregated consumption data construction period. Their original statistics were modified to match the construction periods in this study. Refer back to Section 6.4.1 for more details.

	Simulation Results	Enova Results
Before 1969	341	228
1969 – 1979	255	226
1980 – 1986	276	226
1987 – 1996	266	246
1997 – 2005	261	303

Table 10-2: Annual energy consumption for each construction period from the simulation results and enova's statistics in $^{kWh}/_{m^2}$. Enova's statistics were modified to match the construction periods in this study; See Section 6.4.1.

The simulation results show that the energy consumption was very high, about 341 $^{kWh}/_{m^2}$, for the buildings constructed before 1969. The energy consumption was lower for all the other construction periods, varying from 255 $^{kWh}/_{m^2}$ in the 1969 to 1979 buildings to 276 $^{kWh}/_{m^2}$ for the 1980 to 1986 buildings. There was no clear trend of average energy consumption decreasing or increasing over time. Enova's measurements showed different trends. The older buildings had low energy consumption. The average energy consumption was slightly below 230 $^{kWh}/_{m^2}$ for all the construction periods before 1987. Then the energy consumption increased to 246 $^{kWh}/_{m^2}$ for the 1987 to 1996 construction period and to 303 $^{kWh}/_{m^2}$ for the 1997 to 2005 construction period.

The drastic increase in energy consumption in new construction in Enova's statistics was attributed to increased use of air condition systems, greater portions of the facade covered by windows, and increased occupant density within the buildings [Solem 2006] [Thyholdt 2005]. The input data for the simulation program introduced air conditioning systems for the 1987 to 1996 construction period. It also included a modest increase in window area for the buildings in the 1997 to 2005 construction period, from 15 to 20% of the floor area, which is the maximum glass area specified in the building code. It has been anecdotally reported that the portion of the facade covered by windows is often greater than 20% of the floor area, but no information is available about how many buildings have mostly glass facades and what other actions the building designers may take to reduce energy consumption [Solem 2006]. Therefore, the input data for the simulation program uses the code values. Similarly, there is no data to determine if occupant densities have truly increased and if so by how much. Therefore, all the buildings use the same occupant density. These discrepancies may explain why the simulation program predicted lower energy consumptions for the buildings building after 1987 than were seen in Enova's results.

It intuitively makes sense that the oldest buildings would consume more energy than new construction. However, it not clear why the simulation program would predict such a high energy consumption for the buildings constructed before 1969 but the data from Enova would not support it. The oldest buildings do have very high U-values for the windows and other facade elements in comparison to the buildings in the other construction periods. It is possible that the buildings constructed before 1969 have already been retrofit to a greater degree than has been documented or was uncovered through interviews in the attempt to compile data for the description of the model buildings.

It is also possible that Enova's results are not representative of Norway as a whole. The statistics used to generate their results come from only 147 office buildings, and all of the buildings were involved in government subsidized projects to reduce their energy consumption. The owners and operators of the buildings must be aware of and interested in energy conservation, so it is possible that the buildings consume less than typical Norwegian office buildings. However, the newest buildings were constructed recently enough that their equipment would still be state of the art. In this case it is possible that the owners chose to get involved with Enova projects because they already knew their building was performing poorly.

10.2.3 Results by End Use

Two of the previous studies included information on the breakdown of total energy consumption by end use. Table 10-3 compares the results of the simulation program to these two studies.

	Simulation Results	Modellbygg	Wachenfeldt
Heating	147	62	164
Ventilation	-	37	-
Cooling	7	7	4
Fans or Pumps	33	38	-
Lighting	35	27	35
Offing Equipment	38	29	38
Water	20	5	20
Total	280	200	262

Table 10-3: Annual energy consumption by end use averaged over the entire building stock for the simulation report compared to two studies in kWh/m^2 [Enova 2002b] [Wachenfeldt 2004].

Recall that the Modellbygg project involved detailed monitoring of 8 office buildings and that Wachenfeldt's results are based on a compilation of multiple monitoring projects (including the Modellbygg project) and statistical sources. Note that the end use categories were not the same in all three studies. This study and Wachenfeldt's study lumped heating and ventilation energy together, while the Modellbygg project split them up. The total heating and ventilation for the Modellbygg project was 99 $^{kWh}/_{m^2}$, which is still about 50 $^{kWh}/_{m^2}$ less than the simulation results or Wachenfeldt's results. The heating energy predicted by the simulation program is similar, but slightly less than Wachenfeldt found.

Wachenfeldt's study also did not include energy consumed by the ventilation fan. If it had included energy for the fans, the total energy consumption of the buildings would likely have been higher than the average predicted by the simulation program. The required fan energy calculated by the simulation program was 33 $^{kWh}/_{m^2}$, which is slightly less than the 38 $^{kWh}/_{m^2}$ found in the Modellbygg project.

The energy consumed by the lighting, office equipment, and water heaters are identical for the simulation program and Wachenfeldt's study. Recall that these parameters are inputs to the program and that the inputs were taken from his results. They are similar to but higher than the consumption seen in the Modellbygg study. If the Modellbygg results had been used for the program inputs, the overall energy consumption predicted by the simulation program would have been slightly lower.

In all three studies the energy consumed by the cooling system is very low, less than 10 $^{kWh}/_{m^2}$. However, this result is a product of the fact that cooling systems were not commonly installed in office buildings in Norway until the mid-1980's. When the cooling energy is averaged over the entire building stock, it is significantly lower than the actual consumption of a single building.

10.2.4 Conclusions

The results from the simulation program do not perfectly match the data available from previous studies. However, as was shown in Chapter 6, comparing the previous studies or even different years within the same study also reveals many inconsistencies. Recall Figure 6-4 which showed the energy consumption of the office buildings managed by Statsbygg. Two sets of data are shown. One represents all of the buildings that Statsbygg managed in a given year; the other represents a set of buildings that was consistently managed for a ten year time period. Neither group of buildings consistently consumed more or less energy than the other. The average consumption for the buildings managed for the full ten years fluctuated by about 25 kWh/m^2 from one year to the next. For the other data set, the fluctuation could be as much as 50 kWh/m^2.

The results of the simulation program were never designed to match the previous results perfectly. A new simulation program was written because the accuracy of the input data did not warrant using a very accurate simulation program which would require many input variables that could not be defined on a national level. The comparisons above show that the results of the simulation program in combination with the data on the model buildings produce predictions that are reasonable. The overall average is within the +/- 25 to 50 kWh/m^2 yearly variation shown in the Statsbygg data. The end use breakdowns are similar to those from the Modellbygg project and Wachefeldt's study. The breakdown by construction year in Enova's overall statistics showed the greatest discrepancies, but they are based on a small data set that was not chosen to be representative of the building stock as a whole.

In general, the simulation program produced reasonable results within a range of accuracy that is appropriate for national scale data.

11 Sensitivity of the Energy Simulation Program

Chapter 10 compared the overall results of the energy simulation program to data for the actual performance of Norwegian office buildings and showed that the results from the simulation program are valid. It is also important to understand which input parameters have the most control over the estimated annual energy consumption. A sensitivity analysis was performed to determine how the predicted energy consumption changes when the input values are altered. The input parameters that exert the greatest influence over the energy consumption should ideally have the most accurate values. The same input parameters are also likely to be the most efficient ways to decrease energy consumption, so finding them will suggest potential retrofit strategies. The sensitivity analysis will also determine which input parameters have minimal effect on total energy consumption. These parameters do not need to be considered in the retrofit analysis. Since there more than 20 input parameters in the simulation program, each elimination will considerably simply the process.

Finally, several best-practice assumptions were made to compile the descriptions of the model buildings, as described in Chapter 7. For example, all the model buildings were assumed to have been constructed or retrofit with a heat recovery system. This chapter will describe the effect that those best-practice assumptions have on the total energy consumption of the building and demonstrate the energy savings that buildings that have not instituted them could gain from performing these retrofits.

11.1 Sensitivity Analysis

This section will analyze which parameters have the most control over the simulation program's determination of the annual energy consumption. The buildings constructed before 1969 are used for demonstration because they have the highest energy consumption and will show the largest relative changes. The buildings constructed between 1997 and 2005 are also used to show if and how the cooling system affects the sensitivity of the program.

11.1.1 Most Sensitive Attributes

A sensitivity analysis was performed on each building attribute to determine how much the predicted annual energy consumption changed when the input values were changed. Each value was varied in a realistic range around the best value described in Table 7-20. Figure 11-1 and Figure 11-2 show the results for the six most sensitive attributes, those with the steepest slope, for the buildings constructed before 1969 and those constructed between 1997 and 2005. The percent change in annual energy consumption is graphed on the y-axis. A positive value indicates that greater energy consumption was predicted; a negative value indicates less energy would be consumed. The x-axis represents the ratio of the value used in the simulation to the best guess value listed in Table 7-20.

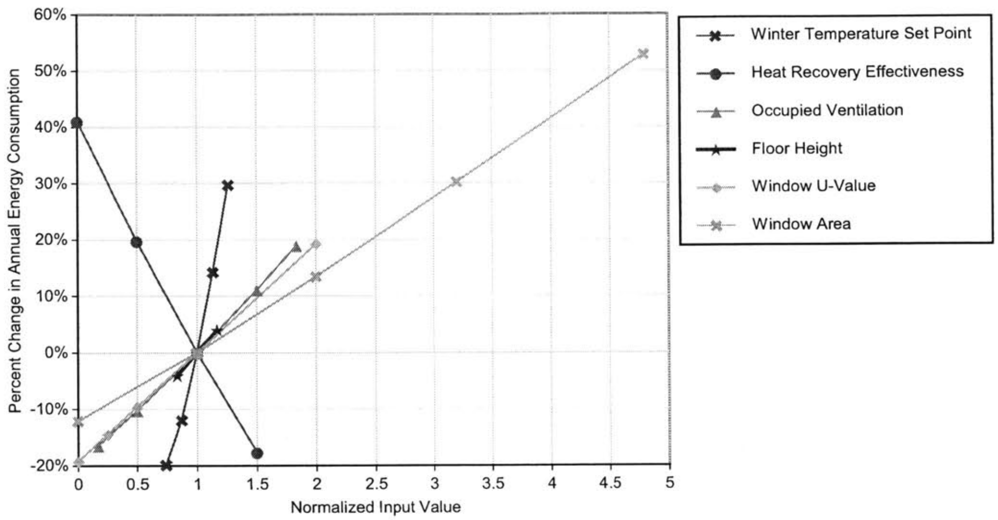


Figure 11-1: Change in annual energy consumption for the six most sensitive parameters in simulations on the buildings constructed before 1969. Values for the winter temperature set point were calculated in °C.

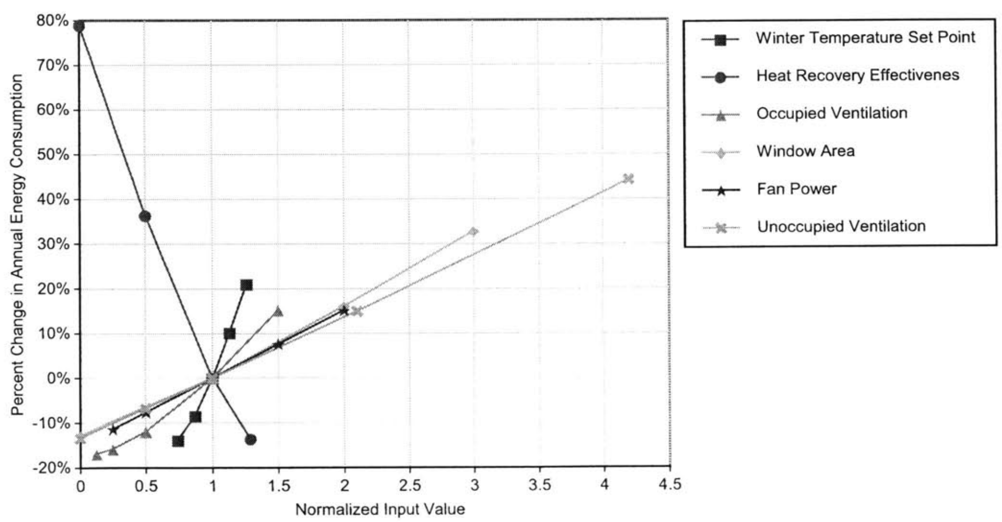


Figure 11-2: Change in annual energy consumption for the six most sensitive parameters in simulations on the buildings constructed between 1997 and 2005.

The winter set point temperature, heat recovery effectiveness, and occupied ventilation rate are the three most sensitive attributes for both starting conditions. This result indicates that these parameters are likely to be the most important attributes for influencing the energy consumption in the retrofit study. It also indicates that small differences in these parameters would change the predicted energy consumption significantly. If one or more of these parameters is slightly off, it may indicate why the simulation program predicts higher consumptions than has been seen in statistics.

The area of the facade covered by windows also appears in both lists. The window area is related to the heat gain or loss through transmission as well as the heat gains from solar radiation. The total length of the line representing window area on Figure 11-1 and Figure 11-2 indicates the difference in energy for a building with no windows to one with an entirely glass facade. The slope of the line indicates that if the total area of the windows varies from the maximum code value, which was used to define the area of the windows, by a factor of 0.5 or 1.5, the total energy consumption will only vary by about +/- 7%. However, if the glass facade area covers the majority of the facade, the energy consumption is predicted to be about 55% higher for the buildings constructed before 1969 and about 35% higher for the buildings constructed between 1997 and 2005. The influence is significantly greater for the older buildings, which have windows with high U-values. These results demonstrate that the behavior of a building with a complete glass facade is significantly different from the model buildings in this study. The results from the retrofit study in Chapter 12 should be applied cautiously to glass facade buildings.

The other two attributes in the top six were floor height and window U-value for the buildings constructed before 1969 and the specific fan power and unoccupied ventilation rate for the buildings constructed between 1997 and 2005. These attributes correspond to the least energy-efficient characteristics of the existing buildings. For the buildings constructed before 1969, the low U-value of the windows and other facade elements cause the very high heating requirement. Both the window U-value and the floor height greatly effect the predicted energy consumption. The area of the windows was fixed, but the floor height was used to calculate the total facade area, which affected the area of the walls. For the buildings constructed between 1997 and 2005, the least energy efficient element is the very high occupied ventilation rate. Therefore, the specific fan power becomes more important. The unoccupied ventilation rate was the seventh most important parameter for the Pre-1969 buildings. It is relatively more important for the 1997 to 2005 buildings because the U-values of the windows and other facade elements are significantly lower.

11.1.2 Effect of Building Geometry

The retrofit analysis assumes that the building geometry is constant and cannot be changed as a retrofit strategy. Since the effect of changing the geometry characteristics is not considered, it is especially important to estimate the sensitivity of the annual energy consumption to the accuracy of the geometry data. Figure 11-3 and Figure 11-4 show the change in annual energy consumption for a given change in input for each of the attributes describing the building's geometry for the buildings constructed before 1969 and those constructed between 1997 and 2005.

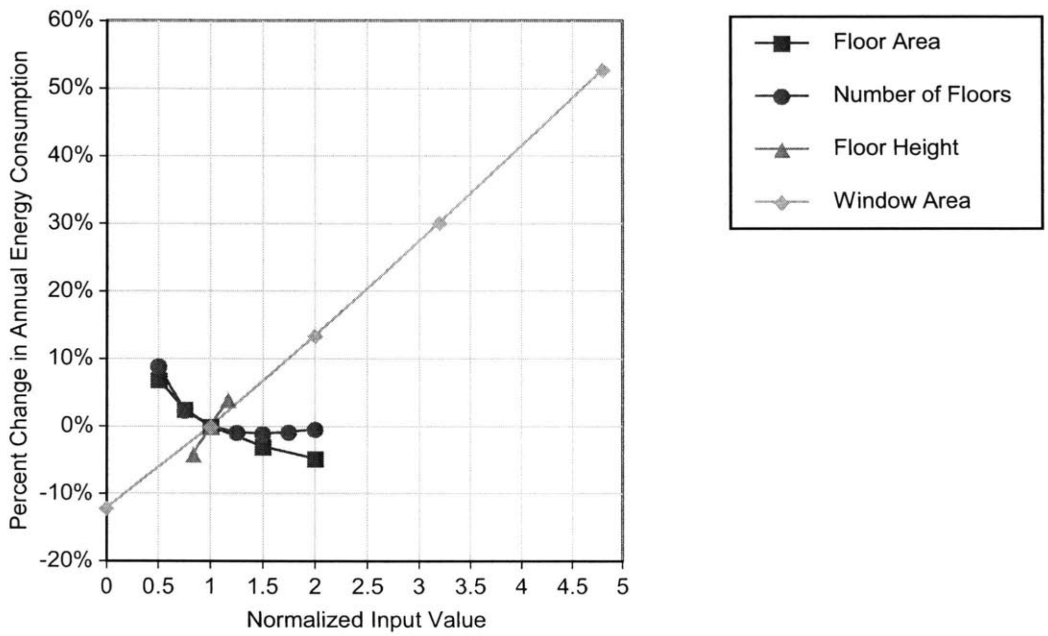


Figure 11-3: Sensitivity of building geometry attributes for buildings constructed before 1969.

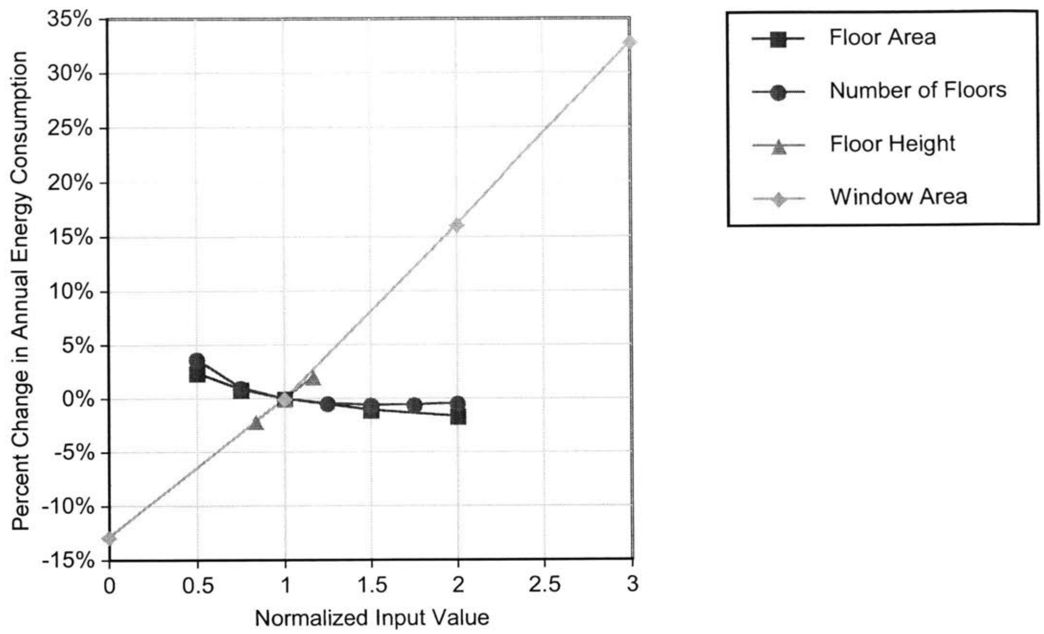


Figure 11-4: Sensitivity of building geometry attributes for buildings constructed between 1997 and 2005.

As was noted above, the percent of the facade that is covered by windows has a large effect on the estimation of annual energy consumption. It is unlikely that an office building would be constructed with no windows at all or a window area less than half of the code maximum. Therefore, decreases in window area would only change the determination for energy consumption by about 7%. However, for a building with a complete glass facade, the total energy consumption would be about 35 to 55% greater than the model buildings. Therefore, results from this study should be applied cautiously to buildings with glass facades.

The other geometry factors had a much smaller effect on total energy consumption. Reducing the building floor area or number of floors by half increased the annual energy consumption by about 8% for buildings constructed before 1969 and by about 3% for buildings constructed between 1997 and 2005. Increasing the floor area by a factor of two decreased the annual energy consumption about 5% for the buildings constructed before 1969 and only 2% for buildings constructed between 1997 and 2005. Increasing the number of floors had a 2% or less effect on energy consumption for both time periods. Annual energy consumption is fairly sensitive to the floor height in terms of the slope, but there is a fairly small range of reasonable floor heights. Therefore, the total effect that the floor height has on energy consumption would only vary by +/- 4% or less. The buildings constructed before 1969 are more sensitive to changes to the building geometry than those constructed between 1997 and 2005 because the geometry affects the surface area of the building. The building facade in the older buildings has much higher U-values, so greater changes are seen in energy consumption. However, none of the changes are more than about 8%. These are fairly minor changes, so keeping the geometry constant in the retrofit analysis should not be a problem. The greatest changes were seen in smaller buildings with only two floors, so real buildings with these characteristics might consume more energy than is predicted by the retrofit analysis.

11.1.3 Determine Attributes to Exclude from the Retrofit Analysis

The sensitivity analysis revealed that one building attribute, the U-value of the door, had a negligible effect on the determination of annual energy consumption. Changing the U-value of the door from 0 to 11 W/m^2K changed the annual energy consumption by less than 1% in the buildings constructed before 1969 and by less than 0.5% in buildings constructed between 1997 and 2005. The door area is a very small portion of the total facade area, so altering the U-value does not significantly change the total energy consumption of the buildings. Since the U-value of the door does not have a significant effect on the total energy consumption, it will not be included in the retrofit analysis.

Only the insulative properties of the door were considered in the analysis. Any additional losses for air leakage through the doorway were assumed to be included in the overall infiltration rate for the building.

11.1.4 Other Attributes

The other building attributes had the potential to change the annual energy consumption of the model buildings. Therefore, all the remaining attributes must be considered in the retrofit analysis. The effect of changing individual attributes varied between the different construction periods. Their relative importance for decreasing energy consumption will be explored further in Chapter 12 on the retrofit analysis.

11.2 Effect of Best Practice Assumptions

Changing the building attributes from the values determined in Chapter 7 revealed more cases where the buildings could consume more rather than less energy. Several examples of this effect are shown in Figure 11-1 through Figure 11-4. In each case the changes in annual energy consumption are of greater magnitude in the positive direction. Several best practice assumptions were made in defining the building attributes, which assume that the buildings are operated responsibly and that some retrofits had already been adopted. This section will demonstrate how much more energy the buildings would consume if these best practice assumptions have not been adopted.

11.2.1 Temperature Setback

All of the model buildings are assumed to change the indoor temperature by 4°C when the building is not occupied. This practice reduces energy consumption but also allows the building to return to the occupied set point temperature fairly quickly when the occupants return. Table 11-1 shows the change in energy consumption for each model building with and without temperature setback.

	With Temperature Setback [kWh/m^2]	Without Temperature Setback [kWh/m^2]	Percent Change
Before 1969	341	382	12%
1969 – 1979	255	283	11%
1980 – 1986	276	305	10%
1987 – 1996	266	291	9%
1997 - 2005	262	283	8%

Table 11-1: Change in energy consumption for each model building with and without temperature setback.

Neglecting temperature setback increases the total energy consumption in the model buildings by 8 to 12%. The magnitude of the percent change decreased in the more modern buildings, which have lower heating demands.

11.2.2 Ventilation Setback

The model buildings also have ventilation setback. The ventilation rate is reduced to 1 L/sm^2 when the buildings are not occupied. This rate, specified in the 1997 building code, prevents pollutants out-gassed from materials from accumulating within the buildings. Table 11-2 shows the change in energy consumption for each construction period with and without ventilation setback.

	With Ventilation Setback [$^{kWh}/_{m^2}$]	Without Ventilation Setback [$^{kWh}/_{m^2}$]	Percent Change
Before 1969	341	405	19%
1969 – 1979	255	311	22%
1980 – 1986	276	375	36%
1987 – 1996	266	356	34%
1997 - 2005	262	378	44%

Table 11-2: Change in energy consumption for each model building with and without ventilation setback.

Eliminating ventilation setback increases the annual energy consumption by 19 to 44%. All of the construction periods except the 1997 to 2005 buildings have the same assumed ventilation rate. The changes in the magnitude of the percent change in energy consumption are due to differences in the buildings' heat recovery effectiveness. More effective heat recovery systems could alleviate the additional heating requirements from the ventilation rate to some degree. The buildings constructed from 1997 to 2005 have a higher ventilation rate than the other construction periods. Therefore, the energy for heating and the energy required by the fan increased more for this construction period. That is why it has a 10% higher percent change than the other construction periods.

11.2.3 Heat Recovery

All of the model buildings are assumed to have a heat-recovery system, but the effectiveness varies. Table 11-3 shows the effect of removing the heat recovery system from the model buildings.

	With Heat Recovery [$^{kWh}/_{m^2}$]	Without Heat Recovery [$^{kWh}/_{m^2}$]	Percent Change
Before 1969	341	481	41%
1969 – 1979	255	433	70%
1980 – 1986	276	408	48%
1987 – 1996	266	403	51%
1997 - 2005	262	469	79%

Table 11-3: Change in energy consumption for each model building with and without heat recovery.

Removing the heat recovery system increases the annual energy consumption of the model buildings by 40 to 80%. Both the original effectiveness and the ventilation rate affect the magnitude of the change. Buildings with a low heat recovery effectiveness (before 1969, 1980 to 1986, and 1987 to 1996) have a smaller percent change because the heat recovery system was recovering less energy. In contrast, for the buildings constructed between 1969 and 1979, which have a heat recovery effectiveness of 80%, removing the heat recovery system has a very large effect. The percent change is the highest for the buildings constructed between 1997 and 2005 because those buildings have high heat recovery effectiveness and a high ventilation rate. The two act together to show a very large increase in energy consumption if the heat recovery system were not present.

11.2.4 Glass Facade

The glassed areas on the facade in the model buildings are defined as the maximum value listed in the relevant building code. However, buildings with a complete glass facade are constructed. Table 11-4 shows the effect constructing a building with a glass facade has on energy consumption.

	Code Designated Glass Area [kWh/m^2]	100% Glass Facade [kWh/m^2]	Percent Change
Before 1969	341	521	53%
1969 – 1979	255	366	44%
1980 – 1986	276	358	30%
1987 – 1996	266	375	41%
1997 - 2005	262	348	33%

Table 11-4: Change in energy consumption for each model building with and without a complete glass facade.

Having a glass facade increased the energy consumption of the model buildings by about 30 to 55%. The percent change decreased with time for the buildings in the first three construction periods. As the U-value of the windows decreased, the glass facade had a smaller effect on energy consumption. The percent change increased again for the buildings constructed from 1987 to 1996 and 1997 to 2005 when cooling systems were introduced. The additional heat gains during the cooling season created additional energy requirements. The energy consumption increased more in the 1987 to 1996 time period than the 1997 to 2005 time period because the U-value of the windows is higher and the ventilation rate is lower in the 1987 to 1996 time period, so the airflow cannot offset as much of the additional heat gain.

12 Retrofit Analysis

This section describes the methodology and results of the retrofit analysis. The results of the sensitivity analysis in Chapter 11 were used to determine which building attributes had a significant role in determining the annual energy consumption of the buildings. A standard and a low-energy retrofit condition were chosen for each of these attributes for the retrofit analysis. The effect of the retrofit options on annual energy consumption will be simulated alone, in combination with other options in the same building system, and in combination with options from multiple systems for each model building. The systems approach is necessary because millions of potential scenarios would be created by looking at the effect of combining every single attribute and retrofit option in combination with every other. The systems approach breaks down these scenarios into manageable data sets. It is also useful because real building owners or managers are likely to retrofit buildings when individual components or several components in a system need to be replaced due to failure or fatigue. The systems approach will reveal how much energy could be saved by considering the energy use of the replacement components.

12.1 Methodology

The building attributes described in Table 7-20 were all considered as potential retrofit options. First, the attributes that define the building's geometry were removed from consideration. The size and structure of the building will not be changed in the retrofit analysis. Based on the sensitivity analysis described in Chapter 11, the U-value of the door had a negligible influence on total energy consumption. It was also removed from consideration. The remaining building attributes were organized into five building systems: controls; heating, ventilation, and air-conditioning (HVAC); windows; non-window building facade; and other energy services.

Retrofit options were defined for each building attribute under consideration. A standard retrofit option and a low-energy option were defined for most of the attributes. The standard retrofit option generally involved updating the building to be in accordance with the 1997 building code. The low-energy options were an estimate of the best practice retrofits available. In other cases the options simply defined whether or not an attribute, like a heat pump, was present in the building. For the attributes included in the other energy services system, only a low-energy retrofit option was defined because there was no clear middle ground between current practice and best practice. Figure 12-1 through Figure 12-5 give an overview of the retrofit options available for each model building. The highlighted blocks represent the original condition of the building. The white boxes represent the possible retrofit conditions. The cost of each retrofit project was described in Chapter 8. Note that no retrofit conditions were defined for the infiltration rate. No specific method and cost estimate were found for reducing the infiltration rate in an existing office building. The simulation program assumed that the infiltration rate was reduced by a factor of 1/3 if the windows or the walls and roof of the building were retrofit. If the windows, walls, and roof were all retrofit, then the infiltration rate was reduced by a factor of 2/3.

The standard retrofit condition for the occupied and unoccupied ventilation rate correspond to the minimum ventilation rate listed in the 1997 Norwegian building code [Thyholdt 2005]. The low-energy ventilation rates are the minimum values required by AHRAE Standard 62.1-2004 for the size and occupant density of the model buildings [ASHRAE 2004b].

The standard retrofit condition for heat recovery effectiveness is 70%, the effectiveness used in current construction [Mathisen 2005]. The low-energy condition for heat recovery effectiveness, 80%, was chosen because this was the highest average effectiveness used in several case studies of new, low-energy office buildings [AEE Christophorus] [AEE W.E.I.Z]. Heat recovery units that strive for a higher effectiveness likely have problems with very high pressure drops across the system. This deficiency increases the draw on the ventilation fans, negating any additional reductions in energy consumption.

The standard and low-energy specific fan powers correspond to efficiencies currently recommended by the Scandinavian Federation of the Societies of Heating, Air-Conditioning, and Sanitary Engineers [Nilsson 1995].

The standard retrofit window was a double-paned, argon-filled, aluminum frame window. The low-energy window was a triple-paned, argon filled window with a vinyl frame [ASHRAE 2005].

The standard retrofit U-values were the values required in the 1997 building code [Codes 2005]. The low-energy retrofit condition decreased the U-values to be about half of those in the 1997 code.

Using the total energy consumption of the lighting and the number of hours the building is occupied, the average power consumption of the lights was 11 W/m^2, which is a typical power consumption for high efficiency lighting [Energy Star 2004]. For the low-energy condition the average power draw was reduced to 9 W/m^2. This condition assumes that high efficiency lighting is installed in the building and that the building occupants do not use the electric lights when there is sufficient light from windows.

The retrofit condition for hot water assumed that the current consumption can be divided in half, which was consistent with the consumptions for individual buildings described in Section 6.5. For office equipment, the low-energy retrofit consumption assumed that the equipment consumed 17 kWh/m^2 or 5.4 W/m^2, which is consistent with the lowest recommendation for heat gain that ASHRAE makes for medium density office equipment [ASHRAE 2005].

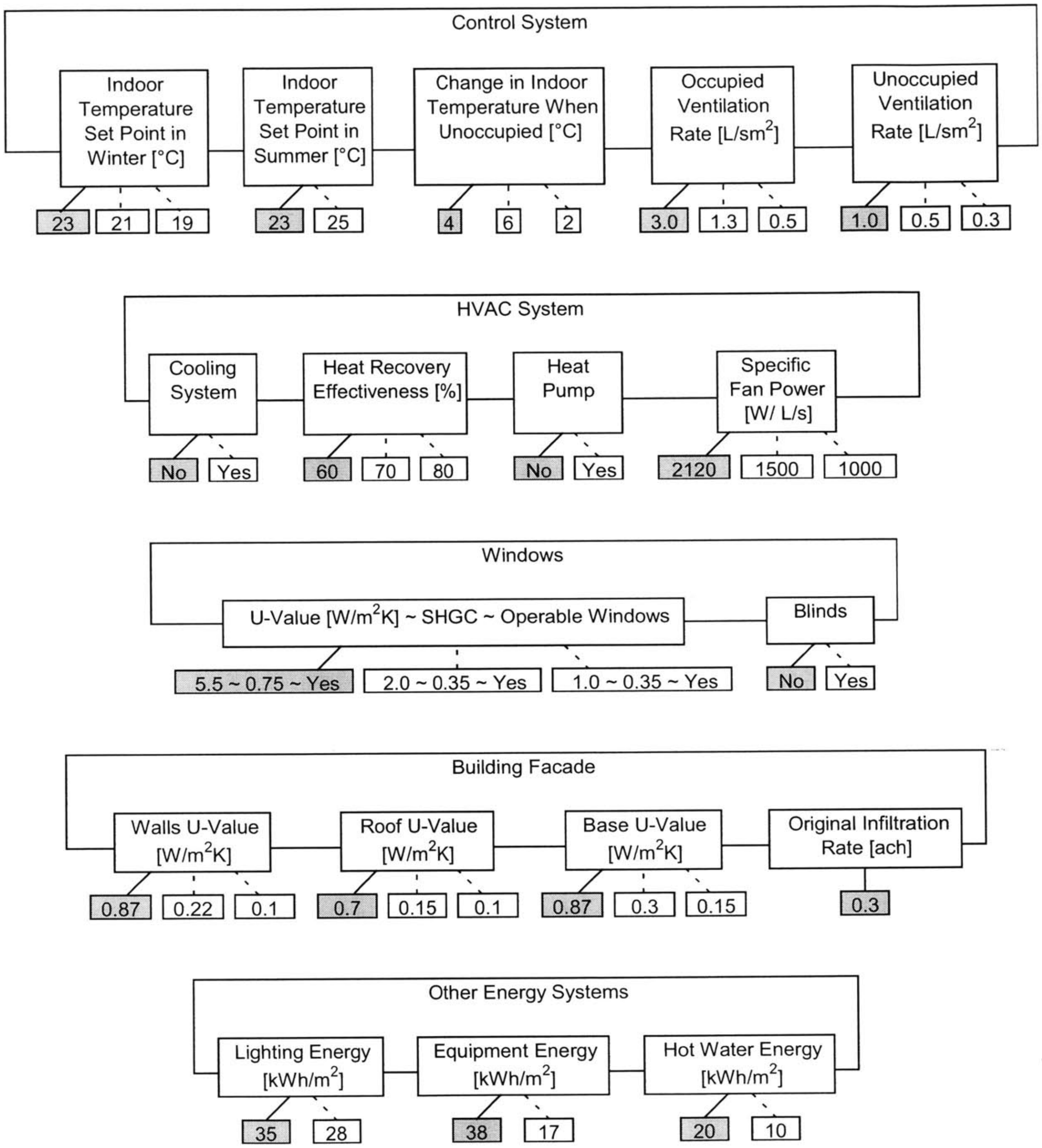


Figure 12-1: Retrofit schematic for the buildings constructed before 1969. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options.

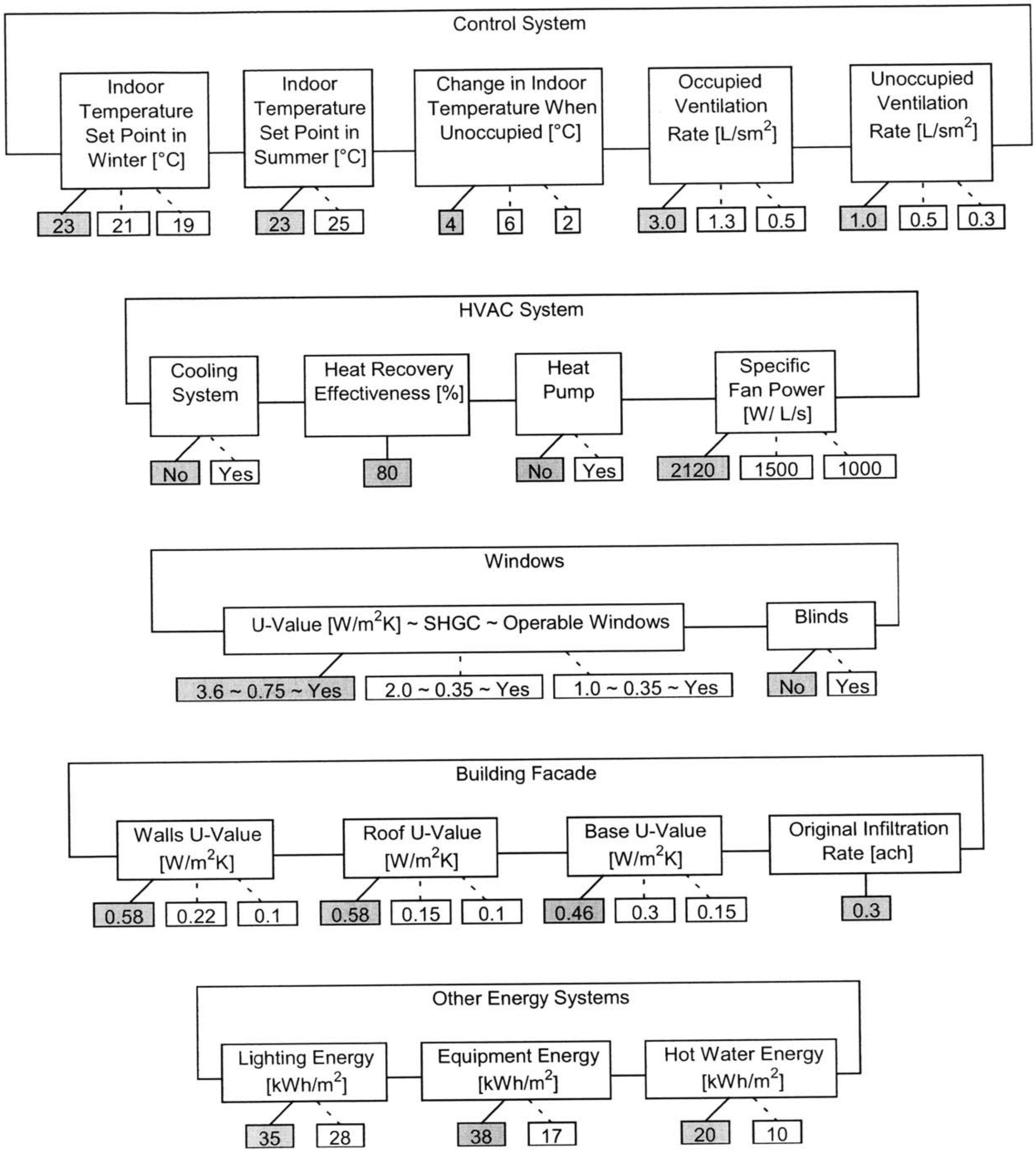


Figure 12-2: Retrofit schematic for the buildings constructed between 1969 and 1979. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options.

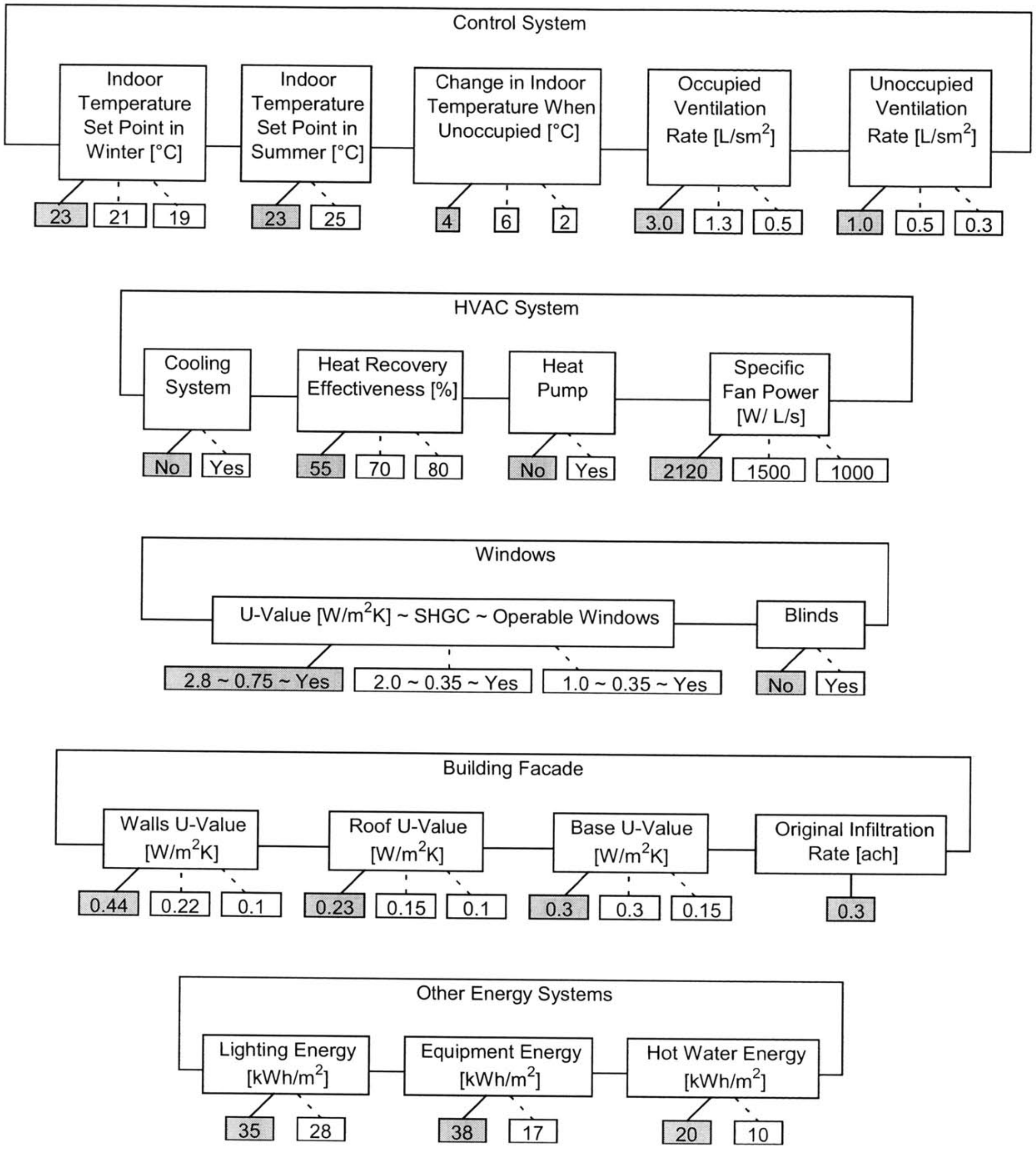


Figure 12-3: Retrofit schematic for the buildings constructed between 1980 and 1986. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options.

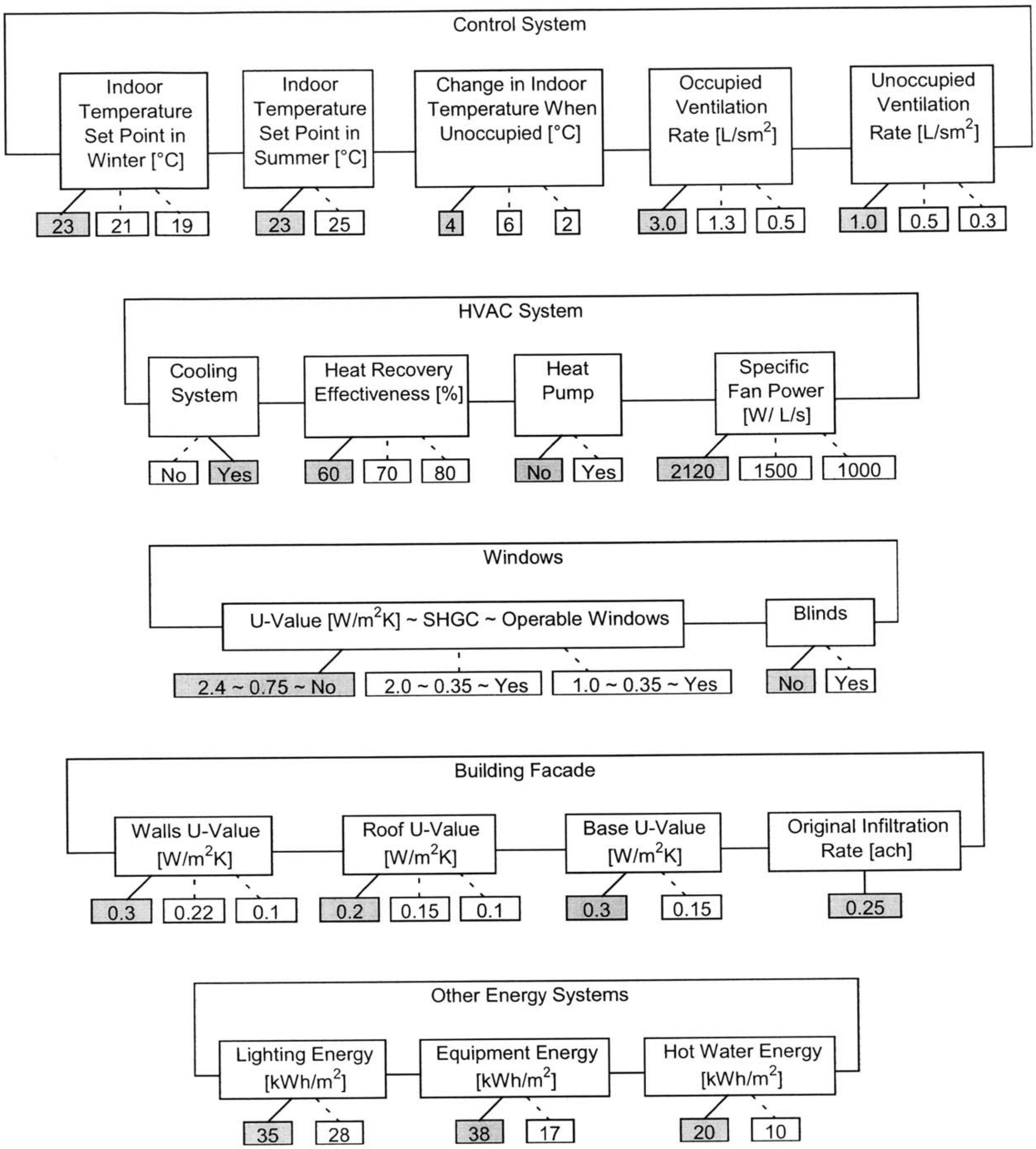


Figure 12-4: Retrofit schematic for the buildings constructed between 1987 and 1996. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options.

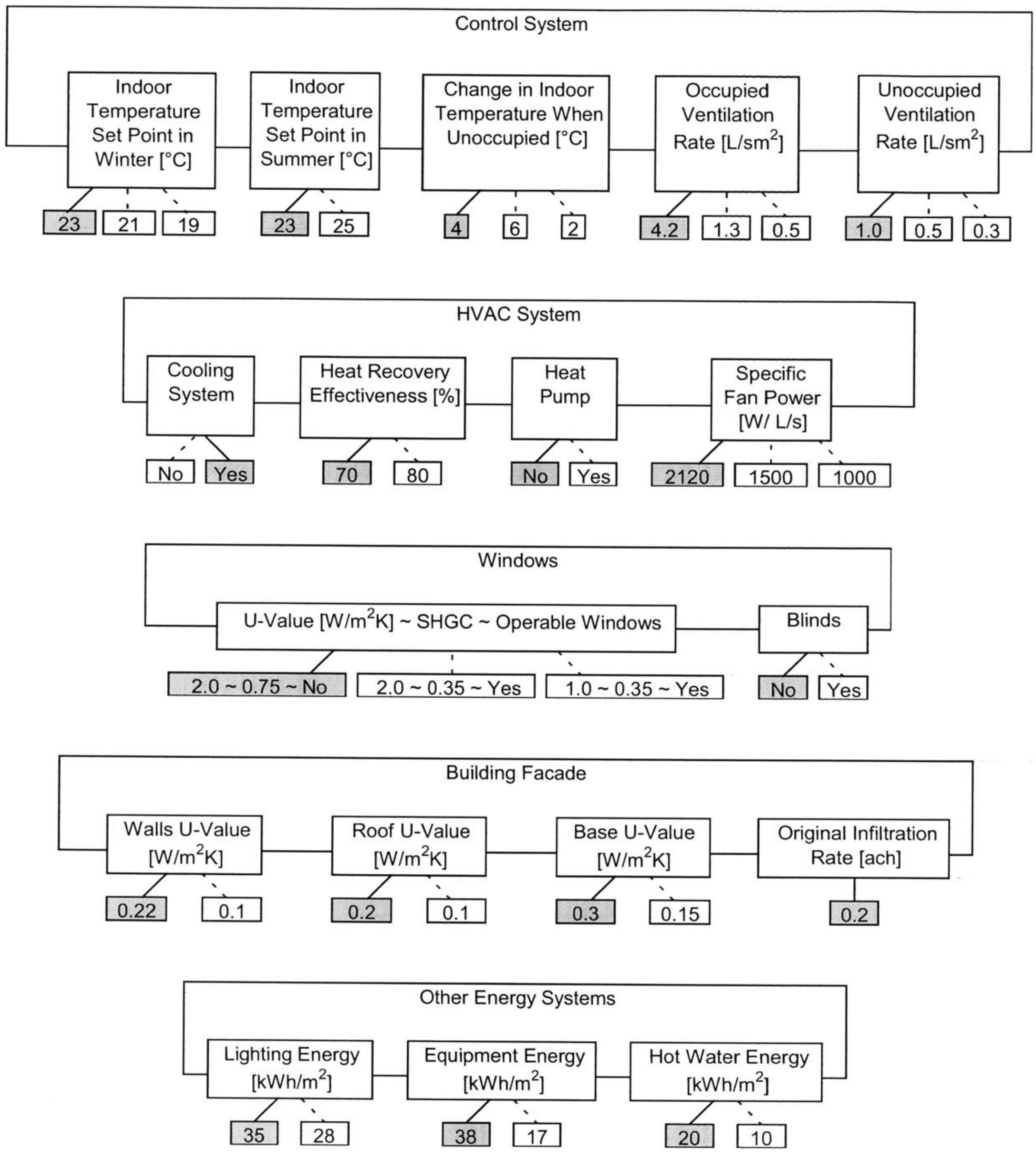


Figure 12-5: Retrofit schematic for the buildings constructed between 1997 and 2005. The highlighted boxes represent the original condition of the building. The white boxes represent the potential retrofit options.

12.2 Retrofitting a Single Attribute

The first retrofit analysis considered the effect of changing each attribute from its original condition to the retrofit conditions described above. All of the other attributes would retain their original value, as highlighted on Figure 12-1 through Figure 12-5. This step helped identify the components that have the greatest potential for decreasing the building's energy consumption. It is also useful for building owners or managers to see the effect that replacing even a single component can have on the total energy consumption of a building. They will have a context to understand the importance of considering a low-energy option rather then just replacing the component with the same model that was used before when existing components must be replaced.

Most of the single attribute changes affect only one end use. Figure 12-6 shows how reducing the indoor set point temperature in winter decreased the required heating energy for the buildings constructed before 1969 and those constructed between 1997 and 2005.

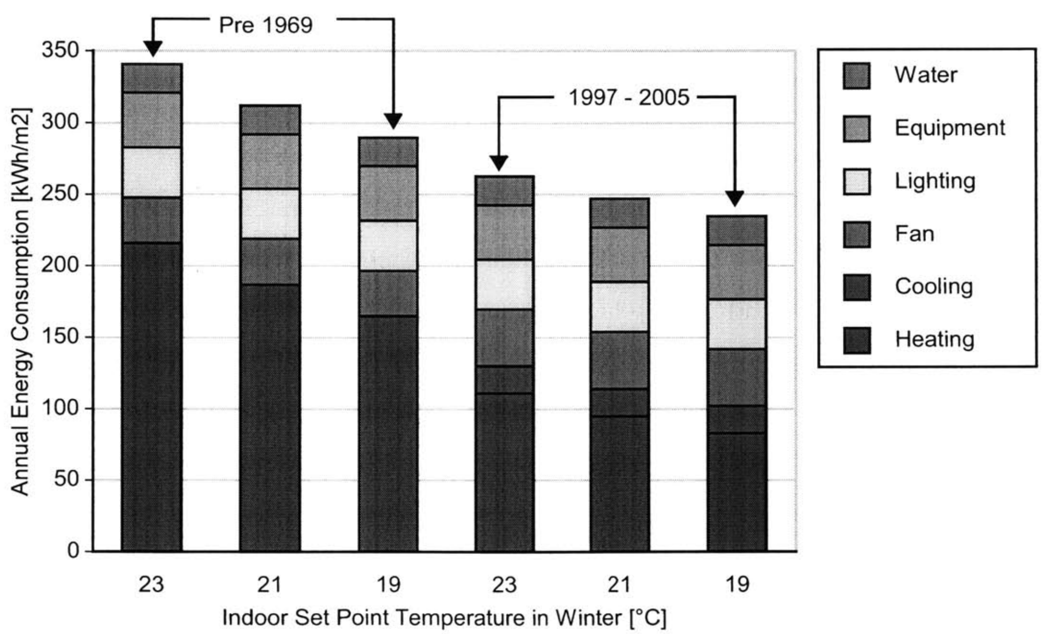


Figure 12-6: Effect of reducing the indoor set point temperature in winter on the annual energy consumption of the buildings constructed before 1969 and those constructed between 1997 and 2005.

The energy used for heating was reduced for buildings from both construction periods, but the energy consumed for other purposes was unchanged. Retrofitting some attributes caused more complicated effects on energy consumption. For example, the ventilation rate had an effect on heating energy, cooling energy, and fan energy. Figure 12-7 shows the change in energy consumption when the occupied ventilation rate was decreased for buildings constructed before 1969 and those constructed between 1997 and 2005.

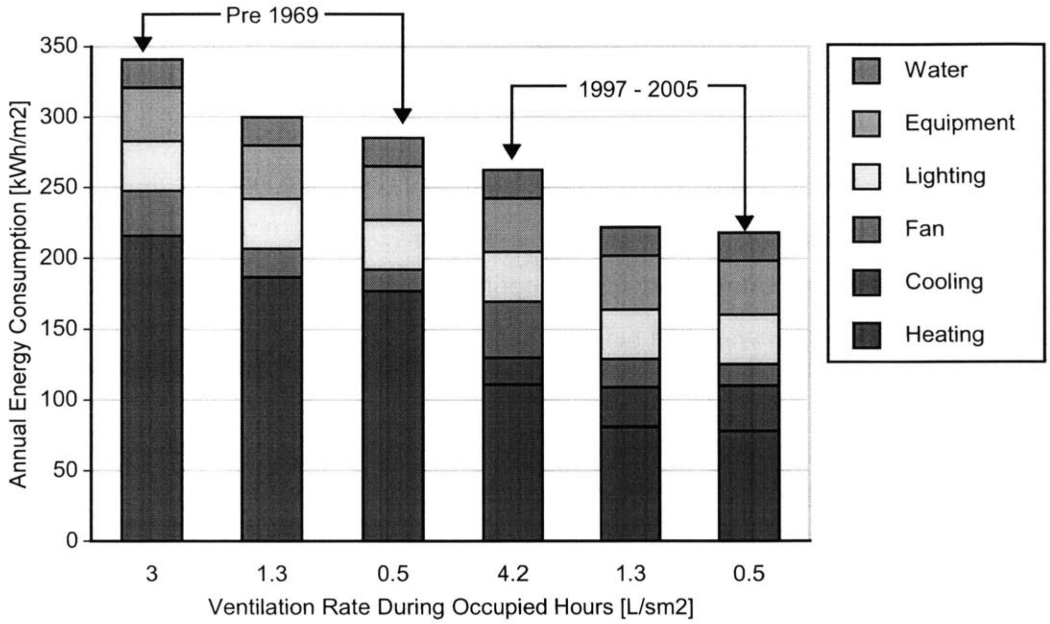


Figure 12-7: Effect of reducing the ventilation rate during occupied hours on annual energy consumption by end use for buildings constructed before 1969 and those constructed between 1997 and 2005.

The energy required for heating and the ventilation fan was reduced when the occupied ventilation rate was decreased for buildings from both construction periods because there was less air to be heated and less air to move through the ventilation system. However, for the buildings constructed between 1997 and 2005, which had a cooling system, the energy required to cool the building increased when the ventilation rate was reduced. Most of the cooling done by the buildings occurs when it is cool outside, but the heat gains in the building cause the indoor air temperature to be uncomfortably warm. The additional air flow from the ventilation system can absorb some of this heat and decrease the cooling energy that must be supplied by the cooling system. Therefore, reducing the ventilation rate reduced the heat sink from the ventilation air and caused a greater strain on the cooling system. The ideal strategy might be to use a low ventilation rate during the winter and a higher rate during the summer. The lower cooling energy would be offset to some degree by additional fan energy for the higher ventilation rate.

Data like that shown in Figure 12-6 and Figure 12-7 was generated for each building attribute for all of the construction periods. Figure 12-8 shows the maximum percent decrease in annual energy consumption possible from retrofitting each building attribute. A positive number indicates that the energy consumed by the building decreased; a negative number indicates that the energy consumption increased.

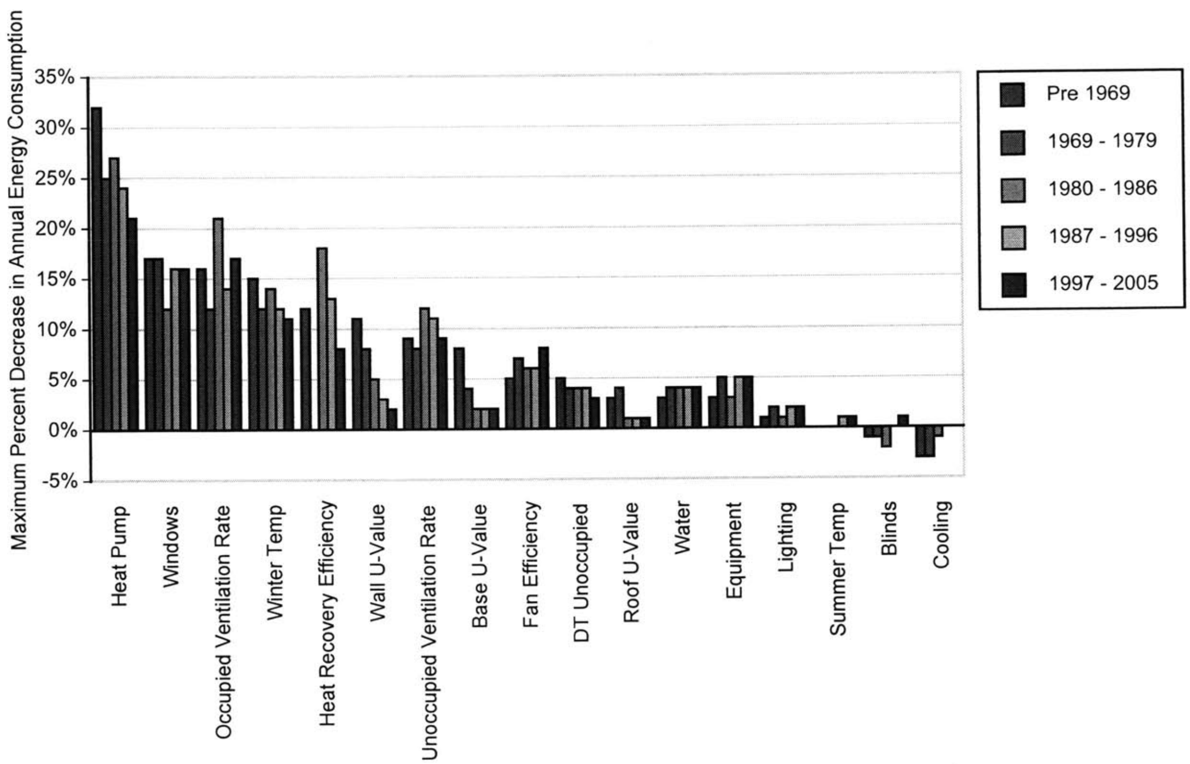


Figure 12-8: Maximum percent decrease possible from retrofitting each building attribute while leaving the other attributes unchanged. Attributes are organized in decreasing order of benefit for the buildings constructed before 1969.

Figure 12-8 shows that there is significant potential to decrease the energy consumption of the buildings from all construction periods. Retrofitting one building component can decrease the total energy consumption by up to 30%. Several retrofits caused a decrease in energy consumption of more than 10% for all the construction periods. Installing a heat pump, improving the windows, decreasing the occupied ventilation rate, and decreasing the indoor set point temperature during the winter were consistently the most effective retrofits. However, the original condition of the building was important. The attributes on Figure 12-8 were arranged in decreasing order of benefit for the buildings constructed before 1969. The order would have been different for any of the other construction periods.

The results show less potential for decreasing energy consumption by increasing the insulation level in the facade for more recent buildings because each new building code required lower U-values. The current insulation level in new buildings was close to the best practice retrofit condition, so there was little room for improvement. The exception to this result is the windows. The maximum potential decrease in energy was about 16% for all of the construction periods except those built between 1980 and 1986 where it dropped to about 12%. The U-value of the windows decreased with each new building code, decreasing the energy leaving the building through transmission. The difference between the 1980 to 1986 buildings and the buildings constructed after 1987 was the presence of a cooling system. Buildings with cooling systems generally do not have operable windows. The simulation program assumed that the replacement windows were operable and that building occupants chose to open them whenever it was possible to maintain the indoor set point temperature. The main benefit from retrofitting windows for the buildings constructed from 1987 to 1996 and from 1997 to 2005 was the decrease in cooling energy from installing operable windows.

Decreasing the ventilation rate was especially important for the buildings constructed between 1980 and 1986 because that time period had heat recovery units with the lowest effectiveness, 55%. The effectiveness of heat recovery units in buildings constructed before 1969 was 60%, only 5% higher than in the 1980 to 1986 time period. Heat recovery effectiveness was much more important on a relative basis for the 1980 to 1986 buildings because the U-values of the windows and other facade elements were much lower. The heat recovery system was the building attribute leading to the greatest heat loss. Heat recovery effectiveness was also only 60% for buildings constructed between 1987 and 1996. Decreasing the ventilation rate had a smaller effect in this case because the U-values and infiltration rate were lower, so less heating energy was required.

Installing adjustable blinds on a building increased the total energy consumption for buildings without a cooling system. The blinds blocked radiation from the sun, which was used as free heating energy during the winter. For buildings with a cooling system, this effect was offset by the need to eliminate radiation heat gains during the summer. The results from the buildings constructed between 1987 and 1996 show no net change in total energy consumption when blinds were installed. For buildings constructed between 1997 and 2005 there was a slight decrease in total energy consumption. The most recent buildings had a larger window area, which admitted more solar radiation into the building, and increased the required energy for cooling. Therefore, the radiation blocked by the blinds was more beneficial for buildings in this construction period.

Adding a cooling system to the older buildings led to only small increases in total energy consumption, about 3%. All of the older buildings were assumed to have operable windows. Because the outdoor temperature in the summer is fairly cool in Norway, the increased air flow from operable windows can cover the majority of the cooling requirements of the building.

Decreasing the energy consumption of lights or office equipment decreased the total energy consumption of the buildings by less than 5%. The decrease was slightly larger for the buildings with a cooling system than without. The simulation program assumed that all of the energy used by lights and office equipment entered the building as heat. These heat gains reduced the energy that the heating system had to supply to the building. When the energy consumed by the lights or office equipment and the resulting heat gains were reduced, the required energy from the heating system was increased. Therefore, there was no net change in heating energy. The small percent decrease in total energy was only from the improved efficiency of the electric equipment. However, there were additional benefits when the cooling system was present. Reducing the heat gains from lights and office equipment reduced the heat that the cooling system had to eliminate. Therefore, the cooling system required less energy and the total decrease in annual energy consumption was greater.

The percentages shown in Figure 12-8 are not simply additive. The building attributes influence one another. For example, increasing the specific fan power and decreasing the ventilation rates will lead to a greater decrease in consumption than the sum of doing either alone. However, taking any action to reduce the heating energy in the building will lower the perceived effectiveness of installing a heat pump. The next step was to look at what combinations of retrofit options lead to the greatest decreases in energy consumption.

12.3 Retrofitting Building Systems

Recall from Figure 12-1 through Figure 12-5 that the building attributes are divided into five systems: controls, HVAC, windows, facade, and other energy consumption. This section will examine the changes in annual energy consumption resulting from retrofitting multiple attributes within a single building system, including the investment cost necessary for each retrofit project. For more information on the cost of the retrofit projects see Chapter 8. Scenarios were generated by running the simulation program for every possible combination of the original condition and each retrofit option for all of the attributes in each system. Figure 12-9 through Figure 12-13 show the total energy consumption for all the possible scenarios.

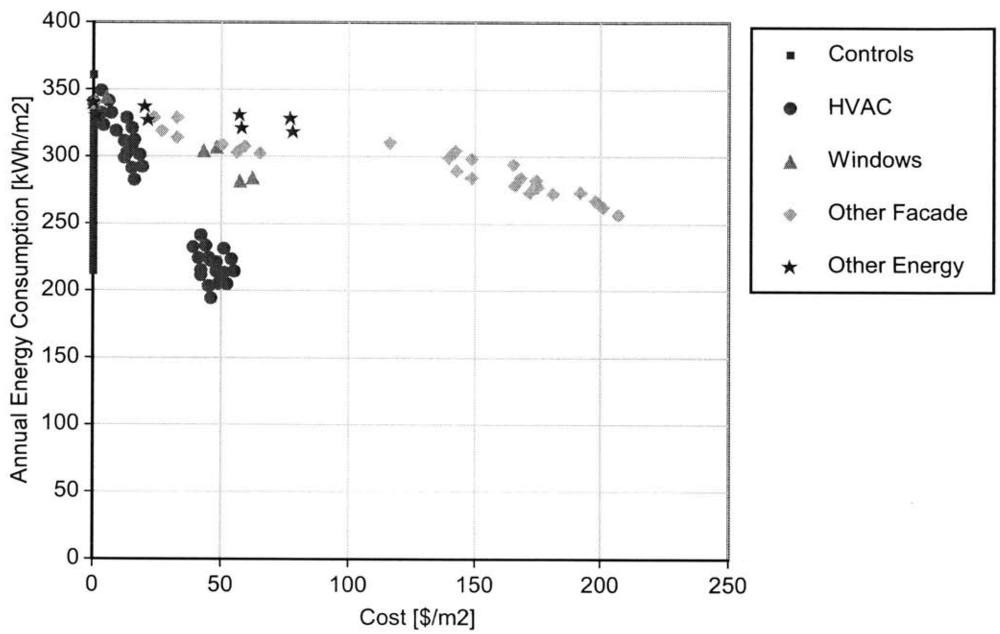


Figure 12-9: Scenarios for retrofitting each building system in buildings constructed before 1969. Note that the controls scenarios fall along the y-axis at 0 cost.

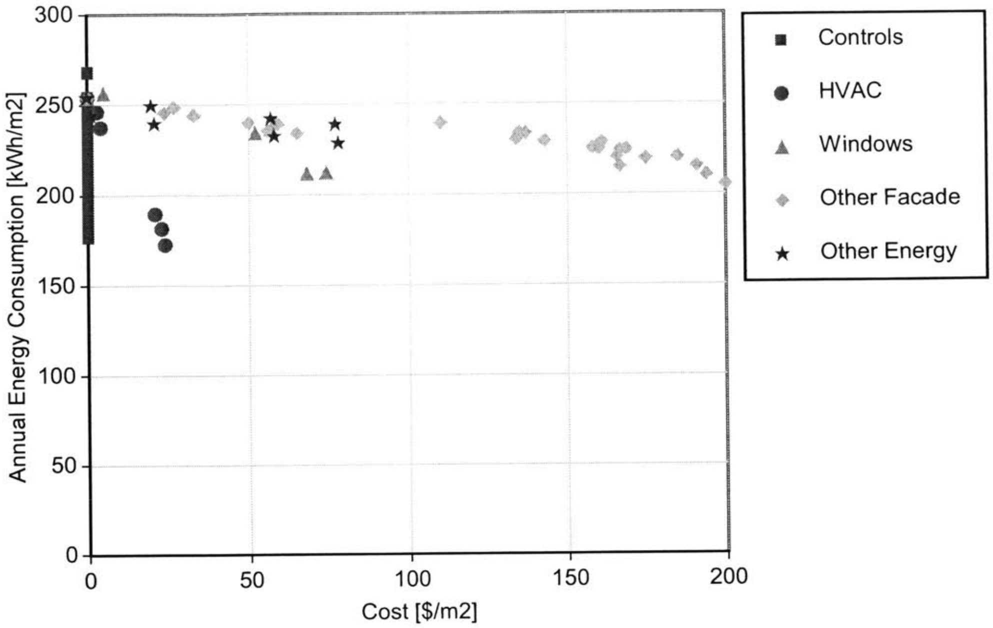


Figure 12-10: Scenarios for retrofitting each building system in buildings constructed between 1969 and 1979. Note that the controls scenarios fall along the y-axis at 0 cost.

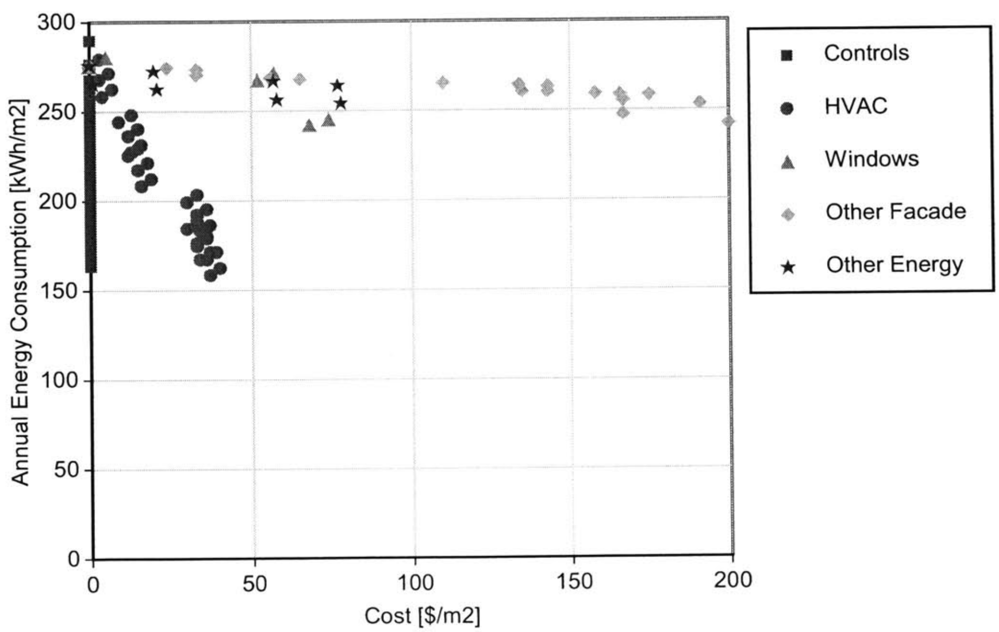


Figure 12-11: Scenarios for retrofitting each building system in buildings constructed between 1980 and 1986. Note that the controls scenarios fall along the y-axis at 0 cost.

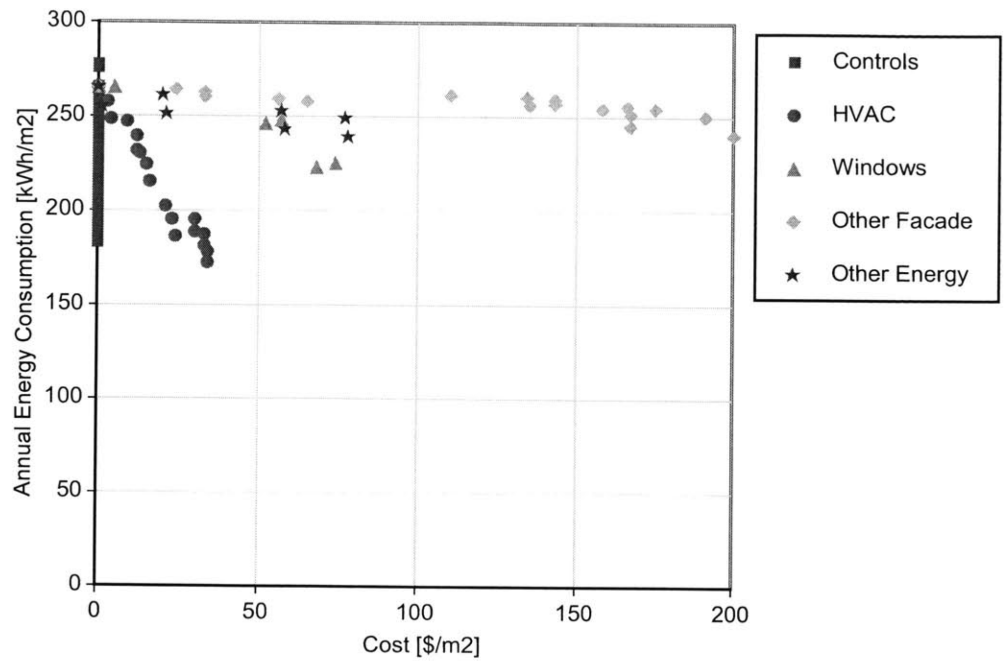


Figure 12-12: Scenarios for retrofitting each building system in buildings constructed between 1987 and 1996. Note that the controls scenarios fall along the y-axis at 0 cost.

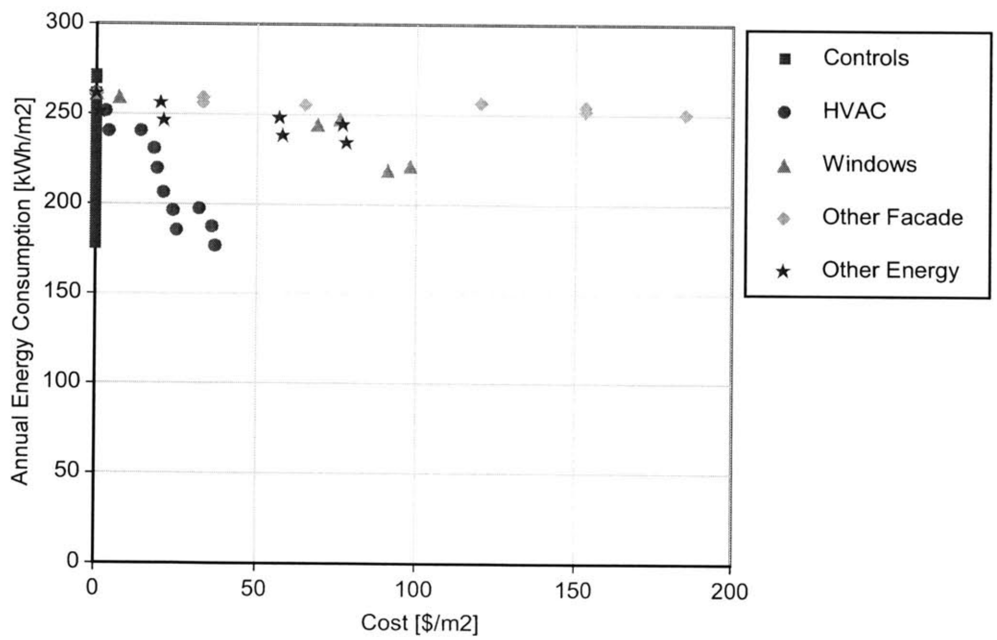


Figure 12-13: Scenarios for retrofitting each building system in buildings constructed between 1997 and 2005. Note that the controls scenarios fall along the y-axis at 0 cost.

Qualitatively, the results from all five construction periods were the same. Retrofitting the HVAC system led to the lowest energy consumptions. However, the controls system was only slightly less effective, and the benefits were essentially free. Retrofits to all of the other systems were significantly less effective and more expensive.

However, the starting condition of the building does effect the total energy consumption. Figure 12-14 through Figure 12-17 show the retrofit scenarios each building system and construction period. A graph for the controls system is not shown because all of the scenarios have no associated investment cost.

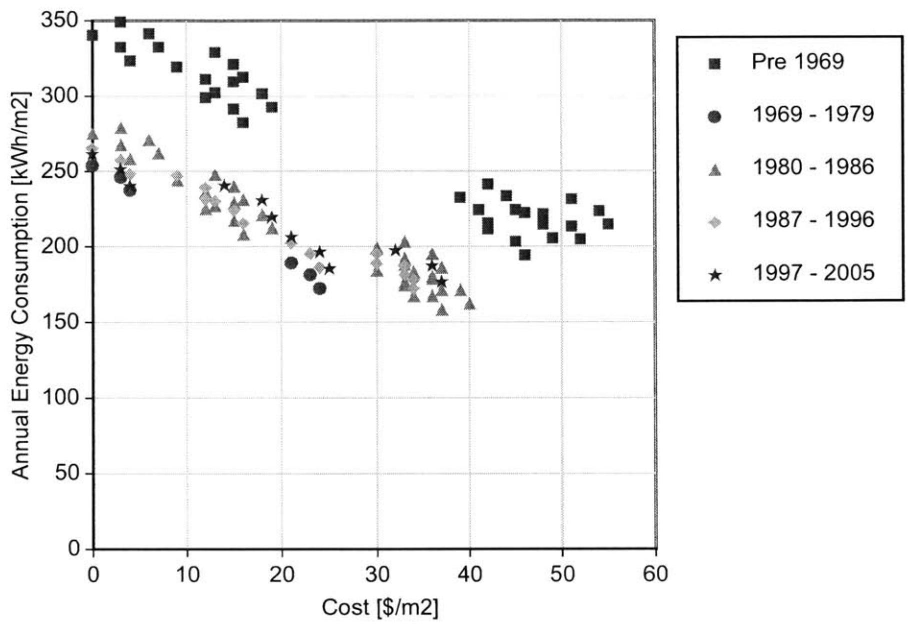


Figure 12-14: Scenarios for retrofitting the HVAC system for each construction period.

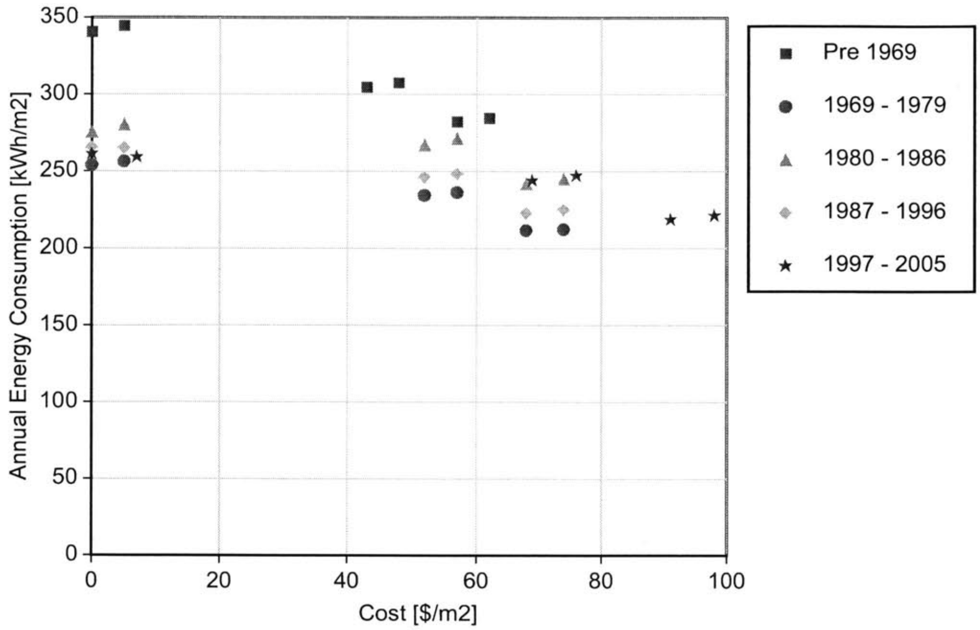


Figure 12-15: Scenarios for retrofitting the windows of each construction period.

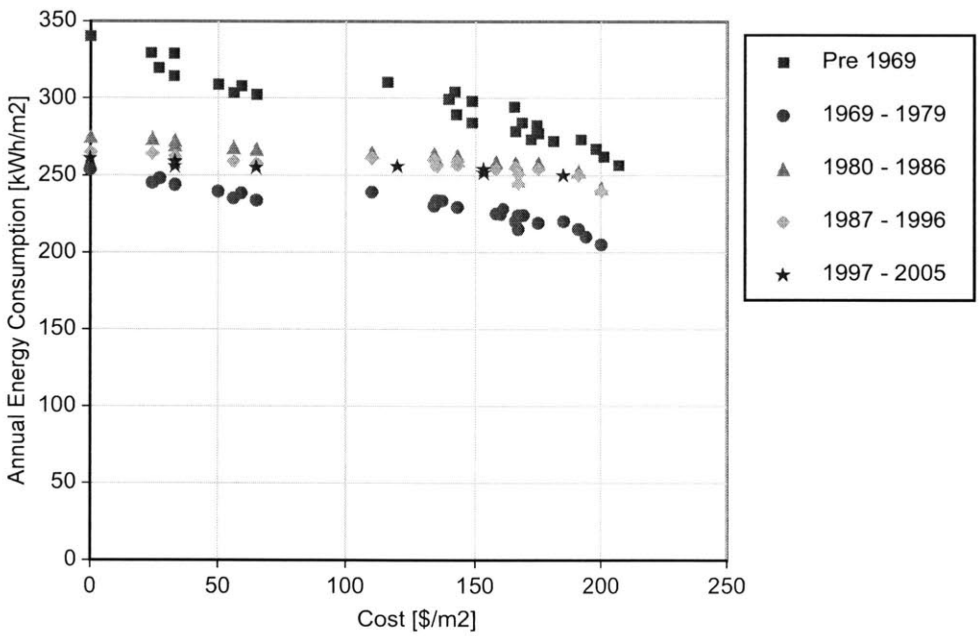


Figure 12-16: Scenarios for retrofitting the other facade elements for each construction period.

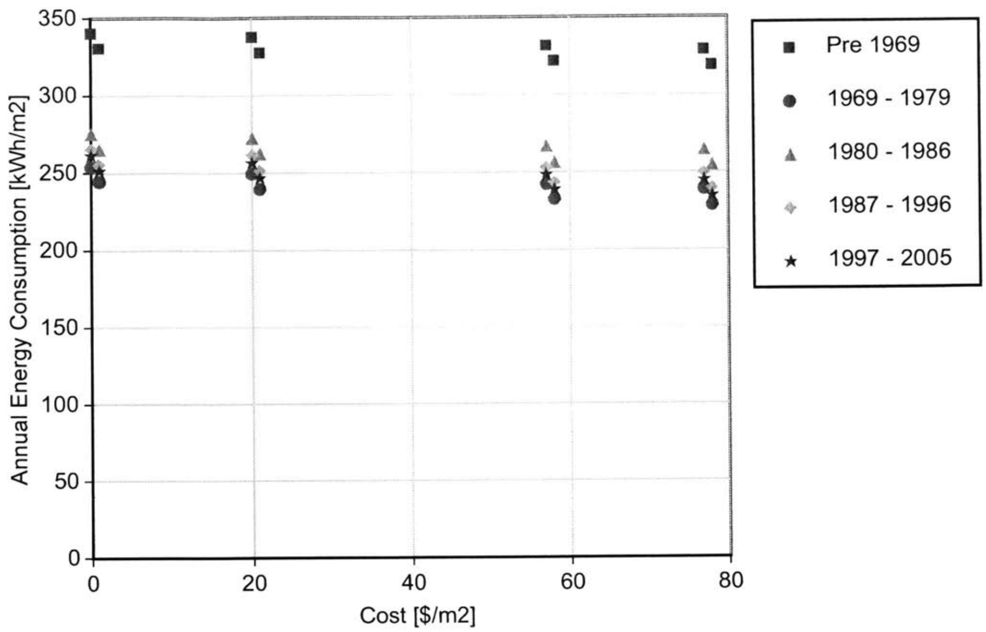


Figure 12-17: Scenarios for retrofitting the other energy services for each construction period.

The energy consumption in the buildings from each construction period decreased with investment cost at approximately the same rate within each building system for all of the construction periods. There were still differences in cost and energy consumption because attributes from only one system were retrofit. All of the other attributes were not changed from the original condition specific to each construction period.

Figure 12-14 shows the scenarios from retrofitting the HVAC system. There was a big gap in cost between two groups of scenarios for the buildings constructed before 1969, which was not present in the other construction periods. All of the scenarios in the high cost grouping for the buildings constructed before 1969 included installation of a heat pump. These buildings have a much higher heating requirement than buildings from the other construction periods. Therefore, the heat pumps used for retrofitting must have a greater capacity and are significantly more expensive than the models appropriate for more recent construction periods. The low cost group for the buildings constructed before 1969 included retrofits to the heat recovery system and the ventilation fan. The scenarios in the middle group for the other construction periods have retrofits including the heat pump and either the ventilation fan or the heat recovery system but not all three.

Figure 12-15 shows the scenarios for retrofitting the buildings' windows. The scenarios for the buildings constructed before 1969 required the smallest investment cost. The cost of the new windows is defined on a per square meter basis. These buildings have the lowest window area, 12.5% of the buildings floor area, and therefore the window retrofits are the least expensive. The cost for the buildings constructed between 1969 and 1979, 1980 and 1986, and 1987 and 1996 were the same because all of the model buildings had window areas equal to 15% of the floor area. The investment cost for the buildings constructed between 1997 and 2005 were the most expensive because they had the greatest window area, equal to 20% of the floor area. The scenarios from each retrofit period are arranged in pairs. The more costly scenario includes blinds; the less costly scenario does not.

Figure 12-16 shows the scenarios for retrofitting the other facade elements for each construction period. The costs for all of the scenarios were similar for all of the model buildings. The roof and base were the same size, so the total cost of those retrofit projects were the same for all of the buildings. The area of the walls decreased as the area of the windows increased. Therefore, retrofitting the walls was less expensive for new construction than for older construction. A significant change in energy consumption was seen in the older buildings. The total energy consumption of the building decreased by about 90 $^{kWh}/_{m^2}$ for the buildings constructed before 1969 and by about 50 $^{kWh}/_{m^2}$ for those constructed between 1969 and 1979. The model buildings from these construction periods had U-values that were significantly higher than the retrofit U-values. The more recent buildings have much lower U-values to begin with, so the total change in energy consumption was much smaller, around 25 $^{kWh}/_{m^2}$.

Finally, Figure 12-17 shows the scenarios the result from decreasing the consumption of the other energy services system. In this case the attributes from all of the model buildings have the same original conditions and retrofit conditions. Therefore, the cost of the projects and the change in energy consumption was the same for each scenario. The difference in total energy consumption resulted from differences in the attributes in the other systems.

Figure 12-18 shows the percent that the annual energy consumption of the building decreased between the original condition of the building and the most efficient retrofit scenario for each building system and construction period.

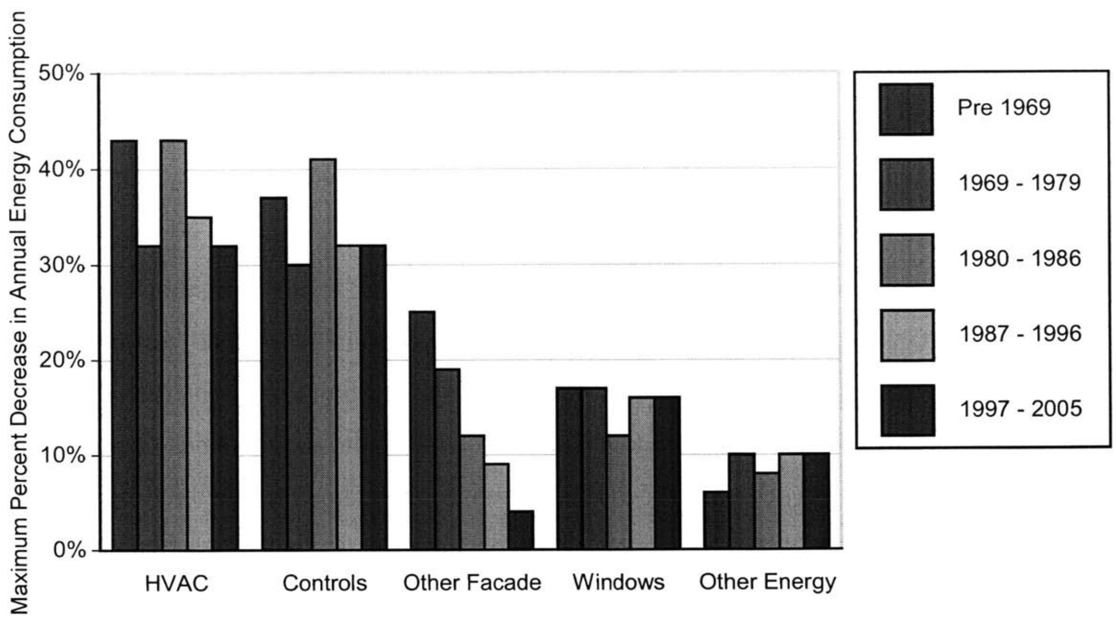


Figure 12-18: Maximum percent decrease in annual energy consumption between the original building condition and the lowest-energy retrofit scenario for each construction period. The systems are organized in decreasing order of benefit for the buildings constructed before 1969.

The results verify that retrofitting the controls and HVAC systems was the most effective strategy for decreasing the annual energy consumption of the buildings. A total decrease between about 30 and 45% was seen for both systems in all the construction periods. The retrofits were 5 to 10% more effective in the buildings constructed before 1969 than those constructed between 1980 and 1986 because these buildings had the highest heating requirement. Therefore, they benefited the most from retrofitting the HVAC and controls systems to decrease the required heating energy.

Retrofitting the other systems led to decreases in annual energy consumption of about 5 to 25%, which are still significant energy savings over the lifetime of a building. Retrofitting the non-window facade elements was significantly less effective for the more recent buildings because the U-values of the buildings became closer to the retrofit conditions. The percent of energy saved drops from about 25% in the buildings constructed before 1969 to about 5% for the buildings constructed between 1997 and 2005.

Like Figure 12-8, Figure 12-18 shows that retrofitting the windows becomes less effective for the buildings constructed between 1980 and 1986 and then becomes more effective again for all construction after 1987. The cooling system and inoperable windows are responsible for this change. The U-values of the windows of buildings constructed after 1987 are fairly low, 2 or 2.4 $W/_{m^2K}$, but the windows are generally not operable. The simulation program assumed that the replacement windows were operable and that the occupants opened the windows whenever it was possible to maintain the indoor set point temperature through increased air flow from open windows. The resulting decrease in cooling energy caused the benefit from retrofitting the windows to go back up to around 16%.

Retrofitting the other energy services system reduced the annual energy consumption of the buildings by about 10% for buildings constructed between 1969 and 1979 and all buildings constructed after 1987. The lowest percent change, about 5%, was for buildings constructed before 1969. These buildings have the highest total energy consumption, so the same decrease in energy consumption was a smaller percent of the total consumption. Likewise, the buildings constructed between 1969 and 1979 have the lowest total consumption, so the decrease in energy consumption from the other energy services was a larger portion of the total. The buildings constructed after 1987 showed additional losses because the energy from the lights and office equipment affected the cooling system. Reducing the electricity loads for lights and office equipment reduced the heat gains in the building. Therefore, the cooling system had to eliminate less heat during the cooling season, and the energy consumed by the building was decreased more on a percent basis than for buildings without a cooling system.

12.4 Retrofitting Multiple Systems

The previous section described the benefits of retrofitting multiple attributes in the same building system. Comparing Figure 12-8 to Figure 12-18 showed that changing multiple attributes in combination can decrease the energy consumption more than any one attribute can alone. The same result should be true for changing attributes from multiple systems. For example, lowering the ventilation rate affects both the heating energy and the fan energy. Therefore, lowering the ventilation rate and installing a more efficient fan will lead to lower total energy consumption than either would alone. This section describes the potential benefit from making changes to attributes in multiple building systems.

12.4.1 Setup

To generate the retrofit scenarios in Section 12.3 the annual energy consumption was simulated for every possible combination of the original and retrofit conditions for each attribute in each building system. If all of the retrofit options were combined in all the possible combinations for every attribute in every system, more than 2 million scenarios would be generated. This data set would be too large to be useful. Instead, a few scenarios were chosen from the analysis of the individual systems. Then the simulation program was run for each combination of the selected scenarios.

The scenarios were chosen to represent the range of potential energy reductions and required investment costs for each building system. A scenario was chosen to represent the original condition, the lowest energy consumption possible, and up to three moderate scenarios in between for each building system. The scenarios for the controls systems and the other energy services system were identical for the different time periods because the original conditions were similar or the same for all of the construction periods. The retrofit scenarios for the controls system included the low-energy scenario with a low winter set point temperature, a high summer set point temperature, a large temperature change during unoccupied hours, and low ventilation rates. Three moderate cases were also selected, one with moderate temperatures and moderate ventilation rates and two with unchanged temperatures but moderate or low ventilation rates. For the other energy services system the moderate case included only retrofitting the hot water heater and the low-energy scenario included retrofitting the lighting, office equipment, and hot water heater. For the HVAC system, windows, and other facade elements different combinations of retrofits were chosen for each construction period. The original condition of the attributes differed more for these systems than for the controls and other energy services systems, so different combinations of retrofits led to the best performance for a particular cost.

Table 12-1 through Table 12-5 describe the values input into the simulation program for each scenario included in the multi-systems analysis. The performance of these scenarios in the analysis of the individual systems and a visual schematic of the selected retrofit conditions is described in Appendix B.

Controls System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Moderate Scenario (3)		Low-Energy Scenario	
Winter Temp. [°C]	23	Winter Temp. [°C]	21	Winter Temp. [°C]	23	Winter Temp. [°C]	23	Winter Temp. [°C]	19
Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	25
Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	6
Occ. Vent. $[L/sm^2]$	3	Occ. Vent. $[L/sm^2]$	1.3	Occ. Vent. $[L/sm^2]$	1.3	Occ. Vent. $[L/sm^2]$	0.5	Occ. Vent. $[L/sm^2]$	0.5
Unocc. Vent. $[L/sm^2]$	1	Unocc. Vent. $[L/sm^2]$	0.5	Unocc. Vent. $[L/sm^2]$	0.5	Unocc. Vent. $[L/sm^2]$	0.3	Unocc. Vent. $[L/sm^2]$	0.3

HVAC System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Heat Recovery η	60%	Heat Recovery η	80%	Heat Recovery η	60%	Heat Recovery η	80%
Fan Power $[W/(m^3/s)]$	2120	Fan Power $[W/(m^3/s)]$	1000	Fan Power $[W/(m^3/s)]$	2120	Fan Power $[W/(m^3/s)]$	1000
Heat Pump	No	Heat Pump	No	Heat Pump	Yes	Heat Pump	Yes

Windows

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
U-Value $[W/m^2K]$	5.5	U-Value $[W/m^2K]$	2	U-Value $[W/m^2K]$	1
SHGC	0.75	SHGC	0.35	SHGC	0.35
Operable	Yes	Operable	Yes	Operable	Yes
Blinds	No	Blinds	No	Blinds	No

Non-Window Facade Systems

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Base U-Value $[W/m^2K]$	0.87	Base U-Value $[W/m^2K]$	0.15	Base U-Value $[W/m^2K]$	0.87	Base U-Value $[W/m^2K]$	0.15
Walls U-Value $[W/m^2K]$	0.87	Walls U-Value $[W/m^2K]$	0.87	Walls U-Value $[W/m^2K]$	0.22	Walls U-Value $[W/m^2K]$	0.1
Roof U-Value $[W/m^2K]$	0.7	Roof U-Value $[W/m^2K]$	0.15	Roof U-Value $[W/m^2K]$	0.1	Roof U-Value $[W/m^2K]$	0.1

Other Energy Services

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Lights $[kWh/m^2]$	35	Lights $[kWh/m^2]$	35	Lights $[kWh/m^2]$	28
Office Equipment $[kWh/m^2]$	38	Office Equipment $[kWh/m^2]$	38	Office Equipment $[kWh/m^2]$	17
Hot Water $[kWh/m^2]$	20	Hot Water $[kWh/m^2]$	10	Hot Water $[kWh/m^2]$	10

Table 12-1: Retrofit scenarios selected for the multi-systems analysis for buildings constructed before 1969.

Controls System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Moderate Scenario (3)		Low-Energy Scenario	
Winter Temp. [°C]	23	Winter Temp. [°C]	21	Winter Temp. [°C]	23	Winter Temp. [°C]	23	Winter Temp. [°C]	19
Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	25
Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	6
Occ. Vent. [L/sm^2]	3	Occ. Vent. [L/sm^2]	1.3	Occ. Vent. [L/sm^2]	1.3	Occ. Vent. [L/sm^2]	0.5	Occ. Vent. [L/sm^2]	0.5
Unocc. Vent. [L/sm^2]	1	Unocc. Vent. [L/sm^2]	0.5	Unocc. Vent. [L/sm^2]	0.5	Unocc. Vent. [L/sm^2]	0.3	Unocc. Vent. [L/sm^2]	0.3

HVAC System

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Heat Recovery η	80%	Heat Recovery η	80%	Heat Recovery η	80%
Fan Power [$W/\frac{m^3}{s}$]	2120	Fan Power [$W/\frac{m^3}{s}$]	2120	Fan Power [$W/\frac{m^3}{s}$]	1000
Heat Pump	No	Heat Pump	Yes	Heat Pump	Yes

Windows

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
U-Value [W/m^2K]	3.6	U-Value [W/m^2K]	2	U-Value [W/m^2K]	1
SHGC	0.6	SHGC	0.35	SHGC	0.35
Operable	Yes	Operable	Yes	Operable	Yes
Blinds	No	Blinds	No	Blinds	No

Non-Window Facade Systems

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Base U-Value [W/m^2K]	0.46	Base U-Value [W/m^2K]	0.15	Base U-Value [W/m^2K]	0.46	Base U-Value [W/m^2K]	0.15
Walls U-Value [W/m^2K]	0.58	Walls U-Value [W/m^2K]	0.58	Walls U-Value [W/m^2K]	0.1	Walls U-Value [W/m^2K]	0.1
Roof U-Value [W/m^2K]	0.58	Roof U-Value [W/m^2K]	0.15	Roof U-Value [W/m^2K]	0.1	Roof U-Value [W/m^2K]	0.1

Other Energy Services

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Lights [kWh/m^2]	35	Lights [kWh/m^2]	35	Lights [kWh/m^2]	28
Office Equipment [kWh/m^2]	38	Office Equipment [kWh/m^2]	38	Office Equipment [kWh/m^2]	17
Hot Water [kWh/m^2]	20	Hot Water [kWh/m^2]	10	Hot Water [kWh/m^2]	10

Table 12-2: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1969 and 1979.

Controls System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Moderate Scenario (3)		Low-Energy Scenario	
Winter Temp. [°C]	23	Winter Temp. [°C]	21	Winter Temp. [°C]	23	Winter Temp. [°C]	23	Winter Temp. [°C]	19
Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	25
Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	6
Occ. Vent. $[L/sm^2]$	3	Occ. Vent. $[L/sm^2]$	1.3	Occ. Vent. $[L/sm^2]$	1.3	Occ. Vent. $[L/sm^2]$	0.5	Occ. Vent. $[L/sm^2]$	0.5
Unocc. Vent. $[L/sm^2]$	1	Unocc. Vent. $[L/sm^2]$	0.5	Unocc. Vent. $[L/sm^2]$	0.5	Unocc. Vent. $[L/sm^2]$	0.3	Unocc. Vent. $[L/sm^2]$	0.3

HVAC System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Heat Recovery η	55%	Heat Recovery η	80%	Heat Recovery η	70%	Heat Recovery η	80%
Fan Power $[W/(m^3/s)]$	2120	Fan Power $[W/(m^3/s)]$	1000	Fan Power $[W/(m^3/s)]$	2120	Fan Power $[W/(m^3/s)]$	1000
Heat Pump	No	Heat Pump	No	Heat Pump	Yes	Heat Pump	Yes

Windows

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
U-Value $[W/m^2K]$	2.8	U-Value $[W/m^2K]$	2	U-Value $[W/m^2K]$	1
SHGC	0.5	SHGC	0.35	SHGC	0.35
Operable	Yes	Operable	Yes	Operable	Yes
Blinds	No	Blinds	No	Blinds	No

Non-Window Facade Systems

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Base U-Value $[W/m^2K]$	0.3	Base U-Value $[W/m^2K]$	0.15	Base U-Value $[W/m^2K]$	0.3	Base U-Value $[W/m^2K]$	0.15
Walls U-Value $[W/m^2K]$	0.44	Walls U-Value $[W/m^2K]$	0.44	Walls U-Value $[W/m^2K]$	0.1	Walls U-Value $[W/m^2K]$	0.1
Roof U-Value $[W/m^2K]$	0.23	Roof U-Value $[W/m^2K]$	0.1	Roof U-Value $[W/m^2K]$	0.1	Roof U-Value $[W/m^2K]$	0.1

Other Energy Services

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Lights $[kWh/m^2]$	35	Lights $[kWh/m^2]$	35	Lights $[kWh/m^2]$	28
Office Equipment $[kWh/m^2]$	38	Office Equipment $[kWh/m^2]$	38	Office Equipment $[kWh/m^2]$	17
Hot Water $[kWh/m^2]$	20	Hot Water $[kWh/m^2]$	10	Hot Water $[kWh/m^2]$	10

Table 12-3: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1980 and 1986.

Controls System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Moderate Scenario (3)		Low-Energy Scenario	
Winter Temp. [°C]	23	Winter Temp. [°C]	21	Winter Temp. [°C]	23	Winter Temp. [°C]	23	Winter Temp. [°C]	19
Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	25
Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	6
Occ. Vent. [L/sm^2]	3	Occ. Vent. [L/sm^2]	1.3	Occ. Vent. [L/sm^2]	1.3	Occ. Vent. [L/sm^2]	0.5	Occ. Vent. [L/sm^2]	0.5
Unocc. Vent. [L/sm^2]	1	Unocc. Vent. [L/sm^2]	0.5	Unocc. Vent. [L/sm^2]	0.5	Unocc. Vent. [L/sm^2]	0.3	Unocc. Vent. [L/sm^2]	0.3

HVAC System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Heat Recovery η	60%	Heat Recovery η	80%	Heat Recovery η	60%	Heat Recovery η	80%
Fan Power [$W/(m^3/s)$]	2120	Fan Power [$W/(m^3/s)$]	1000	Fan Power [$W/(m^3/s)$]	1000	Fan Power [$W/(m^3/s)$]	1000
Heat Pump	No	Heat Pump	No	Heat Pump	Yes	Heat Pump	Yes

Windows

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
U-Value [W/m^2K]	2.4	U-Value [W/m^2K]	2	U-Value [W/m^2K]	1
SHGC	0.35	SHGC	0.35	SHGC	0.35
Operable	No	Operable	Yes	Operable	Yes
Blinds	No	Blinds	No	Blinds	No

Non-Window Facade Systems

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Low-Energy Scenario	
Base U-Value [W/m^2K]	0.3	Base U-Value [W/m^2K]	0.15	Base U-Value [W/m^2K]	0.3	Base U-Value [W/m^2K]	0.15
Walls U-Value [W/m^2K]	0.3	Walls U-Value [W/m^2K]	0.3	Walls U-Value [W/m^2K]	0.1	Walls U-Value [W/m^2K]	0.1
Roof U-Value [W/m^2K]	0.2	Roof U-Value [W/m^2K]	0.1	Roof U-Value [W/m^2K]	0.1	Roof U-Value [W/m^2K]	0.1

Other Energy Services

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Lights [kWh/m^2]	35	Lights [kWh/m^2]	35	Lights [kWh/m^2]	28
Office Equipment [kWh/m^2]	38	Office Equipment [kWh/m^2]	38	Office Equipment [kWh/m^2]	17
Hot Water [kWh/m^2]	20	Hot Water [kWh/m^2]	10	Hot Water [kWh/m^2]	10

Table 12-4: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1987 and 1996.

Controls System

Original Condition		Moderate Scenario (1)		Moderate Scenario (2)		Moderate Scenario (3)		Low-Energy Scenario	
Winter Temp. [°C]	23	Winter Temp. [°C]	21	Winter Temp. [°C]	23	Winter Temp. [°C]	23	Winter Temp. [°C]	19
Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	23	Summer Temp. [°C]	25
Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	4	Temp. Setback [°C]	6
Occ. Vent. $[L/sm^2]$	4.2	Occ. Vent. $[L/sm^2]$	1.3	Occ. Vent. $[L/sm^2]$	1.3	Occ. Vent. $[L/sm^2]$	0.5	Occ. Vent. $[L/sm^2]$	0.5
Unocc. Vent. $[L/sm^2]$	1	Unocc. Vent. $[L/sm^2]$	0.5	Unocc. Vent. $[L/sm^2]$	0.5	Unocc. Vent. $[L/sm^2]$	0.3	Unocc. Vent. $[L/sm^2]$	0.3

HVAC System

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Heat Recovery η	70%	Heat Recovery η	70%	Heat Recovery η	80%
Fan Power $[W/(m^3/s)]$	2120	Fan Power $[W/(m^3/s)]$	1000	Fan Power $[W/(m^3/s)]$	1000
Heat Pump	No	Heat Pump	Yes	Heat Pump	Yes

Windows

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
U-Value $[W/m^2K]$	2	U-Value $[W/m^2K]$	2	U-Value $[W/m^2K]$	1
SHGC	0.35	SHGC	0.35	SHGC	0.35
Operable	No	Operable	Yes	Operable	Yes
Blinds	No	Blinds	No	Blinds	No

Non-Window Facade Systems

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Base U-Value $[W/m^2K]$	0.3	Base U-Value $[W/m^2K]$	0.15	Base U-Value $[W/m^2K]$	0.15
Walls U-Value $[W/m^2K]$	0.22	Walls U-Value $[W/m^2K]$	0.22	Walls U-Value $[W/m^2K]$	0.1
Roof U-Value $[W/m^2K]$	0.15	Roof U-Value $[W/m^2K]$	0.15	Roof U-Value $[W/m^2K]$	0.1

Other Energy Services

Original Condition		Moderate Scenario (1)		Low-Energy Scenario	
Lights $[kWh/m^2]$	35	Lights $[kWh/m^2]$	35	Lights $[kWh/m^2]$	28
Office Equipment $[kWh/m^2]$	38	Office Equipment $[kWh/m^2]$	38	Office Equipment $[kWh/m^2]$	17
Hot Water $[kWh/m^2]$	20	Hot Water $[kWh/m^2]$	10	Hot Water $[kWh/m^2]$	10

Table 12-5: Retrofit scenarios selected for the multi-systems analysis for buildings constructed between 1997 and 2005.

12.4.2 Results

Figure 12-19 through Figure 12-23 show all of the scenarios that result from combining each scenario in each building system described in Table 12-1 through Table 12-5.

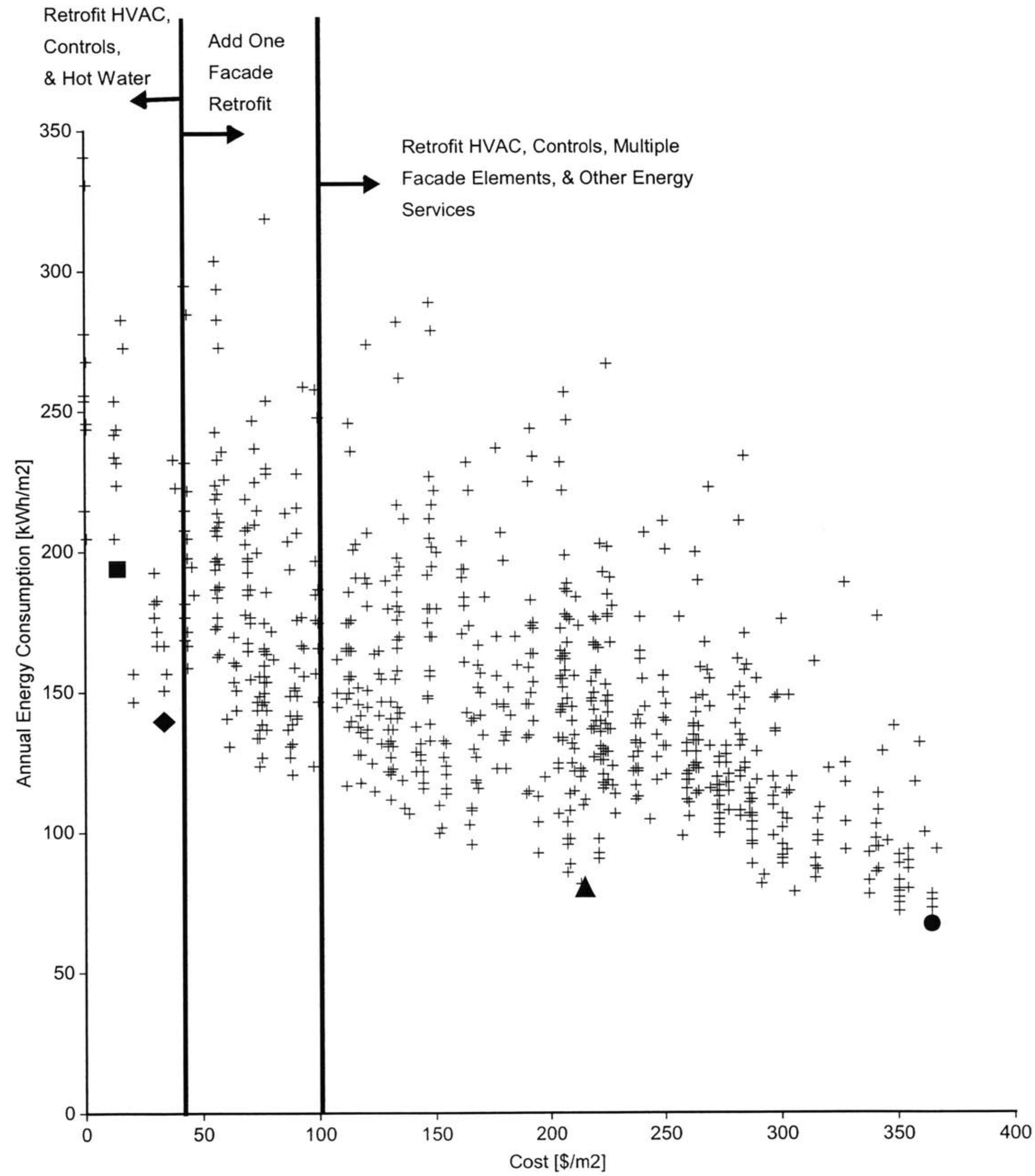


Figure 12-19: Scenarios for retrofitting multiple systems for the buildings constructed before 1969. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below.

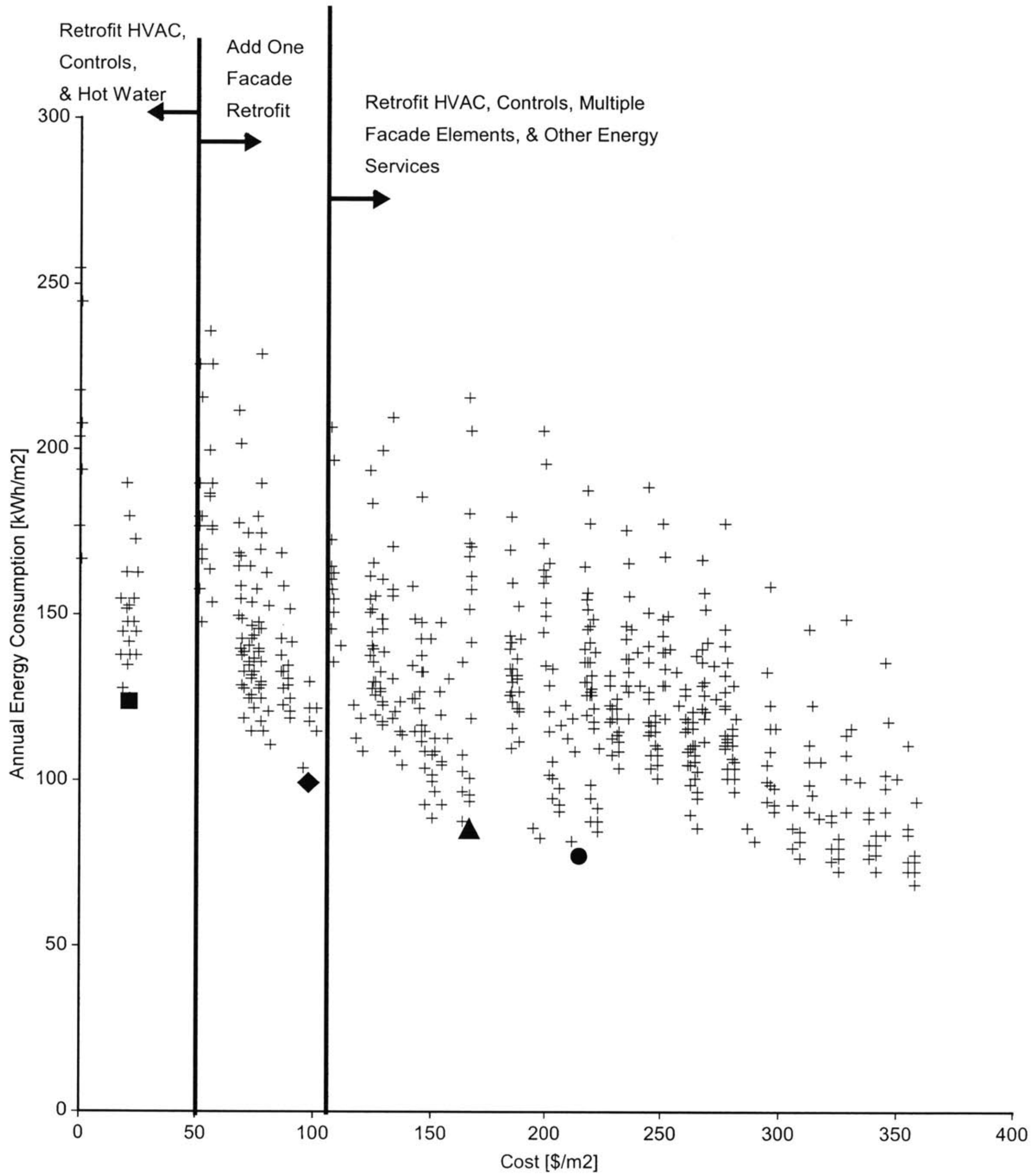


Figure 12-20: Scenarios for retrofitting multiple systems for the buildings constructed between 1969 and 1979. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below.

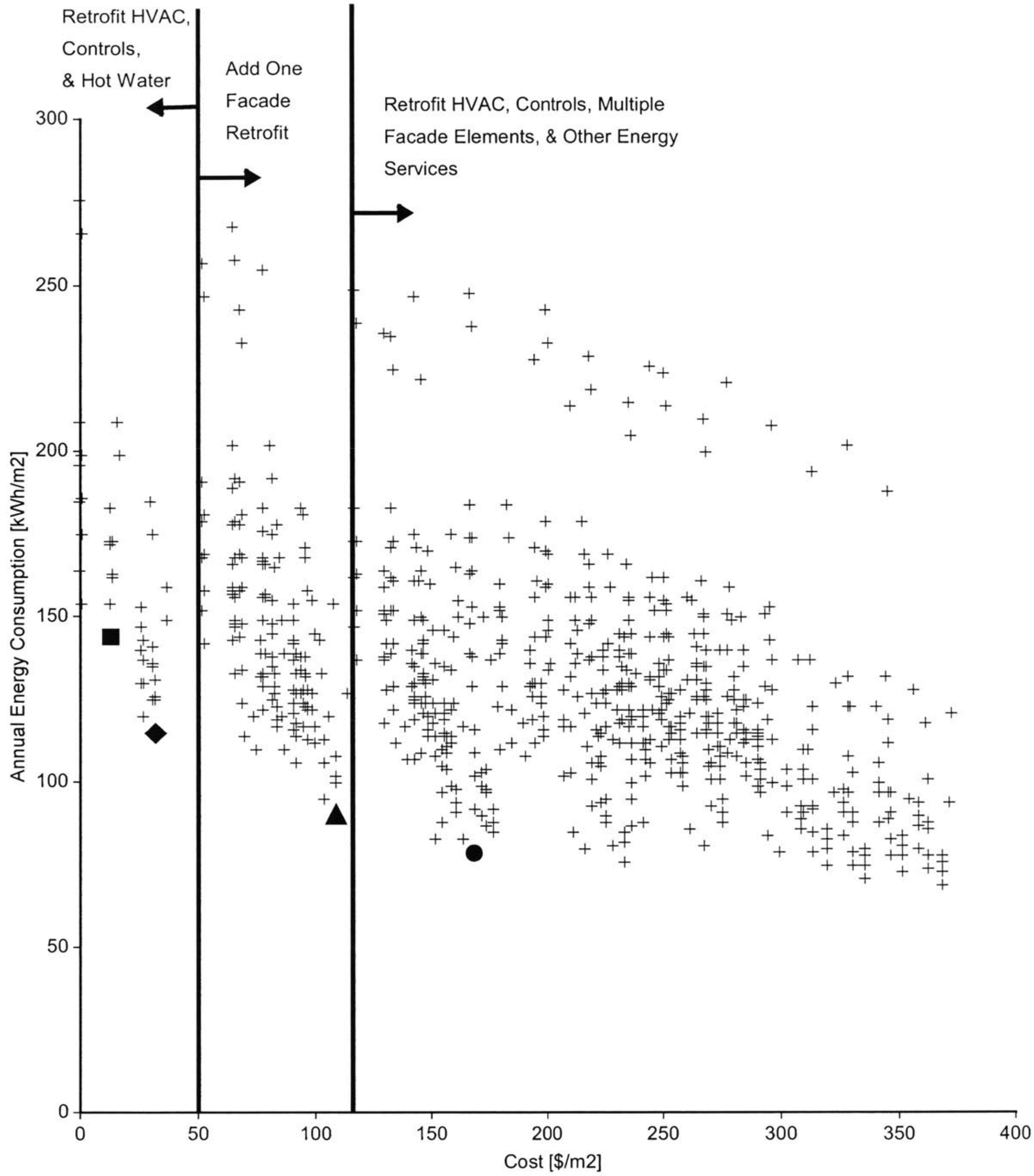


Figure 12-21: Scenarios for retrofitting multiple systems for the buildings constructed between 1980 and 1986. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below.

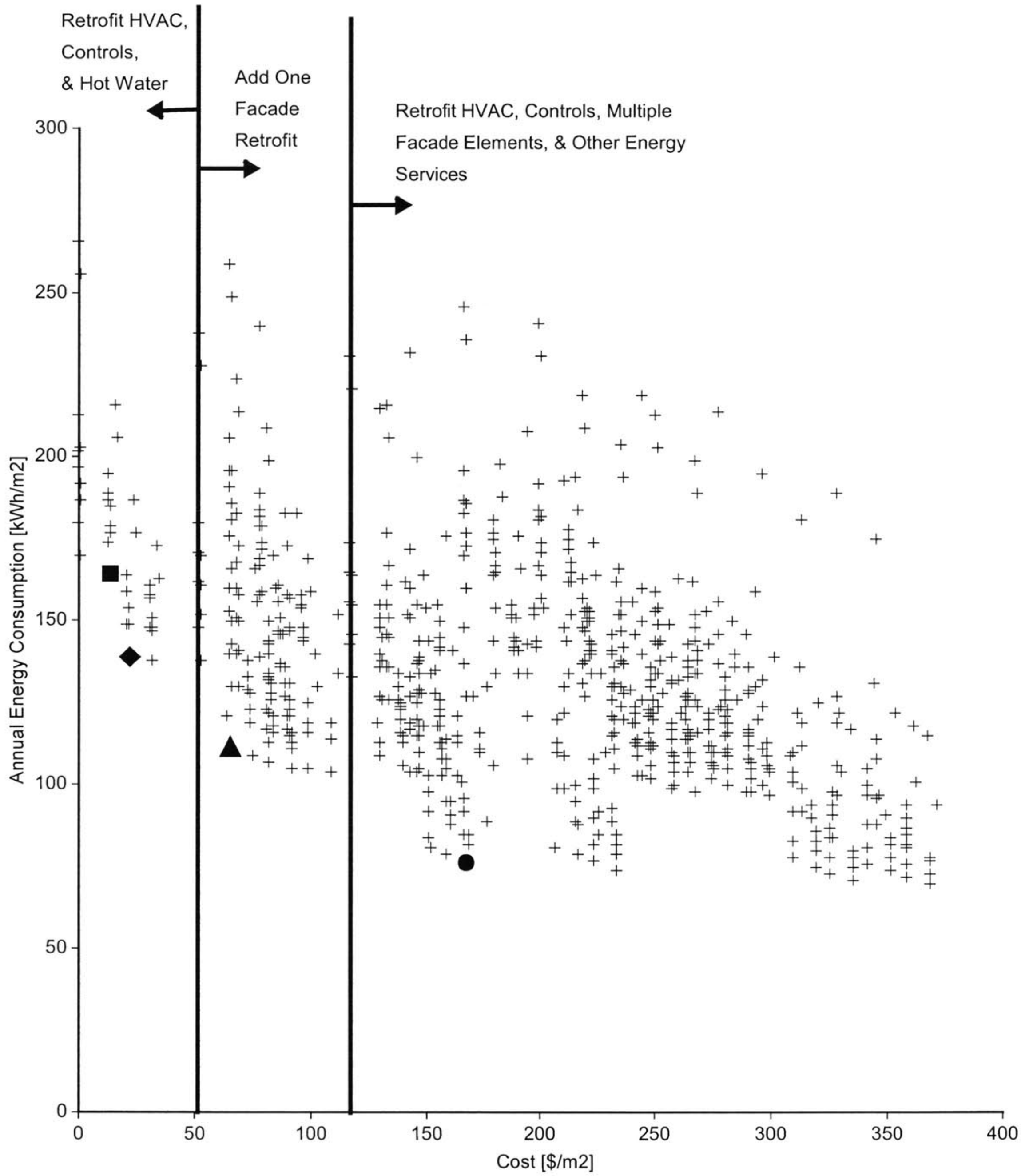


Figure 12-22: Scenarios for retrofitting multiple systems for the buildings constructed between 1987 and 1996. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below.

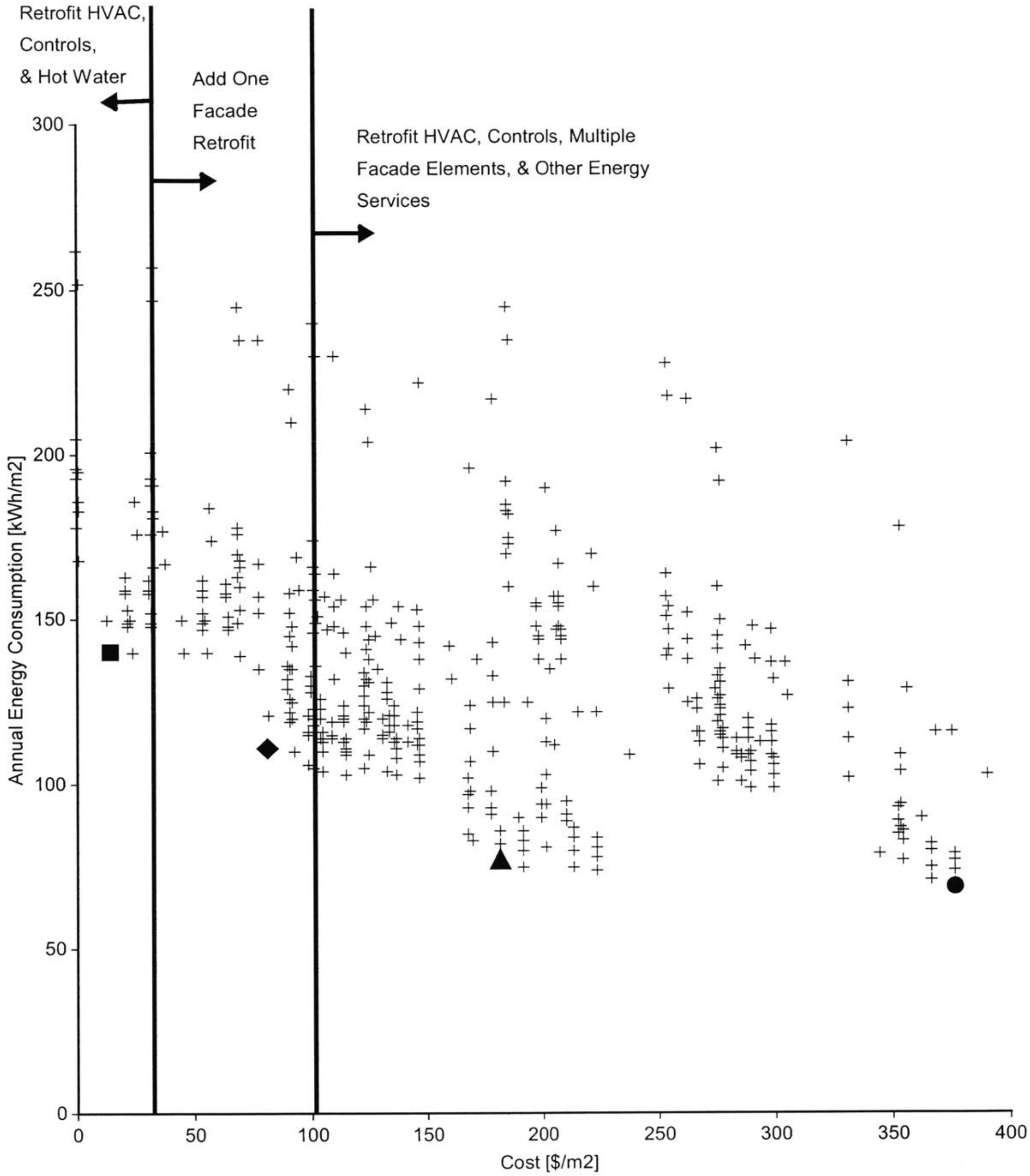


Figure 12-23: Scenarios for retrofitting multiple systems for the buildings constructed between 1997 and 2005. The bold, enlarged points have the best performance for a given investment cost. Descriptions of their energy consumption by end use are provided below.

Overall Results

Each analysis showed that the minimum possible annual energy consumption was about 70 kWh/m^2 and that there are many pathways to get to any desired energy consumption between the building's original energy consumption and 70 kWh/m^2. Each figure also showed diminishing returns. As the energy consumption of the building was reduced, a greater investment cost was necessary to continue to reduce energy consumption.

Each figure includes lines dividing the typical makeup of scenarios into three investment cost ranges. The scenarios in the left most section included retrofits to only the controls system, the HVAC system, and the water heater. The first line was drawn at the cost of the least expensive retrofit to one of the facade elements, including windows. It occurred between about 30 and 50 $\$/m^2$ for each construction period. The second line was drawn at the cost of the least expensive retrofit scenario that included a retrofit to both the windows and the other facade elements. This line was drawn between about 100 and 120 $\$/m^2$ for each construction period. Therefore, the middle section includes scenarios resulting from combining the controls, HVAC, and water heater scenarios with one scenario from the windows or other facade systems. The right most section includes scenarios from combining the controls, HVAC, and other energy services scenarios with multiple scenarios from the windows and other facade systems.

There is a set of scenarios that consume the smallest amount of energy for a given investment cost. These scenarios will be investigated to determine which combinations of retrofit strategies lead to the best building performance. There is also a set of scenarios for each construction period with high investment costs that only lead to small decreases in energy consumption. These scenarios were the combinations where the facade elements or other energy services systems were retrofit, but no changes were made to the controls or HVAC system.

Highlighted Points

Four scenarios were highlighted on Figure 12-20 through Figure 12-23 with large solid blocks in the shape of a square, diamond, triangle, or circle. The highlighted points represent the best performing scenarios from places on the graphs where a large decrease in annual energy consumption occurred. Figure 12-24 through Figure 12-28 show the annual energy consumption divided by end use for the original condition of the buildings from each construction period and for each of the highlighted points.

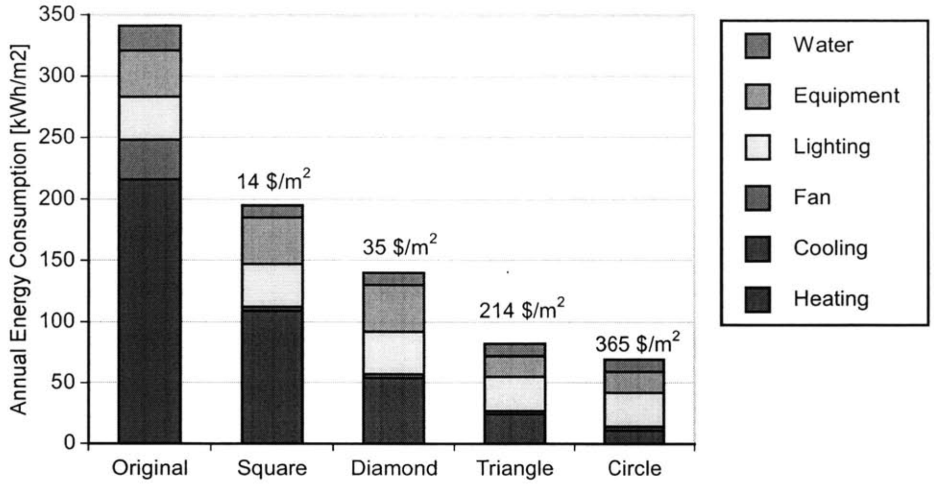


Figure 12-24: Annual energy consumption by end use for the points highlighted on Figure 12-20 for the multi-systems retrofit analysis of the buildings constructed before 1969. Each of the highlighted points included the low-energy controls scenario. The square point used the Moderate 1 HVAC scenario, but all the other points had the low-energy HVAC scenario. The square and diamond points had no changes to the windows, but the triangle and circle points used the low-energy windows scenario. The square and diamond points included no changes to the facade, but the triangle point used the Moderate 1 scenario, and the circle point included the low-energy scenario. Both the square and diamond points used the Moderate 1 scenario for the other energy services, and both the triangle and circle points included the low-energy scenario.

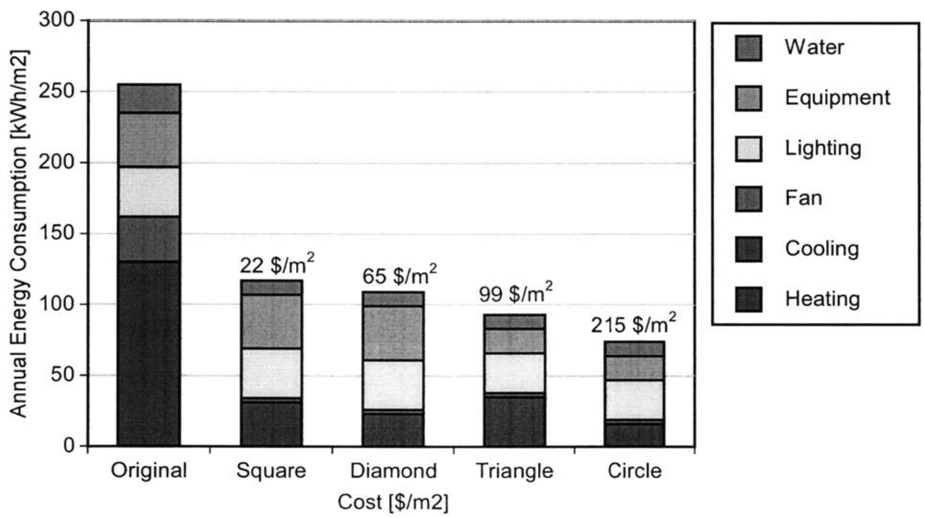


Figure 12-25: Annual energy consumption by end use for the points highlighted on Figure 12-21 for the multi-systems retrofit analysis of the buildings constructed between 1969 and 1979. All of the retrofitted points included the low-energy facade scenario and the low-energy HVAC scenario. The square and triangle points had no changes to the windows. The diamond point used the moderate windows scenario, and the circle used the low-energy windows scenario. Only the circle point included changes to the other facade elements; it included the Moderate 1 scenario. Both the square and diamond point used the Moderate 1 scenario for the other energy services, and both the triangle and circle points included the low-energy scenario.

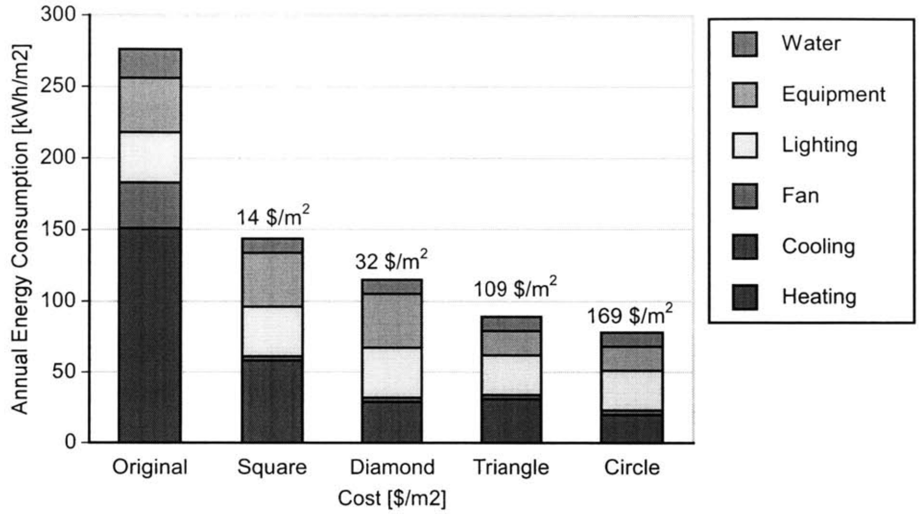


Figure 12-26: Annual energy consumption by end use for the points highlighted on Figure 12-22 for the multi-systems retrofit analysis of the buildings constructed between 1980 and 1986. Each of the highlighted points included the low-energy controls scenario. The square point used the Moderate 1 HVAC scenario, but all the other points had the low-energy HVAC scenario. Only the circle point included changes to the other windows; it used the low-energy scenario. None of the scenarios included changes to the other facade elements. Both the square and diamond points used the Moderate 1 scenario for the other energy services, and both the triangle and circle points included the low-energy scenario.

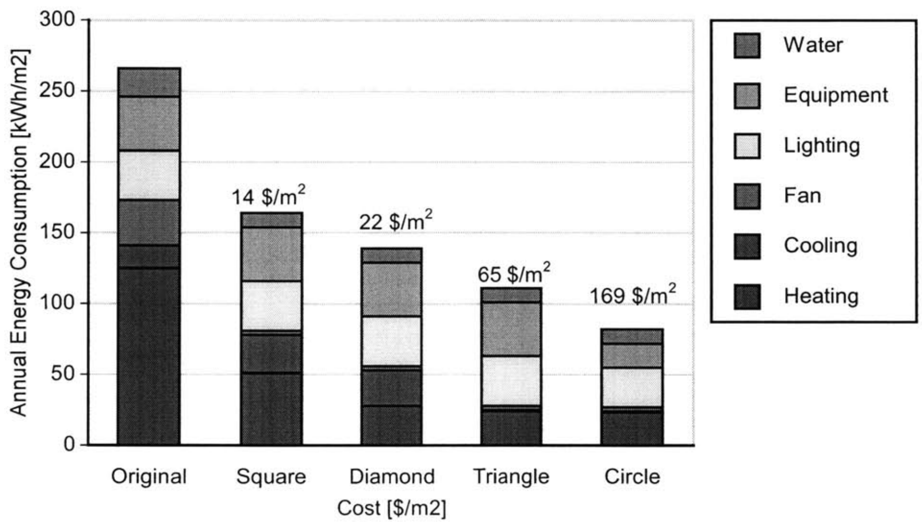


Figure 12-27: Annual energy consumption by end use for the points highlighted on Figure 12-23 for the multi-systems retrofit analysis of the buildings constructed between 1987 and 1996. All of the points used the low-energy controls scenario, except the circle point which used the Moderate 3 scenario. The square point used the Moderate 1 HVAC scenario. Both the diamond and triangle points used the Moderate 2 scenario, and the circle point used the low-energy scenario. The windows were not changed for the square and diamond points. The triangle point used the Moderate 1 windows scenario, and the circle point had the low-energy windows. None of the scenarios included changes to the other facade elements. The square, diamond, and triangle points used the Moderate 1 scenario from the other energy services system; only the circle point used the low-energy scenario.

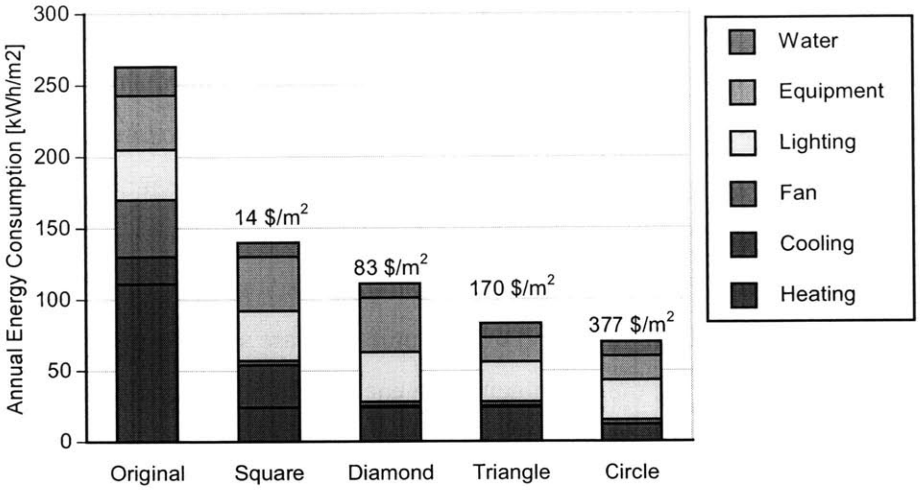


Figure 12-28: Annual energy consumption by end use for the points highlighted on Figure 12-24 for the multi-systems retrofit analysis of the buildings constructed between 1997 and 2005. All of the points used the low-energy controls. The circle point used had every possible low-energy retrofit. The square and diamond points used the Moderate 1 HVAC scenario, but the triangle point used the low-energy scenario. Neither the square, diamond, nor triangle point had any changes to the facade. The square and diamond points used the Moderate 1 other energy services scenario, but the triangle point used the low-energy scenario.

Each of these selections of scenarios show that the majority of the decrease in annual energy consumption comes from decreasing the energy used for heating and by the ventilation fan. All of the decreases in energy consumption for the ventilation fan come from changes to the HVAC and controls system. The majority of the savings in heating energy also come from retrofitting the HVAC and controls systems. Some additional decreases in energy consumption for heating are possible by increasing the insulation in the facade or replacing the windows, but they significantly increase the required investment cost for the retrofit.

For the buildings constructed after 1987, for which the highlighted points are shown in Figure 12-27 and Figure 12-28, there was also a significant potential to reduce the energy required to cool the building. In this case, the cooling energy was slightly increased by making changes to the controls system. The lower ventilation rates in the retrofit scenarios did not provide enough outdoor air to eliminate the heat gains in the buildings. This problem could be alleviated to some degree by using a high ventilation rate during the cooling season and a lower one during the heating season. However, this method would also increase the energy consumed by the fan. The most effective method for reducing the cooling energy was to install operable windows.

A total reduction of 38 $^{kWh}/_{m^2}$ was possible by improving the efficiency of the lights, office equipment, and water heater for all the construction periods. The water heater was retrofit in every highlighted case, but the lights and office equipment were expensive to replace and were only included in the high investment cost highlighted points. However, the costs determined in Chapter 8 were for replacing all of the lights and office equipment in the building at one time. These components have very short lifetimes in comparison to the building as a whole. The benefits from improving the efficiency of the lighting and office equipment are significant and could be gained over time by simply replacing old equipment with energy efficient models when the old equipment breaks or becomes obsolete. These improvements are very important because once changes are made to reduce the heating energy, the other energy services consume the majority of the energy in the building. For each construction period, changes to this system were necessary to reduce the total energy consumption of the building below 100 $^{kWh}/_{m^2}$.

HVAC and Controls

All of the analyses so far indicate that retrofitting the HVAC and controls systems lead to the greatest decreases in energy consumption. Since changing the controls system comes with no investment cost, it is necessary to determine if a particular combination of temperature and ventilation set points consistently leads to the lowest energy consumption. These set points also affect occupant comfort, so the analysis must also consider if setting the controls to be just on the edge of discomfort leads to significant improvements in the building's performance.

Figure 12-29 through Figure 12-33 show the annual energy consumption by end use for all five controls strategies combined with the Moderate 1 HVAC scenario for each construction period. This scenario generally included changes to the ventilation fan and the heat recovery effectiveness. For the buildings constructed between 1969 and 1979, the Moderate 1 scenario was adding a heat pump. For the buildings constructed between 1997 and 2005, the scenario included improving the fan and adding a heat pump. No changes were made to the windows, other facade elements, or other energy services to generate these figures.

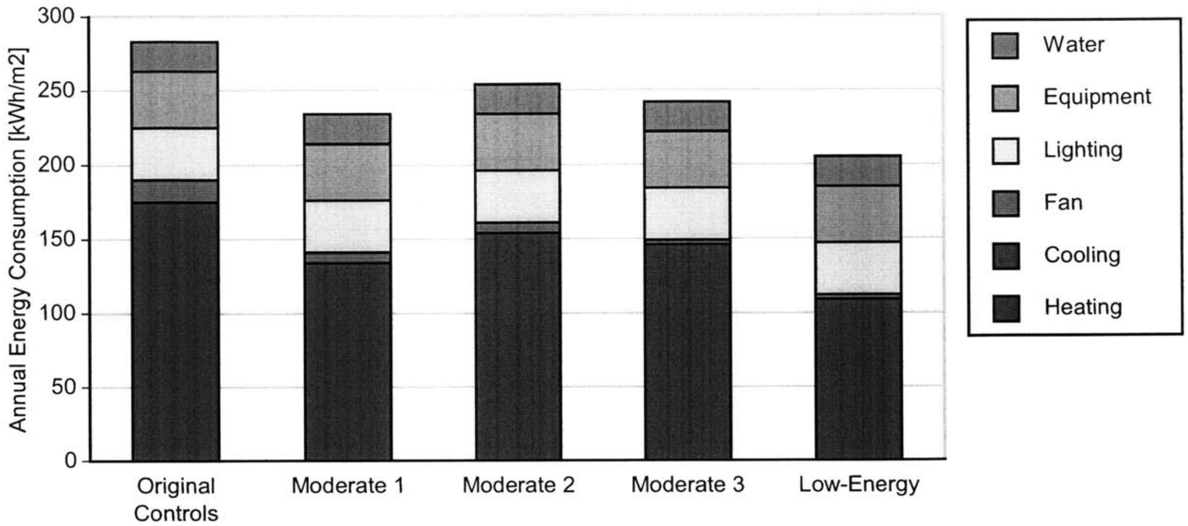


Figure 12-29: Annual energy consumption by end use for each controls scenarios for the buildings constructed before 1969 where the fan and heat recovery system have been retrofit (Moderate 1 for the HVAC system).

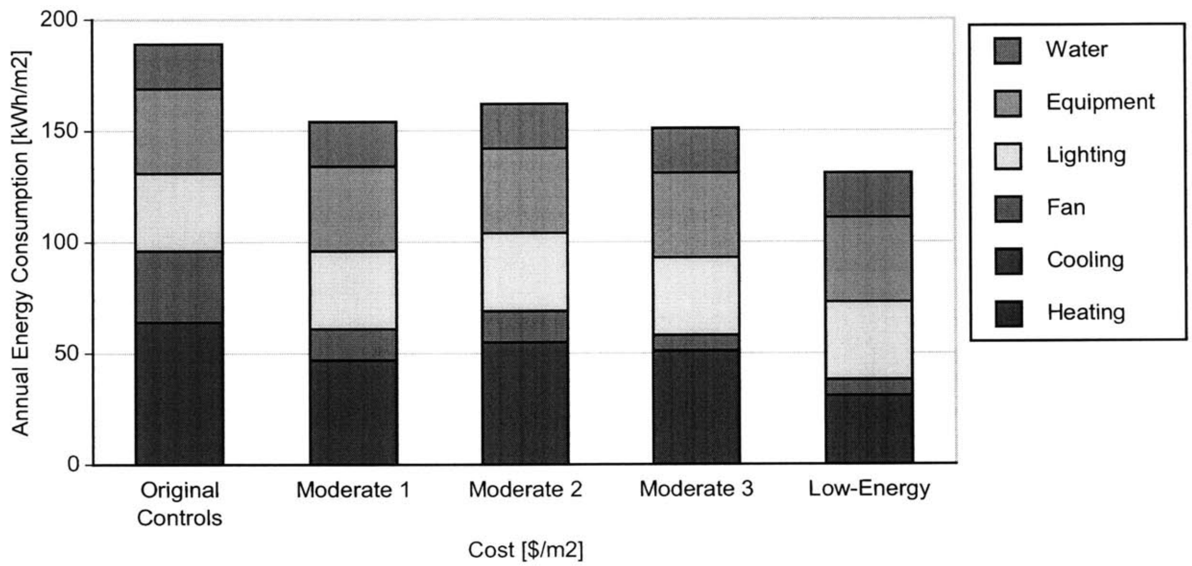


Figure 12-30: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1969 and 1979 where a heat pump has been installed (Moderate 1 for the HVAC system).

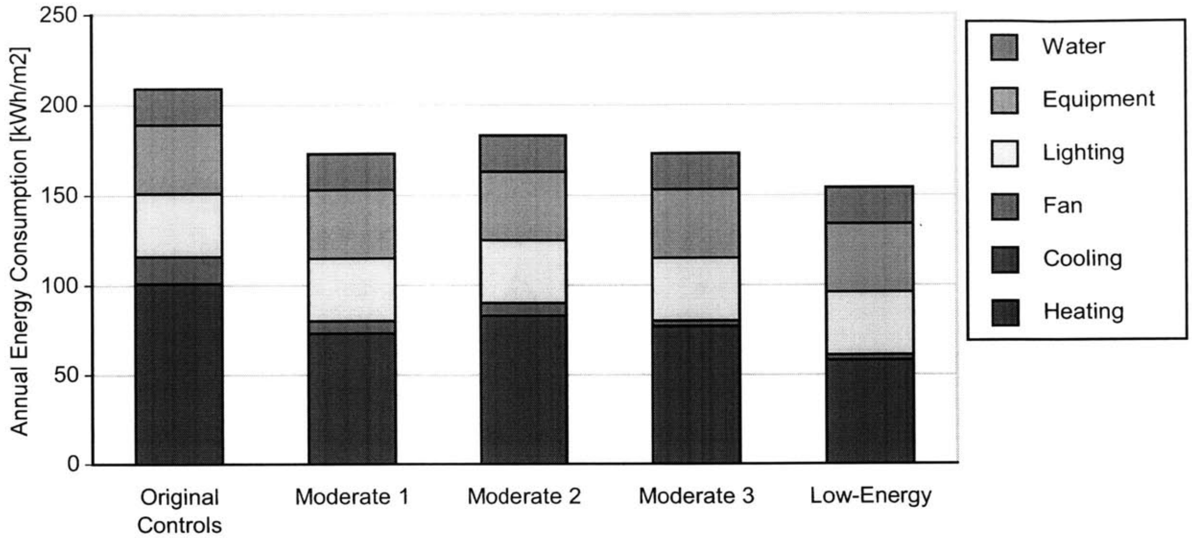


Figure 12-31: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1980 and 1986 where the fan and heat recovery system have been retrofit (Moderate 1 for the HVAC system).

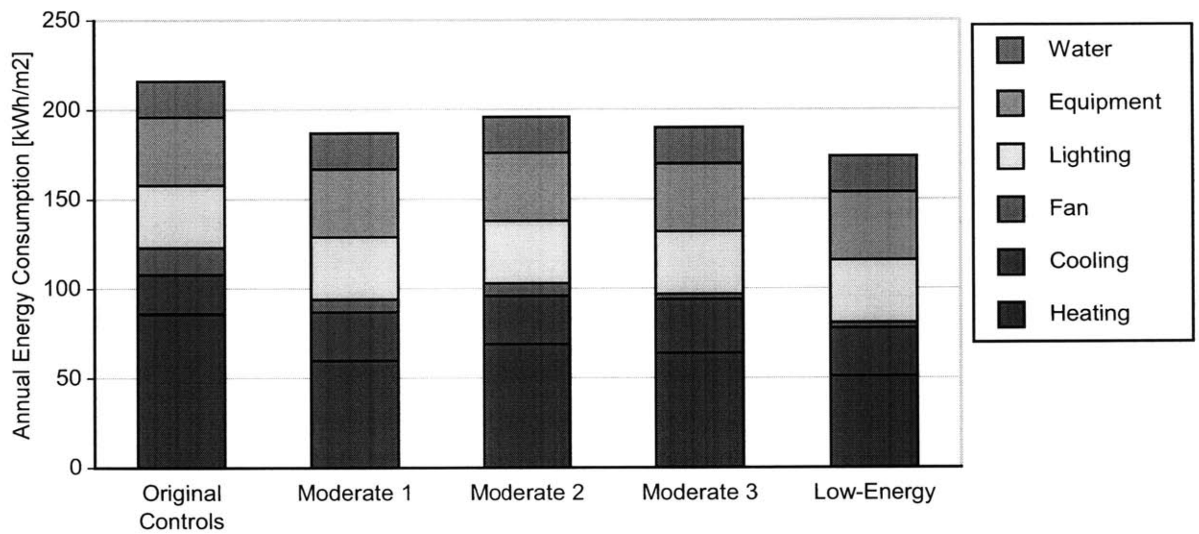


Figure 12-32: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1987 and 1997 where the fan and heat recovery system have been retrofit (Moderate 1 for the HVAC system).

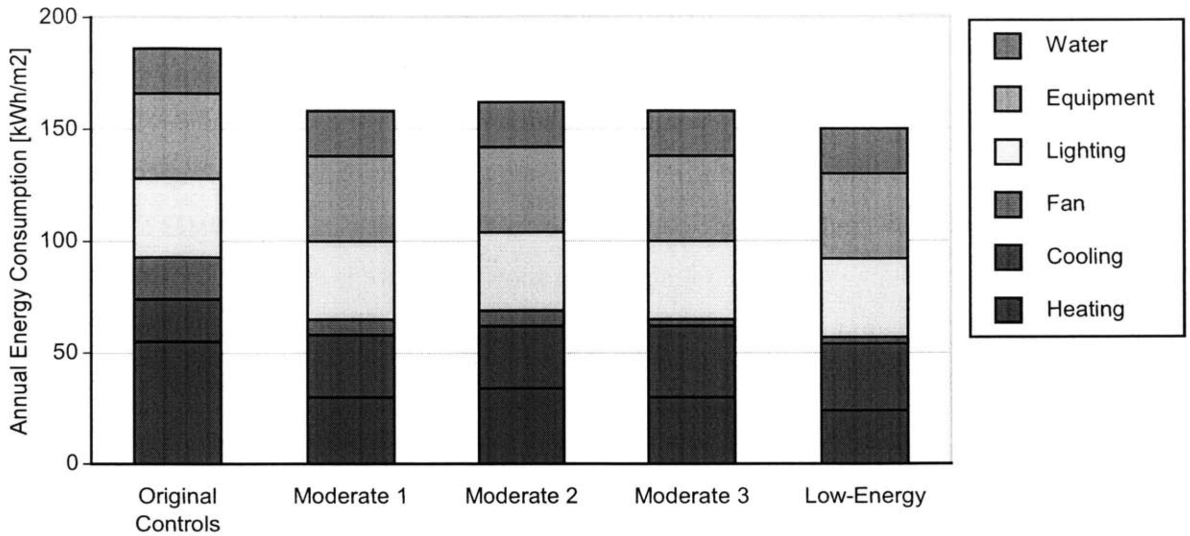


Figure 12-33: Annual energy consumption by end use for each controls scenarios for the buildings constructed between 1997 and 2005 where the fan has been retrofit and a heat pump installed (Moderate 1 for the HVAC system).

The relative benefits of the different controls strategies differed for the buildings with and without cooling systems. For the buildings without cooling systems, changing from the original controls strategy to the Moderate 1 scenario reduced energy consumption by about 75 $^{kWh}/_{m^2}$. The Moderate 2 and Moderate 3 controls scenarios resulted in energy consumptions somewhere between the original controls scenario and the Moderate 1 scenario for the buildings constructed before 1969 or between 1980 and 1986. These scenarios included reductions in the ventilation rate but no changes to the temperature set points. The Moderate 3 control scenario had an energy consumption slightly above the Moderate 1 scenario for the buildings constructed between 1969 and 1979 because the ventilation fan was not replaced. Therefore, the energy consumed by the fan was greater for this construction period than the other two scenarios. The low-energy scenario reduced total energy consumption by another approximately 25 $^{kWh}/_{m^2}$ off of the Moderate 1 scenario for all of the construction periods without a cooling system. In general, these scenarios show that for buildings without a cooling system, the low-energy scenario is best, but occupants may not find the low temperature set points comfortable. Most of the benefit, however, can be still be acquired from less extreme control strategies that are more conservative than the current strategies.

For buildings with a cooling system, low-ventilation rates still decrease the energy used for heating, but they also slightly increase the energy used for cooling. The low-energy controls scenario still led to the greatest total decrease in energy because the additional decreases in heating energy were greater than the increase in cooling energy. The cooling energy could be reduced through the controls system by separate ventilation rates for the heating and cooling seasons. Increasing the ventilation rate during the summer would decrease the cooling energy, but that decrease would have to be balanced against the resulting increases in fan energy. In general, the results for buildings with a cooling system show that there is also great potential for decreasing the energy consumption in the building by altering the controls strategy. Significant decreases can be made while maintaining occupant comfort.

12.5 Conclusions

Retrofitting every possible building attribute reduced the energy consumption of the model buildings to about 70 $^{kWh}/_{m^2}$, 70 to 80% less than their original consumption. However, a complete building overhaul would cost several hundred dollars per square meter of floor area in the building. Such an investment is unlikely to be cost effective.

Each section of this analysis highlighted the HVAC and controls systems as both the most effective and least expensive retrofitting strategies. Retrofitting all the attributes in the HVAC system led to decreases in energy consumption between about 30 and 45%. Retrofitting the attributes in the controls system led to decreases in energy consumption between about 30 and 40%. Retrofitting attributes from both systems at the same time decreased the energy consumption of the model buildings by 45 to 55%, about two-thirds of the total possible reduction.

Retrofitting the controls system as analyzed in this study was essentially free. The only changes considered were altering the indoor set point temperatures and the ventilation rates. These settings should be the building attributes considered for retrofit. Lower energy consumption is likely to be possible for any building from more conscientious use of the preexisting components. Greater decreases in energy could be possible from installing more complicated controls. For example, occupancy sensors can turn off ventilation to a room and the lights in that room when it is not in use. Light sensors can dim electric lights when there is not adequate sunlight light for working but the full strength of the electric lights is not necessary. These changes were outside of the scope of this project, but could provide additional decreases in energy consumption.

Retrofits to the HVAC system were the most effective and least expensive changes to physical components in the building. If reductions in energy consumption are desired beyond what can be achieved with the controls system, the HVAC system should be considered first. The specific components that could lead to the greatest decreases in energy consumption depend on the current condition of the building.

All of the components in a building are likely to be replaced several times during the lifetime of a building. The results from this chapter show that there is significant potential to decrease energy consumption by using more energy efficient components in all of the building systems. Therefore, low-energy components should be considered any time the existing component must be replaced due to damage or fatigue. However, some of the retrofit scenarios are cost-effective in the short term for their energy savings alone. More details about these projects are presented in Chapter 13.

13 Economic Ramifications

Chapter 12 described the potential for decreasing energy consumption through retrofitting the model buildings. The scenario analysis compared the reduction in annual energy consumption from retrofit projects to the required investment cost. It showed that there were large variations in the performance of the buildings for a given investment cost and that there were diminishing returns as the annual energy consumption approached the minimum possible consumption of about 70 kWh/m^2. The information presented gave only a very general idea of which scenarios decreased energy consumption the most efficiently for a given investment cost. This section will use two economic indicators, the payback period and the cost of conserved energy, to identify the scenarios that represent economically viable retrofit projects.

13.1 Payback Period

The payback period represents the time period necessary for the savings through reduced energy costs to match the investment cost of a project. It is calculated as:

$$PaybackPeriod = \frac{Investment\ Cost}{Change\ in\ Consumption * Cost\ of\ Energy} \qquad \textbf{13-1}$$

In this project, the payback period was most useful for identifying the sets of retrofit options that reduce energy consumption most efficiently. It is not sufficient for a project to be inexpensive or to cause a large reduction in energy consumption. The payback period analysis identified the retrofit projects that achieved the greatest decrease in energy consumption for their investment cost.

13.1.1 Cost of Electricity

All of the energy saved in the retrofit projects was assumed to be supplied through electricity. In reality, more than 90% of the energy used in office buildings in Norway is supplied by electricity, but the remainder is a combination of oil and district heat [SSB 2006]. This analysis used the current average electricity price for calculations. A more rigorous economic analysis could use the marginal cost of electricity. There is little room to expand the capacity of hydroelectric plants in Norway, so electricity will be more expensive in the future if it must be purchased from elsewhere or generated through fossil fuels. Figure 13-1 and Figure

13-2 show the monthly average electricity price in Norway for January of 2001 through April of 2006.

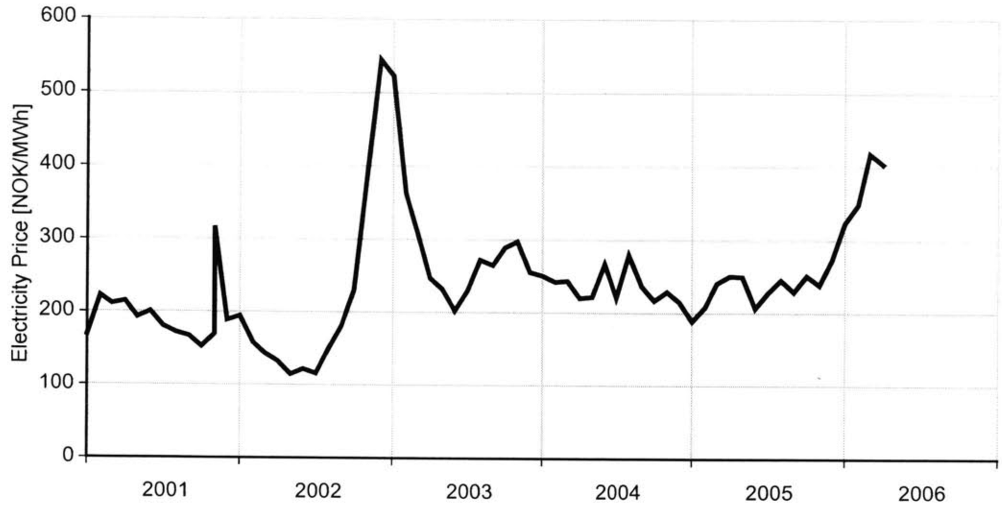


Figure 13-1: Nordel Elspot monthly average electricity spot price for January of 2001 through April of 2006 in NOK/MWh with a focus on long term trends. [Nordpool 2006].

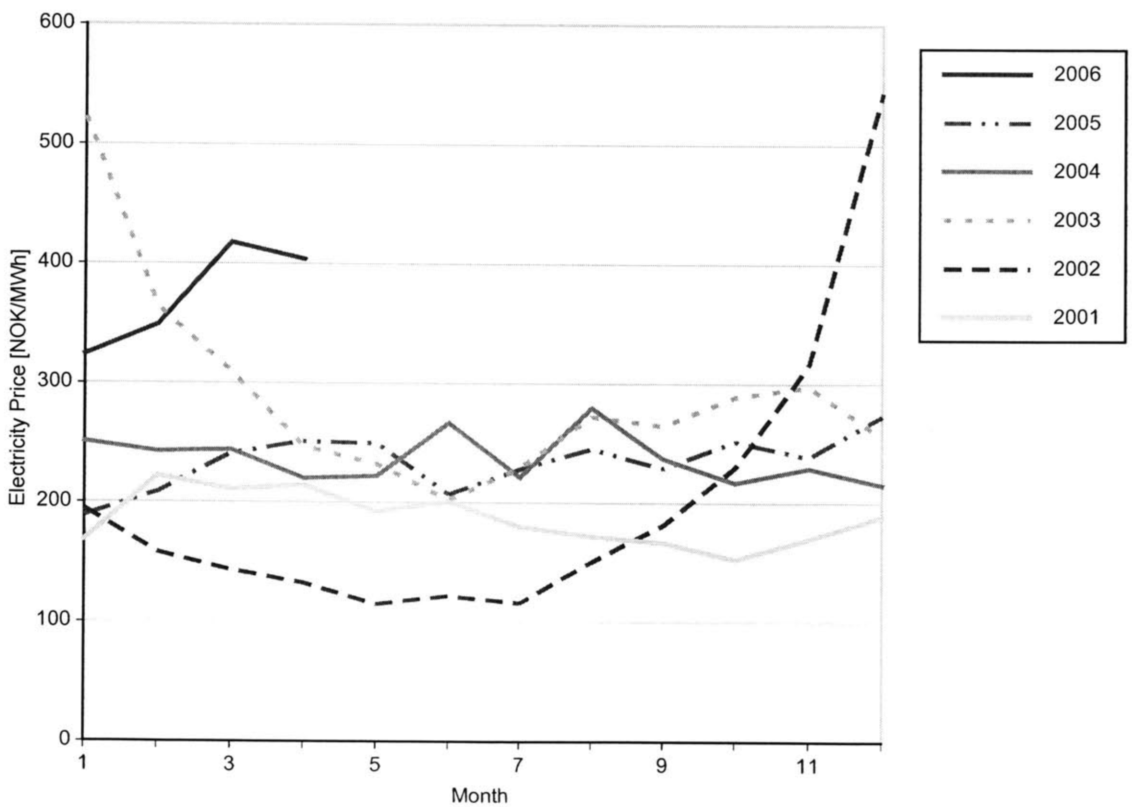


Figure 13-2: Nordel Elspot monthly average electricity spot price for January of 2001 through April of 2006 in NOK/MWh with a focus on short term variations. [Nordpool 2006].

The average electricity price was about 250 NOK/MWh between 2001 and 2006, although it varied from about 100 to about 550 NOK/MWh. There was a large increase in price during the winter of 2002 to 2003. The average electricity cost went up to a maximum of 550 NOK/MWh due to a drought, which reduced the capacity of the hydroelectric dams. Prices in general settled at a higher rate after the drought than they were before. More recently, electricity prices started to go up during the winter of 2005 and were still above 400 NOK/MWh in April of 2006, although they had started to decrease. Month to month variations of about 25 NOK/MWh were typical, but prices were not consistently higher in any particular season.

13.1.2 Payback Periods of Retrofit Projects

Standard Analysis

Calculations of payback period for the multi-systems retrofit projects were performed on the buildings from all construction periods. The calculations used the typical price of electricity, 250 NOK/MWh (0.0385 $/kWh). The most recent electricity prices are higher. As of April of 2006, the price is about 400 NOK/MW (0.0616 $/kWh), but it is projected to continue decreasing over the next few months [Nordpool 2006]. An example of payback periods with electricity prices of 400 NOK/MWh will also be considered to show how the spread of economically reasonable projects would change with consistently higher electricity prices.

Figure 13-3 through Figure 13-7 show the payback period for retrofits to attributes from multiple building systems for each construction period. The buildings constructed before 1969 experienced the greatest changes in energy consumption when retrofits were performed. Therefore, there were many scenarios with payback periods of ten years or less. For buildings from the other construction periods most of the retrofits that included windows or other facade elements had payback periods greater than ten years. Therefore, scenarios with payback periods of 15 years or less were graphed for these construction periods.

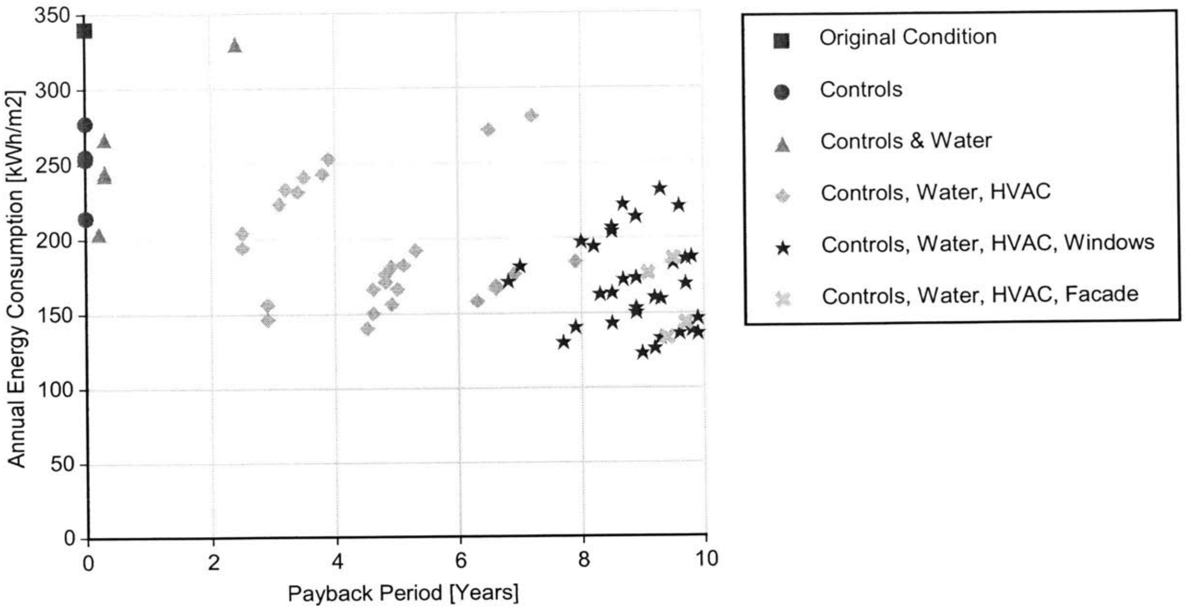


Figure 13-3: Scenarios with payback periods of ten years or less by retrofit type for the buildings constructed before 1969.

For the buildings constructed before 1969 all of the scenarios defined for the controls system and the HVAC system were included in the set of multi-systems retrofit scenarios with payback periods of 10 years or less. The scenarios with the shortest payback periods used the controls strategies with the lowest ventilation rates. The scenarios with both short payback periods and low annual energy consumption included the moderate or low-energy controls scenarios as well as modifications to the HVAC system. The low-energy HVAC scenarios had the best overall energy performance. However the scenarios that used the moderate 2 HVAC scenario had similar total energy consumptions and payback periods about two years shorter.

Most of the scenarios that included retrofits to the windows used the moderate windows scenario. The scenarios that used the low-energy windows were always paired with the controls scenarios with the lowest ventilation rates and still had higher total energy consumptions than the ones that included the moderate windows retrofit. The scenarios that used the moderate windows scenario could also include some changes to the HVAC system to achieve lower energy consumptions with the same payback period as the scenarios using the low-energy windows. The scenarios that included changes to the facade system always included the low-energy controls scenario as well. The best performing scenarios overall included the low-energy or moderate 3 controls scenario and retrofits to the HVAC system. Most of them included the moderate window scenario as well, but adding the windows retrofit added about 4 years to the payback period.

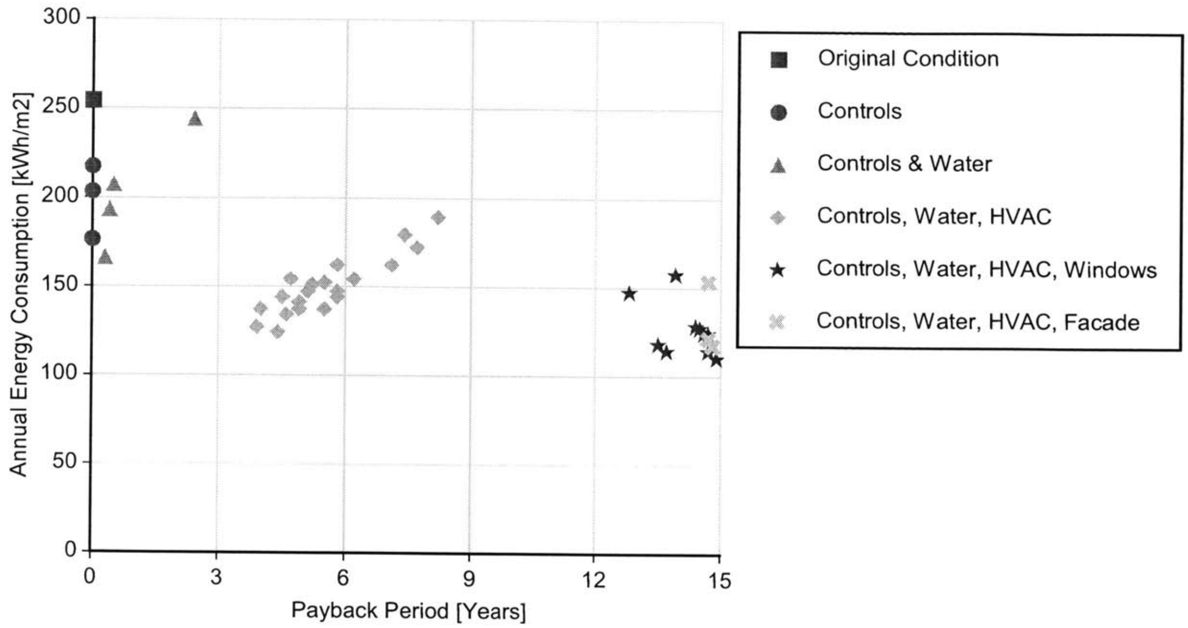


Figure 13-4: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1969 and 1979.

For the buildings constructed between 1969 and 1979 the scenarios with payback periods of 15 years or less included all of the controls strategies and the HVAC scenarios. The retrofit projects that included the windows only included the moderate windows scenario. These scenarios always included the low-energy or moderate 3 controls strategies, those with the lowest ventilation rates, but could be combined with any of the HVAC retrofits. Three scenarios included the moderate facade retrofit. They each had the low-energy controls settings and one of the three HVAC scenarios. The scenarios with the lowest annual energy consumption all included the low-energy or moderate 3 controls scenarios as well as retrofits to the HVAC system. They also included the moderate window retrofit, but this approach added about 10 years to the payback period for an additional decrease in energy consumption less than 15 $kWh/_{m^2}$.

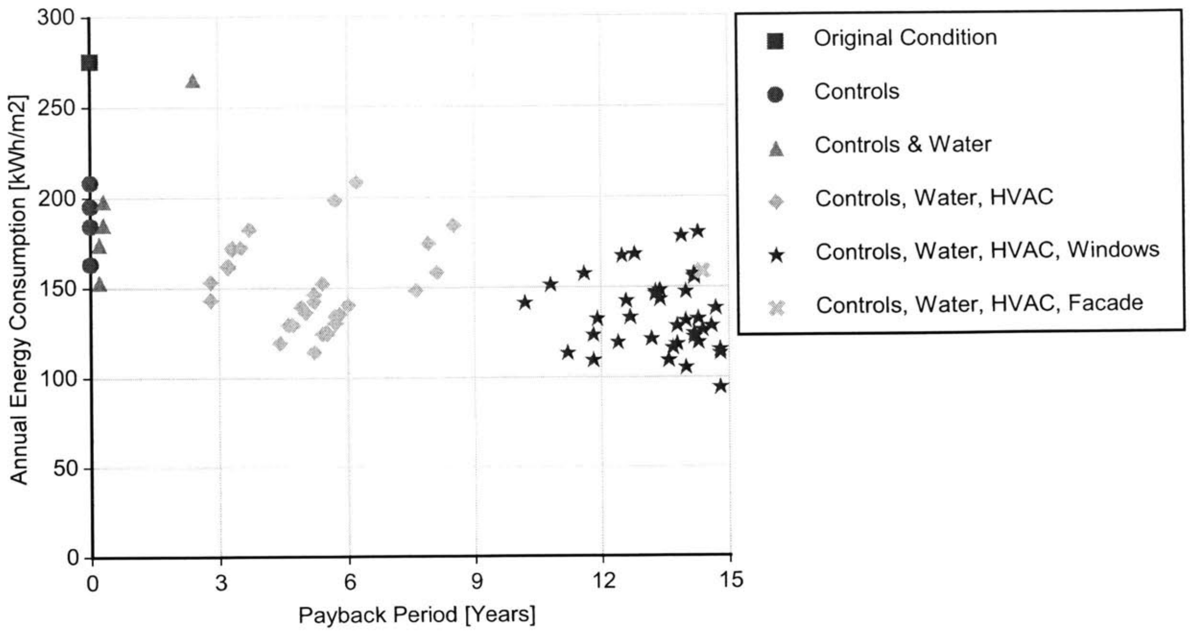


Figure 13-5: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1980 and 1986.

For the buildings constructed between 1980 and 1986 the set of multi-systems retrofit scenarios with payback periods of 15 years or less included all of the controls scenarios and HVAC scenarios. The scenarios that included retrofits to the windows included both the moderate and low-energy cases. The scenarios with the low-energy windows always were always paired with the low-energy control strategy. Only one scenario included a retrofit to the facade, combining the moderate facade scenario with the low-energy controls scenario. The scenarios with the lowest annual energy consumption included the low-energy controls or moderate 3 controls strategies, which had the lowest ventilation rates. They also included the moderate 2 or low-energy HVAC strategies. Retrofitting the windows could reduce annual energy consumption by about 20 $^{kWh}/_{m^2}$ over controls and HVAC alone, but required an additional 6 years to the payback period.

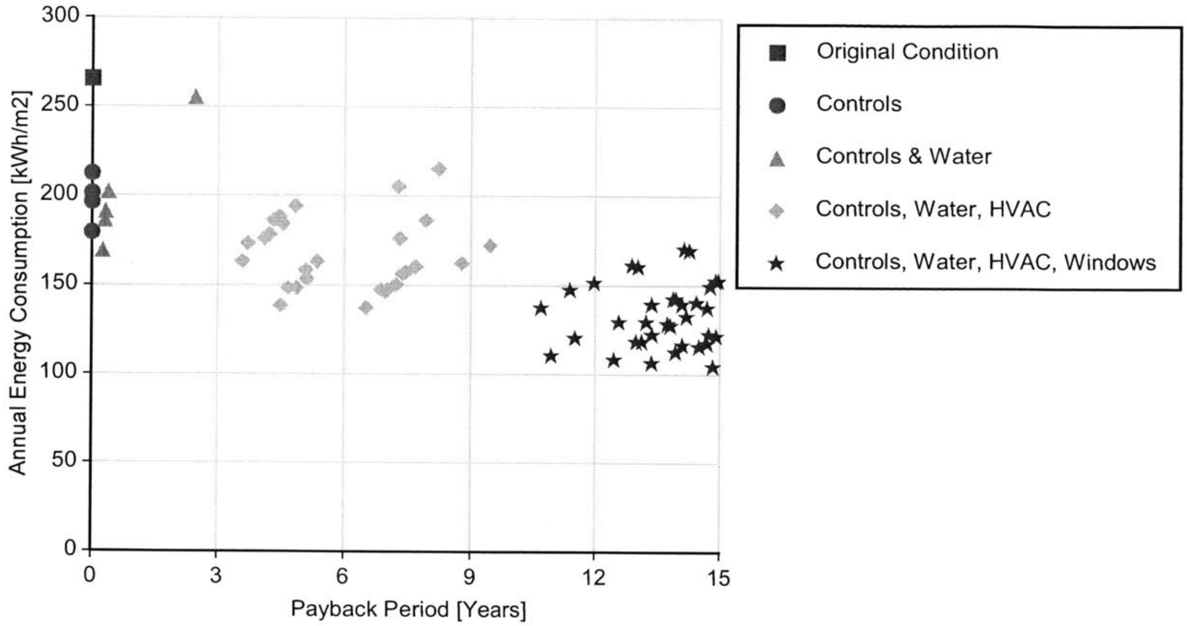


Figure 13-6: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1987 and 1996.

The scenarios with short payback periods for the buildings constructed between 1987 and 1996 also included all of the possible controls and HVAC scenarios. Many of the scenarios included the moderate or low-energy window retrofit as well. All of the scenarios that included the low-energy windows also included the low-energy or moderate 3 controls scenarios. None of the retrofits that included changes to the facade had a payback period of less than 15 years. The best performing scenarios all included retrofits to the windows and had payback periods of ten years or greater. The scenarios with window retrofits consumed about 30 $kWh/_{m^2}$ of energy per year less than those without because the buildings in this construction period had cooling systems and inoperable windows. The new windows are operable which eliminated almost all of the required cooling energy.

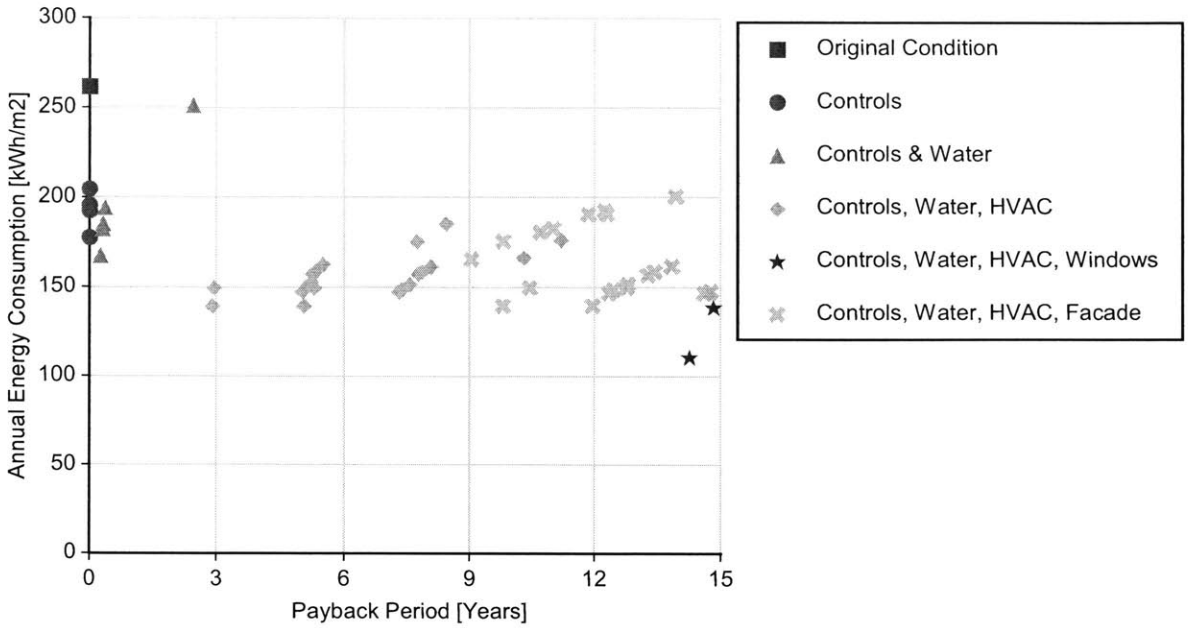


Figure 13-7: Scenarios with payback periods of 15 years or less by retrofit type for the buildings constructed between 1997 and 2005.

The scenarios for buildings constructed between 1997 and 2005 included all of the controls and HVAC scenarios. Only two of the scenarios with payback periods of 15 years or less included retrofits to the windows and they were paired with the low-energy controls scenario. A number of scenarios included the moderate facade scenario with various combinations of retrofits to the controls and HVAC system. The scenarios with the lowest energy consumption included the retrofit to the windows and had a payback period of about 14 years. The annual energy consumptions of the scenarios that included changes to the facade were similar to those where only the controls system, the HVAC system, and the water heater were retrofit. However, the payback periods for the scenarios that included changes to the facade system were about 7 years longer.

There were many similarities for the best retrofit strategies amongst the model buildings. Retrofits to the controls system, the HVAC system, and the water heater had the shortest payback period and produced the majority of the reduction in energy consumption. Additional retrofits to the windows or other facade elements could reduce the energy consumption further but added about 5 to 10 years to the payback period. The best possible performance of the buildings for a 15 year payback period was about 100 $^{kWh}\!/_{m^2}$.

The controls strategy selected had a lot of control over the annual energy consumption. Figure 13-8 shows the scenarios with payback periods of ten years or less for the buildings constructed before 1969, categorized by the controls strategy.

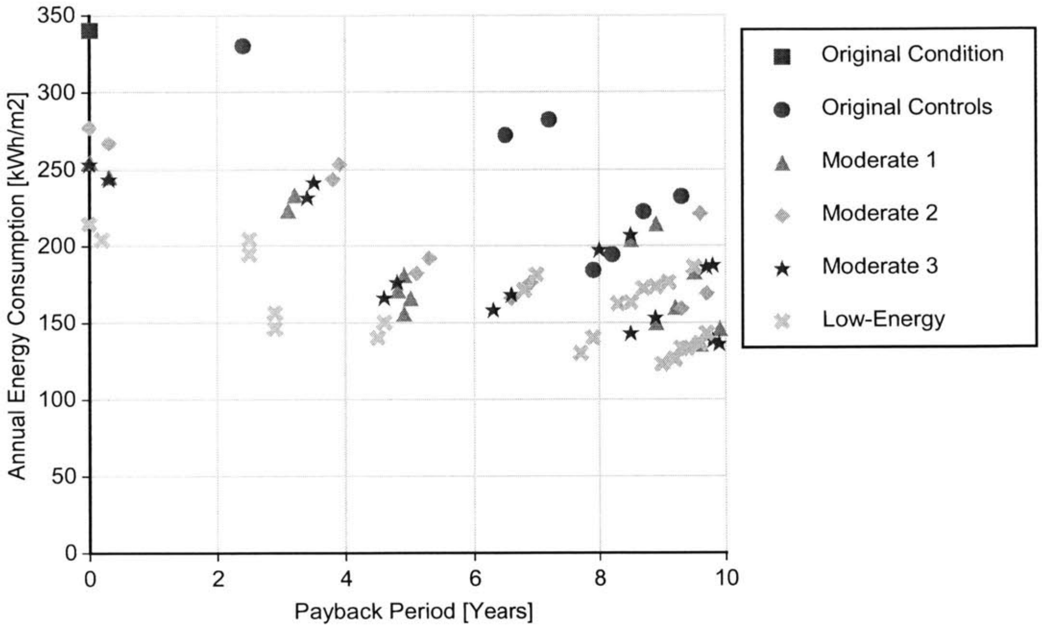


Figure 13-8: Scenarios for the buildings constructed before 1969 with payback periods of ten years or less by controls strategy.

The scenarios that included the low-energy controls strategy consistently had the lowest energy consumption for a given payback period. The moderate 1 and moderate 3 controls strategies were also excellent performers. The choice of controls strategy had less influence when several additional retrofits were performed to other systems. The retrofits to the HVAC system reduced the energy lost due to high ventilation rates, and the improvements to the facade reduced the energy lost from high indoor temperatures. However, it was clear that the scenarios with the lowest energy performance for a given payback period consistently included the most restrictive controls scenarios.

There were also some differences in the scenarios based on the original condition of the buildings. There was overlap in the groups of scenarios that included and did not include retrofits to the windows for the buildings constructed before 1969. The other construction periods had clear separations between the two groups of scenarios. For the buildings constructed before 1969, the retrofit scenarios for the HVAC system that included a heat pump were unusually expensive due to the high heating requirement. The windows from this time period also had the highest U-value, so replacing them led to the greatest decrease in energy consumption of any of the model buildings. Both of these factors worked together to make certain projects from both categories of retrofits have similar payback periods.

Most of the model buildings had many more scenarios with payback periods less than 15 years that included retrofitting windows than included retrofitting the facade elements. However, the trend was reversed for the buildings constructed between 1997 and 2005. Some of the scenarios that included retrofits to the facade also had similar payback periods as those with only changes to the controls system, water heater, and HVAC system, which was not seen in the other construction periods. This result was unexpected because the buildings constructed between 1997 and 2005 had the lowest U-values for the facade in their original condition. Changes to the facade were shown to have a very small effect on total energy consumption for these buildings in Chapter 12, so there was not expected to be a large enough decrease in energy consumption to produce a short payback period. However, all of the facade scenarios used the moderate 1 scenario. This scenario only included changes to the insulation in the ground floor. For all the other construction periods, the moderate scenarios included simultaneous changes to two facade elements, which increased the total cost of the project. Therefore, the cost of changes to the facade was less for the newest buildings, and the payback period was shorter. Adding the facade retrofit still did not significantly reduced the annual energy consumption below what could be achieved through retrofitting the controls system, HVAC system, and water heater alone.

Other Cost Possibilities

The scenarios for the buildings constructed between 1997 and 2005 were used as an example to show how the payback period would change for different electricity prices and investment costs. Figure 13-9 shows the payback period versus annual energy consumption for the same scenarios as in Figure 13-7 but with an electricity price of 400 NOK/MWh (0.0616 $/kWh) instead of 250 NOK/MWh (0.0385 $/kWh).

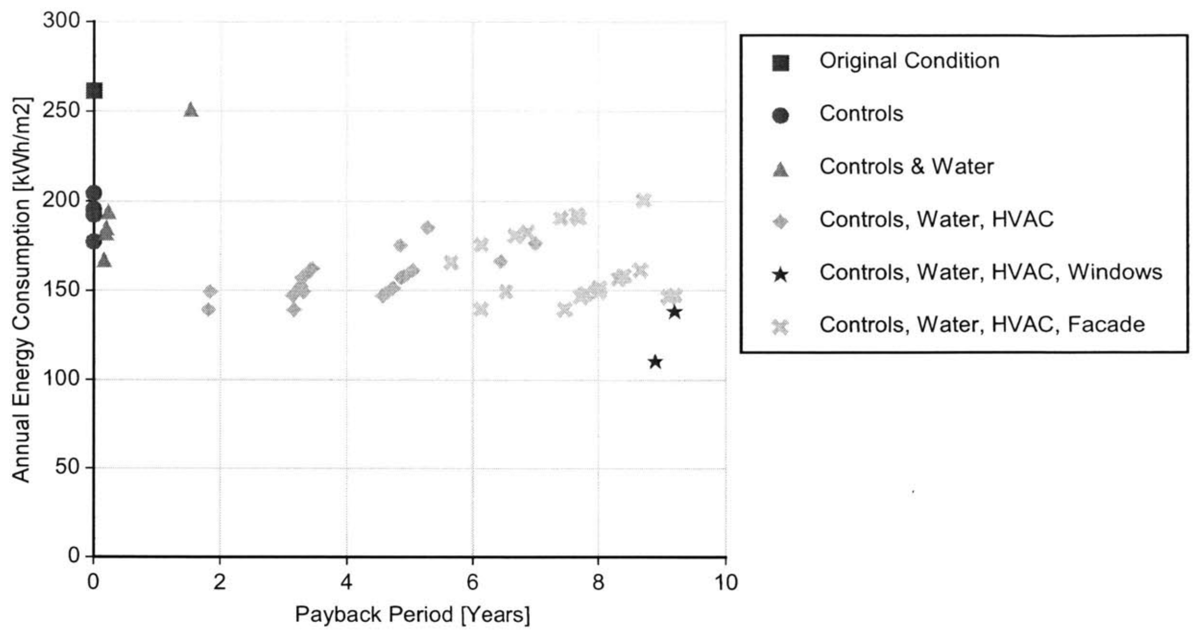


Figure 13-9: Same scenarios as in Figure 13-7 but with electricity price of 0.0616 $^{\$}/_{kWh}$ instead of 0.0385 $^{\$}/_{kWh}$.

All of the payback periods decreased with the higher electricity price because the retrofit project saved more money each year for the same decrease in annual energy consumption. The payback period was always reduced by a factor of 1.6, the ratio of the two electricity prices. However, the relative impact was greater for the scenarios with high payback periods than low ones. In Figure 13-7 there are two scenarios that included retrofits to the controls system, water heater, and HVAC system with payback periods of about 3 years. With the higher electricity price, the payback period was reduced to just under two years, a reduction of a little more than one year. However, the maximum payback period shown on Figure 13-7 was about 15 years. The same scenarios on Figure 13-9 had payback periods of about nine years, a change of about 6 years.

Not only were the retrofit projects that were economically viable with a low electricity cost still economically viable with a higher electricity cost, many projects that were too expensive with the low electricity cost had significant reductions in payback period when the electricity cost was increased. Therefore, if the electricity cost does remain at 400 NOK/MWh, instead of going back down to 250 NOK/MWh, many more retrofit projects will become economically viable.

Recall from Chapter 8 that the investment costs for the retrofit projects were compiled from the average costs in the United States. There was no systematic way to convert the US costs to costs for Norwegian construction, but it is likely that the costs in Norway would be greater. Selected data from Statsbygg suggested that construction projects in Norway could be similar to the US mean costs or as much as 1.7 times greater [Hellberg 2006]. Figure 13-10 shows the same scenarios with the same electricity price as Figure 13-7 but with the investment cost increased by 30%.

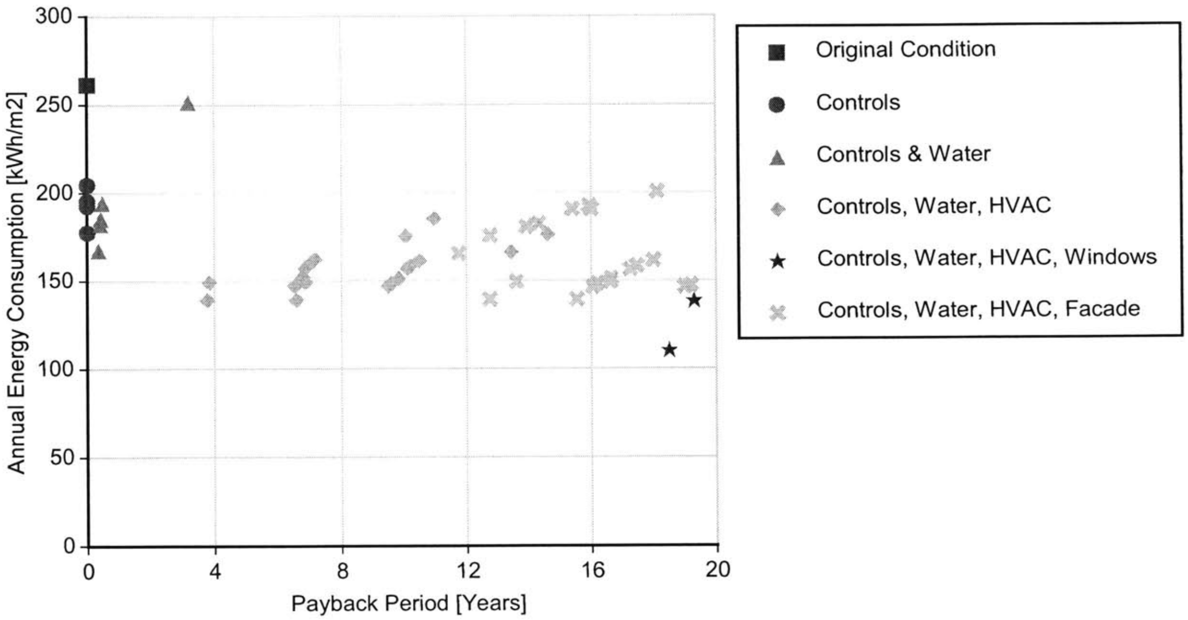


Figure 13-10: Same scenarios as in Figure 13-7 but with 30% higher investment cost.

Again, the relative benefit of the projects was unchanged. The scenarios were still grouped in the same order. The two scenarios that included changes to the controls system, the water heater, and the HVAC system that had payback periods of about 3 years in Figure 13-7 have payback periods of about 4 years in Figure 13-10. The maximum payback period for this set of scenarios increased from about 15 years to about 19 years. The most economically viable scenarios are the same in both figures. However, the payback period increased when the investment cost was increased, which would make it less likely that changes to the windows or facade would have a reasonable payback period.

13.2 Cost of Conserved Energy

The payback period has limited use as an economic indicator because it does not consider interest rates or the lifetime of the retrofit projects. A building owner is likely to need to take out a loan to pay for the retrofit projects. Therefore, the money saved from reduced energy consumption must be greater than the initial investment by the relevant interest rate as well as the minimum profit the owner is willing to accept for the project. The lifetime of the retrofit projects are also important. A retrofit to a component of the HVAC system is less expensive than a retrofit to the facade, but the HVAC component is likely to only last for 10 or 15 years whereas the facade retrofit could last for much longer. An economic indicator that includes both of these factors is called the cost of conserved energy. The cost of conserved energy determines the required average energy cost to make a project economically viable. If it is less than the current or projected energy cost, then the project is worthwhile. If the cost of conserved energy is greater than the current or projected energy price, more money would be saved without completing the project [Martinaitis 2004]. It is calculated as:

$$CCE = \frac{I}{S} * \frac{d}{1-(1+d)^{-n}} \qquad \textbf{13-2}$$

where CCE is the cost of conserved energy, I is the investment cost, S is the annual reduction in energy consumption, d is the discount rate, and n is the lifetime of the project in years.

The cost of conserved energy was calculated for the same scenarios as were shown on Figure 13-3 through Figure 13-7. These scenarios had payback periods with an assumed electricity price of 250 NOK/MWh of ten years or less for the buildings constructed before 1969 and 15 years or less for the buildings constructed between 1997 and 2005. The lifetime of retrofits to the HVAC system or the water heater was assumed to be 15 years. The lifetime of retrofits to the windows or other facade elements was assumed to be 30 years. The calculation of the cost of conserved energy was straightforward for the retrofit projects that only included changes to mechanical components. However, it was more complicated for retrofits that included changes to mechanical components and facade elements because they had different lifetimes. For these projects the cost of conserved energy was average cost of conserved energy weighted by the portion of energy savings for retrofits with each lifetime. Therefore, for retrofit projects including both mechanical and facade retrofits, the average cost of conserved energy was calculated as:

$$\overline{CCE} = \frac{S_{mechanical} CCE_{mechanical} + S_{facade} CCE_{facade}}{S_{mechanical} + S_{facade}} \qquad \textbf{13-3}$$

The investment cost and annual reduction in energy consumption attributed to mechanical components and facade elements had to be separated in order to perform this calculation. Any reduction to the heating energy through transmission or infiltration was attributed to changes to the facade. The reductions in energy for ventilation, the fan, and the water heater were attributed to the mechanical components. Any increases in energy consumption for cooling were also attributed to the mechanical components because they were primarily caused by the reduction in ventilation rate in the scenarios with inoperable windows. Decreases in cooling energy due to installation of operable windows were attributed to energy savings from a change to the facade.

Figure 13-11 through Figure 13-13 show the cost of conserved energy in NOK/MWh for each scenario for the buildings constructed before 1969 with discount rates of 5%, 10%, and 20%. A higher discount rate often indicates that the building owner wants to not only break even from the investment in the retrofits, but make a profit over their lifetime. It can also mean that the investor does not intend to stay in the building for a long period of time. Therefore, the investment cost must be recovered in a shorter period of time than the lifetime of the investment. A lower discount rate can indicate that the investor is willing to break even on the project and that the reduction in energy consumption itself was the main goal of the retrofit project. It can also indicate that the investor plans to stay in the building for the full lifetime of the project. Therefore, the profits can be spread over a longer period of time. The scenarios analyzed were the same as those in the payback analysis, shown in Figure 13-3. A conversion rate of 6.5 NOK per US dollar was used to convert the US investment costs to Norwegian kroner.

The results for cost of conserved energy were similar to those from the payback period analysis. The projects that included retrofits to the controls system, HVAC system, and water heater achieved reduced energy consumptions most efficiently. Projects that included retrofits to the windows or other facade elements could be economically viable but had higher costs of conserved energy. Figure 13-11 through Figure 13-13 show that some of the retrofit projects that include improvements to the windows or other facade elements had similar costs of conserved energy to the projects that did not. However, as the discount rate was increased, the groups of scenarios separated. The two groups of scenarios had similar ratios of cost to energy savings, but the total investment cost was greater for the projects that included facade retrofits. Therefore, those scenarios were more affected by the increasing discount rate.

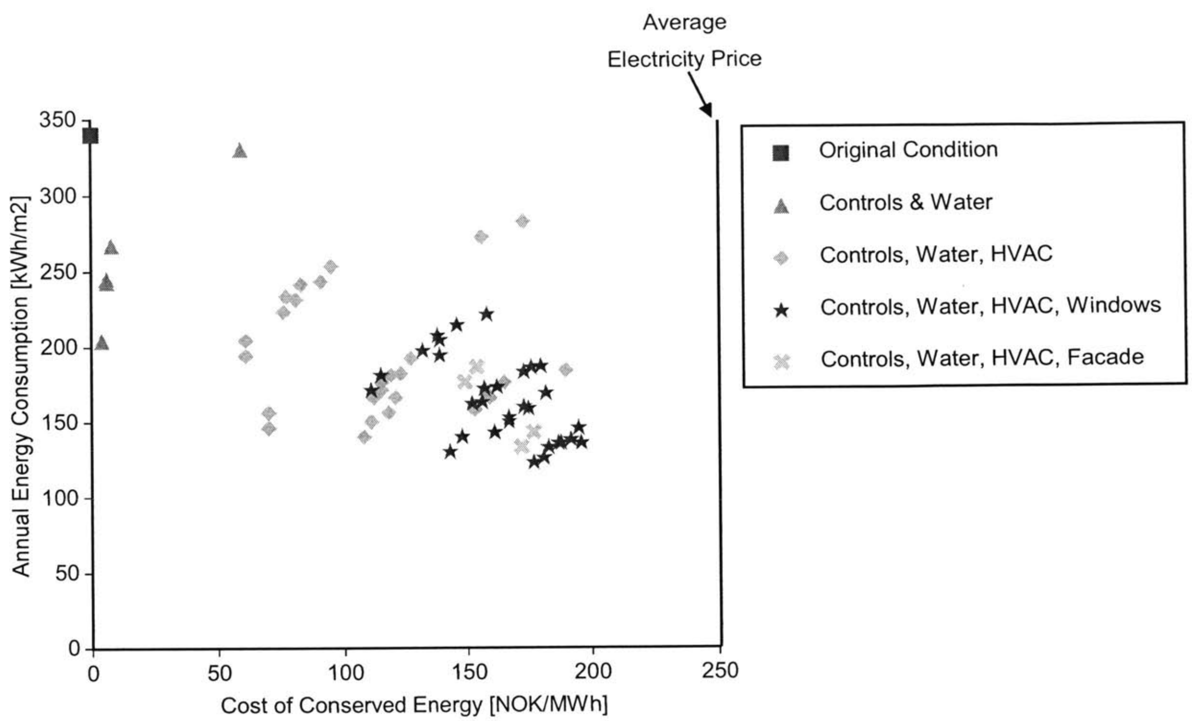


Figure 13-11: Cost of conserved energy at a 5% discount rate for scenarios with payback periods of ten years or less for the buildings constructed before 1969.

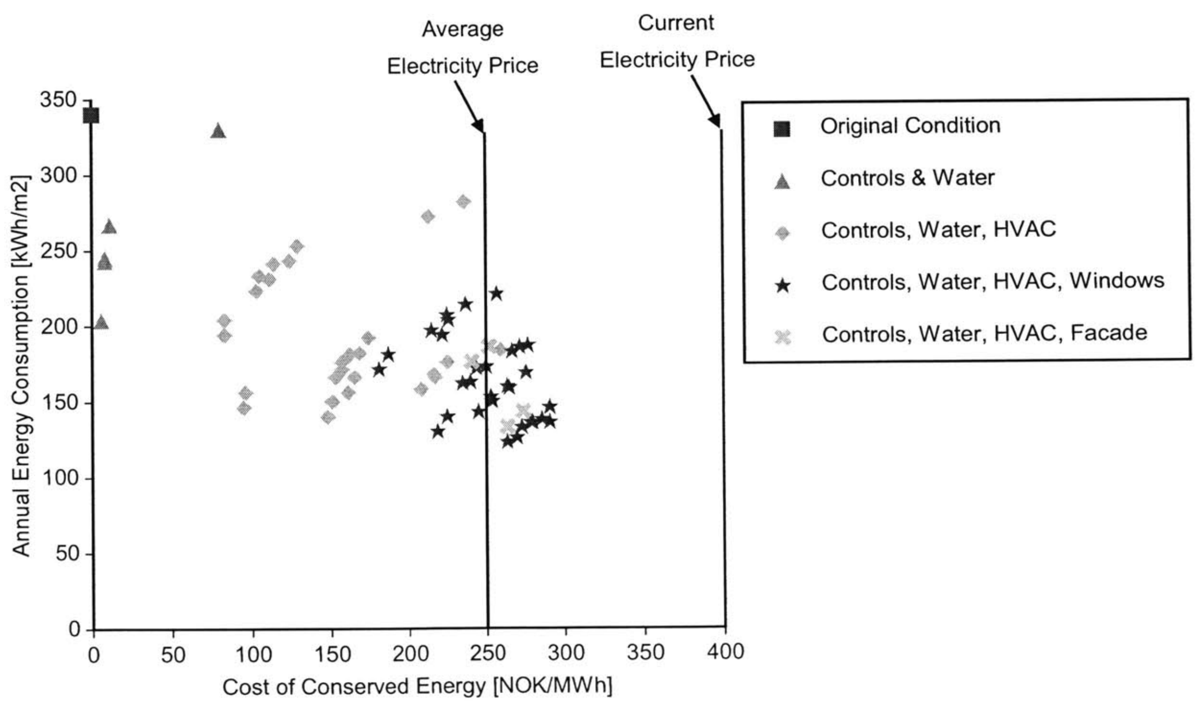


Figure 13-12: Cost of conserved energy at a 10% discount rate for scenarios with payback periods of ten years or less for the buildings constructed before 1969.

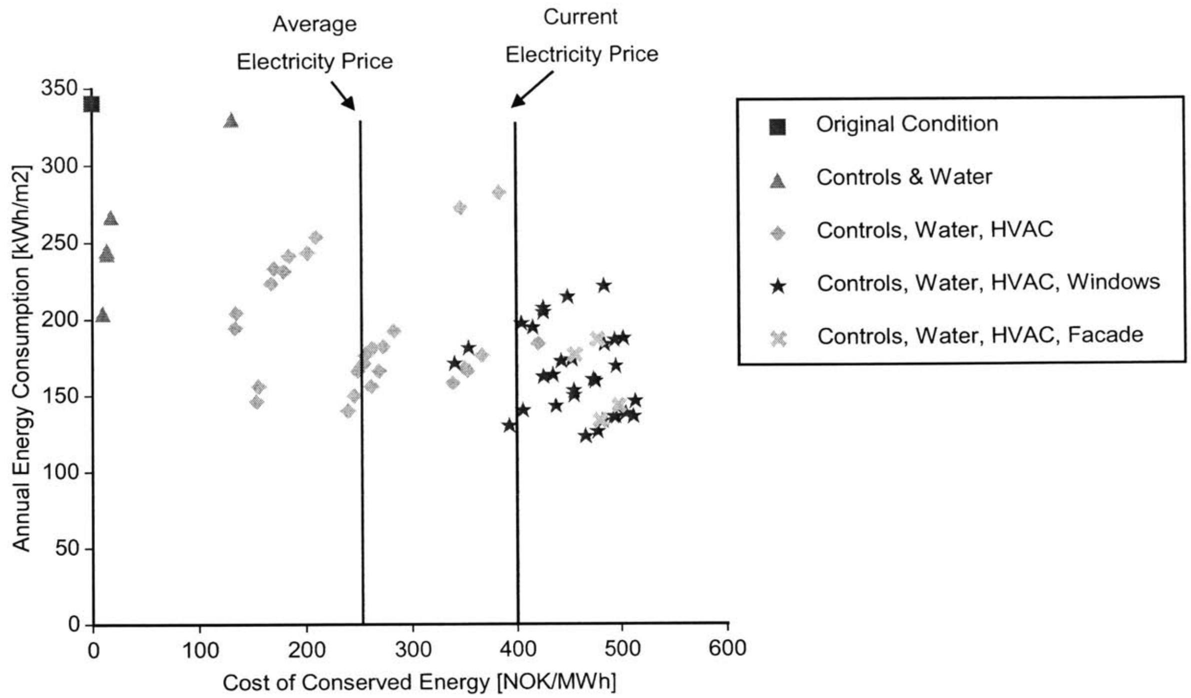


Figure 13-13: Cost of conserved energy at a 20% discount rate for scenarios with payback periods of ten years or less for the buildings constructed before 1969.

Figure 13-11 shows the scenarios for an assumed 5% discount rate. In this case all of the scenarios had a cost of conserved energy below 250 NOK/MWh, the average price of electricity in Norway. Figure 13-12 shows the same scenarios but with a discount rate of 10%. At this rate a group of scenarios, including about half of the scenarios with retrofits to the windows or other facade elements, had costs of conserved energy greater than 250 NOK/MWh. The scenarios with the high cost of conserved energy generally included a heat pump retrofit in addition to the retrofit to the windows or other facade elements, which caused a high investment cost. However, the price of electricity in April of 2006 was about 400 NOK/MWh. If the price of electricity remains this high, all of the scenarios become economically viable. Figure 13-13 shows the results for a discount rate of 20%. In this case about half of the scenarios that included retrofits to the controls system, the HVAC system, and the water heater had costs of conserved energy less than 250 NOK/MWh. These scenarios were primarily combinations of the moderate 1 HVAC scenario in combination with different control scenarios and the retrofit to the water heater. The moderate 1 scenario included the low-energy retrofit to the ventilation fan and the heat recovery system. Two of the scenarios included other HVAC scenarios where a heat pump was installed. These scenarios had the lowest energy consumption, though the cost of conserved energy was just under 250 NOK/MWh. Most of the other scenarios for retrofits to the controls system, HVAC system, and water heater would still be economically viable if the electricity price remains at 400 NOK/MWh. Only three of the retrofit scenarios that included retrofits to the windows were economically viable even at the higher current electricity price. These projects all included the low-energy controls and one of the moderate HVAC retrofits.

The cost of conserved energy for the retrofit projects for the buildings constructed between 1997 and 2005 were also calculated. The results for the scenarios with payback periods of 15 years or less are presented in Figure 13-14 through Figure 13-16.

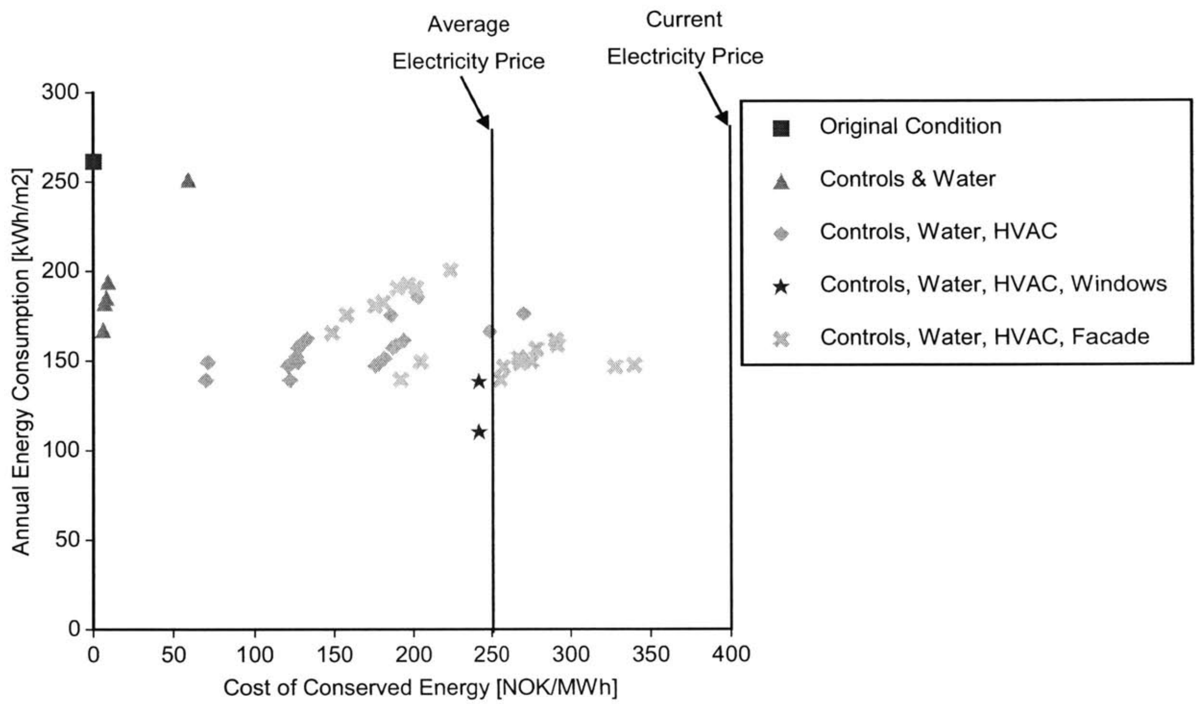


Figure 13-14: Cost of conserved energy at a 5% discount rate for scenarios for the buildings constructed between 1997 and 2005.

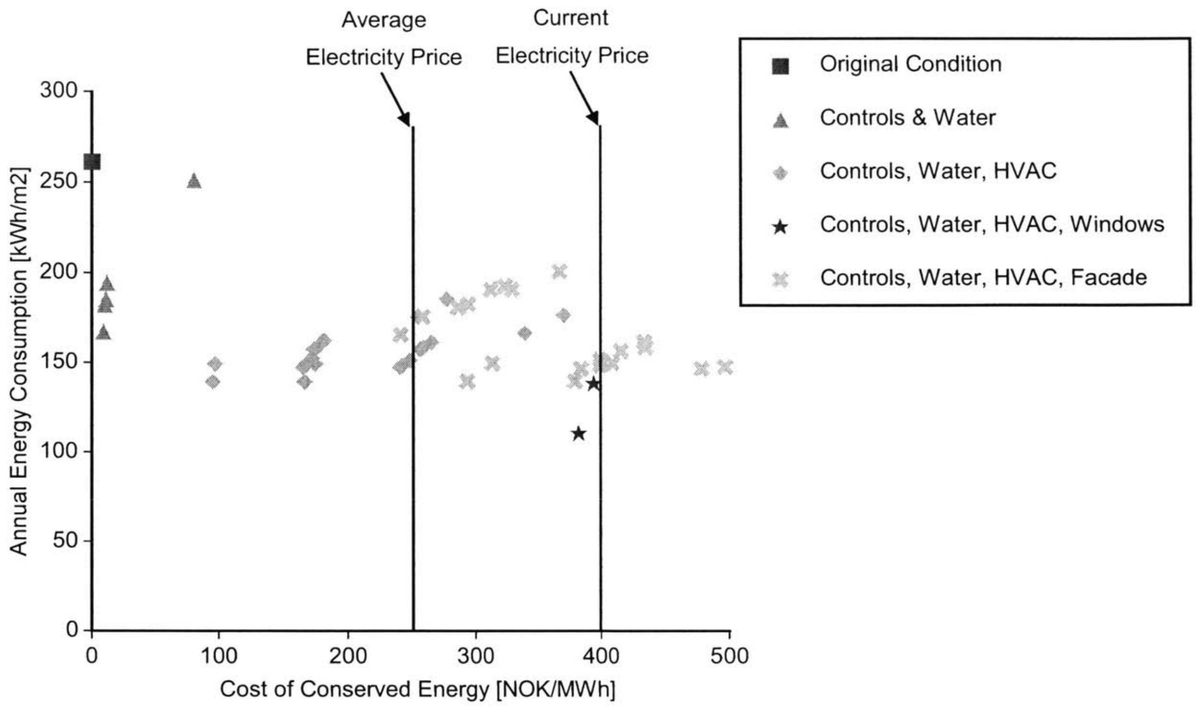


Figure 13-15: Cost of conserved energy at a 10% discount rate for scenarios for the buildings constructed between 1997 and 2005.

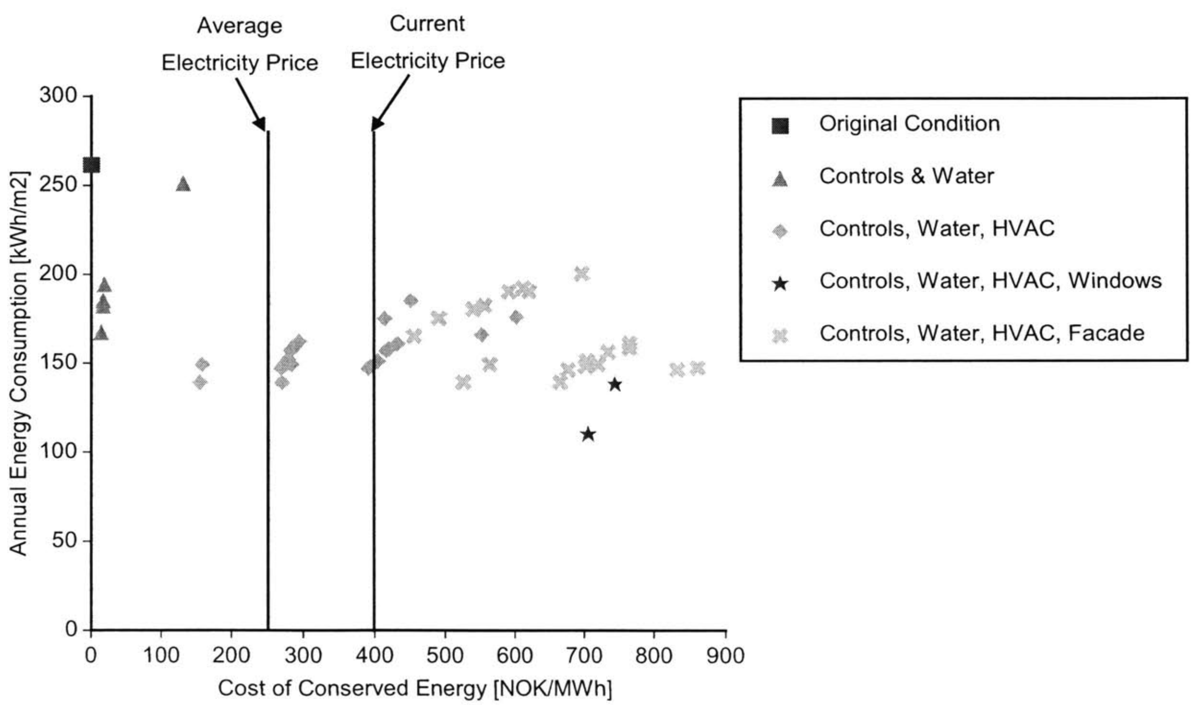


Figure 13-16: Cost of conserved energy at a 20% discount rate for scenarios for the buildings constructed between 1997 and 2005.

The results for the buildings constructed between 1997 and 2005 were similar to the results for the buildings constructed before 1969. Some of the projects that included retrofits to the windows and other facade elements were economically viable even at the current average electricity price. However, if the investor requires a high discount rate, fewer scenarios are economically viable. Many of the retrofit scenarios for the buildings constructed between 1997 and 2005 had higher costs of conserved energy than similar scenarios for the buildings constructed before 1969. This effect was especially apparent for the scenarios that included retrofits to the windows and other facade elements. The investment costs for the buildings from the two construction periods were similar, but the reductions in energy consumption were smaller for the recently constructed buildings. The buildings constructed between 1997 and 2005 had lower annual energy consumption in their original condition than the buildings constructed before 1969, so there was less room for improvement.

13.3 Conclusions

The scenarios that included retrofits to the controls system, the water heater, and the HVAC system were the most economical choice for both indicators. They had payback periods between zero and eight years with an assumed electricity price of 250 NOK/MWh. The cost of conserved energy was less than 250 NOK/MWh if the mechanical equipment had an assumed lifetime of 15 years at a discount rate of 5%. As the discount rate was increased, the cost of conserved energy increased. However, even with a discount rate of 20%, some of the scenarios still had costs of conserved energies less than 250 NOK/MWh. These scenarios always included the low-energy controls settings, but the relevant HVAC scenarios varied between the construction periods. Both analyses also showed that it could be economical to perform retrofits on the facade elements. These retrofit projects had longer payback periods or higher costs of conserved energy, but they were necessary to get the annual energy consumption of the building close to 100 $^{kWh}/_{m^2}$.

14 Extension to National Consumption

The existing office buildings in Norway are not evenly distributed across the construction periods examined in this study. Recall from Chapter 7 that three sources were used to estimate the portion of the existing building stock in each construction period. Data from SINTEF was used to estimate the number of buildings in each construction period. The results were presented in Table 7-3. Data from Enova's statistics and the Office Project were based on divisions of the total floor area. The two results were compared in Table 7-6. All three data sets were used to scale up the energy savings from the individual model buildings to estimate the total effect on national energy consumption. This section will look at the potential reduction in national energy consumption assuming that all office buildings were retrofit. It is unlikely that all buildings would be retrofit at one time, but the results give an upper bound on energy saved and the necessary investment cost. Several of the more attractive scenarios from the retrofit analysis and the economic analysis were selected for comparison including the complete overhaul, two controls system scenarios, installing a heat pump, and two scenarios with a 5 year or less payback period. For more information on how payback periods were calculated, see Chapter 13.

14.1 Original Consumption

The simulation program estimated energy consumptions for the model buildings in their original condition between 255 and 341 $^{kWh}/_{m^2}$. These values and the proportions of total floor area or number of buildings from each construction period were used to estimate the total consumption of all office buildings in Norway. Using the floor area from the Enova study predicted a total consumption of about 47 PJ; the floor area data from the Office Project predicted a total consumption of about 30 PJ. The data for number of buildings from SINTEF estimated a total consumption of 56 PJ.

Recall from Section 6.3 that the best estimate for the total consumption of office buildings was 19 PJ. Another estimate, which included both office and retail buildings was, 51 PJ. The estimations of total energy consumption from the simulation program are much closer to 51 PJ than 19 PJ. The estimation for total energy consumption was expected to be high because the specific energy consumptions predicted by the simulation program were higher than those reported in the building monitoring projects. It was not expected that the estimated consumption would be almost as high as considering both office and retail buildings.

However, the existing estimations for total energy consumption and total floor area are inconsistent with the data on specific energy consumption of office buildings. The total floor area estimated from the Enova data and the Office Project were 53 million and 30 million m^2 [Enova 2004] [Burton 2002]. Estimates of the specific energy consumption of office buildings based on these figures for total floor area and the two estimates for total energy consumption of office buildings are provided in Table 14-1. Recall that the specific energy consumption from building monitoring projects varied from about 200 to about 265 $^{kWh}/_{m^2}$. Enova's floor area combined with the high total energy consumption produced an estimate for specific energy consumption of office buildings close to the measured data. With the Office Project's estimated floor area, the low total energy consumption had to be used to get a specific energy consumption close to measured data.

National Energy Consumption Estimates	**Floor Area Estimates** Enova: 53 million m^2	Office Project: 30 million m^2
Office Buildings Only: 19PJ	100 $^{kWh}/_{m^2}$	269 $^{kWh}/_{m^2}$
Office and Retail Buildings: 51PJ	177 $^{kWh}/_{m^2}$	467 $^{kWh}/_{m^2}$

Table 14-1: Specific energy consumption of office buildings based on estimates of total energy consumption and total floor area of office buildings [Enova 2004] [Burton 2002].

It is not clear if these inconsistencies are the fault of errors in the estimations for total energy consumption or total floor area of office buildings. However, using the specific energy consumptions with the best estimates of floor area or number of buildings in each construction year produces estimates for total energy consumption that are reasonable in comparison to the best available data. The change in energy consumption between the model buildings original state and their retrofitted states should apply, even if the exact totals are questionable.

14.2 Reduction in National Energy Consumption

Table 14-2 shows the percent reduction in calculated national energy consumption for six retrofit scenarios using the scaling data from Enova, the Office Project, and SINTEF. The percent reduction was between the calculated total consumption for the model buildings' original conditions and the calculated new consumption after retrofitting. The six scenarios were: complete overhaul, best controls, moderate controls, best payback of five years or less, and best payback of five years or less with moderate controls. The complete overhaul scenario indicated that all attributes in all the building systems were retrofit to the low-energy condition for all the model buildings. The best controls scenario indicated that all the model buildings used the low-energy control system scenario in the simulations, but none of the other systems were altered. The moderate controls scenario used the moderate 1 controls scenario in the simulations, but none of the other systems were altered. The heat pump scenario assumed that all of the buildings installed a heat pump, but no other conditions were altered. The final two scenarios were chosen from the multi-systems retrofitting strategies with payback periods of five years or less. The applicable scenarios were combinations of changes to the controls system, the HVAC system, and replacing the water heater. No changes were made to the buildings' windows or other facade elements. For the best payback scenario, all of the buildings used the low-energy controls and replaced the water heater. For the HVAC scenario the buildings constructed before 1969 used the low-energy scenario, the buildings constructed between 1969 and 1979 and between 1997 and 2005 used the moderate 1 scenario, and the both construction periods between1980 and 1996 used the moderate 2 scenario. The scenarios for the best payback less than five years with moderate controls were very similar. They all used the moderate 1 controls scenario. The HVAC and water heating scenarios were unchanged, except that the buildings constructed before 1969 did not retrofit the water heater.

	Enova		Office Project		SINTEF	
	% Reduction	**Cost**	**% Reduction**	**Cost**	**% Reduction**	**Cost**
Complete Overhaul	76%	19	77%	11	76%	21
Best Controls	35%	0	36%	0	36%	0
Moderate Controls	24%	0	25%	0	25%	0
Heat Pump	27%	1.5	29%	0.9	27%	1.6
Best Payback 5 Years or Less	53%	1.3	55%	0.8	54%	1.3
Best Payback 5 Years or Less with Moderate Controls	47%	1.4	49%	0.8	48%	1.4

Table 14-2: Percent decrease in energy consumption for office buildings for six scenarios based on the scaling factors for the portion of buildings or floor area in each construction period from Enova, the Office Project, and SINTEF. Costs are the initial investment cost in billions of US dollars.

Retrofitting every attribute of every building system with the low-energy option would reduce the total consumption of office buildings by about 76% and cost between 10 and 20 billion dollars. Simply changing the controls system, which has no associated investment cost, could reduce the energy consumption by up to 36%. However, the low-energy controls scenario had temperature set points slightly below accepted comfort conditions. The total energy consumption was reduced by about 25% by simply turning ventilation rates down to the rates defined in the 1997 building code and operating the building at 21°C during the winter.

The controls scenarios were attractive because they do not require an investment cost. However, the best payback scenarios reduce the energy consumption by 20 to 30% more, and the costs would be returned through saved energy expenditures in five years or less. The costs listed on Table 14-2, which vary from 0.8 to 1.5 billion dollars, were the total investment costs required to complete the projects. All of that money would be paid back in five years or less at current electricity prices in Norway.

Table 14-3 and Table 14-4 show the percent reduction in total energy for the buildings sector and total domestic consumption that resulted from the six scenarios for retrofitting the office buildings. The retrofit scenarios and costs are the same as in Table 14-2. The total energy consumed by buildings, 300 PJ, and the total domestic consumption, 800 PJ, were based on statistical information in 2004 [SSB 2006]. The decreases in consumption were the difference in calculated energy consumption between the model buildings original consumption and the consumption after completing the retrofit projects.

	Enova		**Office Project**		**SINTEF**	
	% Reduction	**Cost**	**% Reduction**	**Cost**	**% Reduction**	**Cost**
Complete Overhaul	14%	19	8%	11	15%	21
Best Controls	6%	0	4%	0	7%	0
Moderate Controls	4%	0	3%	0	5%	0
Heat Pump	5%	1.5	3%	0.9	5%	1.6
Best Payback 5 Years or Less	10%	1.3	6%	0.8	11%	1.3
Best Payback 5 Years or Less with Moderate Controls	9%	1.4	5%	0.8	9%	1.4

Table 14-3: Percent decrease in energy consumption for the entire buildings sector based on the six scenarios of decreasing energy consumption in office buildings and all three scaling methods. Costs are the initial investment cost in billions of US dollars.

	Enova		Office Project		SINTEF	
	% Reduction	Cost	% Reduction	Cost	% Reduction	Cost
Complete Overhaul	5%	19	3%	11	6%	21
Best Controls	2%	0	1%	0	3%	0
Moderate Controls	2%	0	1%	0	2%	0
Heat Pump	2%	1.5	1%	0.9	2%	1.6
Best Payback 5 Years or Less	4%	1.3	2%	0.8	4%	1.3
Best Payback 5 Years or Less with Moderate Controls	3%	1.4	2%	0.8	4%	1.4

Table 14-4: Percent decrease in energy consumption for all domestic consumption based on the six scenarios of decreasing energy consumption in office buildings and all three scaling methods. Costs are the initial investment cost in billions of US dollars.

Completely overhauling the office buildings reduced energy consumption in the buildings sector by 8 to 15% and reduced total domestic consumption by 3 to 6%. Altering the buildings' control systems could reduce energy consumption by 3 to 7% for the buildings sector and by 1 to 3% for total domestic energy consumption. Performing the retrofits in the best payback scenarios reduced energy consumption in the buildings sector by 5 to 11% and the energy consumption of the domestic sector by 2 to 4%. Similar retrofit projects could likely be performed on other building types as well. Significantly higher reductions in total energy consumption could be possible by retrofitting all building types.

15 Conclusions

Retrofitting office buildings has significant potential to reduce national energy consumption in Norway. A complete overhaul of the existing buildings could reduce the energy consumption of a single building by 70 to 80%. If every office building in the country were to undergo a complete overhaul, the total energy consumption of office buildings would be reduced by about 75%. The total consumption of the buildings sector would be reduced by 8 to 15%, and the total domestic energy consumption would be reduced by 3 to 6%.

However, it would cost about 400 $\$/m^2$ to completely overhaul an office building, which is not economical based on the cost of saved energy alone. The main focus of this project was to determine what retrofitting technologies or methodologies achieve significant energy reductions most efficiently. The background research revealed that the majority of Norwegian office buildings are already using some energy-conscious methodologies. Most buildings already use temperature and ventilation setbacks, so less energy is wasted when the buildings are not occupied. Most buildings were also constructed or retrofit with heat recovery in the ventilation system. Therefore, the waste heat from the building is used to preheat the incoming ventilation air and less heat must be supplied by the heating system.

Even with these best-practice techniques, there was a lot of potential to continue to reduce the energy consumption of the office buildings. The model buildings had different initial characteristics depending on the most common construction methods at the time they were built and any retrofits that have likely been performed since. Therefore, the simulation program predicted different energy consumptions for each building. However, the overall trends of the effectiveness of various retrofits held true for all the model buildings, even if the absolute energy consumption was different. Some significant differences in behavior were apparent in buildings with and without cooling systems.

Changing the temperature and ventilation set points in the controls system was the best method for reducing energy consumption for all of the model buildings. Most office buildings in Norway already have night setback of ventilation and indoor temperature through an automated control system or done manually by the building maintenance personnel. Therefore, changing the set points is essentially free. Due to the high ventilation rates currently used, reducing the ventilation rates was more effective than reducing the indoor temperature in winter, though both were beneficial. Changing both the ventilation rates and indoor temperature could reduce the energy consumption of a single building by 30 to 40%, which could reduce the energy consumption of all office buildings by about 35%. However, the assumptions in the lowest energy controls scenarios were slightly below accepted comfort conditions. Even reducing ventilation rates to the minimum values in the 1997 building code and reducing the indoor air temperature from 23°C to 21°C in winter would reduce the energy consumption of the model buildings by 20 to 30%, which could reduce the energy consumption of all office buildings by about 25%. Energy consumption in the buildings sector would be reduced by 3 to 5%, and total domestic energy consumption would be reduced by 1 to 2%.

Retrofitting the HVAC system was the other most effective way to reduce energy consumption in the model buildings. The analysis considered the efficiency of the ventilation fan and heat recovery system as well as the benefits of installing a heat pump. All of the model buildings were assumed to have a preexisting heat recovery system. If an individual building does not, this would be an extremely effective retrofit to perform. Installing a heat pump had a very large effect on total energy consumption when there was a large heating requirement. However, the influence of the heat pump lessened as the overall performance of the building was improved. Heat pumps also still rely on electricity. As there is currently a need in Norway to diversify fuel use away from electricity, broad use of heat pumps may not be reasonable. However, they are still a very effective single retrofit to make to an existing building with a high heating requirement. The effectiveness of changing the heat recovery system or ventilation fan depends on the efficiencies of the current systems and the buildings' ventilation rates. Therefore, there was no one obvious technology within the HVAC system to promote. The best method for decreasing energy consumption depended on the specific conditions in the building. However, there was a large potential to decrease energy consumption by improving the HVAC components in all of the model buildings. The energy consumption of the model buildings could be reduced by 30 to 45% through these retrofits. Energy consumption in the buildings sector would be reduced by about 40%.

Combining changes to the controls system and the HVAC system was the most economical way of achieving a low energy consumption in both the payback period analysis and the cost of conserved energy analysis. Retrofitting components from both systems could reduce the energy consumption of the model buildings by about 45 to 55%, which is about two-thirds of the total possible reduction. This would reduce the energy consumption of the office buildings by about 50%. The energy consumption of the buildings sector would be reduced by about 9 to 13%, and total domestic consumption would be reduced by 3 to 5%.

Retrofitting the buildings' windows could also be an economical choice. It was especially beneficial for buildings that had a cooling system but did not have operable windows. Simulations showed that the fairly cool climate in Norway meant that opening windows during warm weather could essentially eliminate the need for cooling systems. The moderate retrofit was the most economical choice for all the buildings, whether they had cooling systems or not. Additional insulation was provided, but they were inexpensive enough that some retrofits to the HVAC system could also be made to achieve a reasonable payback period. Installing the low-energy windows was too expensive. Changes to the HVAC system could not be made in addition to the windows retrofit, and the buildings would have a higher overall energy consumption. Retrofitting windows in addition to the controls and HVAC retrofits was necessary for the model buildings to achieve an annual energy consumption near 100 $^{kWh}/_{m^2}$. This consumption is a reduction of about 60 to 70%. It would reduce the energy consumption of the office buildings by about 65%. The energy consumption of the buildings sector would be reduced by about 12 to 15%, and total domestic consumption would be reduced by about 4 to 6%.

Performing the moderate retrofits to the facade could have payback periods less than 15 years when paired with changes to the HVAC and controls systems. However, the annual energy consumption of the model buildings was always higher for these scenarios than for similar cases when the windows were retrofit. This result was especially apparent in newer buildings whose insulation levels are already close to best practice. Retrofitting the facade was shown to be unlikely to be an attractive retrofit to perform in order to reduce energy consumption.

Retrofitting the lights and office equipment was shown to reduce energy consumption of the buildings by 6 to 10%, which would reduce the national consumption of office buildings by about 8%. These retrofits were not shown to be economical in this study if performed solely to improve efficiency. However, the economic analysis was set up in a way that all of the replacements had to be performed at one time. These components have very short lifetimes in comparison to the other retrofits in the study. The reduction in energy consumption could easily be achieved and the investment cost spread out if the low-energy choice was made every time a computer, light fixture, or other component had to be replaced.

The main point to take away from this study is the importance of the behavior of the people that work in, own, and operate office buildings. Making energy-conscious choices on a daily basis added up to very large reductions in energy consumption. These choices could include making responsible selections for indoor temperature and ventilation rates that maintain occupant health and comfort but are not overly conservative such that they waste energy. Turning off lights and office equipment when they are not in use could also reduce energy consumption significantly. These choices can in some cases be removed from the occupants' consciousness through more advanced controls systems than were considered in this study.

Energy conscious choices during major building renovations are also important. A building can last for about 100 years. Over the building's lifetime major renovations on the facade are likely to be performed one to four times. Major renovations would be performed on the mechanical equipment 5 to 15 times, and to the interior elements 10 to 100 times. This analysis has shown that many retrofits are profitable during their lifetime due to their energy savings alone. Many more would be worthwhile considered from the perspective of a system or component that is being replaced anyway. The difference in cost between a low-energy component and the original system may not be prohibitive. However, there is currently no organized system to make it easy to compare the cost of low-energy construction projects to more standard choices. Such a system would be useful everywhere, not just in Norway.

This study revealed many economical and effective ways to reduce the energy consumption of Norwegian office buildings. Making people aware of the economical and environmental benefits of retrofits to a single building and on a national scale could drastically reduce energy consumption in the buildings sector. This study only considered the potential for energy reduction from retrofitting office buildings. Similar reductions are likely possible through retrofitting other building types as well. More analysis is needed to determine the total reduction possible from retrofitting other building types.

16 Appendix A

16.1 Frost and Ice in Norwegian Heat Exchangers

Frost and ice formation is typically a negligible problem in rotary heat exchangers. The outdoor temperature where frost begins to form, the frost threshold temperature, is typically around -12 to -17°C depending on the humidity of the indoor air and the heat exchanger effectiveness. In winter, humidity will be low, which lowers the frost threshold temperature even more, unless the ventilation system includes a humidifier. Typically, small heat gains from the ducting systems are enough to completely prevent frost or ice formation [Hogeland 2005]. Rotary heat exchangers have low frost threshold temperatures because they transfer both enthalpy and heat and because frost can only form on a small portion of the surface area [Stang 2005]. Plate heat exchangers with high efficiencies typically have much higher frost thresholds, -7 to -4°C, because they typically do not transfer enthalpy and more of the surface area is susceptible to ice formation [Hogeland 2005].

Several methods exist for preventing or removing frost and ice in both rotary and plate heat exchangers. Frost and ice formation can be prevented by reducing the heat exchanger effectiveness by reducing the speed of rotation in rotary heat exchangers or bypassing some supply air in both plate and rotary heat exchangers. Once formed, frost and ice can be removed by shutting off both the supply and exhaust fans or by recirculating the warm exhaust air while the supply air is shut off. Studies have shown that recirculating the exhaust-air allows both plate and rotary heat exchangers to function at essentially their ideal effectiveness with supply air at -20°C [Phillips 1992].

However, the plate heat exchangers that were installed in Norway in the 1980s and 1990s use bypass air to prevent the formation of frost and ice, so the simulation program must consider if the effectiveness is reduced in these cases. The frost threshold temperature for frost and ice growth without limit in a counter-flow heat exchanger during balanced flow with no latent heat transfer is calculated as:

$$T_{frost} = \left(\frac{-6}{\varepsilon}\right)\left(1 + 1.75\phi_{in}\right)\left[1 + \frac{0.012}{\varepsilon}\left(T_{in} - 20\right)\right] \qquad \textbf{16-1}$$

where T_{frost} is the frost threshold temperature in degrees Fahrenheit for frost and ice growth without limit, ε is the heat recovery effectiveness, ϕ_{in} is the relative humidity of the indoor air, and T_{in} is the indoor air temperature in degrees Fahrenheit [ASHRAE 2004]. The temperature where frost would first begin to form is an unknown temperature, greater than this frost threshold temperature. The frost threshold temperature can be converted to degrees Celsius and compared to the outdoor temperature to determine if frost is a problem for the plate heat exchangers. Assuming typical conditions, an indoor temperature of 23°C, an indoor relative humidity of 40%, and an effectiveness of 60%, the outdoor temperature must be -37°C for frost formation to overwhelm the heat exchanger. The METEONORM weather data for Oslo does not list a single hour with an outdoor temperature below -19°C. This is a great enough difference to assume that frost will not be a serious problem for heat exchangers used in Norway in the 1980s and 1990s.

Since frost should not be a problem in the specific heat exchangers used in Norway, the simulation program does not take frost into account.

16.2 Heat Loss with Heat Recovery

The effectiveness of a balanced counterflow heat exchanger is defined as:

$$\varepsilon = \frac{T - T_i}{T_h - T_i} \qquad \textbf{16-2}$$

where T is outlet the temperature of the cold stream (the supply temperature) °C, T_h is the inlet temperature of the warm stream (the temperature of the building) in °C, and T_i is the inlet temperature of the cold stream (the outdoor temperature) °C. This definition can be rewritten as:

$$T = T_i + \varepsilon \cdot (T_h - T_i)$$

Or

$$T = T_{out} + \varepsilon \cdot (T_{in} - T_{out}) \qquad \textbf{16-3}$$

The ventilation heat loss must be split into two heat loss terms which separate the portions of ventilation air that do and do not go through the heat recovery system. The total heat loss can therefore be written as:

$$Q_{Av} = \rho \cdot c_p \cdot n_v [(1 - phr)(T_{in} - T_{out}) + phr(T_{in} - T)] \qquad \textbf{16-4}$$

Substituting Equation 16-3 into Equation 16-4 reveals that:

$$Q_{Av} = \rho \cdot c_p \cdot n_v [(1 - phr)(T_{in} - T_{out}) + phr(1 - \varepsilon)(T_{in} - T_{out})]$$

which simplifies to :

$$Q_{Av} = \rho \cdot c_p \cdot n_v (T_{in} - T_{out})(1 - phr \cdot \varepsilon) \qquad \textbf{16-5}$$

16.3 Florida Solar Energy Method

The additional ventilation air from open windows was calculated using the Florida Solar Energy Method [Allard 1998]. This method assumes that the building has equal inlet and outlet areas for wind driven natural ventilation and that the windows have screens with a porosity of 0.6. From a design perspective, the necessary open area for a given air change rate is empirically defined as:

$$TotalOpenArea = \frac{0.00079V(ach)}{Wf_1 f_2 f_3 f_4} \qquad \textbf{16-6}$$

where the TotalOpenArea is the inlet and outlet areas in ft^2, V is the building volume in ft^3, ach is the ventilation rate in air changes per hour, W is the wind velocity at a meteorological station in miles per hour, f_1 takes into account the incident angle of the wind, f_2 is the terrain factor, f_3 is the neighborhood correction factor, and f_4 accounts for the height of the building.

The ventilation rate from open windows can be estimated using this empirical formula, since the window area is defined in the simulation program. Assuming that half of the window area is open when a window is opened, the open area for one building wall is about 225 m^2 or 2422 ft^2. The building volume is about 18,000 m^3 or 635,700 ft^3, the average wind velocity is Oslo is about 2.12 m/s or 4.7 mph, f_1 was chosen to be 0.35 for perpendicular wind, f_2 was chosen to be 0.67 for a suburban terrain, f_3 was chosen to be 0.5 for moderately spaced buildings, and f_4 was chosen to be 1.15 for a normal building height [Allard 1998] [Schild 2002].

The calculated air change rate is about 2.3 air changes per hour or 11.5 m^3/s. To verify that this is a reasonable number, this air change rate was converted to a wind velocity at the window assuming that wind is only incident on one wall and that half of the total window area is open. The wind velocity at the window is 0.4 m/s.

The wind velocity at the window can also be calculated by assuming there is no resistance to flow within the building [ASHRAE 2005]. In this case, assuming the inlet and outlet areas are equal, the velocity at the window is defined as:

$$V = C_D \sqrt{0.45 V_\infty^2} \qquad \textbf{16-7}$$

where V is the velocity at the window in m/s, C_D is the discharge coefficient, and V_∞ is the velocity at the meteorological station in m/s. Assuming a discharge coefficient of 0.6 for a rectangular box, the velocity at the window is about 1 m/s, which is a little more than double the value from the using the Florida Solar Energy Method.

Since a real building will have internal resistance and be affected by its surrounding environment, the value from the Florida Solar Energy Method will be used. Given the uncertainty in choosing the empirical coefficients, the simulation program assumes that the velocity at the window is about 0.5 m/s. The factor of 0.0625 in Equation 9-18 is this 0.5 m/s times ¼, assuming wind is incident on only one wall, times ½, assuming half of the window area is open.

17 Appendix B

This section describes the retrofit scenarios chosen from the results of the systems analysis for use in the multi-systems analysis. The graph of total energy consumption for each scenario of each system and construction period will be presented. The points that correspond to the selected scenarios will be highlighted with large solid block points in the shape of a square, diamond, triangle, circle, or star. These points correspond to the original conditions, the moderate 1 scenario, the moderate 2 scenario, the moderate 3 scenario, and the low-energy scenario. A visual schematic of the combination of attributes included each scenario will also be included.

17.1 Pre 1969 Construction Period

17.1.1 Controls System

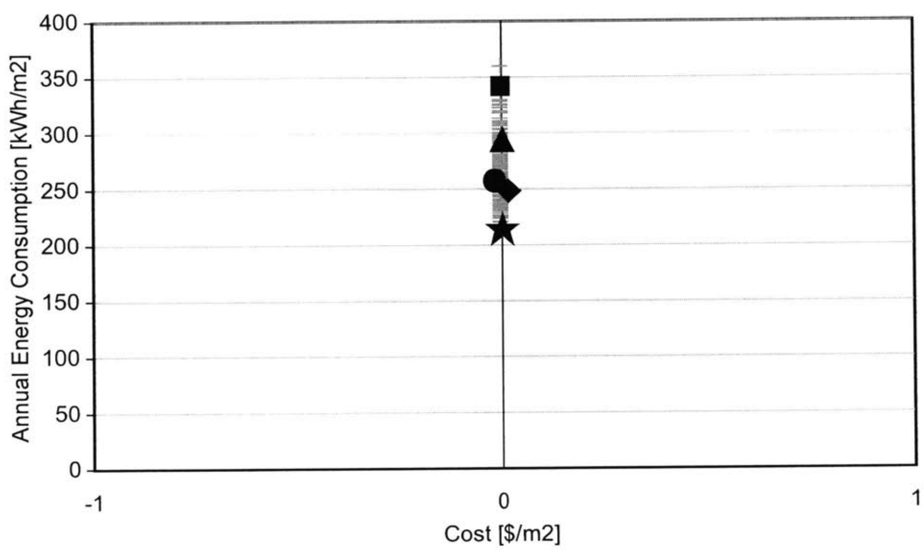
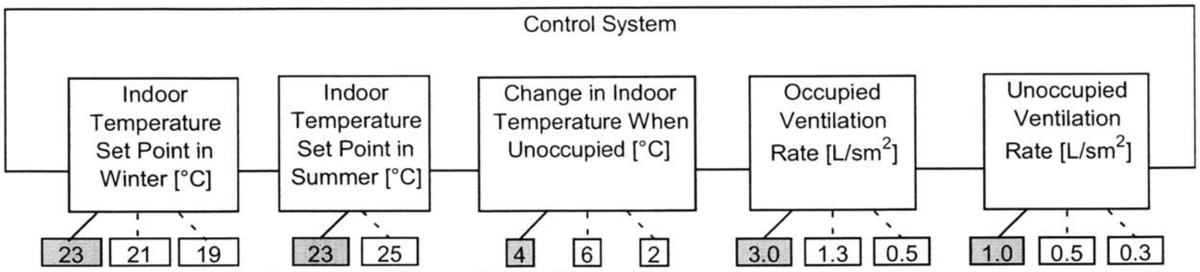
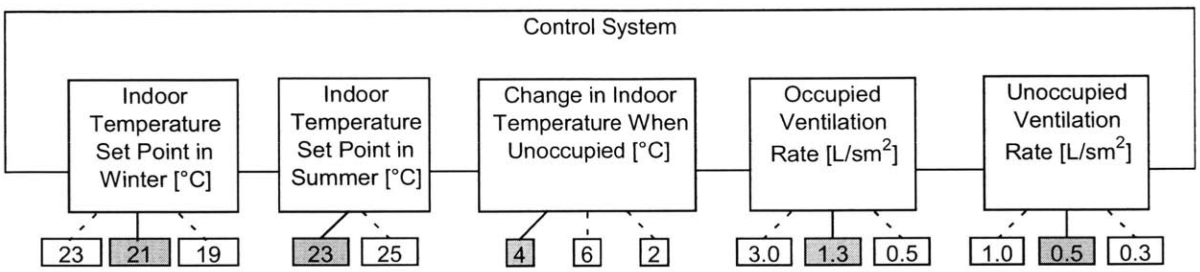


Figure 17-1: Retrofit scenarios for the controls system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

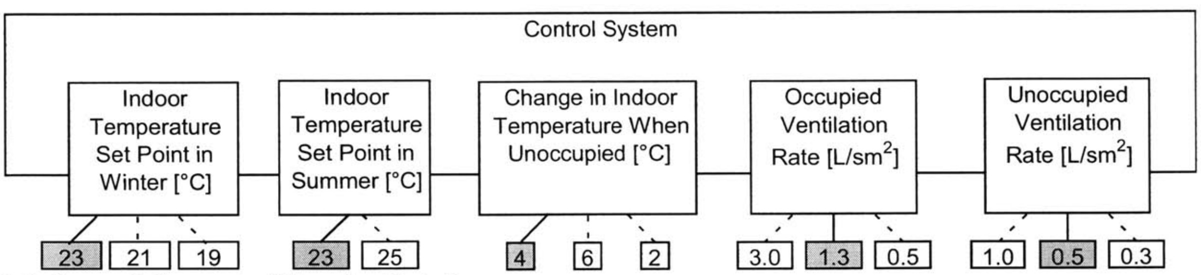
Original Conditions (Square Point):



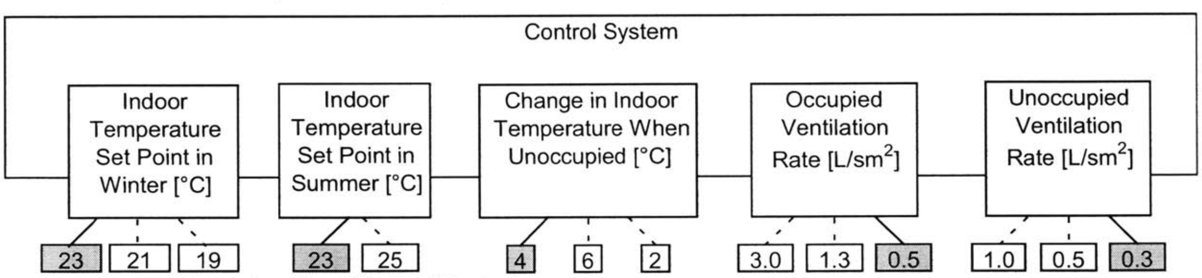
Moderate 1 Scenario (Diamond Shaped Point):



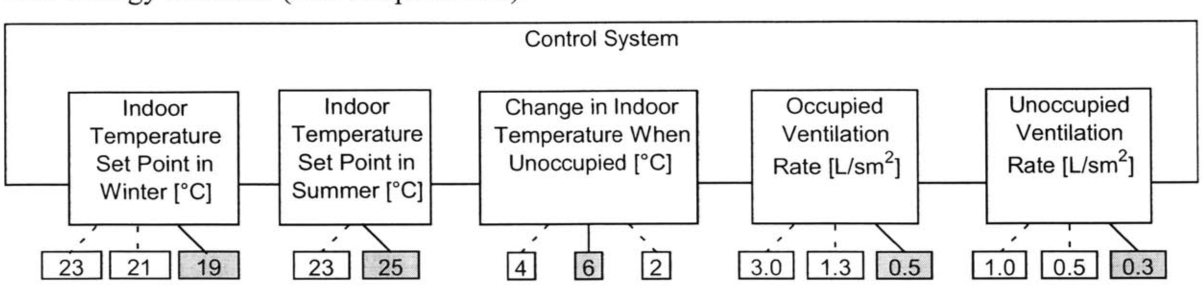
Moderate 2 Scenario (Triangular Point):



Moderate 3 Scenario (Circular Point):



Low-Energy Scenario (Star Shaped Point):



17.1.2 HVAC System

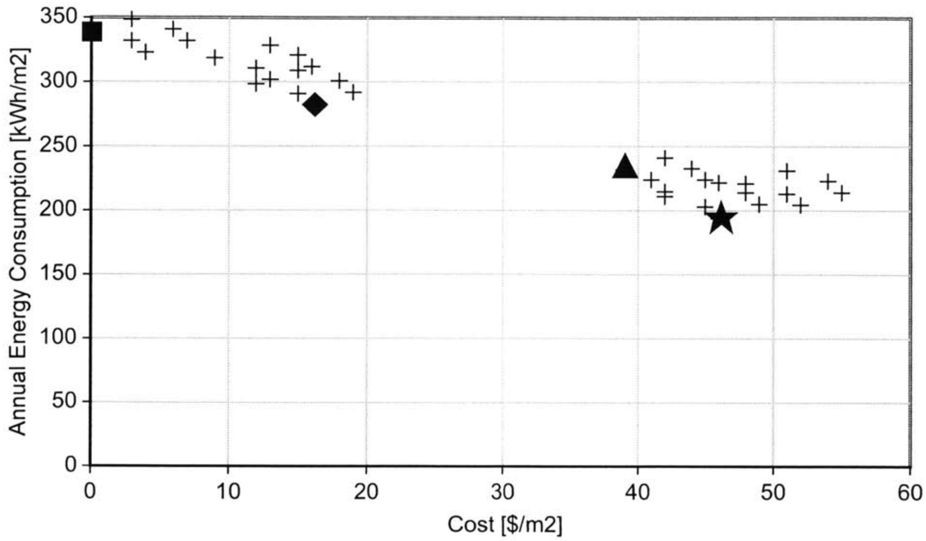
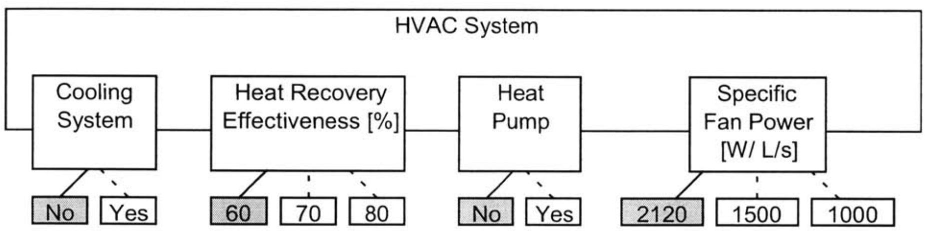
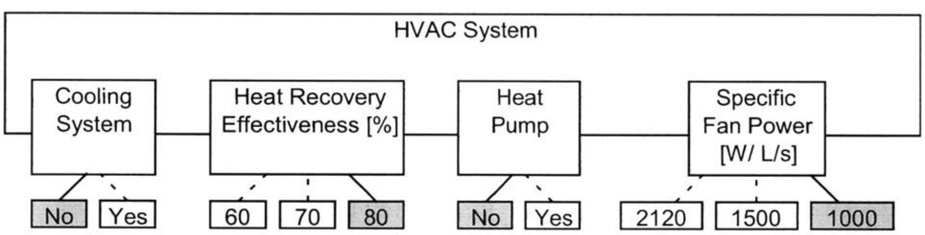


Figure 17-2: Retrofit scenarios for the HVAC system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

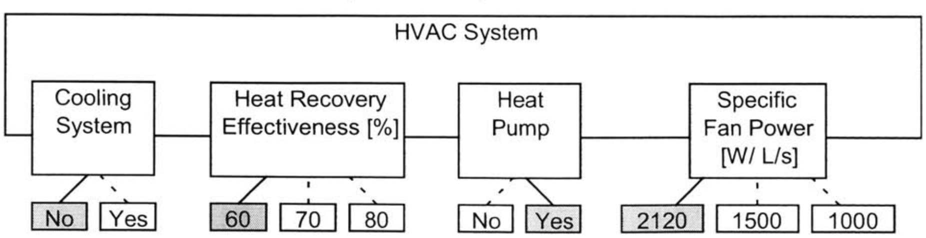
Original Conditions (Square Point):



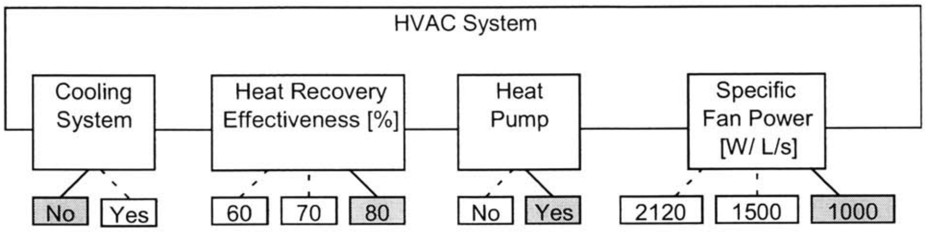
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.1.3 Windows

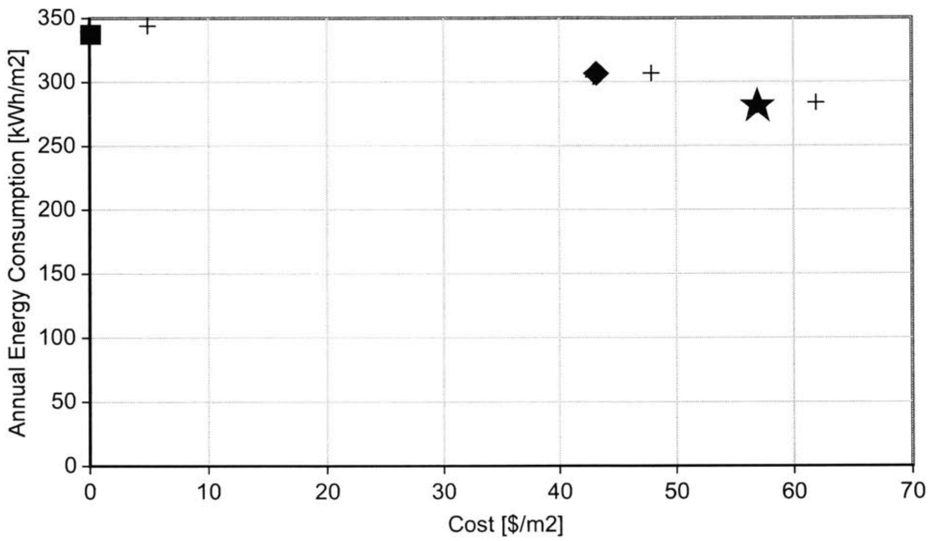
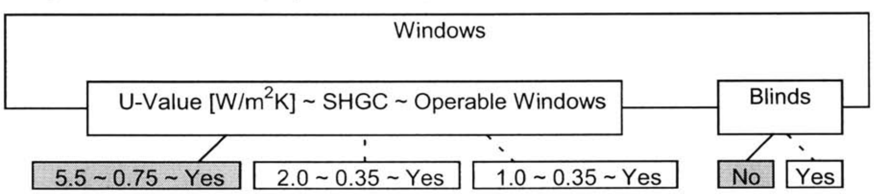
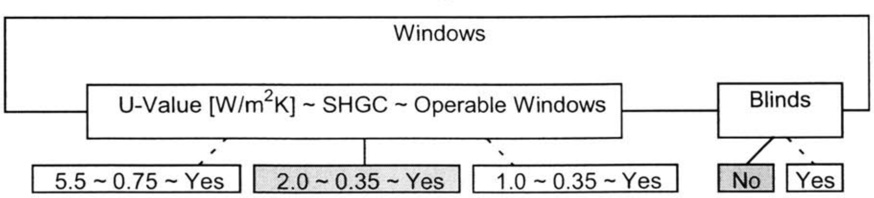


Figure 17-3: Retrofit scenarios for the windows of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

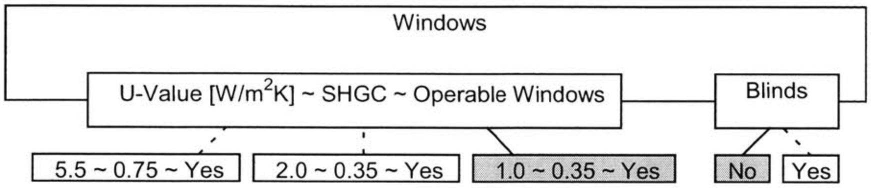
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.1.4 Non-Window Facade System

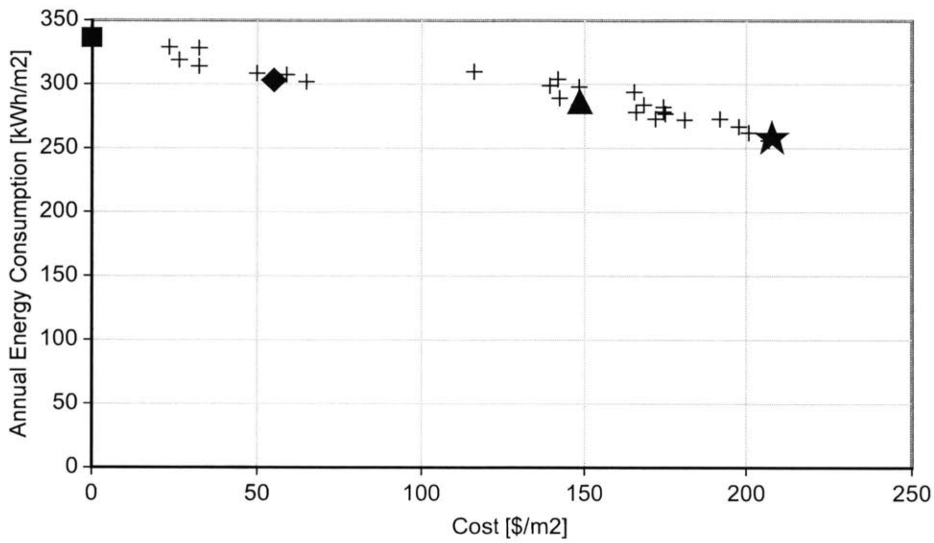
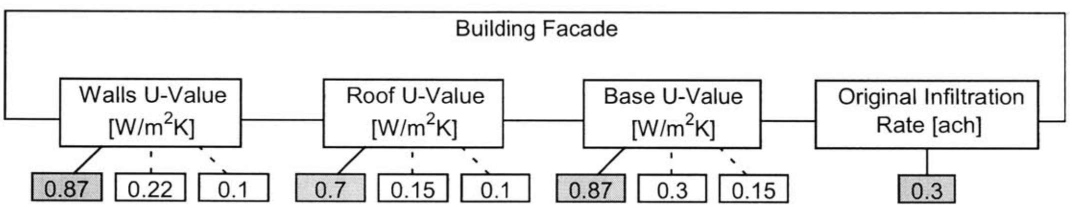
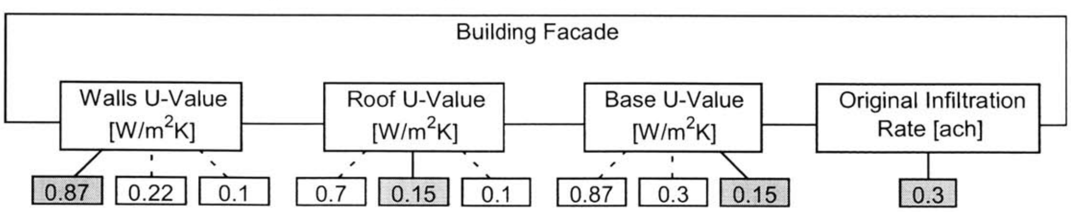


Figure 17-4: Retrofit scenarios for the non-window facade system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

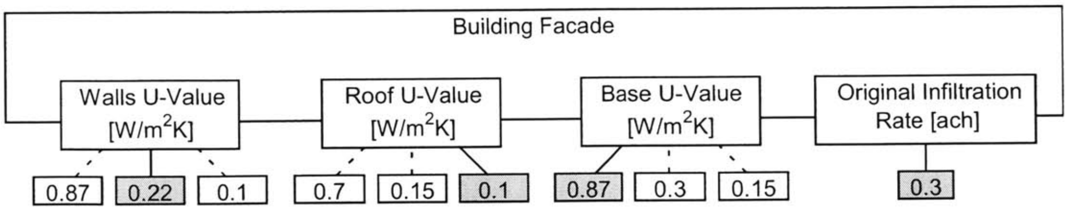
Original Conditions (Square Point):



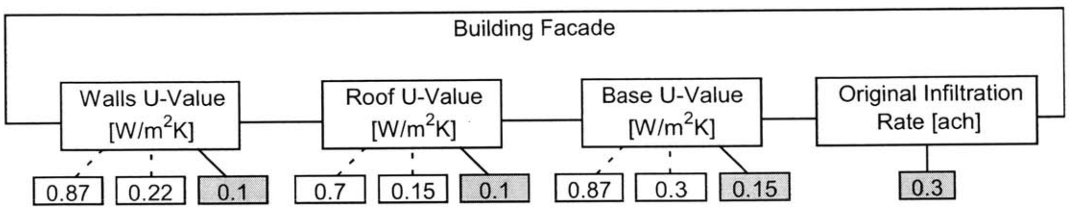
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.1.5 Other Energy Services System

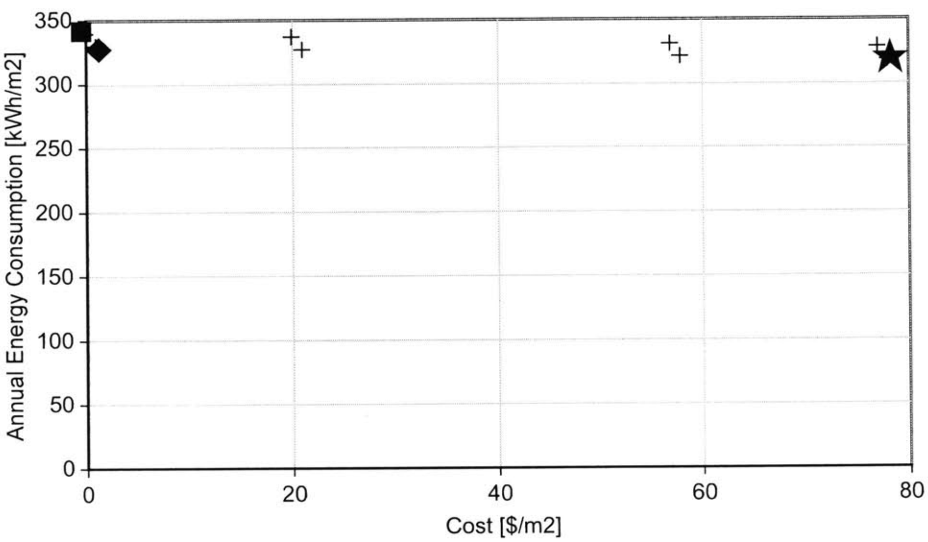
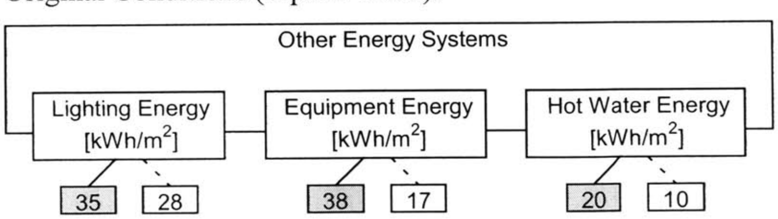
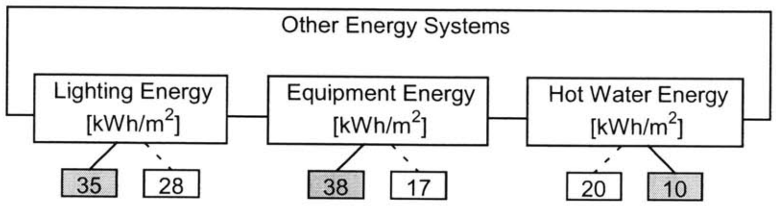


Figure 17-5: Retrofit scenarios for the other energy services system of the buildings constructed before 1969. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

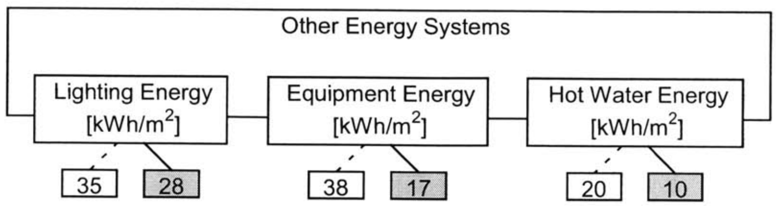
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.2 1969 to 1979 Construction Period

17.2.1 Controls System

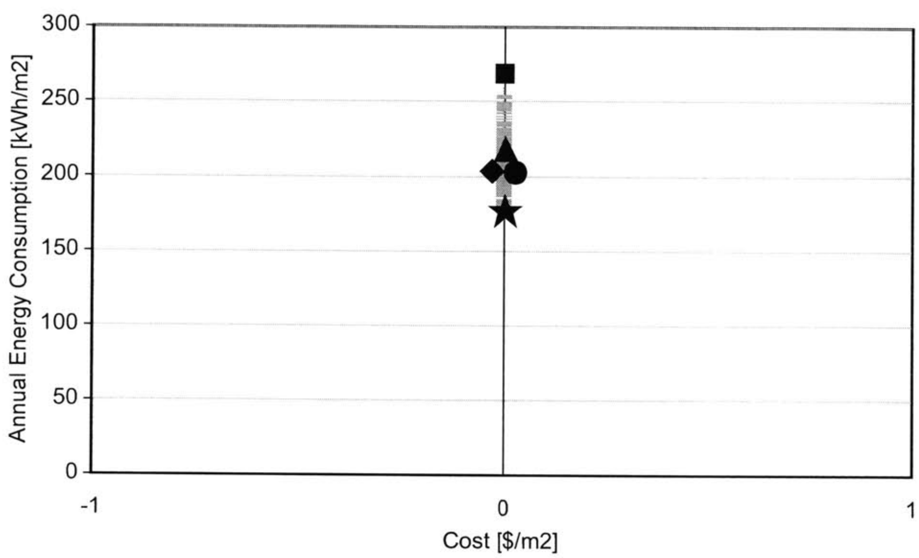
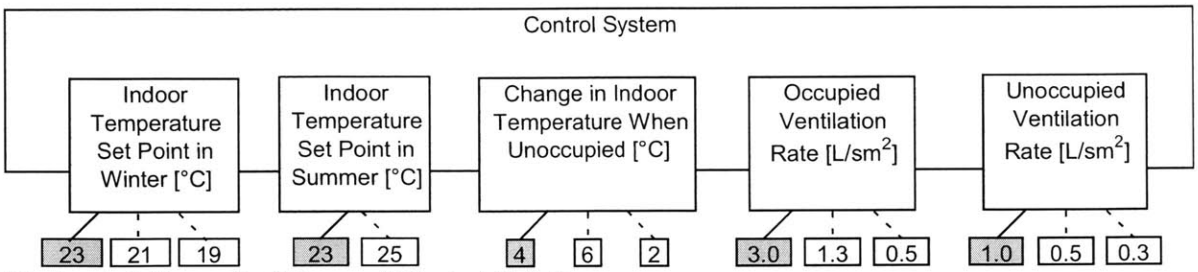
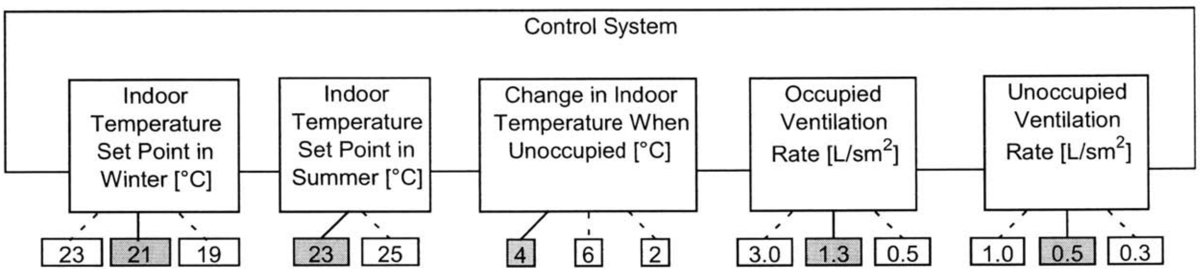


Figure 17-6: Retrofit scenarios for the controls system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

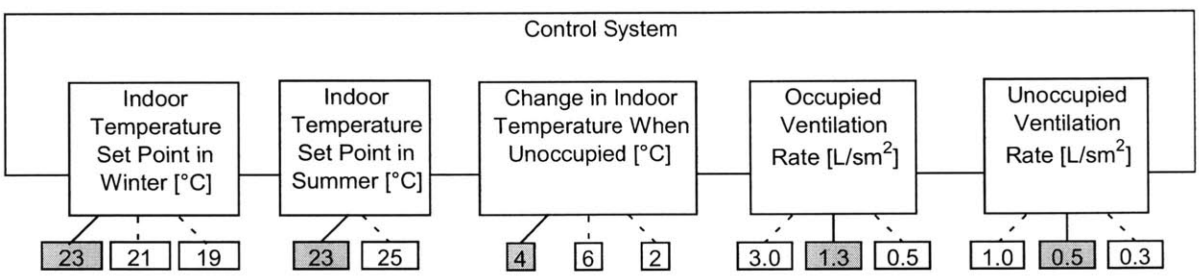
Original Conditions (Square Point):



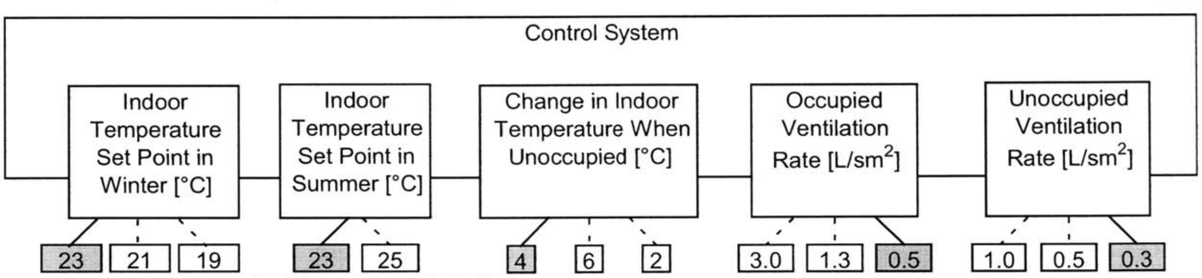
Moderate 1 Scenario (Diamond Shaped Point):



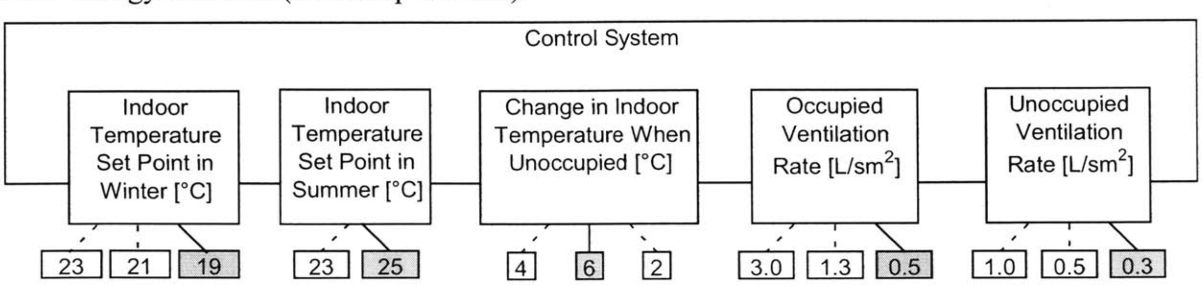
Moderate 2 Scenario (Triangular Point):



Moderate 3 Scenario (Circular Point):



Low-Energy Scenario (Star Shaped Point):



17.2.2 HVAC System

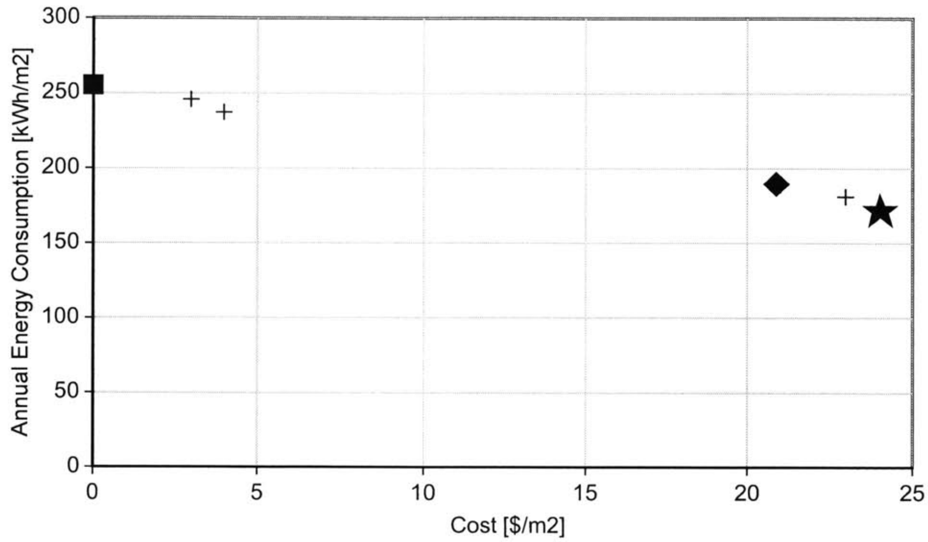
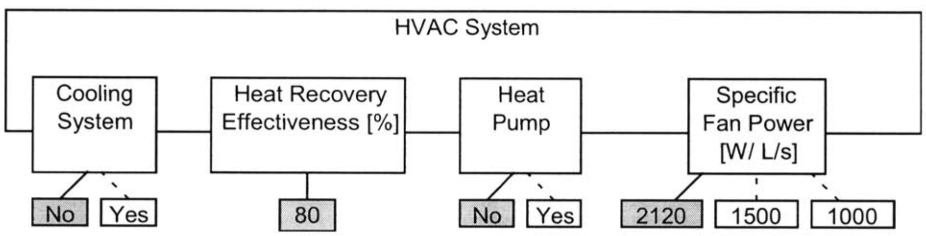
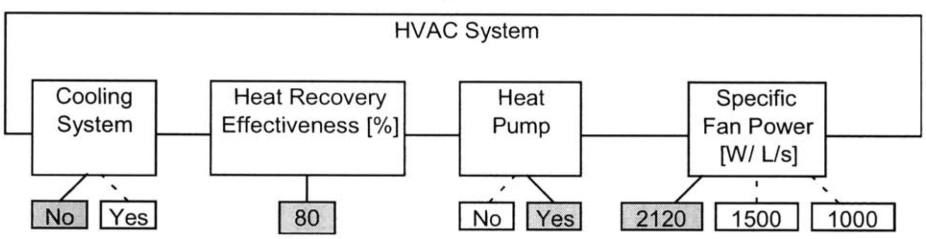


Figure 17-7: Retrofit scenarios for the HVAC system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

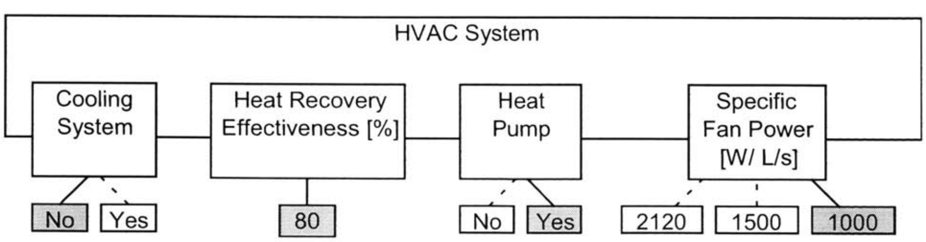
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.2.3 Windows

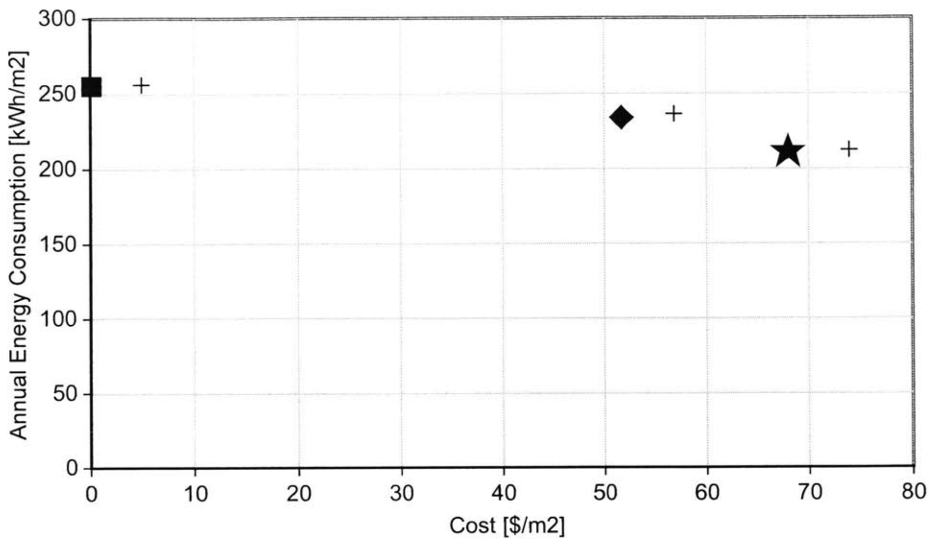
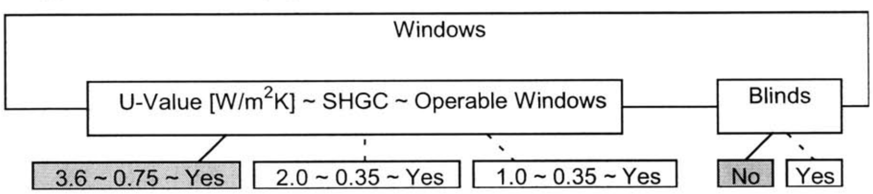
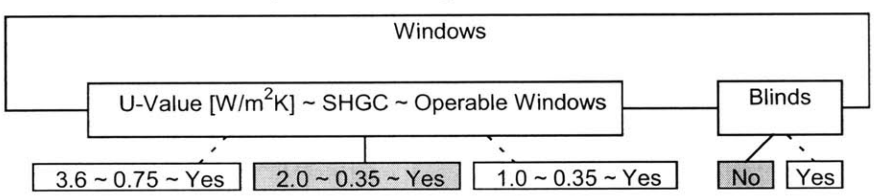


Figure 17-8: Retrofit scenarios for the windows of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

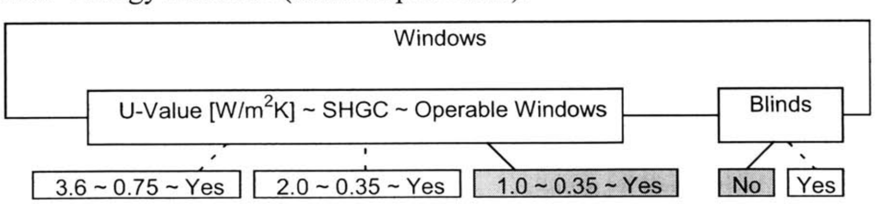
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.2.4 Non-Windows Facade System

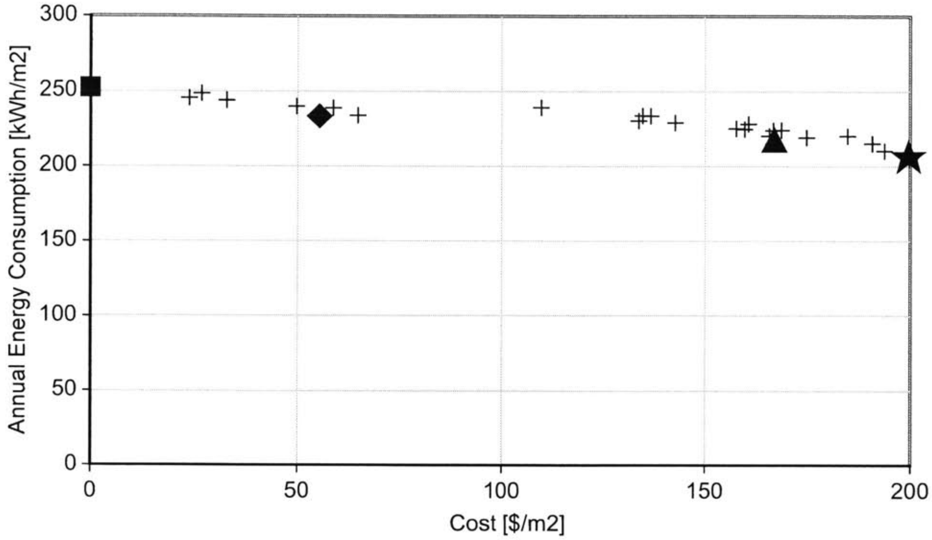
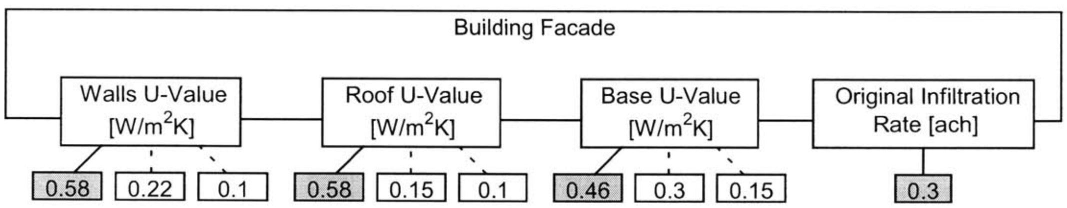
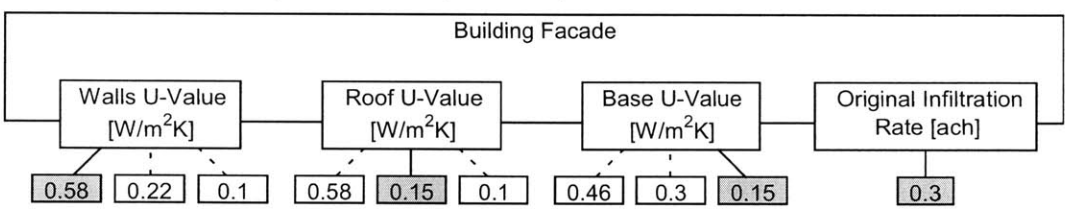


Figure 17-9: Retrofit scenarios for the non-window facade system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

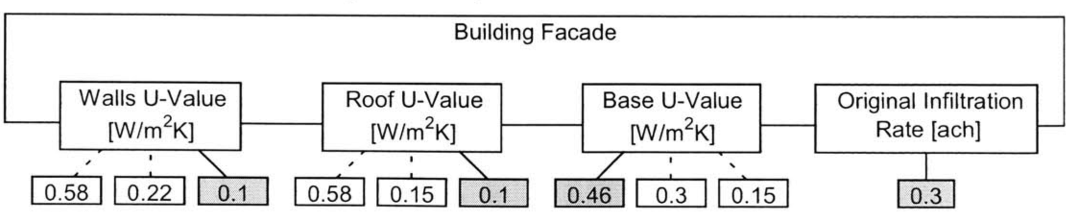
Original Conditions (Square Point):



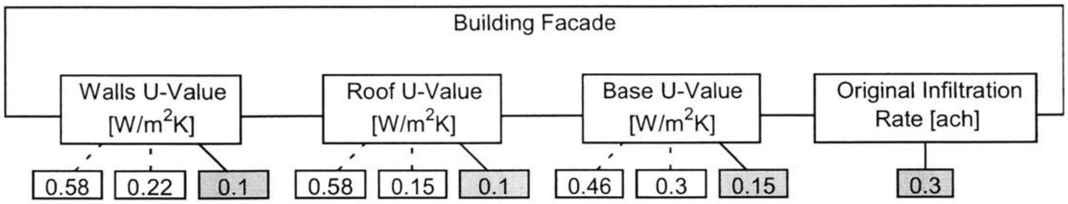
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.2.5 Other Energy Services System

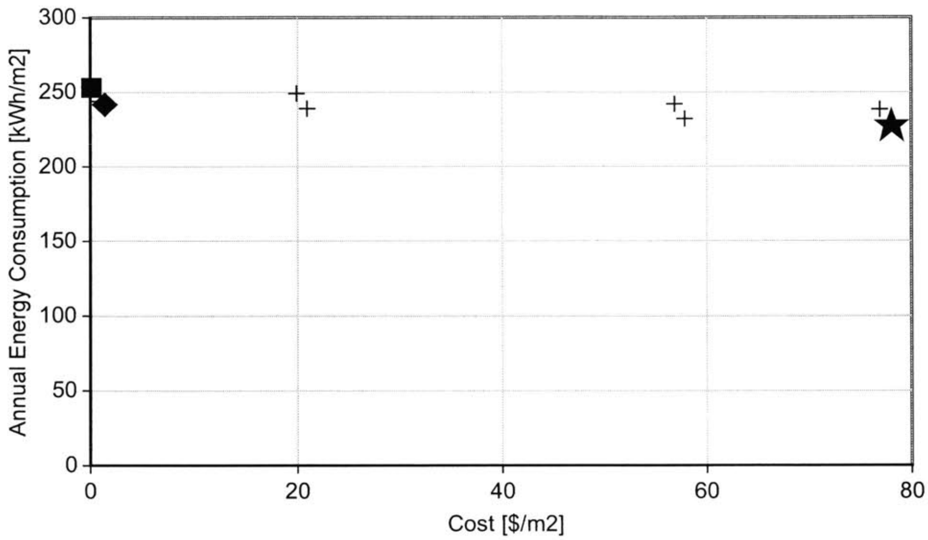
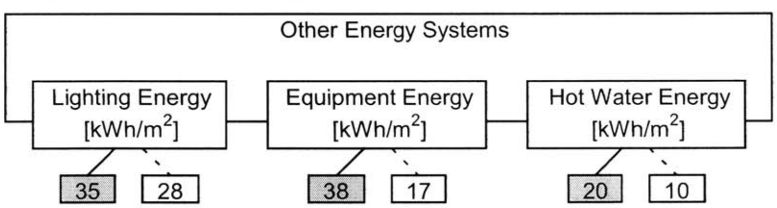
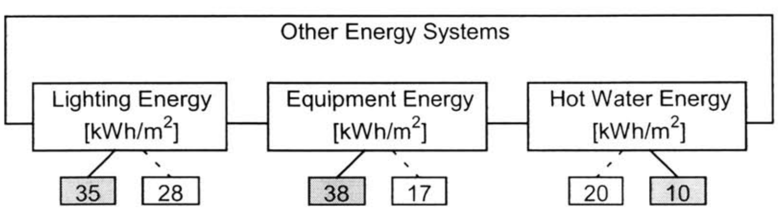


Figure 17-10: Retrofit scenarios for the other energy services system of the buildings constructed between 1969 and 1979. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

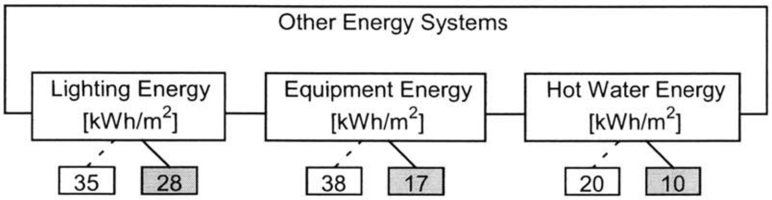
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.3 1980 to 1986 Construction Period

17.3.1 Controls System

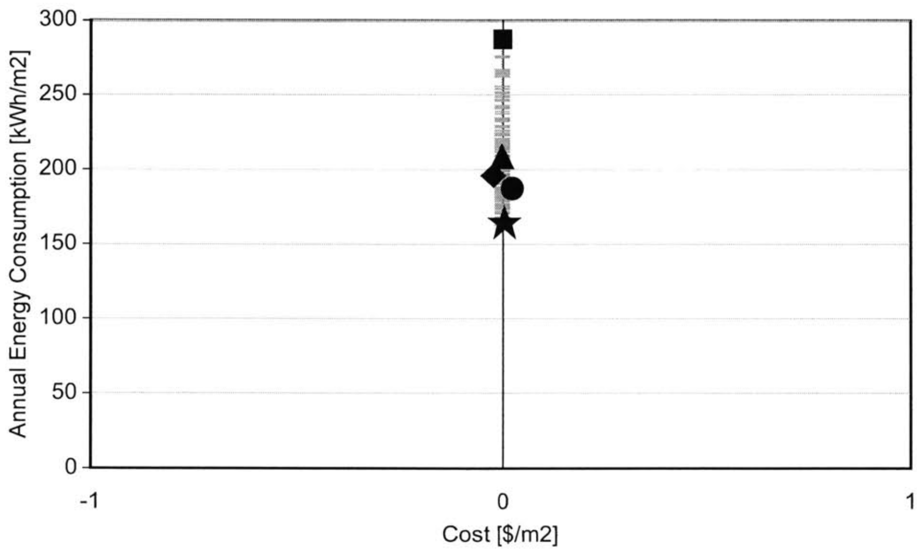
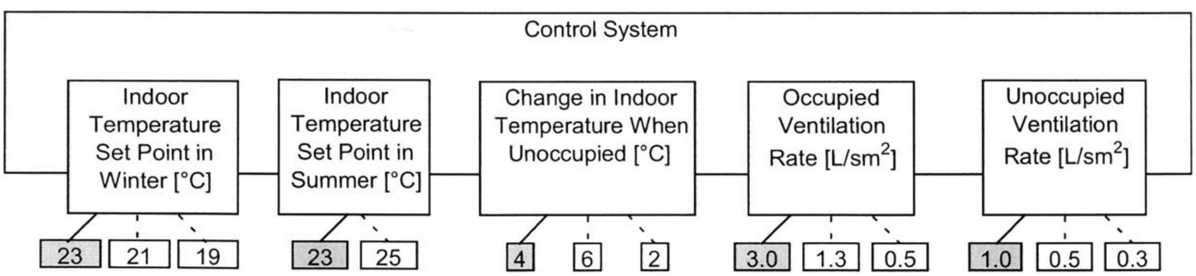
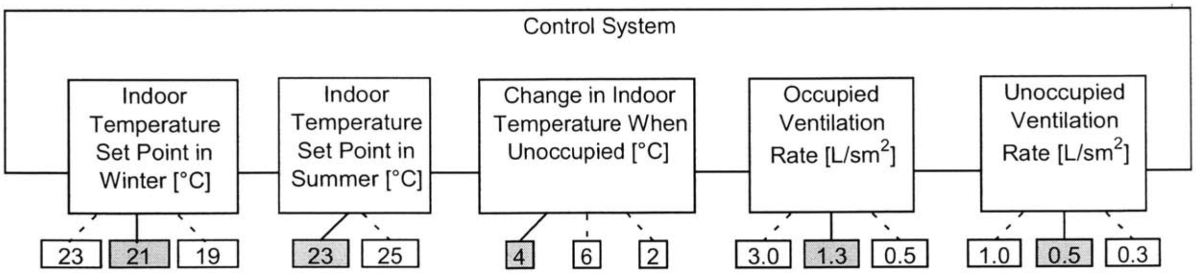


Figure 17-11: Retrofit scenarios for the controls system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

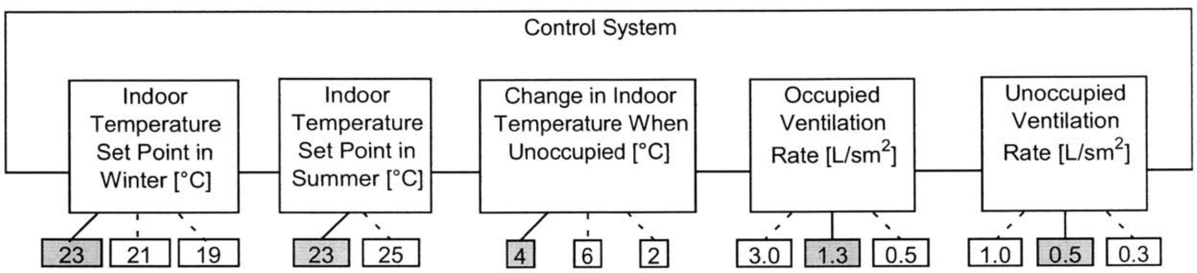
Original Conditions (Square Point):



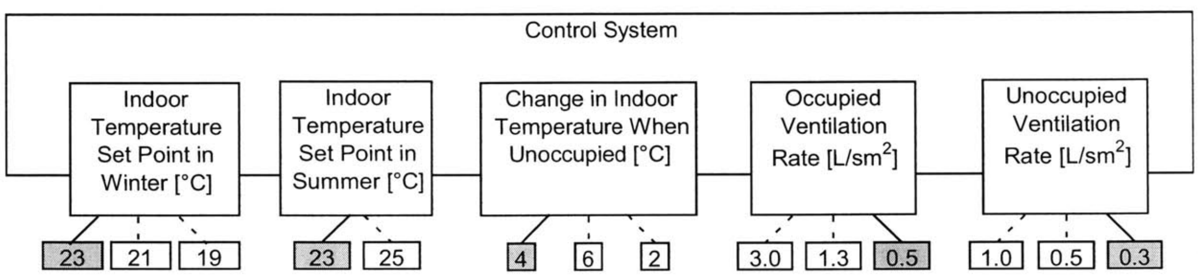
Moderate 1 Scenario (Diamond Shaped Point):



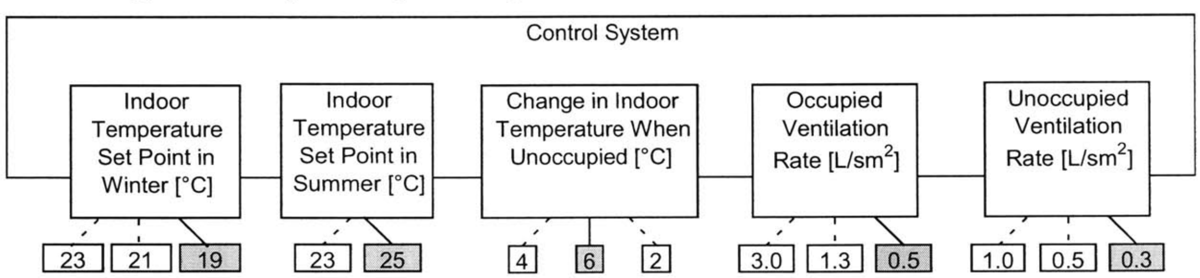
Moderate 2 Scenario (Triangular Point):



Moderate 3 Scenario (Circular Point):



Low-Energy Scenario (Star Shaped Point):



17.3.2 HVAC System

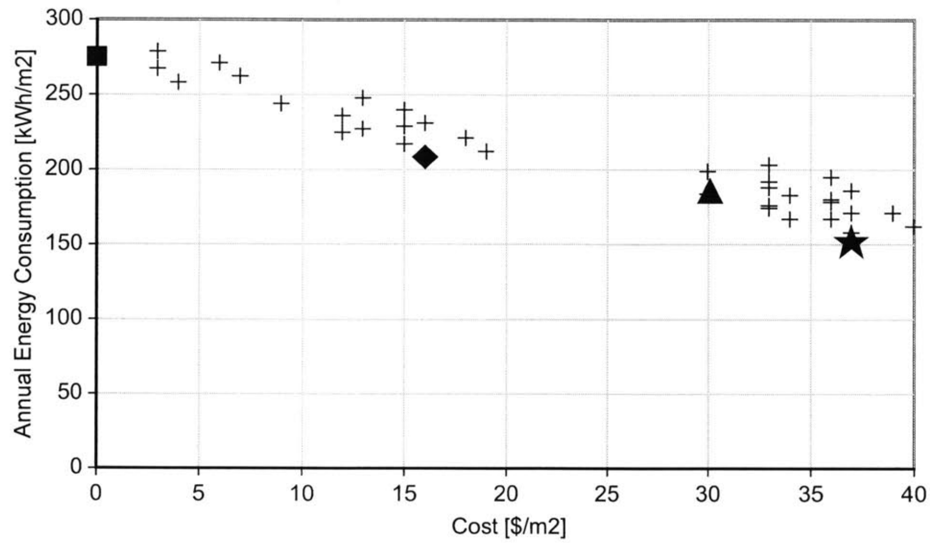
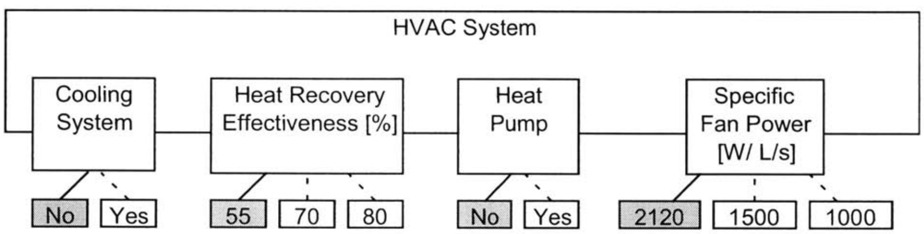
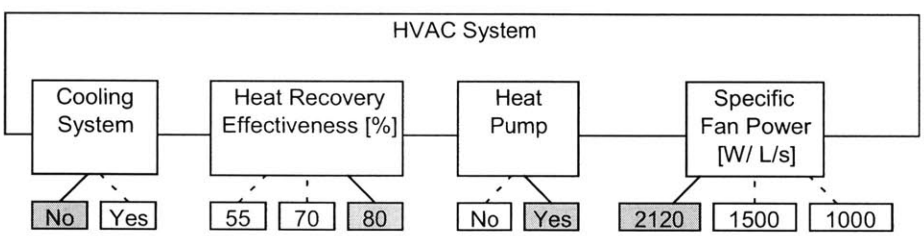


Figure 17-12: Retrofit scenarios for the HVAC system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

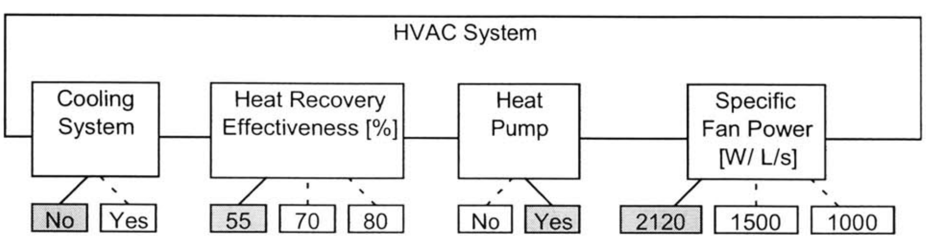
Original Conditions (Square Point):



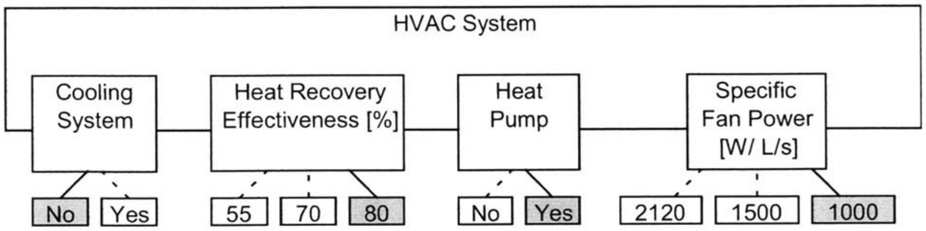
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.3.3 Windows

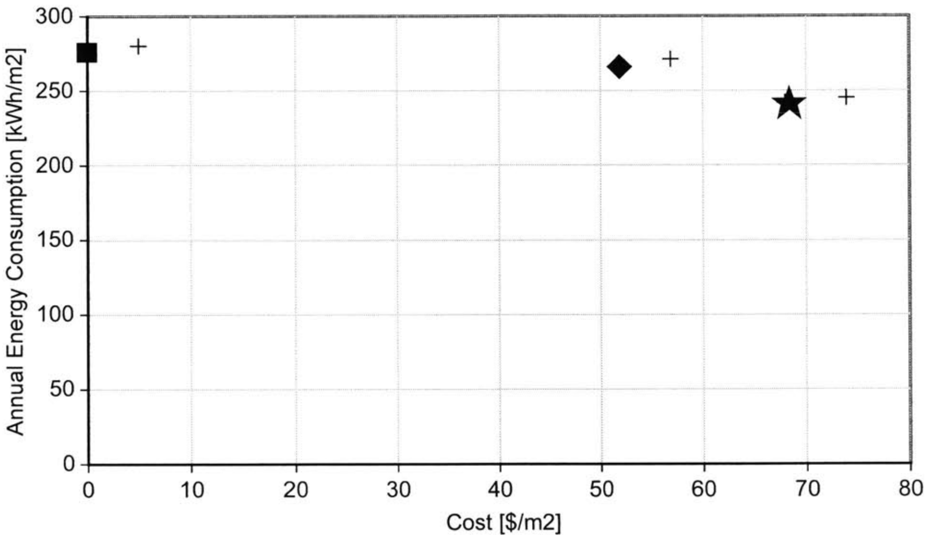
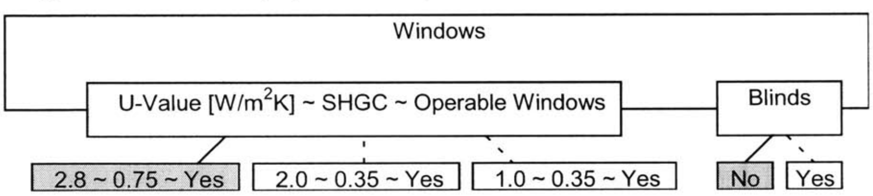
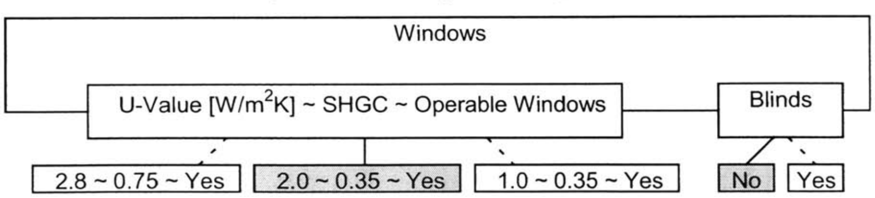


Figure 17-13: Retrofit scenarios for the windows of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

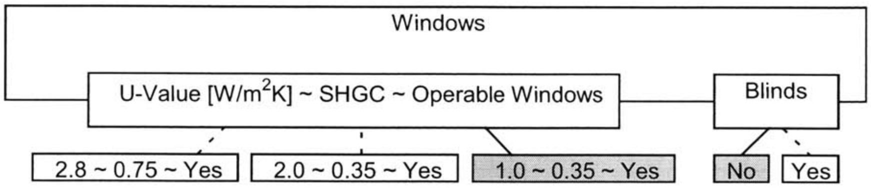
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.3.4 Non-Windows Facade System

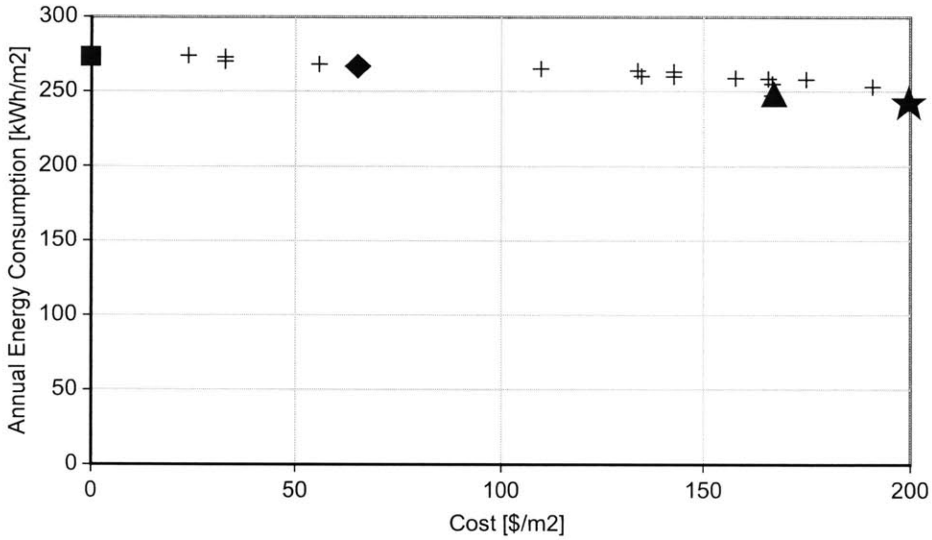
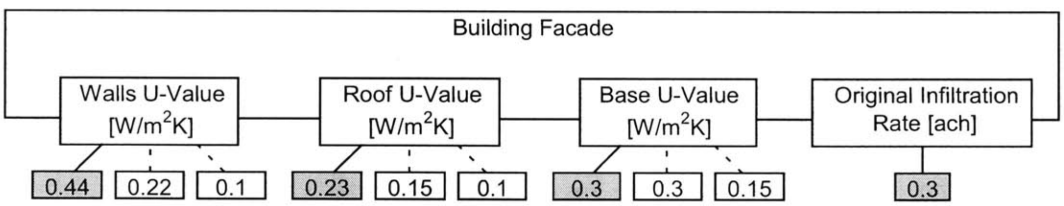
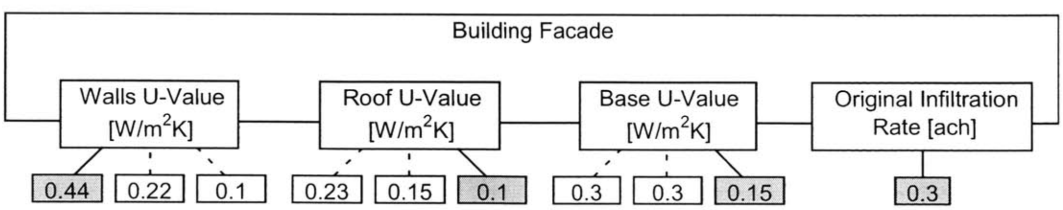


Figure 17-14: Retrofit scenarios for the non-window facade system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

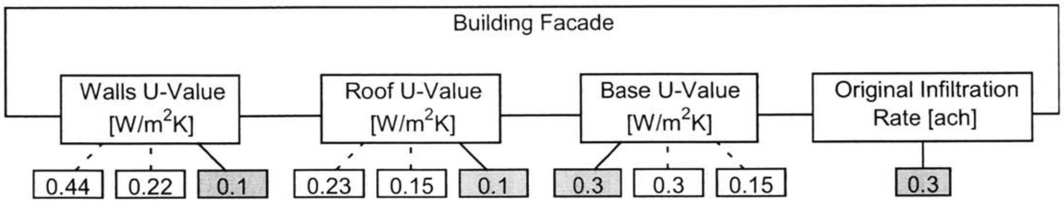
Original Conditions (Square Point):



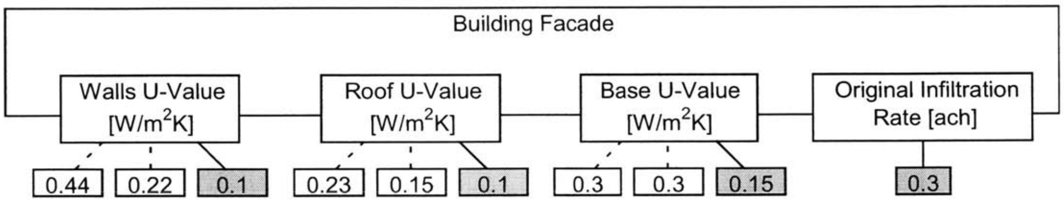
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.3.5 Other Energy Services System

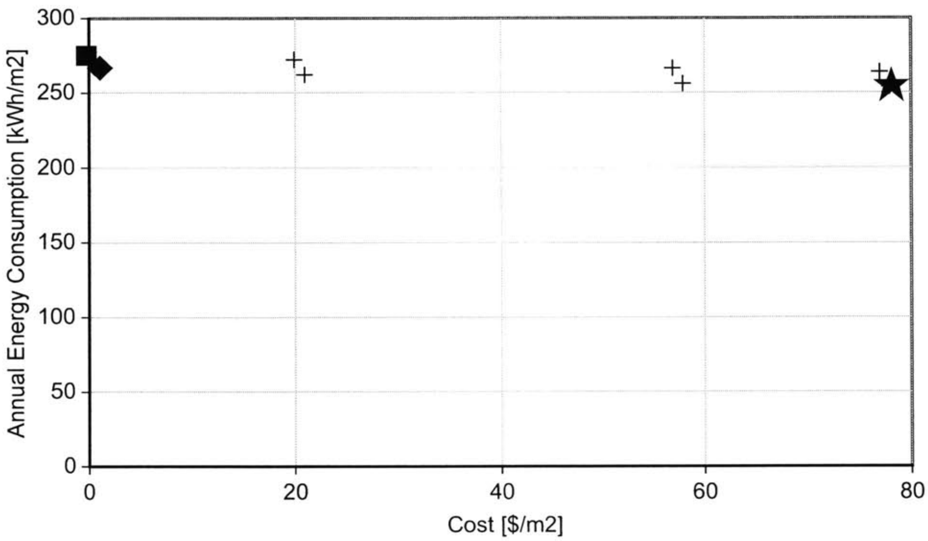
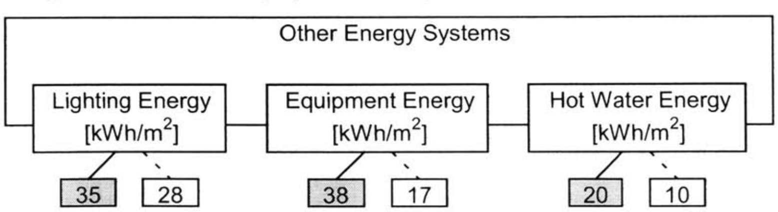
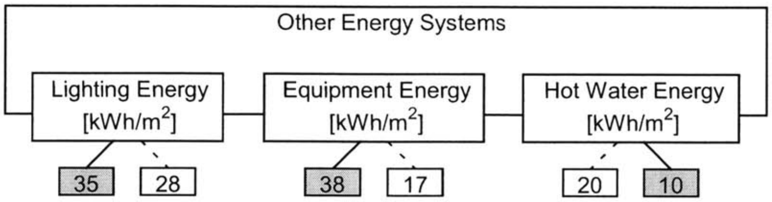


Figure 17-15: Retrofit scenarios for the other energy servies system of the buildings constructed between 1980 and 1986. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

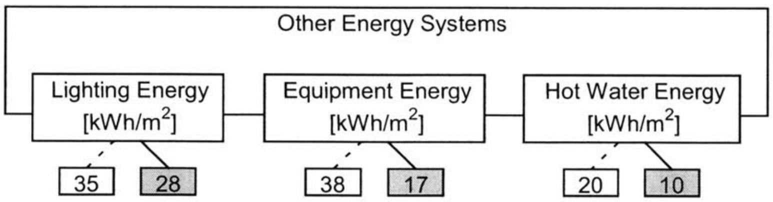
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.4 1987 to 1997 Construction Period

17.4.1 Controls System

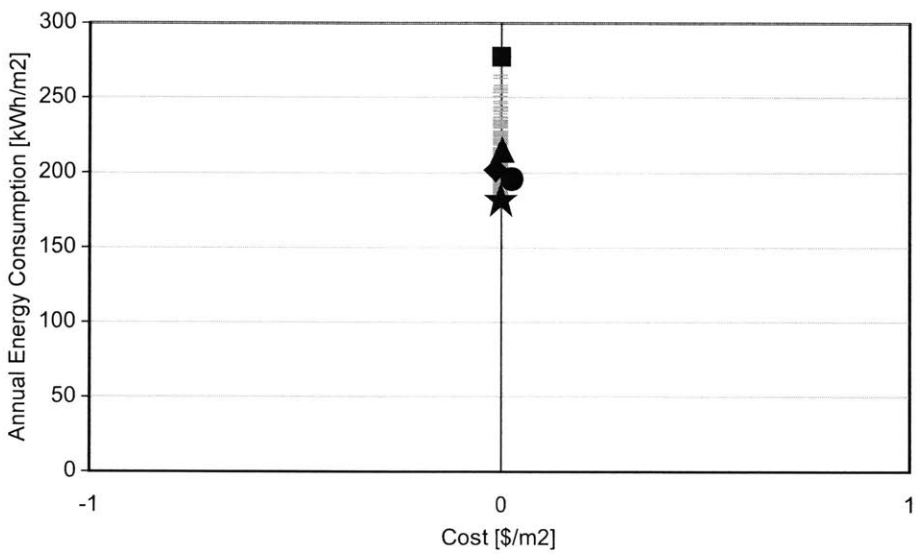
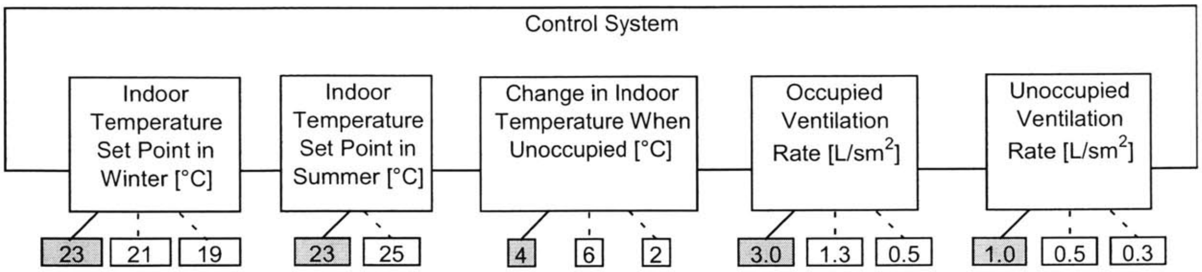
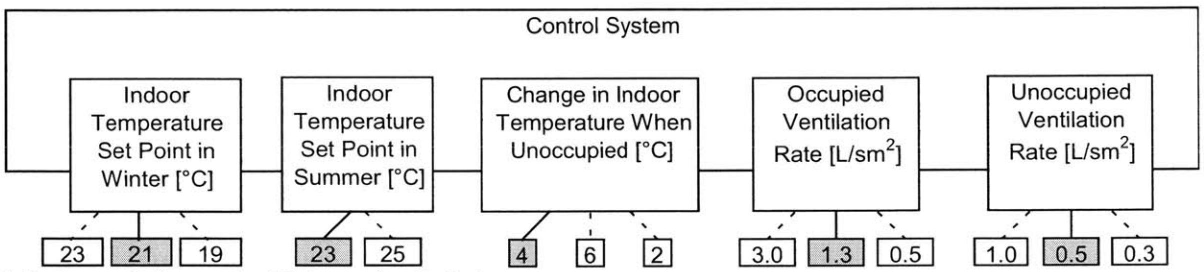


Figure 17-16: Retrofit scenarios for the controls system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

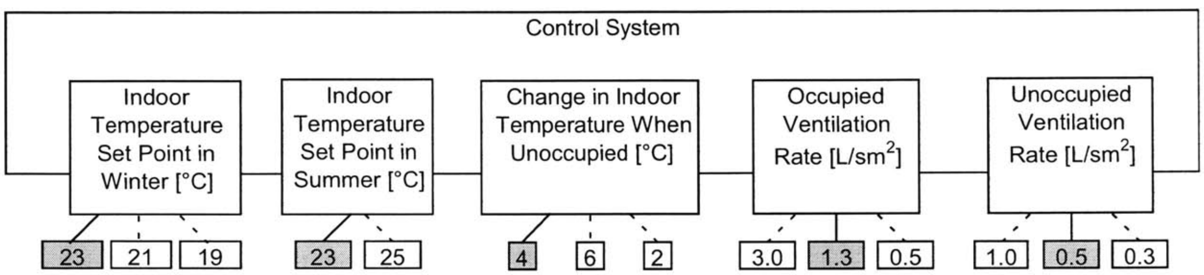
Original Conditions (Square Point):



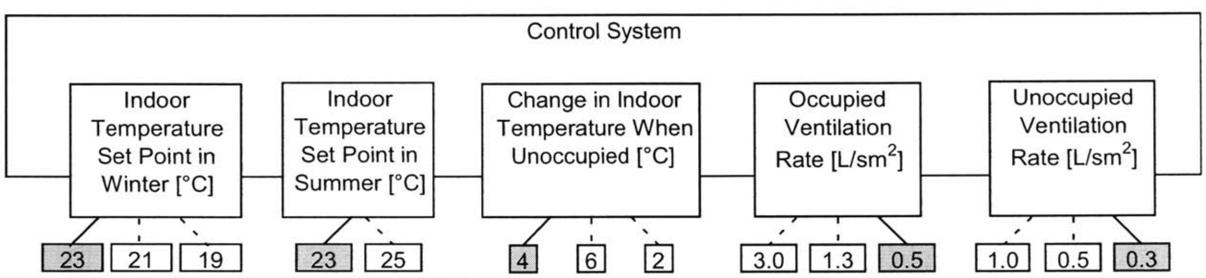
Moderate 1 Scenario (Diamond Shaped Point):



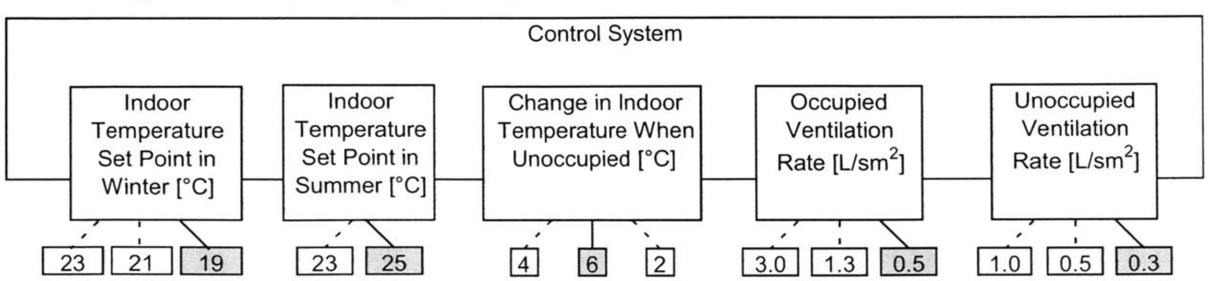
Moderate 2 Scenario (Triangular Point):



Moderate 3 Scenario (Circular Point):



Low-Energy Scenario (Star Shaped Point):



17.4.2 HVAC System

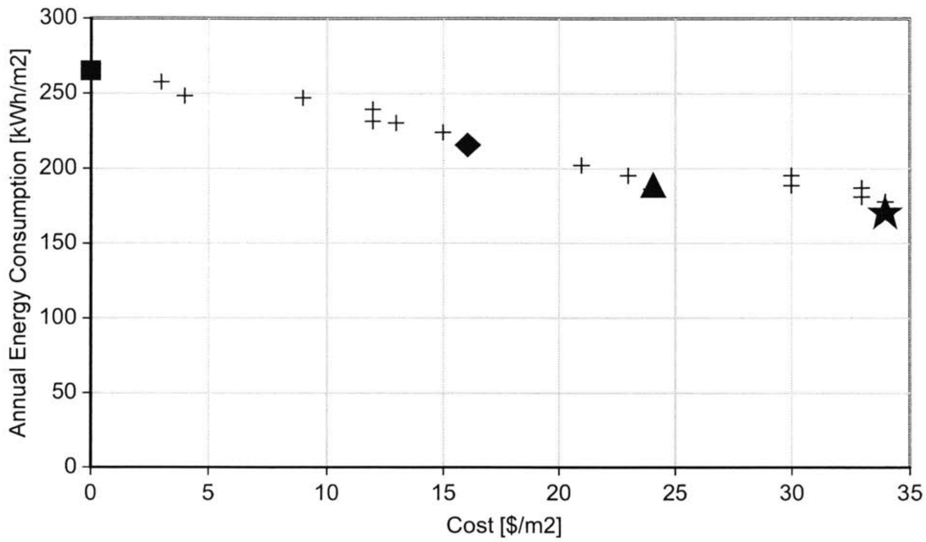
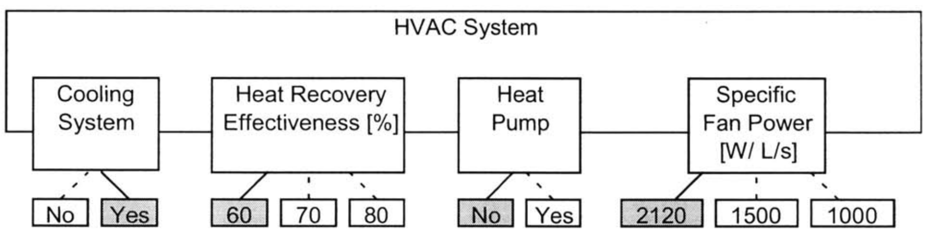
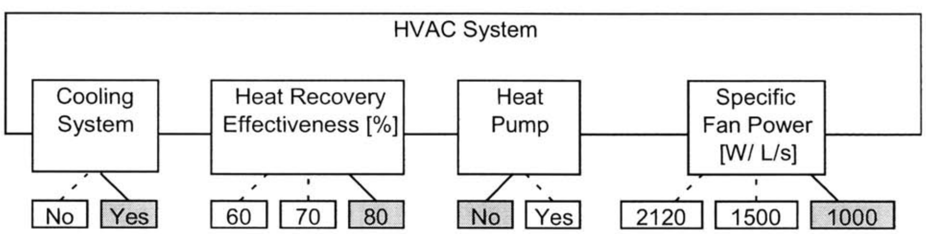


Figure 17-17: Retrofit scenarios for the HVAC system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

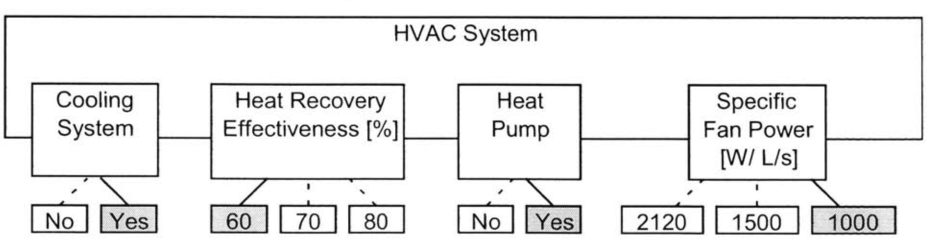
Original Conditions (Square Point):



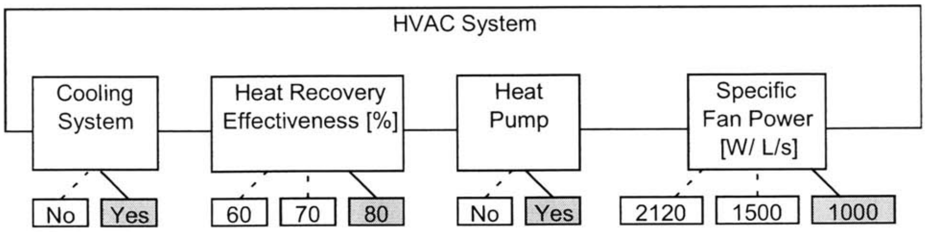
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.4.3 Windows

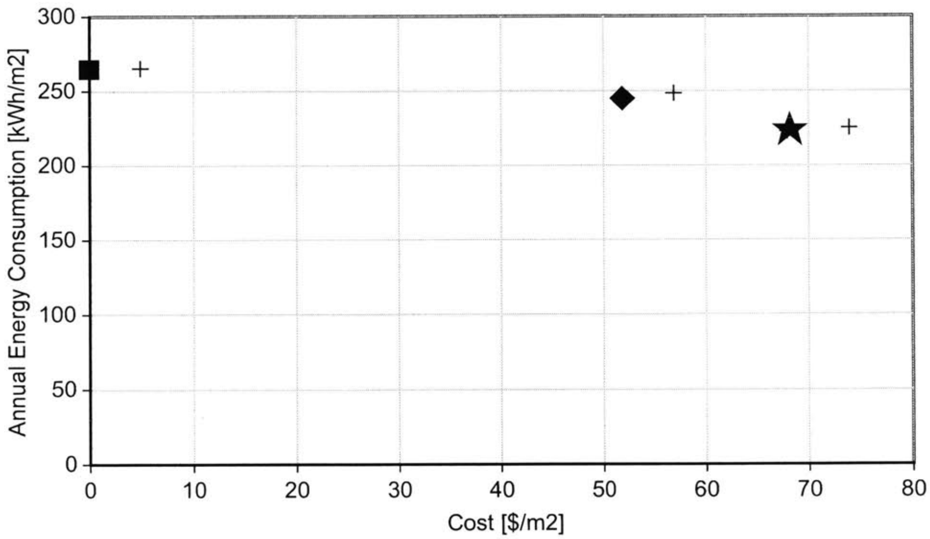
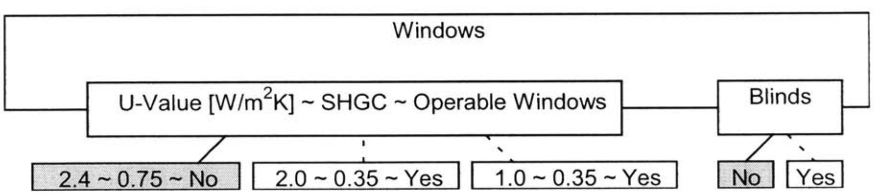
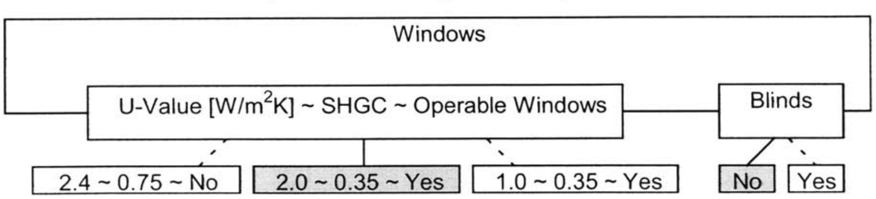


Figure 17-18: Retrofit scenarios for the windows of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

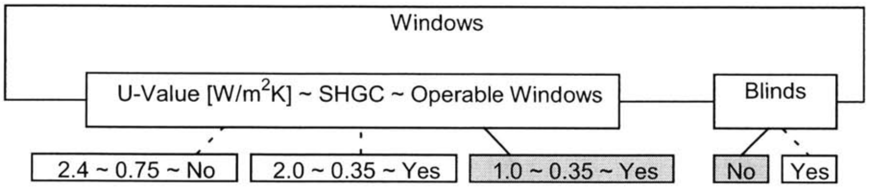
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.4.4 Non-Window Facade System

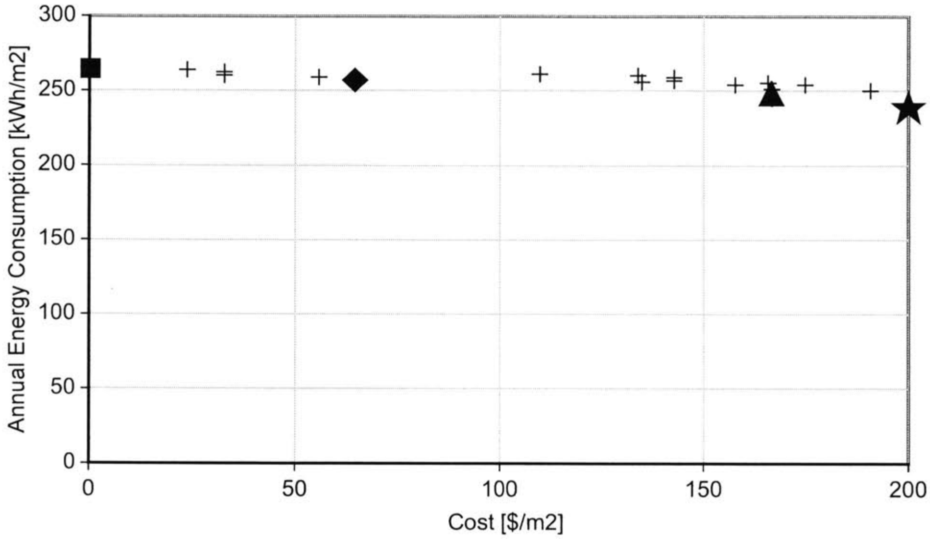
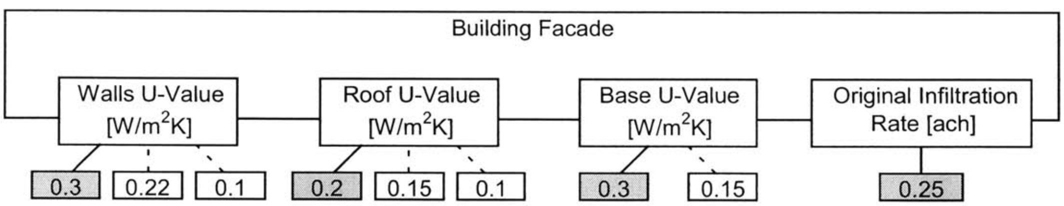
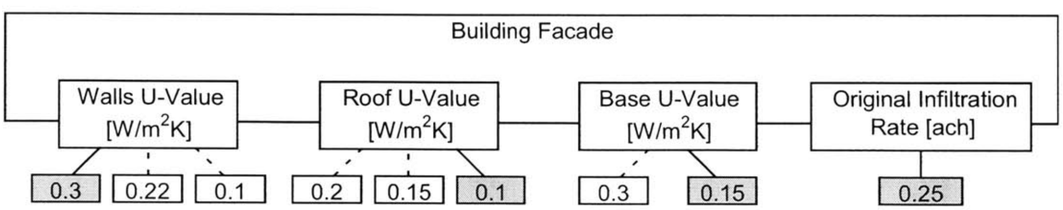


Figure 17-19: Retrofit scenarios for the non-window facade system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

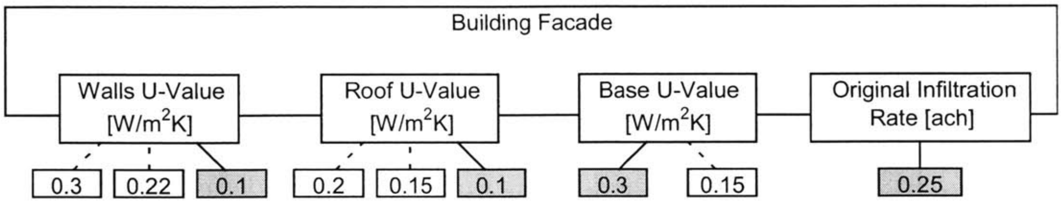
Original Conditions (Square Point):



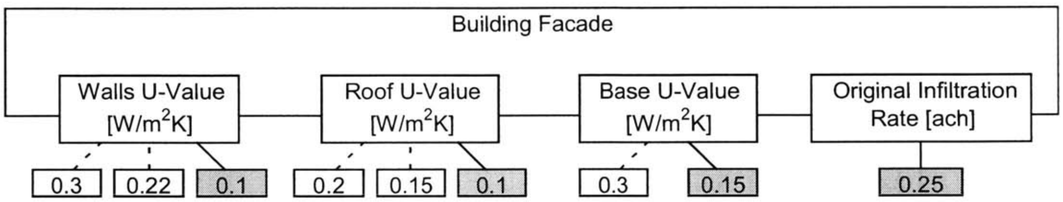
Moderate 1 Scenario (Diamond Shaped Point):



Moderate 2 Scenario (Triangular Point):



Low-Energy Scenario (Star Shaped Point):



17.4.5 Other Energy Services System

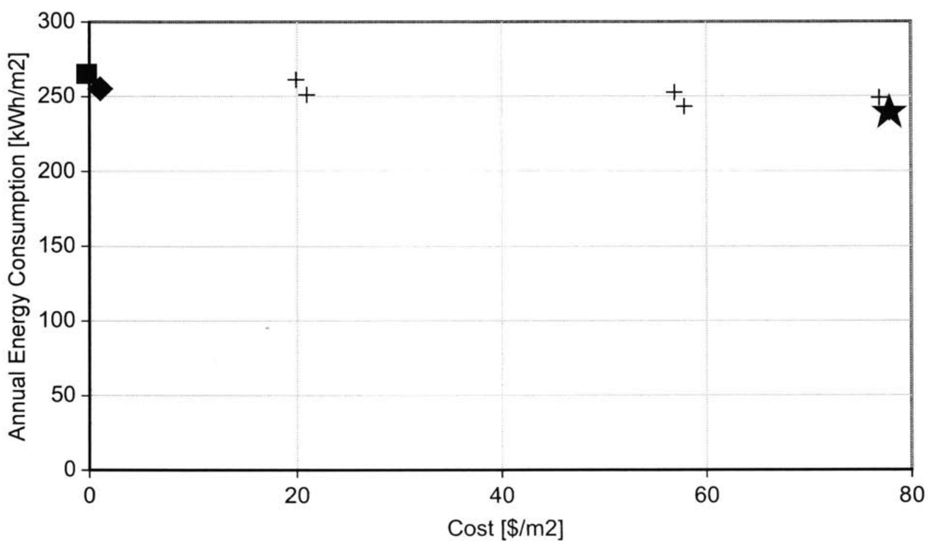
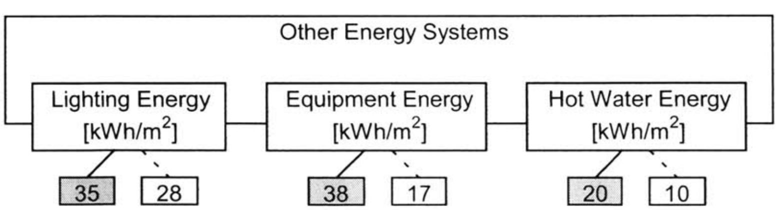
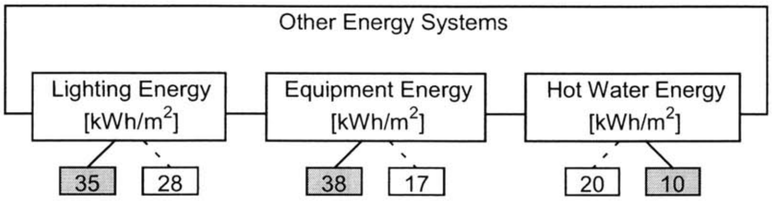


Figure 17-20: Retrofit scenarios for the other energy services system of the buildings constructed between 1987 and 1996. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

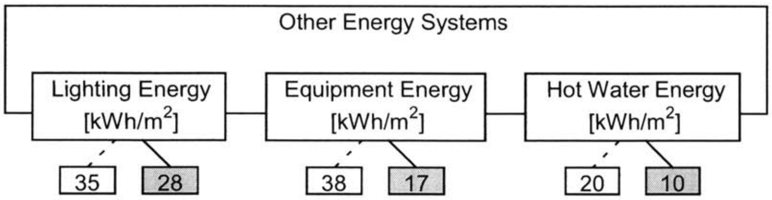
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.5 1997 to 2005 Construction Period

17.5.1 Controls System

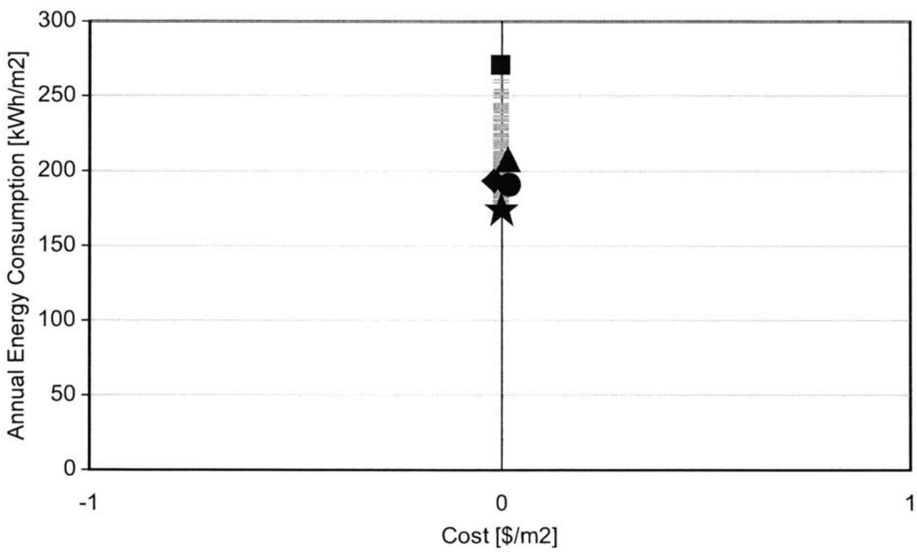
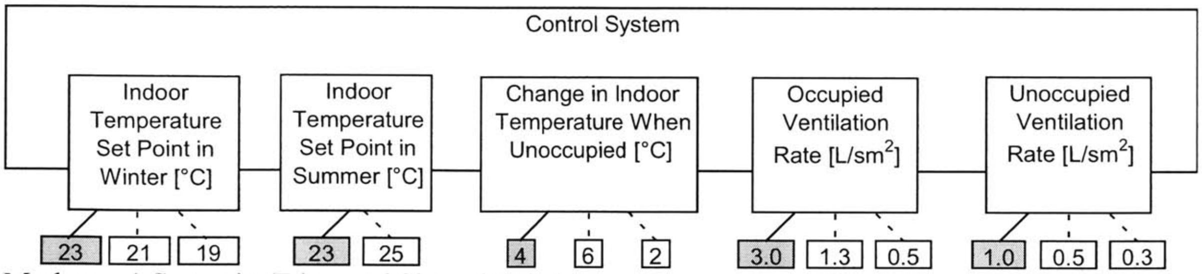
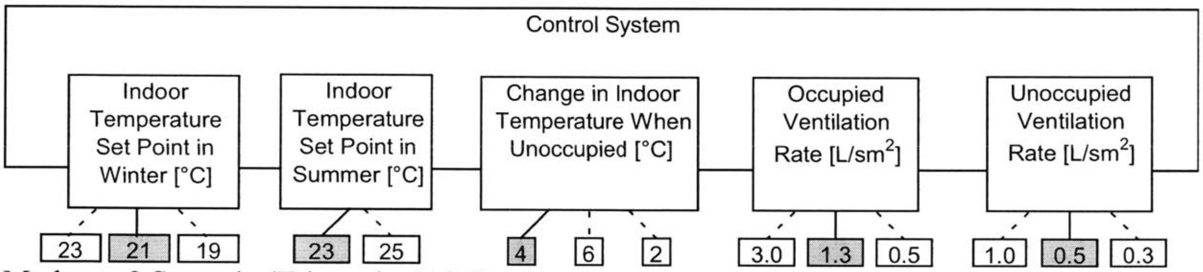


Figure 17-21: Retrofit scenarios for the controls system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

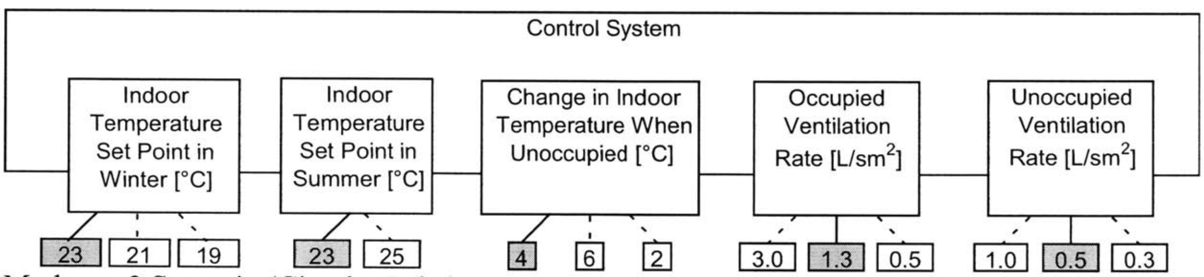
Original Conditions (Square Point):



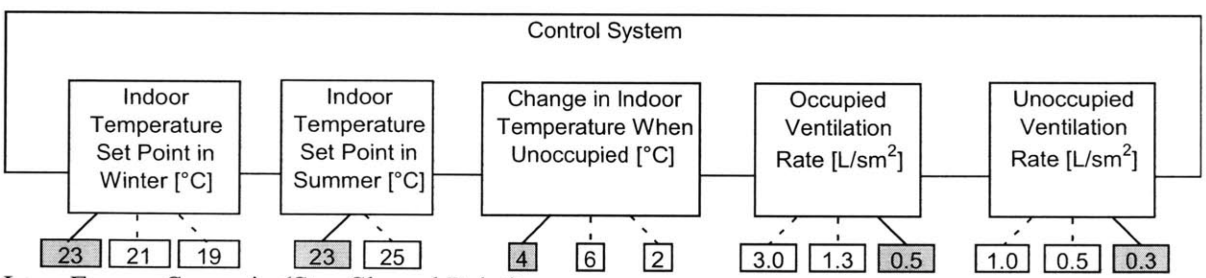
Moderate 1 Scenario (Diamond Shaped Point):



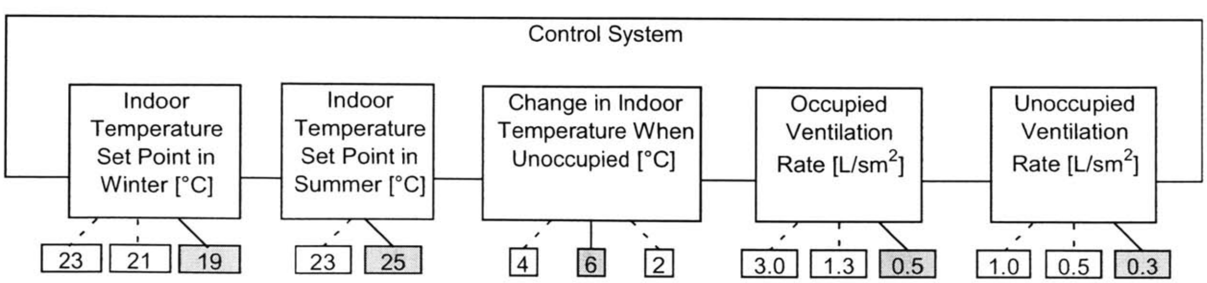
Moderate 2 Scenario (Triangular Point):



Moderate 3 Scenario (Circular Point):



Low-Energy Scenario (Star Shaped Point):



17.5.2 HVAC System

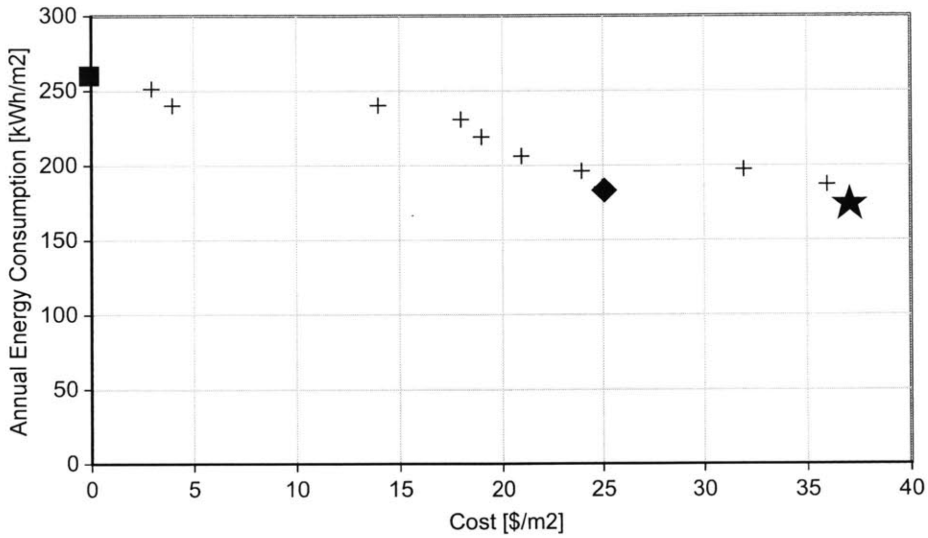
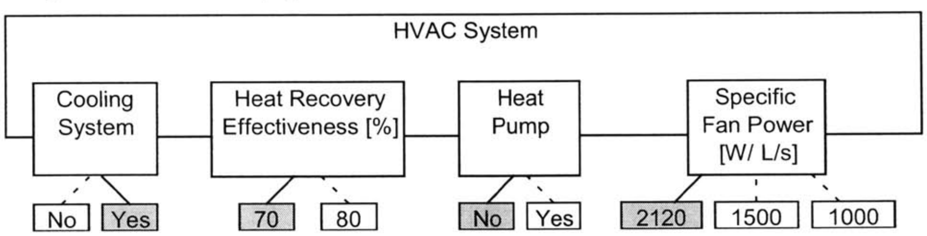
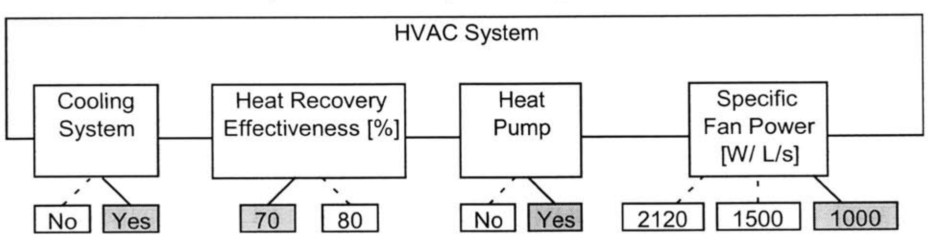


Figure 17-22: Retrofit scenarios for the HVAC system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

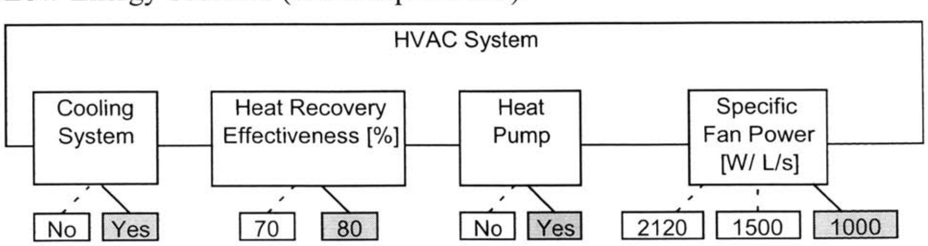
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.5.3 Windows

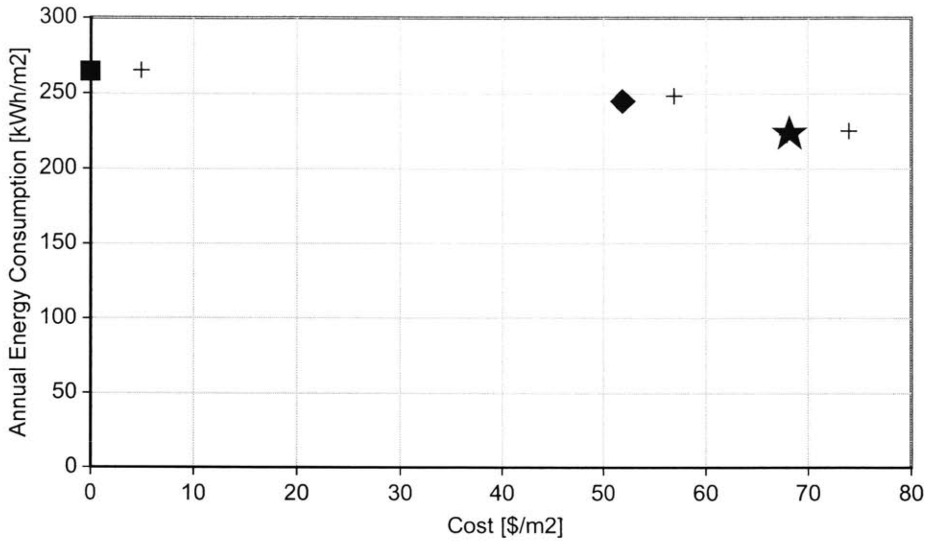
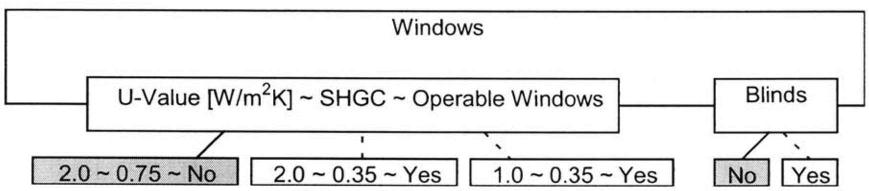
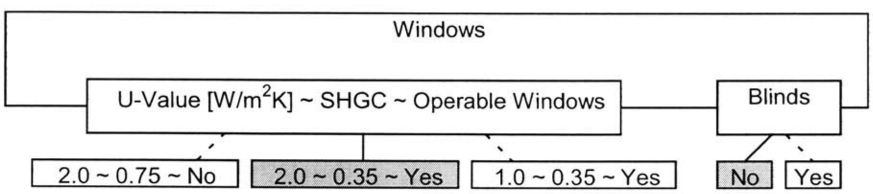


Figure 17-23: Retrofit scenarios for the windows of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

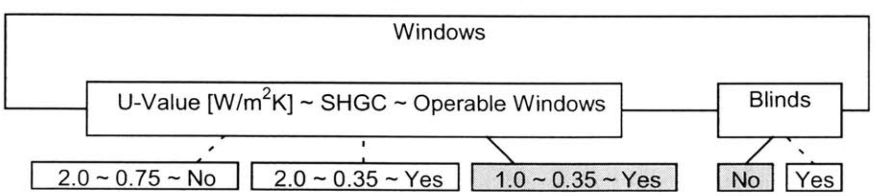
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.5.4 Non-Window Facade System

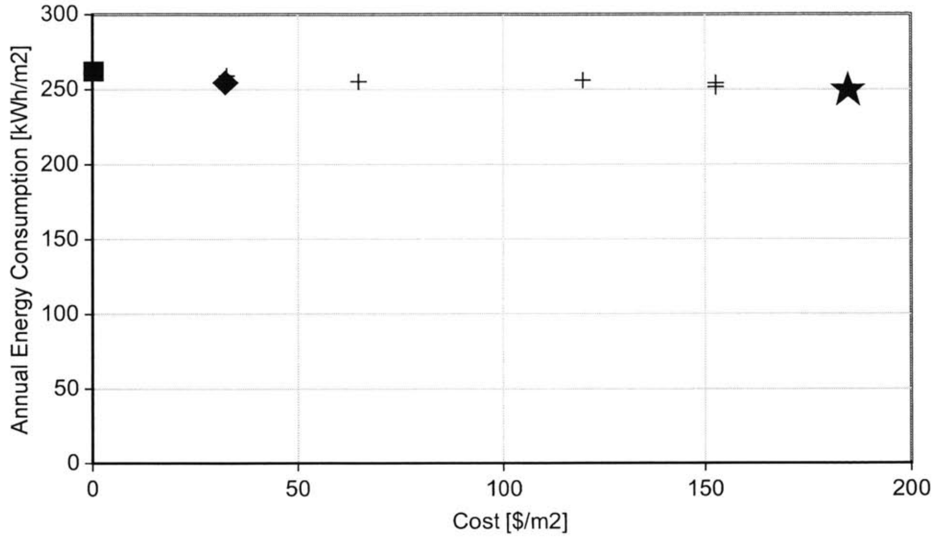
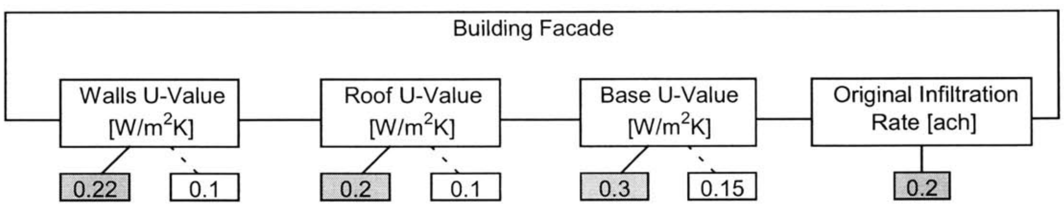
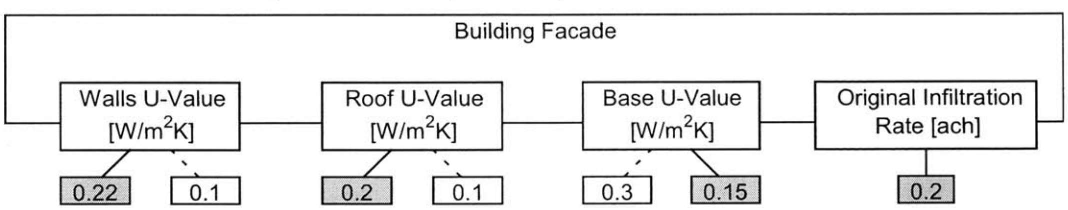


Figure 17-24: Retrofit scenarios for the non-window facade system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

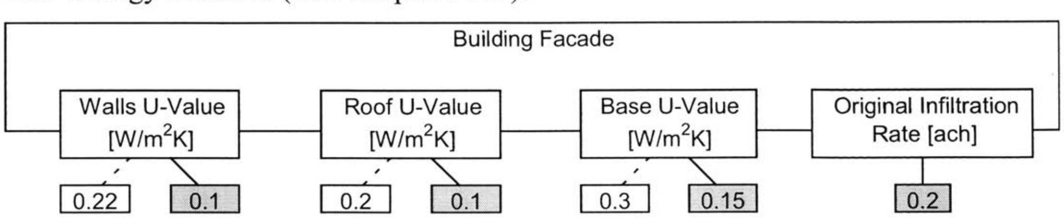
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



17.5.5 Other Energy Services System

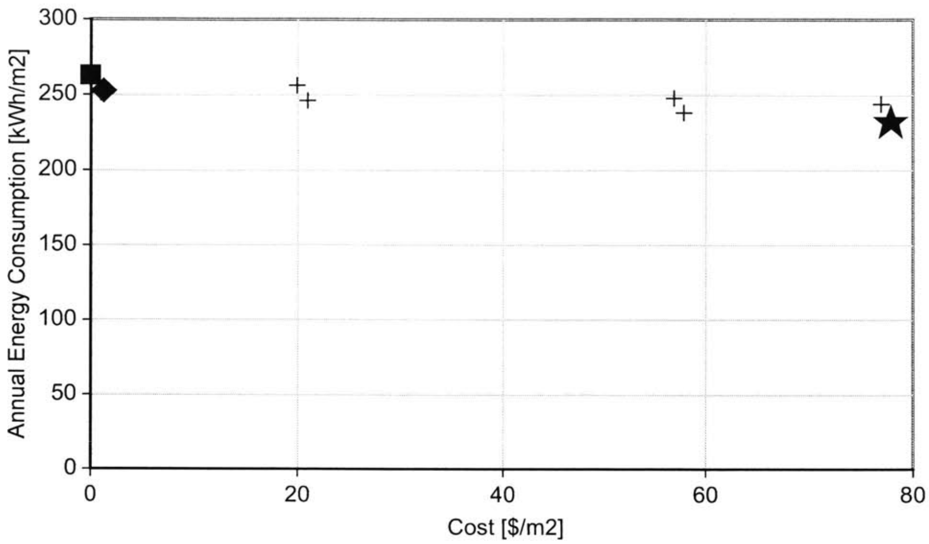
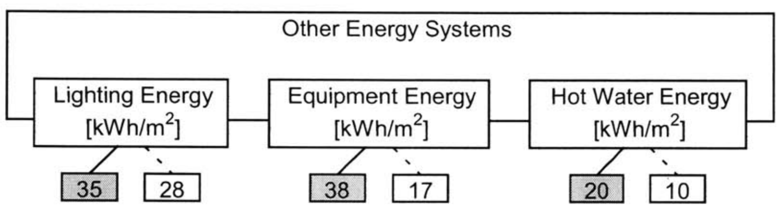
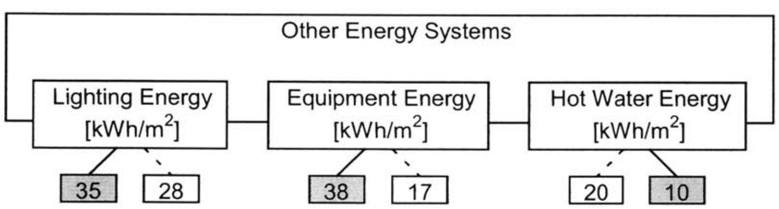


Figure 17-25: Retrofit scenarios for the other energy services system of the buildings constructed between 1997 and 2005. The highlighted points correspond to the scenarios selected for the multi-systems analysis.

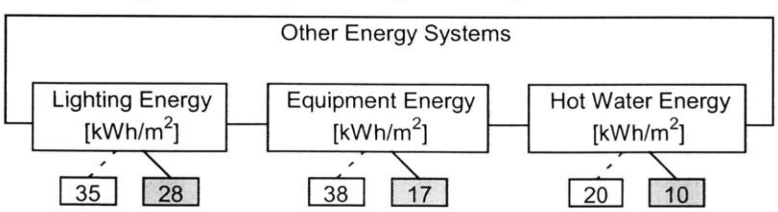
Original Conditions (Square Point):



Moderate 1 Scenario (Diamond Shaped Point):



Low-Energy Scenario (Star Shaped Point):



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