ENERGY AND ECONOMIC LIFE-CYCLE ANALYSIS OF AN OFFICE BUILDING

by

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ABSTRACT

This thesis investigates the life-cycle economic and energy implications of a commercial office building, located in Vancouver, British Columbia. The work is based on the premise that the commercial building stock is designed and built to sub-optimal levels of performance. In the present context, the criteria for analyzing optimality are defined in terms of energy and monetary accounting. The building is designed in compliance with the energy efficiency code for Vancouver. The energy performance of the building is improved to achieve an energy efficient office building through the adoption of a series of design strategies.

Conclusions resulting from the work are:

- The operating performance of the case study building may be improved 77% through the adoption of simple, proven technologies. As a result, the life-cycle energy may be reduced 66 to 68% for building lives of 40 and 80 years, respectively.

- The life-cycle embodied energy is 0.21 $GJ/m^2.yr$ and 0.16 $GJ/m^2.yr$. for building lives of 40 and 80 years, respectively. These figures are valid for all the building configurations studied.

- For a building life of 40 years, the life-cycle energy is

reduced from 1.6 to 0.54 GJ/m^2.yr by the cumulative adoption of energy conservation strategies. This corresponding to a 66% reduction in energy consumed.

- For a building life of 80 years, the life-cycle energy is reduced from 1.55 to 0.49 GJ/m^2.yr by the cumulative adoption of energy conservation strategies. This corresponding to a 68% reduction.

- Reducing the operating energy of the case study building results in a savings with a net present value of $0.246 million and $0.253 million for building lives of 40 and 80 years, respectively.

- If only those strategies which are cost effective are implemented, a 60% reduction in operating energy may be achieved. The corresponding decrease in life-cycle energy is 50% and 48% for building lives of 40 and 80 years, respectively.

- Methodological pluralism is a central characteristic of the energy debate. Competing models and their solutions provide a number of policy alternatives based on pricing, utility sponsored DSM, and regulatory options. All strategies provide opportunities to reduce energy consumption, and should continue to form components of future policy initiatives.

TABLE OF CONTENTS

ABSTRACT	ii
TABLE OF CONTENTS	iv
LIST OF TABLES	xi
LIST OF FIGURES	xiv
CHAPTER ONE: INTRODUCTION	**1**
1.1 THESIS OBJECTIVES	2
1.2 BACKGROUND INFORMATION	3
1.2.1 The Case study Building	3
1.2.2 Choosing an End Use	5
1.2.3 Rationale for the Work	6
1.2.4 Scope of the Analysis	7
1.2.5 An Interdisciplinary Approach	9
1.2.6 The Building Industry	10
1.3 THESIS STRUCTURE	11
CHAPTER TWO: ENERGY ANALYSIS	**14**
2.1 INTRODUCTION	14
2.2 DEFINING AN ENERGY ANALYSIS	14
2.3 ENERGY ANALYSIS AS A PUBLIC POLICY TOOL	14
2.4 WHAT AN ENERGY ANALYSIS CAN DO	18
2.5 USE OF ENERGY ANALYSIS IN THE PRESENT WORK	20

2.6 SYSTEM BOUNDARIES 21

2.6.1 Human Energy 21

2.6.2 Infrastructure 22

CHAPTER THREE: OPERATING ENERGY OF CASE STUDY BUILDING 24

3.1 INTRODUCTION 24

3.2 BACKGROUND 24

3.3 QUANTIFYING THE OPERATING ENERGY OF BUILDINGS 26

3.3.1 Site Versus Source Energy 27

3.4 DESIGN PROCESS 28

3.5 IMPROVING THE OPERATING ENERGY OF THE CASE STUDY BUILDING 29

3.6 RESULTS OF THE OPERATING ENERGY MODEL 32

3.7 OBSERVATIONS ON THE OPERATING ENERGY MODEL 36

3.8 MODEL VERIFICATION AND UNCERTAINTY 37

3.9 CONCLUDING REMARKS 39

CHAPTER FOUR: EMBODIED ENERGY OF CASE STUDY BUILDING 40

4.1 CHAPTER LAYOUT 40

4.2 DEFINING THE EMBODIED ENERGY OF A BUILDING 40

4.3 SIGNIFICANCE OF THE EMBODIED ENERGY OF BUILDINGS 41

4.4 METHODS OF ANALYSIS 41

4.4.1 Input-Output Analysis 41

4.4.2 Process Analysis 43

4.4.3 Statistical Analysis 44
4.5 REVIEW OF THE LITERATURE 44
4.5.1 Energy Intensity of Building Materials 44
4.5.2 Embodied Energy of Buildings 47
4.6 INITIAL EMBODIED ENERGY OF BASE CASE STUDY BUILDING 52
4.6.1 Energy to Produce the Building Components 53
4.6.2 Materials Wastage 54
4.6.3 Construction Energy 54
4.6.4 Results 55
4.6.5 Comparison With Other Studies 58
4.7 RECURRING EMBODIED ENERGY OF CASE STUDY BUILDING 59
4.7.1 Building Life 59
4.7.2 Replacement and Refurbishment 60
4.7.3 Changes to Embodied Energy of Building Components With Time 60
4.7.4 Two Methodologies 61
4.7.4.1 Recurring Embodied Energy Based on Input-Output Analysis 62
4.7.4.2 Recurring Embodied Energy Based on Replacement Schedule 63
4.7.3 Comparison of Results 63
4.8 DEMOLITION AND RECYCLING 64
4.9 LIFE-CYCLE EMBODIED ENERGY OF CASE STUDY BUILDING 65
4.9.1 Comparison With Other Studies 68
4.10 INITIAL EMBODIED ENERGY OF IMPROVED BUILDINGS 69

4.11 RECURRING EMBODIED ENERGY OF IMPROVED BUILDINGS 72

4.12 LIFE-CYCLE EMBODIED ENERGY OF IMPROVED BUILDINGS 74

4.13 REDUCING THE LIFE-CYCLE EMBODIED ENERGY OF THE CASE STUDY BUILDING 76

4.14 MODEL UNCERTAINTY 79

4.15 CHAPTER SUMMARY 81

CHAPTER FIVE: LIFE-CYCLE ENERGY ANALYSIS 84

5.1 INTRODUCTION 84

5.2 LIFE-CYCLE ENERGY ANALYSIS 84

5.2.1 Operating Energy 84

5.2.2 Life-cycle Embodied Energy 85

5.3 LIFE-CYCLE ENERGY ANALYSIS 87

5.4 DISCUSSION OF RESULTS 90

5.5 COMPARISON WITH OTHER STUDIES 90

5.6 CHAPTER SUMMARY 91

CHAPTER SIX: LIFE-CYCLE COST ANALYSIS 93

6.1 INTRODUCTION 93

6.2 ASSUMPTIONS AND DEFINITIONS 93

6.2.1 Inflation Rate 93

6.2.2 Discount Rate 94

6.2.3 Energy Prices 94

6.2.4 Discount Rate Adjustment 95

6.2.5 Present Value Calculations 96

6.2.6 Economic Efficiency, Energy Efficiency and Cost Effectiveness 96

6.3 CAPITAL COST OF CASE STUDY BUILDING 97

6.4 OPERATING COSTS 98

6.5 LIFE-CYCLE COSTS 101

6.5.1 Sensitivity Analysis 105

6.5.2 Payback Period 105

6.6 LEVELIZED COST ANALYSIS 106

6.6.1 Comparing the Net Present Value Calculations to the Levelized Cost Analysis 111

6.7 COMPARISON OF THE ENERGY ANALYSIS AND ECONOMIC ANALYSES 112

6.8 CHAPTER SUMMARY 115

CHAPTER SEVEN: POLICY ISSUES 117

7.1 INTRODUCTION 117

7.2 NATURE OF THE POLICY DEBATE 117

7.3 VIEWS OF ENERGY 120

7.3.1 Energy as a Commodity 122

7.3.2 The Behavioralist/Technologist Model 124

7.3.3 Behavioral Barriers to Improving Energy Efficiency 125

7.3.3.1 Energy Invisibility 125

7.3.3.2 Information 126

7.3.3.3 Discount Rates 127

7.3.3.4 The Symbolic Meaning of Energy 127

7.3.3.5 Momentum of Past Behaviour 128

7.3.3.6 Literacy 128

7.3.3.7 Intermediaries 129

7.3.4 A Third Conceptual Model 129

7.4 ANALYSIS OF COMPETING VIEWS 131

7.5 CONSUMER RATIONALITY 133

7.6 MAPPING THE SUB-GOVERNMENT 136

7.7 POLICY ALTERNATIVES 138

7.7.1 Utility Sponsored 139

7.7.2 Competitive Markets 142

7.7.3 Regulatory 143

7.7.3.1 Information 143

7.7.3.2 Standards 144

7.7.3.3 Pricing 146

7.8 RELEVANCE TO THE CURRENT STUDY 149

CHAPTER EIGHT: CONCLUSIONS, SUMMARY, AND RECOMMENDATIONS 153

8.1 SUMMARY OF FINDINGS AND CONCLUSIONS 153

8.1.1 Operating Energy 153

8.1.2 Embodied Energy 153

8.1.3 Life-cycle Energy Analysis 155

8.1.4 Life-cycle Cost Analysis 155

8.1.5 Policy Implications 157

8.2 THESIS CONCLUSIONS 160

8.3 RECOMMENDATIONS 160

REFERENCES **162**

APPENDICES **170**

Appendix A: Building Specifications and Drawings 171

Appendix B: Operating Energy Calculations 176

Appendix C: Embodied Energy Calculations

Appendix C1: Energy Intensity of Building Materials. 187

Appendix C2: Energy Intensity Trends for Materials: 1976-1990. 200

Appendix C3: Initial Embodied Energy of Base Building. 203

Appendix C4: Recurring Embodied Energy of Base Building. 225

Appendix D: Life-cycle Energy Analysis Results 229

Appendix E: Life-cycle Cost Analysis Results 231

LIST OF TABLES

Table 1.1. Components of the Life-cycle Analysis. 8

Table 3.1. Summary of Building Energy Performance Index for Case study Building. 33

Table 4.1. Summary of Initial and Life-cycle Embodied Energy Results. 52

Table 4.2. Initial Embodied Energy and Mass of Building Materials. 56

Table 4.3. Initial Embodied Energy by Building Component. 57

Table 4.4. Comparison of Recurring Embodied Energy Based on two Methods. 64

Table 4.5. Summary of Life-cycle Embodied Energy Based on two Methods. 66

Table 4.6. Comparison of the Life-cycle Embodied Energy by Building Component. 67

Table 4.7. Summary of Initial and Life-cycle Embodied Energy Results, Including Results of Present Study. 69

Table 4.8. Changes in Initial Embodied Energy due to Changes in Building Design. 72

Table 4.9. Recurring Embodied Energy for Improved Buildings. 74

Table 4.10. Summary of Life-cycle Embodied Energy of Building With Improvements. 75

Table 4.11. Results of Sensitivity Analysis. 81

Table 5.1. Summary of Building Energy Performance Index for Case Study Building. 85

Table 5.2. Summary of Life-cycle Embodied Energy of Case Study Building. 86

Table 5.3. Life-cycle Energy Results of Case Study Building. 88

Table 6.1. Capital Cost of Building Under Different Design Scenarios. 98

Table 6.2. Annual and Life-cycle Operating Costs. 100

Table 6.3. Building Life-cycle Costs. 102

Table 6.4. Net Present Value of Strategies. 103

Table 6.5. Investment Payback Period for Cost Effective Strategies. 106

Table 6.6. Levelized Cost per Unit of Energy Saved. 108

Table 6.7. Levelized Cost per Unit of Energy Purchased. 109

Table 6.8. Difference Between Levelized Cost per Unit of Energy Saved and the Levelized Cost per unit of Energy Purchased. 110

Table 6.9. Improvements to the Operating Performance of Building Using Cost Effective Strategies. 114

Table A1. Building Specifications. 174

Table B1. Energy Consumption of Case Study Building. 181

Table C1. Energy Intensity of Building Materials. 187

Table C2. Energy Intensity Trends for Building Materials in Canada, 1976-1990. 200

Table C3.1. Initial Embodied Energy of Case Study

Building. 203

Table C3.2. Mechanical Takeoff. 218

Table C3.3. Electrical Takeoff. 224

Table C4. Recurring Embodied Energy of Base Building. 224

LIST OF FIGURES

Figure A1. Building Drawings. 171

Figure A2. Building Drawings. 172

Figure A3. Building Drawings. 173

Figure B1. Monthly Energy Consumption, Build 7A. 175

Figure B2. Monthly Heating Loads, Build 7A. 177

Figure B3. Building Energy Performance Index 178

Figure B4. Energy Consumption by End Use. 179

Figure B5. Energy Consumption by End Use. 180

Figure D1. Lifecycle Energy, Building Life = 40 years. 229

Figure D2. Lifecycle Energy, Building Life = 80 years. 230

Figure E1. Net Present Value of Strategies. 231

Figure E2. Ranking of Strategies. 232

CHAPTER 1: INTRODUCTION

This thesis investigates the life-cycle economic and energy implications of a commercial office building, located in Vancouver, British Columbia. The work is based on the premise that the commercial building stock is designed and built to sub-optimal levels of performance. In the present context, the criteria for analyzing optimality are defined in terms of energy and monetary accounting.

This work frequently refers to the concept of optimality and sub-optimality. However, this work does not claim to provide a solution for an optimal building. Because of the number of independent variables and the subjective nature of many of those variables, optimality cannot be defined rigorously. It is possible, however, to define the magnitude and direction of improvements to building performance relative to some baseline, thus making it possible to substantiate and quantify the claim of sub-optimality. The baseline used to quantify levels of sub-optimality in this analysis is a case study building conforming to the energy efficiency code for commercial buildings in Vancouver. Therefore, a building that uses less energy, and has lower life-cycle dollar costs relative to the baseline building may be said to be better (less sub-optimal) than the baseline building.

A principal role of the life-cycle energy analysis in this work is

to provide information that may be utilized in the allocation of scarce energy resources. Such a role should be viewed as complimentary to an economic analysis. Whereas the economic analysis will provide information based on market information, the energy analysis may provide an additional perspective based on a physical description of a building. As discussed in Chapter Two, an energy analysis may provide relevant information when analyzing activities where there is evidence of market failures.

1.1 THESIS OBJECTIVES

The major objectives of this work are listed below.

-Validate the premise that commercial buildings are sub-optimal by the criterion of energy. This work will perform a life-cycle energy analysis of a single archetypal commercial office building, located in Vancouver. The building is designed in compliance with the energy efficiency code for Vancouver[1]. The energy performance of the building will be improved to achieve an energy efficient office building through a series of design strategies. The analysis will extend traditional energy analyses, based on operating energy, to

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[1]The energy efficiency code for commercial buildings in Vancouver is consistent with the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standards [ASHRAE, 1989].

include the life-cycle embodied energy of the building[2]. The life-cycle embodied energy is incorporated in the analysis to investigate the total energy requirements of a building.

-Validate the premise of sub-optimality by the criterion of monetary accounting. This work will provide a life-cycle economic analysis of the case study building to observe how changes in the life-cycle energy performance affect the life-cycle dollar costs of the building.

-Compare and contrast the information provided by the energy analysis with the economic analysis.

-Provide a policy framework for reconciling the information based on the energy and economic analyses.

1.2 BACKGROUND INFORMATION

1.2.1 The Case Study Building

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[2]The embodied energy is defined as that component of the energy budget derived from extracting or recycling the raw materials, primary and secondary processing, transporting the building materials, and on-site erection. "Life-cycle" embodied energy expands the boundaries of the embodied energy analysis to include the embodied energy consumed throughout the useful life of a building. This includes the energy consumed in component replacement and maintenance of the building, and the energy required to demolish and dispose of the structure at the end of its useful life.

The design of the case study building used in this work corresponds to a generic office structure that is representative of many office buildings. Drawings of the building, occupancy schedules, operating requirements and systems characteristics are presented in Appendix A. During the preliminary phase of the energy analysis work, the building was designed as a three-story office building. This work is found in Cole [1994]. The three-storey configuration permitted a comparison of embodied energy of wood, steel and concrete structures. The building used in the present work adopts the same floor plate design, but is of a five-storey configuration. In moving from a three to a five-storey structure, it is no longer possible to model the building using wood, due to fire code restrictions. The floor area of the building is 8026 m^2.

The structure of the case study building is steel reinforced concrete. Concrete is chosen as the primary building material in the study due to two related factors: the cost advantage of concrete construction over the steel configuration; and, concrete is more representative of local construction practices. It should be noted that any building is a system of many components, using 50 to 100 materials. In the case study building, steel is a major component of the embodied energy due, in part, to the need for steel reinforcing in the concrete.

A fictitious building is chosen in this analysis (rather than a real building) for two reasons. First, this work continues an

analysis of a case study building started by Cole [1994]. Therefore, a lot of information needed for the analysis has already been generated. Building drawings, the structural analysis, much of the materials take-off and the preliminary operating energy model for the building were available. Second, this work performs a parametric study relating energy and economic variables. If a real building was used as the case study building, information at only one point in the energy and economic analyses would be available.

1.2.2 Choosing an End Use

This analysis deals with economic and energy issues of one case study building. The commercial office sector is studied because of the large potential improvements within this sector, and due to the relative magnitude of this sector within the provincial economy. Considering electricity consumption in the commercial sector, the cost effective electricity savings potential is of the order of 58% in British Columbia [B.C. Hydro, 1993]. B.C. Hydro also predicts the technical electricity savings potential is approximately 68% [B.C. Hydro, 1993][3]. The annual energy consumption in the commercial sector is 93 PJ in British Columbia [State of Environment Report for BC, 1993]. This corresponds to 9% of

[3] The cost effective and technical conservation potential predicted by B.C. Hydro correspond to the reduction of electricity consumption by 2010. The work assumes adoption of the most energy efficient technologies by all commercial electricity consumers. For the economic analysis, the study uses the long run marginal cost of electricity.

provincial energy consumption. Further, the commercial sector is the fastest growing sector of the economy with a growth rate of 1.6% per year. It is expected that by 2015, this sector will require 134 PJ, corresponding to an increase of 45% [Ministry of Energy Mines and Petroleum Resources, 1994]. Therefore, this sector provides an important opportunity to explore improvements in energy and economic efficiency.

1.2.3 Rationale for the Work

In performing an analysis of the performance of a commercial building, one must address the question "Is it worth it?". This work is deemed important for both economic and ecological reasons. As noted previously, B.C. Hydro predicts that commercial electricity users can reduce consumption 58% by the year 2010 by implementing strategies that are cost effective [B.C. Hydro, 1993]. This figure may be optimistic. The survey by Komor and Moyad [1994] of studies investigating the cost effective energy savings potential for commercial buildings in the United States predicts a range of 13% to 45%[4]. Komor and Moyad suggest that a cost effective potential of 33% is more plausible. Although there is wide variation in the predictions, the magnitude of the cost effective

[4]It is not surprising that different studies should predict different cost effective potentials. The results of studies are based on computer simulations which require predictions of the future, including: population growth rates, technology adoption rates, energy prices, economic conditions, and consumption patterns.

potential is sufficiently large to warrant further investigation.

Considering ecological reasoning, there is an obvious link between energy use and environmental quality that is difficult to explore by applying only economic analysis[5]. The environmental implications of burning fossil fuels are well documented [Brown, 1992, Statistics Canada, 1994, British Columbia Energy Council, 1994]. Macdonald (1994, pg. 7.122) has noted that reducing energy consumption by one generic quad/yr in buildings may lead to a reduction in greenhouse gas emissions of approximately 16 million tonnes of carbon equivalent. Alternately, the adverse effect on fish and wildlife populations, the destruction of local habitat and the alteration of micro-climates due to hydro electricity sites is well known [B.C., Hydro, 1994 (c), Northwest Power Planning Council, 1991].

1.2.4 Scope of the Analysis

It is the intent of this work to provide an energy and economic life-cycle analysis for a representative commercial building, located in Vancouver. The research will provide information about the relationship between an economic life-cycle analysis including capital and operating dollar costs, and an energy life-cycle

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[5]There is the growing body of literature exploring the links among natural resources, energy and economic theory. The journal Ecological Economics, works by Daly [1981, 1993], and Constanza [1993] provide examples.

analysis including the embodied and operating energy costs for a case study building. These variables are summarized in Table 1.1.

Table 1.1. Components of the Life-cycle Analysis.

Capital Dollar Costs of Case Study Building	Embodied Energy of Case Study Building
Operating Dollar Costs of Case Study Building	Operating energy of Case Study Building

Finally, this work will investigate public policy options directed towards improving the energy and economic efficiency of the building industry in British Columbia.

This work focuses on the construction and operation of one commercial building in one geographic location. However, there are many important issues this work does not address. This analysis does not address the issue of whether the building should ever be constructed in the first place. The present study does not extend the analysis to investigate the energy and dollar implications to the entire office building stock[6] and does not provide a life-cycle

[6]See B.C. Hydro, [1993] for a model of electricity consumption trends for the entire commercial building stock.

analysis of all the environmental implications of the building[7].

It is argued that energy provides a basic physical and ecological indicator of environmental implications of buildings[8]. By minimizing the energy impacts of a building, other environmental stressors are simultaneously reduced. However, the relationship between energy consumption and, for example, emissions of Volatile Organic Compounds (VOC's) or biodiversity is not quantified or explored in this work.

1.2.5 An Interdisciplinary Approach

This work takes an interdisciplinary approach to the analysis of the energy and economic performance of a building. Buildings and energy are used and valued in many different ways by society. By imposing boundaries on the analysis along disciplinary lines, one may create "conceptual blind spots"[9] and miss essential ingredients to improving building energy performance. An interdisciplinary approach strengthens the understanding of the interactions among architectural, engineering, economic and policy issues of energy, buildings, building occupants and the ecological impacts of the

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[7]See Kohler and Lutzkendorf in [Cole, 1992] for information about life-cycle assessments of buildings.

[8]There are other indicators that may be informative, such as carbon dioxide emissions [CMHC, 1991], or appropriated carrying capacity [Rees, 1992].

[9]P. Stern, 1986

interactions. This work serves as a means of developing an understanding of improving energy efficiency of buildings. However, this information is of limited value if it is not placed within a broader framework. The research provides an economic and energy analysis of an important public policy issue.

1.2.6 The Building Industry

There are a number of differences between the building industry and other sectors of the economy that may influence the type of analysis used in this work. First, the longevity of buildings is typically 40 to 80 years, with many structures lasting hundreds of years. This implies the turnover rate for buildings is of the order of 1 to 2% per year.

Second is the magnitude of the building industry within an economy. The building industry is the second largest in the world, and office buildings are the largest capital assets of developed nations [Brand, 1994]. It has been predicted that the building sector may consume 20% to 30% of all resources in an economy [Cole, pg. 111, 1992]. In British Columbia, operating buildings consume approximately 24% of the provincial energy requirements [Ministry of Energy Mines and Petroleum Resources, pg. 2, 1989]. Due to the size, complexity and inertia of the building industry, changing the way the industry operates is a complex task.

Third is the fragmented nature of the building industry. Much of the building industry is operated by small contractor or tradesman companies. The industry is regulated at the federal, provincial and municipal levels of government, resulting in variations and conflicts in standards and enforcement between regions.

The cumulative effect of these factors is that innovations in the building industry occur at a very slow rate of diffusion. Typically it takes 10 to 20 years for building innovations to be adopted by the industry [Cole, pg. 111, 1992]. In addition, because of the slow turnover rate in buildings, the time for building innovations to saturate the sector is longer than most other sectors of the economy. Therefore, the impact of current design decisions will have a large and a long lasting impact on economic efficiency and environmental quality.

1.3 THESIS STRUCTURE

Chapter Two introduces the concept of an energy analysis and the applicability to the current study. Information regarding the use of energy analysis as a public policy tool is discussed. There has been controversy in the literature regarding the information provided by an energy analysis, and the various viewpoints are presented and discussed.

Chapter Three provides an analysis of the potential to reduce the

operating energy of the case study building through the iterative adoption of simple, proven technologies. Results of the analysis are based on computer simulations of the building, using the software program DOE2.1-D.

Chapter Four quantifies the life-cycle embodied energy of the case study building. The life-cycle embodied energy includes four components:

- -the initial embodied energy from construction of the base building;
- -the recurring embodied energy due to repair and replacement of building components;
- -the embodied energy implications of improving the operating characteristics of the building; and,
- -the energy required to demolish the building at the end of its service life.

Chapter Five uses the information of the previous two chapters to perform an energy analysis of the different building configurations. The relative magnitudes of operating and embodied components of the building are explored.

Chapter Six performs a life-cycle cost analysis of the case study building. This analysis calculates the life-cycle net present value of adopting strategies to improve the performance of the case study

building. Strategies are ranked according to their economic net present value. A comparison is made between the results of the energy and economic analyses.

In Chapter Seven the focus of the discussion changes. Whereas the previous chapters focus attention on the case study building, Chapter Seven discusses the broader policy implications of the present work in the context of current thinking about energy policy. Energy as perceived by economists is compared and contrasted with the views expressed by behavioral and engineering researchers. The second section of the chapter reviews the stakeholders involved in regulating energy efficiency of commercial buildings in British Columbia. The final section of the chapter uses the background information of the preceding sections to provide policy options for improving the performance of the case study building.

Chapter Eight provides a summary and the conclusions of this work. From this information, a set of recommendations is presented.

CHAPTER 2: ENERGY ANALYSIS

2.1 INTRODUCTION

This chapter introduces the concept and use of energy analysis. Information regarding the use of energy analysis as a public policy tool is discussed. There has been controversy in the literature regarding the information provided by an energy analysis, and the opposing viewpoints are presented and discussed.

2.2 DEFINING AN ENERGY ANALYSIS

Energy analysis is a procedure for quantifying the total energy requirement for a good or service. This includes the energy required in the acquisition of raw materials, primary and secondary processing, operating, and final disposal. Although energy is the focus of the present study, it is possible to apply a similar analysis to quantify resource use in general. For example, Statistics Canada has recently developed a system of national accounts based on augmented input-output tables which quantify natural resource use and waste and pollutant output by sector for the Canadian economy [Statistics Canada, 1994].

2.3 ENERGY ANALYSIS AS A PUBLIC POLICY TOOL

There has been a great deal of controversy in the literature dealing with the potential value of energy analysis as a legitimate

and valuable source of information for public policy. Much of this discussion occurred between 1970 and 1980. At one extreme is the work of Webb and Pearce [1975] and Leach, [1975] who argue that energy analysis provides no additional information to an economic analysis. By contrast is the work of Gilliland [1975, 1978] and Odum [1971]. In their work, the authors express the opinion that as energy is the ultimate scarce resource, an energy accounting system should replace the existing monetary system. It is important to discuss these extreme views of energy analysis to both legitimize and provide a context to its use in the present work.

Webb and Pearce [1975] raise several important issues about the use of energy analysis from the point of view of economics. The major criticisms are:

- Prices will rise to reflect scarcity whereas the energy cost will be constant. This is reflected in problems of intertemporal allocation decisions;

- There is no information on the deviation between actual market prices and the shadow prices for commodities, so it is impossible to say whether an energy analysis provides better information than an economic analysis;

- Energy analysis is based on the assumption of homogeneity:

> [t]he problem then is simply that the saving of energy measured in physical units implicitly assumes a one-to-one correspondence of benefits forgone to energy (per therm) saved. In the market type economy there is no reason why this correspondence should exist. [Webb and Pearce, pg. 325, 1975]

In dealing with the first two issues, it is useful to refer to the work of Georgescu-Roegen who states that:

> [e]ven a simple analysis of the energy aspects of man's existence may help us reach at least a general picture of the ecological problem and arrive at a few general conclusions. The truth however, is that the most we can do is prevent any unnecessary depletion of resources and any unnecessary deterioration of the environment, but without claiming that we know the precise meaning of unnecessary in this context. [Georgescu-Roegen, 1975]

It should be acknowledged that defining an optimum intertemporal allocation is not resolved in energy analysis. However, the economics literature does not offer a comprehensive treatment regarding the allocation of scarce resources across generations. For example, the issue of discount rate in utilizing natural resources is subject to a great deal of controversy and ambiguity [Norgaard and Howarth, in Constanza, pg. 88, 1991].

In response to Webb and Pearce's third point, homogeneity is not a necessary feature of energy analysis. It should be stressed that the level of aggregation in an energy analysis follows from the

focus of the analysis and the level of abstraction involved. Examples where the analysis is disaggregated by fuel type include the energy analyses that consider the environmental implications of energy utilization. Specific examples include OPTIMIZE [CMHC, 1991] and the Statistics Canada Environmental Perspectives [Statistics Canada, 1993].

In its analysis of the embodied energy of buildings, the present work attempts to aggregate all sources of energy. This approach may be justified as a useful, albeit rough indication of energy conservation performance and potential.

Gilliland [1975], Odum [1971], and Constanza et al. [1989] promote an alternate argument that energy is the ultimate limiting input factor into production, and should therefore be used as an economic metric. Although the works related to an energy theory of value have interest and merit in terms of proposing a basic biophysical metric for valuing goods and services, there are several problems with the system. Georgescu-Roegen, for example states:

> I have maintained that it would be a great mistake to think that the economic process can be represented by a vast system of thermodynamic equations. The economic process moves through an intricate web of anthropomorphic categories, of utility and labour in the first place. Its true product is not a physical flow of high entropy, but the immaterial flux of the enjoyment of life obtained through the drudgery of work. [Georgescu-Roegen in Daly

and Umana, pg. 68, 1981]

A second criticism of energy analysis as a valuation technique is common to all single factor theories of value. Namely, that by this theory, price levels are defined based on supply information only. The relative price between commodities is based on the single factor input of energy. This implies that commodity demand and other input scarcities are irrelevant to the price [Leach, 1975].

The arguments presented above regarding the value and use of energy analysis as a public policy tool provides a framework for developing an energy analysis for the present work. The views of Web and Pearce [1975], versus those of Odum [1971] and Gilliland [1975, 1978] provide insight into the limits of energy analysis. However, the extreme views of these authors are of limited utility. The next section develops energy analysis as it is used in the present work.

2.4 WHAT AN ENERGY ANALYSIS CAN DO

The last section reviewed the polar viewpoints about the use of energy analysis as a public policy tool. This section provides a more moderate discussion of the abilities and limitations of energy analysis. The work by Berry [1979] provides additional information.

It is a premise of Berry's work that an energy analysis may provide

information that will not be picked up by an economic analysis. A principal role of energy analysis is to provide information that may be utilized in the allocation of scarce resources. Such a role should be viewed as complimentary to an economic analysis. Whereas an economic analysis will provide information based on market information, an energy analysis may provide an additional perspective based on a physical description of a process or system. This information is especially relevant in analyzing activities where there is evidence of market imperfections or market failures. The market failures may take the form of imperfect competition, externalities, or issues of public goods. In a perfectly competitive market where the price of goods and services reflects full social costs, it is anticipated that an economic analysis would provide all the information necessary to make optimum allocation decisions. This implies, for example, the life-cycle energy of buildings and their components would be fully captured in the price of those goods. However, under existing conditions, there are several reasons the life-cycle energy of building components may not be fully picked up in the price. For example, government policies such as taxes, subsides, or utility rate structures may distort the market price of energy and influence decisions about energy use.

The rate structure used by the utilities industry in British Columbia is based on the average cost of supplying energy. This value is less than the long-run marginal cost of providing new

supplies, and may provide incorrect price information to consumers. Second, the declining block rate structure for commercial electricity customers encourages consumption, and does not provide accurate information about the cost of energy services. It is anticipated that the declining block structure will be replaced with a flat rate during the fiscal year of 1995-1996 [British Columbia Utilities Commission, pg. 7, 1994].

A second discontinuity between economic and energy costs may arise when energy flows in the absence of money flow. For example, many natural resources entering a production and consumption cycle, or wastes exiting from that cycle may have zero price, but do have an energy value that will be captured by an energy analysis. For example, during demolition of buildings, used material such as carpets, roofing and gypsum products have zero economic value, and are frequently discarded to landfills. However, all these materials do have an energy value that will be picked up in an energy analysis.

In contrasting the attributes of economic and energy analyses, it is not the intent of this work to suggest or advocate an energy theory of value. However, it is a premise of the present work that energy analysis may provide information that may not be picked up in a distorted market.

2.5 USE OF ENERGY ANALYSIS IN THE PRESENT WORK

In this work, energy analysis is used to provide a process by which the total energy of a case study building may be examined. The total energy includes the life-cycle embodied energy and the operating energy. As noted previously, this should be viewed as providing complimentary information to the economic analysis. There is presently a limited understanding of the interactions between the various components of life-cycle energy use in commercial buildings. Cole [1994] provides an analysis of operating versus embodied energy for a three-storey office building, utilizing three structural materials choices. The present work provides information on the relationship between the operating and embodied energy of an archetypal office building over a range of operating performances. The relationship between operating and embodied energy for the case study building is explored fully in Chapter Five.

2.6 SYSTEM BOUNDARIES

An obstacle in developing an energy analysis of buildings is in the development of the system boundaries. It is important to include all the significant energy inputs, and exclude all insignificant and extraneous inputs. Two examples of boundary problems are the inclusion of human energy and social infrastructure in the energy analysis.

2.6.1 Human Energy

Controversy exists in the literature regarding if and how the energy input from human labour should be accounted for in an energy analysis. At one extreme are the works of Odum [1971] and Punti [1988] who advocate the inclusion of the energetic value of human labour. At the other extreme is the convention set out in the International Federation of Institutes of Advanced Study Workshop [IFIAS, 1974] that does not incorporate human labour in the analysis of industrialised activities. The construction process is labour intensive relative to many other activities. In addition, there are instances where automated and energy intensive processes may replace low energy human energy inputs. Therefore, the choice of whether and how to incorporate the energy value of human input may modify the energy analysis. A Preliminary analysis was performed to compare the energy value of human labour in the building process to the embodied energy of the building materials. The analysis assumed a human labour input based on the metabolic energy input into the building and its components. It is estimated for the case study building in this analysis, the labour component of the initial embodied energy is of the order of 0.4%. This is less than the uncertainty of the energy analysis, and is not investigated further.

2.6.2 Infrastructure

A second boundary problem is how or if one should include in the energy analysis of a building the infrastructure associated with

services to that building. Services may include, for example, electricity generation and transmission, water, communications, roads, fire protection, and waste water treatment. For this analysis, the system boundary has been chosen to include the site and building, but does not extend the analysis to include the embodied energy of social infrastructure. In a similar way, the building design may dictate the furniture used and the clothing worn by occupants. Again, the boundary is chosen to exclude the embodied energy of these components.

CHAPTER 3: OPERATING ENERGY OF CASE STUDY BUILDING

3.1 INTRODUCTION

This chapter provides an analysis of the potential to reduce the operating energy of a commercial office structure. The case study building is consistent with the energy performance requirements of the energy efficiency code for Vancouver, B.C. Similar analyses have been performed for commercial buildings in British Columbia [BC Hydro, 1992]. While the B.C. Hydro study investigates energy conservation potential of the entire building stock, the intent here is to perform an independent and comprehensive analysis of the energy conservation potential for one case study structure.

3.2 BACKGROUND

There are numerous works dealing with the operating characteristics of buildings, and strategies to improve energy efficiency. An example that has relevance to the present work is provided by the B.C. Ministry of Energy Mines and Petroleum Resources [1991:a, b]. These works examine the life-cycle costs of adopting energy efficiency standards, based on the American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) performance standards (ASHRAE, 1989). The Ministry's work considers 13 commercial building types for three climatic regions of British Columbia. The thirteen building types analyzed in the project were:

-Warehouse

-Retail non-food store

-Gas bar/Convenience store

-Retail food/Grocery store

-Low rise office (three-storeys or less)

-High rise office (more than three-storeys)

-Elementary/secondary school

-University/college

-Hotel

-Restaurant

-Hospital

-Refrigerated warehouse

-Shopping mall.

The climatic regions investigated in the work were:

-Temperate coastal

-Central interior

-Upper interior.

The work is based on computer simulations of the energy consumption characteristics of the buildings using the program DOE-2.1D [Lawrence Berkeley Laboratory 1989, 1991]. The analysis suggests it was cost effective to improve all the buildings studied to meet or exceed the ASHRAE 90.1 standards. The analysis is based on a 15-year study period and a discount rate of 10%. Several buildings in the study had a *negative* capital cost for upgrading to meet the

ASHRAE performance standard. This is because improving the performance of the building permitted the installation of smaller and less expensive Heating, Ventilation and Air-conditioning (HVAC) systems.

Focusing on a building similar to the case study building examined in this work, the net present value of implementing the performance standards was found to be $19.45/ m^2. To arrive at the net present value figures requires an estimate of the future cost of energy. The results of the above analysis are based on energy price forecasts found in a report on the forecast demand and supply requirements for British Columbia between 1990 and 2010 [Energy Mines and Petroleum Resources, 1991].

3.3 QUANTIFYING THE OPERATING ENERGY OF BUILDINGS

The unit used to quantify the operating energy of buildings is the Building Energy Performance Index (BEPI)[1]. This corresponds to the operating energy consumed per unit of floor space per year, and is measured in Gigajoules per square metre per year [$GJ/m^2.yr$]. Typical BEPIs for commercial buildings in Vancouver range from 0.4 $GJ/m^2.yr$ to 4.8 $GJ/m^2.yr$, with an average of 1.75 $GJ/m^2.yr$ [Cole, pg. 26, 1994]. Alternately, the average BEPI for office buildings in the United States is estimated at 1.2 $GJ/m^2.yr$ [Houghton, pg. 9.190,

[1]This unit is standard in the literature.

1994]. It is important to note that many of the buildings used in arriving at these figures are not built to ASHRAE 90.1 standards. As a basis of comparison, high energy efficiency designs in European buildings are achieving BEPIs of the order of 0.1 $GJ/m^2.yr$ to 0.3 $GJ/m^2.yr$ [Cole, pg. 27, 1994]. Because of the effect of climatic variations and different operating schedules between Vancouver and the cities of Europe and the United States, direct comparisons of operating energy performance are difficult to make.

The operating energy for the case study structure is calculated using the computer design tool "DOE-2.1D". The program was developed by the United States Department of Energy, and is a highly flexible computer modelling device that is capable of simulating all aspects of the building. This includes climatic conditions, envelope and systems characteristics as well as occupancy schedules and loads. The case study building was introduced in Chapter One. Drawings, details of the occupancy schedule, operating loads and systems characteristics are contained in Appendix A.

3.3.1 Site Versus Source Energy

In quantifying the operating performance of the case study building, it is important to distinguish between the source (primary) energy and the site (secondary) energy. Source energy refers to the primary energy requirement for operating a building,

inclusive of efficiency losses. Site energy refers to the energy actually consumed in the building[2], exclusive of efficiency losses. In the present work, it is assumed that electricity generated by thermal plants represents 15% of electricity use [B.C. Ministry of Energy Mines and Petroleum Resources, 1989], and it is assumed that the thermal plant is 33% efficient. Therefore, one unit of site electricity is equivalent to 1.45 units of source electricity. It is assumed that source and site energy is equivalent for hydro electricity[3] and natural gas serviced to the building[4]. The distinction between source and site energy is made in order to maintain consistency when comparing the operating and embodied energy characteristics of the case study building.

3.4 DESIGN PROCESS

Modelling the building's operating energy was an iterative process. An iterative approach was utilized to minimize potential mistakes and the efforts required to "debug" the operating energy program. The process to model thermal performance was based on the following steps:

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[2]It is assumed that the BEPI's referred to in the last section correspond to site energy. However, the distinction between site and source energy is not made by any of the references.

[3]Transmission losses have not been included.

[4]Natural gas has a net energy ratio of approximately 60. See Nemetz [1993].

-single-storey, single thermal zone[5] structure;

-single-storey, five thermal zone structure;

-three-storeys, five thermal zones per floor;

-five-storeys, five thermal zones per floor; and,

-five-storeys, twenty-one thermal zones per floor, based on a 7.5 m. grid configuration used as the base case study structure.

Once the base building was obtained, the design was altered to observe the operating characteristics under differing design configurations. An identification numbering system was implemented through this design process. Simulation run #1 through #6 correspond to the preliminary models[6] in the iterative process. Test runs #7 to #17 correspond to the test runs of the base case study building and modified buildings.

3.5 IMPROVING THE OPERATING ENERGY OF THE CASE STUDY BUILDING

The base building was systematically upgraded from a typical office building to an energy efficient building. There is a large and diverse set of strategies that may be implemented to improve the operating performance of a building. The strategies employed in the present work were guided by a set of criteria including:

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[5]A single thermal zone implies the entire building is controlled by one thermostat, and the temperature of all areas is to be maintained at a single temperature. This is a simplification, since the core of the building usually requires cooling while the perimeter areas require heating, cooling or both.

[6]Single storey, single thermal zone, etc.

-maintain the air quality of the indoor environment[7];
-implement strategies that are well established in the building community;
-implement strategies that can be modelled within the operating energy simulation program;

It is acknowledged that the operating energy computer model limited the range of strategies incorporated in the case study building. For example, it was not possible to model stack ventilation.

Any design process is a synthesis of technical knowledge, experience, intuition and external constraints. The necessity of utilizing and incorporation of experience and intuition extensively in the process of refining the operating characteristics of the building implies that there is no optimal pathway or building design.

Once the strategies to improve the operating energy were selected, a hierarchy was implemented based on a set of principles outlined in ASHRAE 90.1 [1989].

- *Identify and minimize the impact of the functional requirements of the building. This implies, for example that:*

[7]The indoor environment refers to indoor air quality, visual access to the outside, and sources of noise.

-the building systems should be matched to the occupancy requirements for the building.

- *Identify and minimize the internal and external loads on the building. Strategies carried out here include:*
  -changing the building orientation to maximize passive heating and lighting capability;
  -controlling air infiltration;
  -improving the insulation and glazing;
  -implementing daylighting strategies;
  -reducing lighting levels
  -using high efficiency office equipment, such as high efficiency copiers, printers and facsimiles.

- *Integrate subsystems to improve the efficiency of the building systems. For example:*
  -reducing the lighting load through the implementation of daylighting and high efficiency lights, there is a corresponding reduction in the cooling load of the building and possible increase in heating requirements.

- *Improve the efficiency of subsystems by*:
  -replacing the variable air volume heating system with a heat pump.

The hierarchy of strategies used to improve the performance of the

case study building is consistent with general procedure outlined above. This process was refined by studying the output of the computer simulations after each run to determine which building load contributed the greatest amount to the energy consumption of the building. That load was targeted in the next building simulation.

3.6 RESULTS OF THE OPERATING ENERGY MODEL

Table 3.1 provides summary information of the building energy performance of the case study building under a number of configurations. Specifications of the base building are presented in Appendix A. In addition, complete graphical and tabular data for the operating energy of the case study building is presented in Appendix B.

Table 3.1. Summary of Building Energy Performance Index for Case study Building.

SIMULATION RUN	STRATEGY	BEPI [GJ/m^2.yr]	CUMULATIVE % CHANGE
		site, (source)	
7A	Base Case	0.96 (1.39)	
7B	Orientation	0.95 (1.38)	-3%
7C	Infiltration	0.91 (1.32)	-7%
7D	Infiltration	0.89 (1.29)	-9%
8A	Daylighting	0.56 (0.93)	-43%
8B	Heat Pump	0.44 (0.64)	-55%
9	Glazing	0.41 (0.59)	-58%
10	Lighting Density	0.35 (0.51)	-64%
11	Insulation	0.34 (0.49)	-65%
12	Equipment	0.28 (0.41)	-71%
13	Night Purge	0.28 (0.41)	-71%
14	Lighting Efficiency	0.23 (0.33)	-77%
15	Wall to Window Ratio	0.23 (0.33)	-77%
16	Increase Comfort Zone	0.23 (0.33)	-77%
17	Sun-space	0.23 (0.33)	-77%

The cumulative percent reduction in operating energy corresponds to the reduction in operating energy achieved by implementing the strategies successively. Incremental percent changes are less meaningful in this analysis as the magnitude of performance improvements is dependent on what strategies precede. This characteristic may be attributed to the dependence of building subsystems: for example, lights and cooling systems. Test runs 13, 15, 16 and 17 are strategies that were found to have negligible or negative impact on the operating performance of the building. The results of the operating energy analysis are consistent with other analyses of operating energy[8]. The initial site Building Energy Performance Index (BEPI) is 0.96 $GJ/m^2.yr$. This is consistent with a building conforming to ASHRAE 90.1 standards. Through an iterative design process, a final site BEPI of 0.23 $GJ/m^2.yr$ was achieved, corresponding to a 77% reduction in operating energy of the case study building.

Test runs 7A through 11 imply no behavioral modification by building occupants. Nor does it imply a reduction in the quality or quantity of energy services provided. Test runs 12 and 14 incorporate the potential to reduce energy loads through behavioral modification by building occupants. For example, the electricity

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[8]See Ministry of Energy Mines and Petroleum Resources, [1991], BC Hydro, [1993,1994]. Houghton [1994] presents similar results based on simulation runs using DOE2.1E, and measured energy consumption.

consumption from the elevator was reduced by making stairways the primary mode of transporting occupants between floors. This may be achieved by making stairways more visible or convenient and elevators less so. Reducing the energy load associated with office equipment has been investigated by Danbridge et al. [1994]. The author notes a 57% reduction in energy consumption is currently possible. The reductions in the lighting load in test run 14 is achieved by maintaining low ambient lighting and utilizing high efficiency task lighting.

Because of limitations in the DOE2 program, the full advantage of the sun-space design cannot be explored. For example it is not possible to explore reductions in operating energy through the implementation of passive stack ventilation effects[9] coupled to the sun-space.

Test runs were performed to establish the effect on the building operating energy through the reduction of indoor air circulation. There was no reduction of the outside air supply in this test run. A reduction in the operating energy to a site BEPI of 0.18 GJ/m^2 was achieved. As stated previously, however, a criterion for improving the case study building was that there should be no loss of indoor environmental quality. Indoor air quality is of sufficient

[9]Passive stack ventilation refers to a process of buoyancy driven (as opposed to mechanical fans) ventilation resulting from the temperature differential between interior and exterior spaces.

importance that this strategy was not implemented in the case study building.

3.7 OBSERVATIONS ON THE OPERATING ENERGY MODEL

There are a number of points that should be emphasized in reviewing the data presented in Table 3.1 and Appendix B. First, the data for monthly energy use predicts anomalous behaviour for the month of February. This is explained by the nature of the calculation method. The simulation program performs an hour by hour analysis of energy use. Since there are fewer days in February, there is a corresponding decrease in energy use for this month[10].

Second, uncontrolled air infiltration in commercial buildings is difficult to control and predict. In addition, air infiltration is frequently an important source of heating load. For example, analysis by Public Works Canada [1994, pg. 1-4] has documented a savings potential in heating energy of 20% to 60% through reduced air infiltration. Studies by the Canadian Mortgage and Housing Corporation [CMHC, 1993] suggest that infiltration in buildings may be one to two orders of magnitude larger than design specifications. In the computer analysis performed in this analysis, air infiltration rates prescribed in the ASHRAE 90.1 standards are used. It is not clear, however, how well these design

[10]This anomaly may be removed by normalizing the information for an average month (30.4 days). However, this results in a loss of information, so this step is not performed here.

standards are achieved in practice, nor is it clear that zero uncontrolled air infiltration is possible.

Third, the final level of performance does not imply a limit to the technical or behavioral energy savings potential for the building. Rather, this is the level of performance achieved through the application of simple, inexpensive and familiar strategies to improve the operating characteristics of the building. With the addition of active solar devices such as photovoltaic panels and solar heaters, this building could potentially be transformed into an energy autonomous building. A preliminary analysis of the potential to make the case study building energy autonomous was performed. The capital cost of this step was of the order of one million dollars for the photovoltaic cells alone. Additional capital costs for the invertors and the batteries were not calculated. Due to the capital cost estimated from the preliminary analysis, no further research of a photovoltaic system was performed. A solar water heating system was also investigated. However, this system was only able to augment the central heating system (rather than replace it). Therefore, this option was not explored further.

3.8 MODEL VERIFICATION AND UNCERTAINTY

To gain confidence in the results of the operating energy model, the computer output was verified using two approaches. First, the

data were compared against a set of test runs from the developer of the DOE2 program [Lawrence Berkeley Laboratory, 1986]. The five -storey office tower was compared with a case study structure of similar aspect ratio, but of a thirty-storey design. Assuming the heat transfer between floors is of second order magnitude, the Building Energy Performance indexes (BEPI) for the five and thirty storey office structures were found to be comparable. The assumption of negligible floor to floor heat transfer is based on the observation that the temperature and pressure differences between floors is small or zero. Therefore, the heat transfer between floors will be small.

As a second test of the operating energy model, the computer data were compared to measured results of similar buildings. For an office Building located in Vancouver, conforming to ASHRAE 90.1, the Building Energy Performance Index (BEPI) should be in the range 0.8 $GJ/m^2.yr$ to 0.95 $GJ/m^2.yr$[11].

The verification process is acknowledged to be indirect. However, in the absence of a real building with energy performance data over a range of performance characteristics, it is impossible to verify the operating energy model directly. The uncertainty in the operating energy analysis is inferred from discussions from individuals with experience in applying the model to existing and

[11]Ray Cole

new buildings[12]. Using these estimates, the uncertainty in the analysis of the building operating energy is estimated at 10%.

3.9 CONCLUDING REMARKS

It was found that the operating energy for the case study building could be reduced by 77% below a building conforming to ASHRAE 90.1 standards. This figure is consistent with other investigations of achievable reductions in operating energy [BC Hydro, 1992]. The reduction in operating energy is achieved through the adoption of simple, proven technologies.

[12]Gord Shimco, DW Thompson Inc.

CHAPTER 4: EMBODIED ENERGY OF CASE STUDY BUILDING

4.1 CHAPTER LAYOUT

This chapter begins by defining the concept of embodied energy, and discussing its magnitude in buildings. Methods used to predict the energy intensity[1] of goods and services are reviewed. Published results of analyses of the energy intensity of building materials and embodied energy of buildings are presented. The initial and life-cycle embodied energy for the case study building is calculated over the range of operating performances examined in Chapter Three.

4.2 DEFINING THE EMBODIED ENERGY OF A BUILDING

The embodied energy of a building is that component of the energy budget derived from extracting or recycling the raw building materials, primary and secondary processing, transporting the building materials to the site, and on-site erection. "Life-cycle" embodied energy expands the boundaries of the embodied energy analysis to include the embodied energy consumed throughout the useful life of a building. This includes the energy consumed in component replacement and maintenance of the building, and the energy required to demolish and dispose of the structure at the end

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[1]In this work, energy intensity refers to building materials and embodied energy to the building.

of its useful life.

4.3 SIGNIFICANCE OF THE EMBODIED ENERGY OF BUILDINGS

Depending on the lifespan, the life-cycle embodied energy for a building may be 18% [CMHC, pg. 1, 1991] to 40% (Kohler in Cole, 1991, pg. 29) of the life-cycle energy budget of a building. As the operating energy of the building decreases, the embodied energy may become a larger component of the total energy budget. However, lack of information in the published literature suggests there is no clear understanding how changes to the operating performance of a building will influence the embodied energy of a building.

4.4 METHODS OF ANALYSIS

The present analysis relies on previously published data for the energy intensity of building materials. This section provides a brief description of how the information has been generated. The methods used to estimate the energy intensity values include input-output analysis, process analysis and statistical methods.

4.4.1 Input-Output Analysis

Input-output analysis provides information on the inter-relationships between different sectors of the economy, providing information in terms of energy embodied per monetary unit of

output. The analysis permits the calculation of direct and indirect primary energy required to produce a good or service. The use of input-output analysis techniques to estimate the energy intensity of commodities is developed in Reister [1978], Bush [1981], and Peet [1993].

An advantage of input-output analysis is the ability to capture all the direct and indirect energy inputs of a product. The indirect energy inputs include the upstream energy embodied in materials and equipment, such as the tools required to produce the final good.

A problem with information derived from an input-output table arises from the level of disaggregation of the tables. Specifically, the coefficients derived from an input-output analysis provide estimates of the energy embodied in a dollar's worth of the *average* product of an industry. This implies that an input-output analysis will provide an imprecise estimate of the embodied energy of commodities that have a price that is far away from the average product price [Reister, 1978]. This is less of a problem in Canadian data compared to input-output data from other countries. The Canadian commodity input-output table is disaggregated into 602 commodities (compared to 215 industries for the United States) resulting in fewer atypical products.

A second problem with input-output analysis is the four-year time lag between the age of the data and publication of the tables.

There has been a steady decrease in the embodied energy of commodities produced in Canada of approximately 1.0% per year[2]. Relying only on input-output analysis may result in a systematic over-estimation of the energy intensity of current building materials.

4.4.2 Process Analysis

Process analysis involves the quantification of all the direct and indirect energy inputs to and outputs from a process. Although conceptually simple, a number of limitations of this method have been expressed in the literature, [Baird and Aun, pg. 6, 1983, CMHC, Appendix II, pg., xi, 1991]. First, it is a complex task to keep track of all the indirect energy inputs. This frequently results in truncation error. Second, the inputs to a process may vary by the production technology used. Therefore, the energy intensity figures may be dependent on variables including age of the data, and location specific variables including manufacturer, or plant efficiency.

Input-output analysis and process analysis are the predominant means employed in deriving the data used in the present analysis. A third method, Statistical analysis is used to a lesser extent.

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[2]See Section 4.7.3 for details of the change in energy intensity of materials with time.

4.4.3 Statistical Analysis

The energy input per unit of product output may be calculated from national statistics. This method has been used in the energy intensity data published by Baird and Aun [1983]. However, due to the age of this data set and because the information is generated for the New Zealand economy, the present analysis assumes minimal dependence on this information.

4.5 REVIEW OF THE LITERATURE

4.5.1 Energy Intensity of Building Materials

There has been extensive research into the energy intensity of materials. For the present study, the energy intensity of a number of building materials has been collected from various sources dating from 1968 to 1993. This data is presented in Appendix C1.

The data is derived from several countries, including Canada, the United Kingdom, the United States and New Zealand. The methods used to derive the energy intensity figures are documented with the data. The techniques include input-output analysis, process analysis, and to a lesser extent, national statistics. The level of analysis varies with the material and source, with many of the figures representing an analysis to level two and three boundaries stipulated by the International Federation of Institutes of

Advanced Studies (IFIAS). It is predicted that such an analysis will capture 90% to 95% of the full energy intensity of a commodity [CMHC, 1991].

The divergence in the energy intensity according to the source is large. It should be stressed that there is no absolutely correct value for the energy intensity of any material [Kohler, in Cole, 1991]. Variations may occur due to differences in:

-the specific building products investigated;
-the primary energy sources used, for example, hydro electricity versus natural gas;
-the scope of the energy intensity analysis, including system boundaries and the level of analysis;
-the method of analysis;
-transportation factors included;
-variations in the conventions used in dealing with feedstock material, recycling, and multiple products; or,
-variations in the manufacturing process arising from the technology used to produce the good.

An example of variation in conventions related to feedstock energy value arises when comparing the energy intensity of plastic and wood. In calculating the embodied energy of plastic, the feedstock energy has been incorporated into the energy intensity figures.

Conversely, in estimating the energy intensity of wood, no such addition has been incorporated. In British Columbia, wood accounts for approximately 8% of primary and secondary energy use [Statistics Canada, pg.XX, 1991, b]. It may be argued that it is inconsistent to include the feedstock for plastic and not for wood. However, in the case study building examined in this work, the use of wood accounts for a negligible fraction of the life-cycle embodied energy. Therefore, this inconsistency will create little uncertainty in the results.

Variations in manufacturing processes may in part be due to the age of the data (and corresponding technology), and geographical location. The dependence of energy intensity on age of the data is further explored in Appendix C2. Based on data provided by Statistics Canada, the energy intensity (per $1000 of commodity) is listed for building materials from 1976 to 1990.

Concrete and steel are dominant materials in the case study building. Small inaccuracies in the energy intensity of these materials will have a correspondingly large effect on results. In the present analysis, works by Stelco [1993] and Radian [1993] are used for steel and concrete products, respectively. These publications provide current, location specific information on a range of steel and concrete products, based on Canadian industrial surveys.

4.5.2 Embodied Energy of Buildings

There have been several references dealing with estimates of the embodied energy of residential and commercial buildings over the last 20 years. These published works provide insight to the initial embodied energy of buildings, and explore the relationship between the embodied and operating energy of buildings.

The works of Stein et al. [1976] and Serber [1976] provides the first comprehensive analysis of the embodied energy of buildings. The works are based on input-output information of the United States economy for the year 1967. Results of the analyses predict the embodied energy of an average office building of 18.6 GJ/m^2. Serber's work provides a preliminary analysis of the relative magnitude of operating and embodied energy for two commercial office buildings located in New York. For the buildings used in Serber's analysis, the embodied energy is equivalent in magnitude to five to ten years of operating energy. Because of the age of the data, the results of the analyses are of limited value to the present work. The energy intensity of materials has decreased considerably since 1967, and the operating characteristics of new buildings has improved[3]. However, the methodologies used and insights gained from these works remain important.

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[3]The Building Energy Performance Index (BEPI) in Serber's analysis is 3.97. The BEPI for the base building in the present analysis is 0.96.

Baird and Aun [1983] in New Zealand document the energy cost of buildings, and provide an estimate of the relative magnitude of embodied versus operating energy for houses and light construction. For single family housing, the authors predict the construction energy to be approximately 3 GJ/m^2 and the ratio of construction energy to annual operating energy to be approximately 8. Baird and Aun's work focuses on timber framed buildings. In addition, the age of the study limits the ability to infer information from the analysis.

The Canadian Mortgage and Housing Corporation (CMHC) produced a computer program called "OPTIMIZE" [CMHC, 1991] to investigate the life-cycle energy and environmental impact of housing in Canada. The study is based on energy intensity data obtained from Canadian input-output tables for the year 1987. For a 350 m^2 house with a life-span of 40 years, results of the analysis suggest the life-cycle energy of a house is 29.9 GJ/m^2. The initial embodied energy is calculated to be 2.4 GJ/m^2, and the life-cycle embodied energy is 4.2 GJ/m^2. Levelized over the 40-year lifespan, the life-cycle embodied energy is 0.11 $GJ/m^2.yr$.

Howard and Sutcliffe [1992] provide an investigation of the life-cycle embodied energy characteristics for a number of building designs. The authors predict an initial embodied energy for office buildings of 3.5 GJ/m^2 to 7.3 GJ/m^2, depending on the

characteristics of building fit-out[4]. Considering the life-cycle embodied energy, and levelizing over a 60-year life span, the authors predict a life-cycle embodied energy of 0.18 GJ/m^2.yr to 0.45 GJ/m^2.yr. These values depend on the level of fit-out, and the frequency of component replacement. This compares to the predicted operating energy of 0.84 GJ/m^2yr to 1.41 GJ/m^2yr. Rearranging these numbers, the life-cycle embodied energy may range from 11% to 36% of the total energy budget for the buildings studied.

Oka et al. [1993] have performed an analysis of the total energy consumed and environmental pollution generated in the construction of six commercial buildings in Japan. The buildings range in size from 1500 m^2 to 216,000 m^2. The smaller buildings are reinforced concrete construction and the larger buildings are predominantly steel. The energy intensity figures for the building materials are based on an input-output analysis of the Japanese economy. The major findings of this investigation are:

-the initial embodied energy of office buildings is of the order of 8-12 GJ/m^2;
-the embodied energy of the buildings appears to decrease with increasing office size, although the change is not monotonic.
-the construction cost is proportional to the energy consumption.

The authors predicted that the energy intensity per unit price is

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[4]Office fit-out refers to the quality of finishing work used in the project.

32 MJ/1000 yen (4.6 MJ/$).

Buchanon and Honey [1994] investigated the embodied energy and environmental impacts of a range of building types including housing, industrial and commercial buildings in New Zealand. The results of this work are based on the energy intensity data set of Baird and Aun. For office buildings, the authors predict the initial embodied energy for wood, concrete and steel construction, are 3.7 GJ/m^2, 5.6 GJ/m^2, and 6.6 GJ/m^2, respectively. These figures are for multi-storey buildings in the range from three to six storeys.

Cole [1994] investigated the life-cycle energy use of a three-storey office building located in two geographic locations; Vancouver and Toronto[5]. The building is modelled assuming three structural configurations based on wood, concrete and steel construction. Data for the embodied energy calculations are based on recently published figures. Major findings of this work are:

- the initial embodied energy of a concrete building is 4.66 GJ/m^2 for a building with no underground parking, and 4.93 GJ/m^2 for the same structure, but with underground parking;

[5]The floor plate design in Cole [1994] is identical to the design used in the present work.

- assuming a 50-year building life, the recurring embodied energy is 6.5 GJ/m^2,

- for a building life of 25, 50 and 100 years, the levelized life-cycle embodied energy is 0.3, 0.26 and 0.2 $GJ/m^2.yr$, respectively; and,

- the operating energy for the case study building located in Vancouver is approximately 1.05 $GJ/m^2.yr$, suggesting the life-cycle embodied energy is 20 to 30% of life-cycle energy budget.

In its input-output tables, Statistics Canada [1994] provides estimates of non-residential construction and repair construction. The total energy for these commodity groups, is 5.79, and 5.83 MJ/$, respectively. These figures correspond to the energy intensity in 1990[6], measured in 1986 dollars.

A summary of the findings of the initial and life-cycle embodied energy of buildings is provided in Table 4.1.

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[6]The last year for which data are available.

Table 4.1. Summary of Initial and Life-cycle Embodied Energy Results.

AUTHOR	DATE	INITIAL EMBODIED ENERGY [GJ/m^2]	ANNUAL LIFE-CYCLE EMBODIED ENERGY [GJ/m^2.yr]	ANNUAL OPERATING ENERGY [GJ/m^2.yr]
Stein et al.	1976	18.6		4.8
Baird and Aun	1983	3		0.38
CMHC	1991	2.4	0.11	0.64
Howard & Sutcliffe	1992	3.5-7.5	0.18-0.45	0.84-1.41
Oka et al.	1993	8-12		
Buchanan & Honey	1994	5.6		
Cole	1994	4.9	0.2-0.3	1.05

4.6 INITIAL EMBODIED ENERGY OF BASE CASE STUDY BUILDING

This section describes the methods used and results obtained for the initial embodied energy of the base case study building. The initial embodied energy of the case study building includes:

-the energy required to produce the basic components (e.g. bricks, heating equipment or windows); and,

-the energy required to transport the building materials and components from the manufacturer to the building site, plus the

energy required for on-site assembly.

4.6.1 Energy to Produce the Building Components

To calculate the component of embodied energy resulting from materials production, the following methodology was applied:

- Define the energy intensity of the building materials. This information is obtained from the published sources referred to in Section 4.5. The energy intensity of building materials is found in Appendix C1.

- Based on architectural, structural, mechanical and electrical[7] drawings of the building, quantify the materials required for the building (a materials takeoff). This information is provided in Appendix C3, and corresponds to printouts of the spreadsheets used in the calculation process.

- Combine the information on energy intensity with the materials takeoff[8] for the case study building to calculate the embodied energy of each building component and assembly.

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[7]The mechanical and electrical drawings used in estimating materials were not available for the case study building. Instead, a similar office building having identical systems was used to define an energy/m^2 for mechanical and electrical systems.

[8]A takeoff is a list of all materials used to construct the building.

- Sum the embodied energy of building component to obtain the total embodied energy of the building materials.

4.6.2 Materials Wastage

In the calculation of energy intensity of building materials, an allowance has been made for materials wastage. The allowance is determined for each component of the building, and is in the range of 0 to 5%. The wastage factor is based on the works of Cole [1994], CMHC [1991] and experience.

4.6.3 Construction Energy

Construction energy includes the energy required for transporting building assemblies to the site plus assembly and erection of the components into the building. Cole [1994] suggests a range of 7 to 10% of total embodied energy, and applies a general figure of 7% of the initial embodied energy for the construction energy.

An analysis was performed to investigate the magnitude of transportation energy and site energy requirements. Based on the energy intensity of freight transport of 1.7 MJ/tonne Km[9], an

[9]Based on (dated) 1970 estimates of the energy efficiency of freight transport. See Nemetz [1993].

average travelling distance between supplier and site of 20 Km[10], and a building weight of 9600 tonnes[11], the transport energy corresponds to 330 GJ. To calculate the site energy, it is assumed that 100 KW (400 Volts @ 250 Amps) of power is used for 7.5 hours a day for the duration of the project of 15 months. This corresponds to a site energy of 810 GJ. The total construction energy used in this analysis is the sum of the transportation energy and site energy, 1140 GJ. These numbers are not precise calculations, but provide order of magnitude estimates of the construction energy. It will be shown in the next section that the construction energy is small compared to the embodied energy of building materials. The energy required to transport workers to the site has not been included.

4.6.4 Results

Applying the methodology outlined in the last section, the initial embodied energy of the base building is calculated to be 34300 GJ. Details of the calculation are in Appendix C3. The floor area of the building is 8026 m^2. Therefore, the initial embodied energy of the building, including construction energy and normalized for floor area is 4.26 GJ/m^2. Table 4.2 presents the embodied energy of the building components, summarized from the data in Appendix C3.

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[10]This is a representative travelling distance.

[11] This value is calculated from the materials takeoff.

Table 4.2. Initial Embodied Energy and Mass of Building Materials.

MATERIAL	EMBODIED ENERGY, [GJ]	% BY EMB. ENERGY	MASS [TONNES]	% BY MASS
Steel	12900	38.73	410	4.22
Concrete	4870	14.64	8100	84.34
Aluminum, Copper	3650	10.97	57	0.60
Gypsum	2040	6.14	460	4.76
Insulation	1560	4.70	51	0.53
Roofing	1470	4.43	47	0.48
Plastic	1450	4.37	15	0.16
Paint/adhesives	1120	3.36	26	0.27
Brick	910	2.73	360	3.78
Glass	840	2.54	83	0.87
Other	2310	6.96		
Construction	1140	3.43		
Total	34300	100.00	9600	100.00

The information presented in Table 4.2 suggests that approximately 90% of the initial embodied energy is contained in 10 basic material types. The importance of concrete and steel is worth

noting. 53% of the initial embodied energy and 89% of the building mass may be attributed to these two materials. In Table 4.3, the same information is organized by building component. This information highlights the importance of the structure and mechanical systems in terms of the initial embodied energy.

Table 4.3. Initial Embodied Energy by Building Component.

COMPONENT	EMBODIED ENERGY, [GJ]	%OF INITIAL EMBODIED ENERGY
Structure	10800	31.53
Mechanical	5800	16.93
Envelope	3950	11.55
Glazing	2830	8.25
Interior Partition	2790	8.16
Electrical	2170	6.33
Roof	2130	6.21
Floor Finish	1320	3.85
Other	1320	3.85
Construction Energy	1140	3.33
Total	34300	100.00

4.6.5 Comparison With Other Studies

As noted in the review of the literature, there is a commodity class in Canadian input-output tables for non-residential construction. It may be argued that an adequate prediction of the embodied energy of the case study building can be achieved by utilizing this single figure. However, there is a wide variation in non-residential buildings types, so this figure was not relied on *a priori*. Instead, the input-output value of embodied energy of buildings is used as a check on the results of the analysis performed in the present work. Referring to Appendix C2, the embodied energy of non-residential buildings is approximately 6 GJ/$1000. The capital cost of the case study building (see Chapter Six for details) is 5.2 million dollars, and the floor area is 8026 m^2. Therefore, the initial embodied energy, predicted directly from the input-output tables, is 3.9 GJ/m^2. From the preceding analysis of the building by component, the embodied energy is predicted to be 4.26 GJ/m^2. The difference in these two predictions is of the order of 8%.

The results of the present analysis are lower than many other studies. For example, Howard and Sutcliffe [1992] predict an initial embodied energy of 3.5-7.5 GJ/m^2. Alternately, Buchanon and Honey [1994] predict an initial embodied energy of 5.6 GJ/m^2. Discrepancies between the results may be the result of differences in the age of the data. For example, the results of Buchanon and

Honey are based on information generated in 1976. Because of the importance of concrete and steel in the prediction of initial embodied energy, small differences in energy intensity figures between the present work and other studies will have a significant impact on results.

Cole [1994] predicts an initial energy intensity of 4.93 GJ/m2 for a three-storey concrete structure with underground parking. Differences between the present results and those of Cole may be attributed to differences in the construction energy used in the analysis. In addition, the work of Oka et al. [1993] suggest a decrease in energy intensity with increasing floor area. Therefore, discrepancies between the present work and the work of Cole, may be the result of the trend predicted by Oka et al.

4.7 RECURRING EMBODIED ENERGY OF CASE STUDY BUILDING

The recurring embodied energy corresponds to the energy required to maintain the building over its life. This includes energy to repair and replace building components. In order to calculate the recurring embodied energy of a building, three factors must be quantified: building life; frequency of maintenance and refurbishment; and, future trends in the energy intensity of building materials.

4.7.1 Building Life

It is very difficult to predict the life span of a building. Therefore, representative time spans of 40 years and 80 years are chosen for the life of the case study building.

4.7.2 Replacement and Refurbishment

The second factor to be incorporated into the recurring energy analysis is the schedule of replacement and refurbishment. Replacement is defined as maintenance requiring a completely new assembly or system. Refurbishment implies that less than 100% of an assembly is replaced. In the present work, the replacement and refurbishment schedules used by Cole [1994], and CMHC [1991] are used to formulate recurring embodied energy of the case study building. This information is in Appendix C4.

4.7.3 Changes to Embodied Energy of Building Components With Time

The third factor to be predicted is the energy intensity of building components in the future. This issue has received inadequate attention in the literature. Cole [1994] and CMHC [1991] assume no change in energy intensity with time. However, between 1971 and 1986, there was a 20% decrease in energy intensity for steel, a 24% decrease for non-ferrous metals, and a 33% decrease for cement [Statistics Canada, 1993]. These rates of change in energy intensity may not be sustained into the future, but it is assumed there will continue to be significant reductions in energy

intensities. For example, the work by CANMET predicts the energy intensity of steel produced in Canada will decrease from 27 GJ/Tonne in 1989 to 11.9 GJ/Tonne in 2010 [CANMET, pg. xiii, 1993].

In order to make the predictions of the change in energy intensity of building materials over time, the energy intensity of construction related commodities from 1976 to 1990 was examined. This information is in Appendix C2. The annual rate of change is determined from a graphical analysis of data found in Appendix C2. A Geometric series[12] is used, implying that the energy intensity decreases to zero asymptotically. An annual reduction in energy intensity of materials of 1.0%/yr. is applied in this analysis. Higher order series could have been used to predict the trend in energy intensity. However, the geometric series provides a simple and (over the range of data examined) reasonably accurate means of predicting the time trend.

4.7.4 Two Approaches

Two methods are used to predict the recurring energy of the case study building. The first method applies energy intensity data from the Canadian input-output table [Statistics Canada, 1994], combined with survey results of maintenance expenses [BOMA, 1994]. The method is conceptually simple, and provides an alternate

[12]A geometric series is defined as a set of consecutive numbers that vary by a constant multiple of the previous value in the series.

methodology to that used by Cole [1994], CMHC [1991], and Howard and Sutcliffe [1992].

The second method used is consistent with the authors noted above. This method applies a replacement and refurbishment schedule to all building components, calculates the embodied energy due to the maintenance schedule, and sums over the building life.

4.7.4.1 Recurring Embodied Energy Based on Input-Output Analysis

In order to estimate the embodied energy associated with replacement and maintenance, the energy intensity of building reconstruction is obtained from the 1990 Statistics Canada input-output table. A value of 6.11 MJ/$ is used for 1994. The maintenance expenses are obtained from the most recent survey of the Building Owners and Managers Association (BOMA) exchange report [BOMA, pg. 429, 1994]. For 1994, the maintenance costs of private sector office buildings, located in downtown Vancouver is $\$15.51/m^2$. An annual inflation rate of 2%/yr. is assumed[13]. Multiplying the energy intensity of building reconstruction and the annual maintenance cost results in an estimate for the annual recurring embodied energy. The annual recurring embodied energy is summed over the life of the building, giving an estimate of the recurring

[13]This rate is consistent with the projected inflation rate predicted by the Ministry of Finance and Corporate Relations [1994].

embodied energy. Based on the above assumptions and method, the recurring embodied energy for the case study building is 4.7 GJ/m^2 for a building life of 40 years, and 11.6 GJ/m^2 for a building life of 80 years. Normalized for building life, the 40-year building has an annual recurring embodied energy of 0.12 GJ/m^2.yr, and the 80-year building has an annual recurring embodied energy of 0.15 GJ/m^2.yr.

4.7.4.2 Recurring Embodied Energy Based on Replacement Schedule

The second method used to estimate the recurring embodied energy is based on an assumed maintenance and repair schedule, consistent with the schedule used by Cole [1994]. Details of the maintenance schedule are found in Appendix C4. Based on the above assumptions, the recurring embodied energy for the case study building is 4.2 GJ/m^2 for a building life of 40 years, and 8.5 GJ/m^2 for a building life of 80 years. Normalized for building lives, the 40-year building has an annual recurring embodied energy of 0.11 GJ/m^2.yr, and the 80-year building has an annual recurring embodied energy of 0.11 GJ/m^2.yr.

4.7.3 Comparison of Results

The results of the recurring embodied energy are summarized in Table 4.4.

Table 4.4. Comparison of Recurring Embodied Energy Based on two Methods.

BUILDING LIFE	INPUT-OUTPUT METHOD		MAINTENANCE METHOD	
	Total GJ/m^2	Annual $GJ/m^2.yr$	Total GJ/m^2	Annual $GJ/m^2.yr$
40 years	4.7	0.12	4.2	0.11
80 years	11.6	0.15	8.8	0.11

Agreement between the two methods is good for an assumed building life of 40 years. The difference in results for the case of an 80-year building life is of the order of 25%. It is hypothesized that the input-output values may be high. As a building nears the end of its life, maintenance does not occur as regularly, and building components are allowed to degrade. This is captured in the maintenance schedule method of calculating recurring embodied energy, but not in the input-output method. Therefore, the remaining analysis will utilize the maintenance schedule information.

4.8 DEMOLITION AND RECYCLING

The final component of embodied energy to be quantified is the energy required to demolish or recycle the building at the end of its life. Demolition consists of the actual demolition process, plus hauling away debris to a landfill. Recycling implies sorting

of materials and reuse. There is little recycling of building materials at this time[14]. In addition, it is not clear how recycling should be incorporated into an energy analysis. Due to these limiting factors, recycling is not considered further in the analysis[15]. To predict the demolition energy, the energy intensity figure used in transporting the building materials at the time of original construction is used. It is assumed that the energy required for the actual demolition of the building is small. The energy intensity of demolition is estimated at 330 GJ[16]. The demolition energy is less than 1% of the initial embodied energy.

4.9 LIFE-CYCLE EMBODIED ENERGY OF CASE STUDY BUILDING

The life-cycle embodied energy of the case study building may be calculated by summing the initial, recurring and demolition energy components defined in the previous sections.

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[14]In British Columbia in 1992, approximately 7.5% (by weight) of building demolition material was recycled. Most of this material was asphalt [SENES, 1993].

[15]The role of recycling of building materials requires further investigation. However, it is beyond the scope of this work to perform that analysis.

[16]Because of the uncertainty of in demolition energy, this figure is not adjusted for changes to energy intensity in the future. Therefore, this provides a conservative estimate of demolition energy.

Table 4.5. Summary of Life-cycle Embodied Energy Based on two Methods.

BUILDING LIFE	INPUT-OUTPUT METHOD		MAINTENANCE METHOD	
	Total GJ/m^2	Annual GJ/m^2.yr	Total GJ/m^2	Annual GJ/m^2.yr
40 years	9.0	0.23	8.5	0.21
80 years	15.9	0.20	12.7	0.16

As noted in the last section, the figure for the 80-year building, based on input-output analysis may be high due to the prediction of recurring energy intensity near the end of the building life. The results suggest that by doubling the life of a building, the life-cycle embodied energy may be reduced by 13 to 24%.

As noted in Section 4.6.4, the initial embodied energy is 4.27 GJ/m^2. This implies that the initial embodied energy accounts for between 47% to 50% of the life-cycle embodied energy for a building with a 40-year life. For an 80-year building life, the initial embodied energy accounts for between 27% to 34% of the life-cycle embodied energy.

Table 4.6 examines the relative magnitudes of the life-cycle embodied energy by building component. Comparing the results of Table 4.3, the magnitude of the structure reduces from 31.5% to between 16% and 10.5% for 40 and 80 year buildings, respectively.

Alternately, the importance of interior finishes (including carpets), increases from approximately 12% of the initial embodied energy to 23% and 26% of the life-cycle embodied energy for the 40 and 80-year building lives, respectively.

Table 4.6. Comparison of the Life-cycle Embodied Energy by Building Component.

COMPONENT	% OF LIFE-CYCLE EMBODIED ENERGY	
	40 Year	80 Year
Site	1.39%	1.60%
Structure	16.00%	10.50%
Envelope	7.81%	6.13%
Glazing	14.23%	16.15%
Roof	11.32%	13.12%
Interior Partitions	14.64%	16.33%
Floor Finishes	8.42%	9.52%
Mechanical	13.72%	13.89%
Elevator	0.56%	2.64%
Electrical	3.84%	2.84%
Other	8.07%	7.29%
Total	100%	100%

4.9.1 Comparison With Other Studies

Agreement between the present study and similar works is summarized in Table 4.7 below. The results of this work are in the range of published works. Discrepancies between this study and the results of Cole [1994] may be attributed largely to differences in the methodology employed to calculate the recurring embodied energy. This study assumes a decrease in energy intensity over time, whereas Cole does not. Therefore, the results of Cole are highly dependent on the assumed lifespan of the building.

Differences between this work and the results of Howard and Sutcliffe [1992] may also be attributed to different assumptions and methods employed to calculate the recurring embodied energy of the building. In their work, Howard and Sutcliffe assume three grades of office fit-out, three frequencies of maintenance schedules, and a single lifespan of 60 years. Conversely, this work assumes a single grade of fit-out, two lifespans scenarios and employs two independent methods to calculate the embodied energy associated with recurring energy.

Because of the different assumptions made and the speculative nature employed in quantifying the recurring embodied energy, it is not possible to say which set of results provides the most accurate or "best" results.

Table 4.7. Summary of Initial and Life-cycle Embodied Energy Results, Including Results of Present Study.

AUTHOR	DATE	INITIAL EMBODIED ENERGY GJ/m^2	ANNUALIZED LIFE-CYCLE EMBODIED ENERGY GJ/m^2.yr
Stein et al.	1976	18.6	
Baird and Aun	1983	3	
CMHC	1991	2.4	0.11
Howard & Sutcliffe	1992	3.5-7.5	0.18-0.45
Oka et al.	1993	8-12	
Buchanan & Honey	1994	5.6	
Cole	1994	4.9	0.2-0.3
This Study	1994	4.1	0.16-0.23

4.10 INITIAL EMBODIED ENERGY OF IMPROVED BUILDINGS

As noted in Chapter One, an objective of this thesis is to investigate the relationship between the operating and embodied energy of a building as the design progresses from a basic configuration to an (operating) energy efficient configuration. This section quantifies the effect on the embodied energy due to changes in the case study building operating performance.

The strategies implemented in reducing the operating energy were discussed and quantified in Chapter Three. To quantify the effect on the initial embodied energy due to changes in operating performance, the spreadsheets used to calculate the embodied energy of the base building are modified according to the changes in building design strategy. The program used to calculate the operating characteristics of the building is used to estimate the heating ventilation and air-conditioning (HVAC) equipment sizes.

Changes in the building embodied energy due to rotating by 90 degrees is assumed to be zero. This implies there is no constraint imposed by the building site. Similarly, changes in air infiltration are assumed to cause zero change in building embodied energy. It is assumed that higher quality workmanship will achieve the reductions in air infiltration[17].

The strategies listed in Table 4.8 cumulatively reduce the operating energy of the case study building by 77%. Conversely, the initial embodied energy changes by a maximum of 2%. The negative signs in runs 7B to 10 imply a *reduction* in the initial embodied energy of the building due to smaller HVAC equipment sizes. The changes in sign and the small magnitude of changes in the embodied energy suggest that operating energy and embodied energy are loosely coupled. Intuitively this makes sense. None of the design

[17]There will be an increase in the capital costs of the building. This will be quantified in Chapter Six.

strategies implemented to reduce operating energy significantly alter the building design. Therefore, it is expected that changes to the embodied energy will be small.

Table 4.8. Changes in Initial Embodied Energy due to Changes in Building Design.

RUN	STRATEGY	EMBODIED ENERGY GJ/m^2				% DIFF FROM 7A
		STRUCTURE AND ENVELOPE	MECH-ANICAL	ELEC-TRICAL	TOTAL	
7A	Base	3.29	0.7	0.27	4.26	0
7B	Orien-tation	3.29	0.67	0.27	4.23	-1%
7C	Infil-tration	3.29	0.62	0.27	4.18	-2%
7D	Infil-tration	3.29	0.62	0.27	4.18	-2%
8A	Day-lighting	3.29	0.61	0.28	4.18	-2%
8B	Heat Pump	3.29	0.61	0.28	4.18	-2%
9	Glazing	3.33	0.61	0.28	4.22	-1%
10	Lighting Density	3.33	0.61	0.27	4.21	-1%
11	Insula-tion	3.46	0.61	0.27	4.34	2%
12	Equip. Loads	3.46	0.61	0.27	4.34	2%
14	Lighting Effic.	3.46	0.61	0.26	4.33	2%

4.11 RECURRING EMBODIED ENERGY OF IMPROVED BUILDINGS

The spreadsheet used to calculate the recurring embodied energy of

the base building was modified to calculate the recurring embodied energy associated with building improvements. The method based on the replacement and refurbishment schedule is used. Again, a 1% decrease per year is assumed for the change in energy intensity of building components.

Table 4.9. Recurring Embodied Energy for Improved Buildings.

RUN	STRATEGY	RECURRING EMBODIED ENERGY [GJ/m^2]	
		40 Year	80 Year
7A	Base Case	4.15	8.76
7B	Orientation	4.11	8.65
7C	Infiltration	4.02	8.45
7D	Infiltration	4.01	8.41
8A	Daylighting	4.02	8.44
8B	Heat Pump	4.02	8.44
9	Glazing	4.11	8.62
10	Lighting Density	4.09	8.59
11	Insulation	4.12	8.65
12	Equip. Loads	4.12	8.65
14	Lighting Efficiency	4.11	8.62

4.12 LIFE-CYCLE EMBODIED ENERGY OF IMPROVED BUILDINGS

The life-cycle embodied energy is obtained from summing the initial, recurring and demolition energy for each case study run.

Table 4.10 below summarizes the change in the life-cycle energy for the range of improved buildings.

Table 4.10. Summary of Life-cycle Embodied Energy of Building With Improvements.

RUN	STRATEGY	LIFE-CYCLE EMBODIED ENERGY [GJ/m^2]	
		40 Year	80 Year
7A	Base	8.41	13.02
7B	Orientation	8.37	12.91
7C	Infiltration	8.28	12.71
7D	Infiltration	8.27	12.67
8A	Daylighting	8.28	12.7
8B	Heat Pump	8.28	12.7
9	Glazing	8.37	12.88
10	Lighting Density	8.35	12.85
11	Insulation	8.38	12.91
12	Equip. Loads	8.38	12.91
14	Lighting Efficiency	8.37	12.88

The maximum deviation in life-cycle embodied energy relative to the

base case is less than 2%. If the values in Table 4.10 are levelized for the 40 and 80-year life span of the building, the life-cycle embodied energy (to two decimal places) is 0.21 $GJ/m^2.yr$ for a 40-year life and 0.16 $GJ/m^2.yr$ for the 80-year life span *for all strategies*. This again suggests that changes to the operating energy occur (almost) independently to changes in the embodied energy of the building over the range of operating strategies and performances studied.

4.13 REDUCING THE LIFE-CYCLE EMBODIED ENERGY OF THE CASE STUDY BUILDING

A number of methods that may be useful in reducing the life-cycle embodied energy of the case study building are given below.

The first method is material recycling[18]. The introduction of steel mini-mills and scrap steel processing provides an important means of reducing the energy intensity of steel products. Using recycled steel implies a reduction in the energy intensity of steel by approximately 40%. Similarly, through the adoption of materials recycling, the energy intensity of copper may be reduced by 84% and aluminum by 95% [Nemetz, 1993]

The report by SENES [1993] documents construction waste recycling

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[18]Recycling of buildings is an alternative. For example, office buildings being converted into apartment buildings.

practices in Canada. In 1992, British Columbia recycled 7.5% of its building construction and demolition waste. This figure is well below the national average of 17%. Therefore, recycling provides a potentially important means of reducing the energy intensity of buildings.

A second method of reducing the life-cycle embodied energy of the case study building was found from an analysis of the energy intensity of the Canadian economy since 1976. Appendix C.2 traces the change in the energy intensity of building materials in Canada over the last 20 years. In this work it is assumed that the energy intensity of goods and services produced in Canada decreases by approximately 1% per year. This suggests that technological development in materials production may play an important role in reducing the embodied energy of buildings in the future. It is not clear if this will remain true over the long term. As easily recovered sources of fuel and basic materials are depleted, the energy intensity of materials may begin to rise[19].

A third method for decreasing the life-cycle embodied energy of the case study building is through increased building life. As noted in the last section, by increasing the life of the building, the annual life-cycle embodied energy decreases from 0.21 to 0.16

[19] This argument may be countered by the opportunity for substitution towards low energy intensity materials, or the growing trend in Canada towards recycling material.

$GJ/m^2.yr$, corresponding to a 24% reduction. While increasing building life provides an attractive solution at the building level, it may not be suitable when dealing with the entire building stock over the long run. Due to technical obsolescence, buildings constructed to present standards may be highly inefficient by the standards of 40 or 80 years hence. It may be desirable to decrease the lives of single units in order to increase the energy efficiency of the entire building stock. However, there is insufficient information in the literature regarding the change in building performance over time to quantify optimal replacement intervals of buildings. Therefore, the strategy of increasing the service life of buildings is ambiguous at the macro level.

The methods described above to reduce the embodied energy of the case study building are conceptually quite different from methods used to reduce the operating energy of the building. For example, creating infrastructure to support materials recycling or reducing energy intensity through research and development funding is quite a different decision making process to decreasing the lighting intensity of an office building. The scale of the decision is larger, and the decision is made by stakeholders outside the building design team.

The fourth means of reducing the embodied energy of the case study building involves decisions at the building design level, and includes substitution or omission of building materials.

Substitution implies choosing building materials with low energy intensity. Alternately, omitting certain finishes such as carpets and drywall assemblies is a growing architectural form with a number of attributes. Lower capital and maintenance costs, improved air quality, and attractive appearances (eg. polished concrete floors instead of carpet) provide further incentives to explore this option. As noted in Table 4.6, interior partitions and floor coverings account for 23% to 26% of the life-cycle embodied energy of the case study building. Therefore, omitting certain finishes may provide an important means for reducing life-cycle energy consumption.

While it is valid to examine alternatives to reduce the life-cycle embodied energy of the case study building, it is important to make decisions in the context of the total energy consumed by the building. Chapter Five compares the relative magnitude of the operating and embodied components of the building energy consumption.

4.14 MODEL UNCERTAINTY

It is a difficult task to place a level of confidence on the analysis of this chapter. The value obtained for the initial embodied energy of the case study building is accurate to within the uncertainty of the energy intensity of the base materials. As noted in Section 4.5.1, and assuming a level II analysis, the

uncertainty in the initial embodied energy of the case study building is of the order of 10%.

It is not possible to place a rigorous error estimate on the life-cycle embodied energy of the case study building. The results of the life-cycle analysis are dependent on the assumed frequency of maintenance, and the rate of change of the energy intensity with time. Neither of these variables can be defined without empirical information. A sensitivity analysis was performed to observe the dependence of the results on the assumed frequency of maintenance and assumed change of energy intensity with time. To provide an upper limit on the embodied energy estimates, it is assumed that the frequency of maintenance is doubled for interior fit out[20], and the rate of change of energy intensity is halved (from 1%/yr. to 0.5%/yr.). Under this scenario, the life-cycle embodied energy is 0.26 $GJ/m^2.yr$ and 0.20 $GJ/m^2.yr$ for building lives of 40 and 80 years, respectively. To provide a lower limit, the frequency of interior fit-out is halved and the rate of change of energy intensity is increased to 1.5% per year. Under this scenario, the life-cycle embodied energy is 0.18 $GJ/m^2.yr$ and 0.13 $GJ/m^2.yr$ for building lives of 40 and 80 years, respectively. These results are summarized in Table 4.11 below. The large variation in the results of the sensitivity analysis highlights the need to make cautious

[20]The fit-out is included in the sensitivity analysis since the frequency of maintenance work to interior finishes is highly speculative compared to other building components.

assumptions about future trends in the life-cycle embodied energy of buildings. This places real constraints on the ability to infer general information from the present analysis.

Table 4.11. Results of Sensitivity Analysis.

	LIFE-CYCLE EMBODIED ENERGY [GJ/m^2.yr]	
Building Life	40 Year	80 Year
High Scenario	0.26	0.20
Used in Analysis	0.21	0.16
Low Scenario	0.18	0.13

4.15 CHAPTER SUMMARY

A summary of the findings are:

-The initial embodied energy of the building is 4.26 GJ/m^2. Normalizing for building life, this corresponds to 0.10 GJ/m^2.yr for a building life of 40 years, and 0.053 GJ/m^2.yr for a building life of 80 years.

-Steel accounts for 38.7% of the initial embodied energy and concrete accounts for a further 14.6% of the initial embodied energy.

-The structure accounts for approximately 32% of the initial embodied energy and the HVAC system accounts for a further 17%.

-Using the maintenance method to calculate the recurring embodied energy, the recurring embodied energy is 0.11 $GJ/m^2.yr$ for building lives of 40 and 80 years.

-The life-cycle embodied energy is 0.21 $GJ/m^2.yr$ and 0.16 $GJ/m^2.yr$. for building lives of 40 and 80 years, respectively. These figures are valid for all the building configurations studied in Chapter Three.

-Over the range of performances and strategies studied in this work, the operating energy and life-cycle embodied energy are nearly independent.

-The results of the analysis suggest that over the range of energy performances studied in this work, multiplying building price and the input-output value for non-residential construction provides sufficient accuracy to predict the initial embodied energy of the case study building.

-Options available to reduce the life-cycle embodied energy of buildings include: materials recycling; relying on the natural trend in the Canadian economy to reduce the embodied energy of goods and services; increasing the building life; and, materials

substitution or omission of certain finishes.

-Building life, the future trends in energy intensity of building materials and the frequency (and magnitude) of building maintenance are variables that cannot be quantified in the analysis ex ante. Therefore, the results of the life-cycle embodied energy calculations are highly dependent on assumptions made throughout the analysis.

CHAPTER 5: LIFE-CYCLE ENERGY ANALYSIS

5.1 INTRODUCTION

This chapter combines the results of Chapters Three and Four to explore the life-cycle energy requirements of the case study building. Results of the present analysis are compared to the findings of other studies. The relative magnitudes of the operating and life-cycle embodied energy are compared over the range of case study strategies examined in previous chapters.

5.2 LIFE-CYCLE ENERGY ANALYSIS

In order to obtain the life-cycle energy of the case study building, the total energy consumed by the building must be quantified. The total energy is the sum of the annual operating energy and the life-cycle embodied energy (normalized for assumed building life).

5.2.1 Operating Energy

Table 5.1 summarizes the annual operating performance of the case study building over the range of energy conservation strategies examined in this work. Results are given in terms of the Building Energy Performance Index (BEPI).

Table 5.1. Summary of Building Energy Performance Index for Case Study Building.

SIMULATION RUN	STRATEGY	BEPI [GJ/m^2/year]	CUMULATIVE % CHANGE
		Site, (Source)	
7A	Base Case	0.96 (1.39)	
7B	Orientation	0.95 (1.38)	-3%
7C	Infiltration	0.91 (1.32)	-7%
7D	Infiltration	0.89 (1.29)	-9%
8A	Daylighting	0.56 (0.93)	-43%
8B	Heat Pump	0.44 (0.64)	-55%
9	Glazing	0.41 (0.59)	-58%
10	Lighting Density	0.35 (0.51)	-64%
11	Insulation	0.34 (0.49)	-65%
12	Equipment	0.28 (0.41)	-71%
14	Lighting Efficiency	0.23 (0.33)	-77%

5.2.2 Life-cycle Embodied Energy

The life-cycle embodied energy was explored in Chapter Four. Table 5.2 summarizes the results of the life-cycle embodied energy analysis.

Table 5.2. Summary of Life-cycle Embodied Energy of Case Study Building.

RUN	STRATEGY	LIFE-CYCLE EMBODIED ENERGY [GJ/m^2]	
		40 Year	80 Year
7A	Base Case	8.41	13.02
7B	Orientation	8.37	12.91
7C	Infiltration	8.28	12.71
7D	Infiltration	8.27	12.67
8A	Daylighting	8.28	12.7
8B	Heat Pump	8.28	12.7
9	Glazing	8.37	12.88
10	Lighting Density	8.35	12.85
11	Insulation	8.38	12.91
12	Equip. Loads	8.38	12.91
14	Lighting Efficiency	8.37	12.88

Dividing the lifecycle embodied energy by the building life results in the annualized life-cycle embodied energy. The annualized life-cycle embodied energy is 0.21 GJ/m^2.yr for a 40 year life and 0.16 GJ/m^2.yr for the 80 year life span *for all strategies* examined in

this work.

5.3 LIFE-CYCLE ENERGY ANALYSIS

Combining the annual operating and life-cycle embodied energy data provides an estimate of the annual life-cycle energy requirement for the building. Table 5.3 summarizes the life-cycle energy requirements of the case study building over the range of strategies. The results are presented graphically in Appendix D. In the results presented below, the source[1] operating energy is used in the calculations. Using the source energy ensures consistency of system boundaries when comparing the embodied and operating components of the life-cycle energy.

[1]The source energy refers to the primary energy consumed to produce energy. The distinction between site and source energy is discussed in Section 3.3.1.

Table 5.3. Life-cycle Energy Results of Case Study Building.

STRATEGY EMPLOYED	RUN	LIFE-CYCLE ENERGY [GJ/m^2.yr]		LIFE-CYCLE EMBODIED ENERGY AS % OF TOTAL	
		40 year	80 year	40 year	80 year
Base Case	7A	1.6	1.55	13.13%	10.32%
Orientation	7B	1.59	1.54	13.21%	10.39%
Infiltration	7C	1.53	1.49	13.73%	10.74%
Infiltration	7D	1.5	1.45	14.00%	11.03%
Daylighting	8A	1.14	1.09	18.42%	14.68%
Heat Pump	8B	0.85	0.8	24.71%	20.00%
Glazing	9	0.8	0.75	26.25%	21.33%
Lighting Density	10	0.72	0.66	29.17%	24.24%
Insulation	11	0.7	0.65	30.00%	24.62%
Elevator, Equipment	12	0.62	0.57	33.87%	28.07%
Lighting Efficiency	14	0.54	0.49	38.89%	32.65%

For a building life of 40 years, the life-cycle energy may be reduced from 1.6 to 0.54 GJ/m^2.yr by the cumulative adoption of energy conservation strategies. This corresponds to a 66%

reduction. Similarly, for a building life of 80 years, the life-cycle energy may be reduced from 1.55 to 0.49 $GJ/m^2.yr$ by the cumulative implementation of the energy conservation strategies, corresponding to a 68% decrease.

As hypothesized in Chapter One and confirmed in Table 5.3, the embodied energy becomes a more significant component of the total energy budget as the operating energy decreases. For a building life of 40 years, the ratio of embodied to operating energy ranges from 10.3% for the case study building in its base configuration to 38.9% for an energy efficient building. Similarly, for a building life of 80 years, the ratio of embodied to operating energy ranges from 13.13% for the base case to 32.7% for an energy efficient design. Stated differently, the life-cycle embodied energy is equivalent to 8 to 26 years of (source) operating energy. This is equivalent to 5 to 16 years of (site) operating energy.

In applying the BEPI figures to the life-cycle results in Table 5.3, it is assumed the operating energy will remain constant over the life of the case study building. There is not sufficient information in the literature to validate this assumption. It is not clear whether building performance deteriorates over time, or if it actually improves due to the replacement of obsolete components with newer, more efficient units. This issue deserves further attention.

5.4 DISCUSSION OF RESULTS

A premise of this work is that commercial buildings are built and operated at sub-optimal level of energy performance. The energy analysis presented above confirms this premise, and suggests that a 66-69% reduction of energy consumption is possible through the adoption of simple, proven energy saving strategies.

The life-cycle analysis suggests the magnitude of the embodied energy is significantly less than the operating energy over the range of building performances examined. This suggests that reducing the operating energy of buildings should be the primary focus of further research and policy analysis. This is not to imply that the life-cycle embodied energy is insignificant. For example, reducing the lifecycle embodied energy of the case study building by 25% (through the adoption of strategies examined in Section 4.13) corresponds to an energy savings 16.9 TJ[2] and 25.7 TJ, for building lives of 40 and 80 years, respectively.

5.5 COMPARISON WITH OTHER STUDIES

The results obtained in this analysis are consistent with the results of other studies. Howard and Sutcliffe [1992] explore three grades of office fit-out, assuming three frequencies of renovations

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[2] 1 TJ= one tera joule = 10^{12} joules.

and predicted a life-cycle energy in the range 1.02 to 1.86 GJ/m^2.yr. As discussed in Section 4.5.2, Cole [1994] predicted a life-cycle energy ranging from 1.2 to 1.3 GJ/m^2.yr. The variation occurs as a result of a range of assumed building lives, ranging from 25 to 100 years. No articles were found dealing with the change in life-cycle energy as the operating characteristics of the building are improved.

5.6 CHAPTER SUMMARY

The major findings of this chapter are:

-for a building life of 40 years, the life-cycle energy ranges in magnitude from 1.6 to 0.54 GJ/m^2.yr;

-for a building life of 80 years, the life-cycle energy ranges from 1.55 to 0.49 GJ/m^2.yr;

-the ratio of life-cycle energy attributed to the embodied energy ranges from 13.1% to 38.9% for a building life of 40 years, and from 10.3% to 32.7% for a building life of 80 years, depending on the operating characteristics;

-reducing the operating energy requirements of the case study building provides the largest potential energy savings for the building; and,

-the results of the energy analysis in this work is consistent with the findings of other studies.

CHAPTER SIX: LIFE-CYCLE COST ANALYSIS

6.1 INTRODUCTION

This chapter examines the economic implications of constructing and operating the case study building. In addition, the dollar costs of altering the base building to an energy efficient design are predicted.

6.2 ASSUMPTIONS AND DEFINITIONS

A number of assumptions are required to perform an economic life-cycle analysis. This section defines the inflation rate, discount rate and energy prices used in the analysis.

6.2.1 Inflation Rate

In order to maintain consistency of methods between the present and similar life-cycle analyses [Ministry of energy Mines and Petroleum Resources, 1991, a,b, B.C. Hydro, 1994], the inflation rate is not netted out. An annual inflation rate of 2% is assumed for this analysis. This value is consistent with the projected inflation rate for British Columbia [Ministry of Financial and Corporate Relations, pg.10, 1994]. Additional inflation rates of 1.5% and 3% per year are used to perform a sensitivity analysis.

6.2.2 Discount Rate

In this analysis, a discount rate of 10% has been chosen. This is consistent with guidelines for benefit-cost analysis published by the Province of British Columbia [Environment and Land Use Committee Secretariat, 1977]. Additional discount rates of 8% and 12% are used to provide a sensitivity analysis.

6.2.3 Energy Prices

A third issue in developing a life-cycle cost analysis is defining the energy costs to be used in the life-cycle analysis. Options include private and social costs, average and marginal costs, or time of use versus long run marginal costs. In the present analysis, the long run marginal cost[1] of energy is used. Additional economic analyses are performed using current energy prices.

It is argued[2] that the long run marginal cost of energy is the minimum value that should be used in defining public policy options regarding energy use. This price promotes the efficient[3] allocation of energy resources. The long run marginal cost of electricity used

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[1]The Long Run Marginal Cost of energy is the cost of an additional unit of energy, supplied through increasing the capacity of the generating system.

[2]See, for example, Sutherland [1993] or the British Columbia Utilities Commission [1992].

[3] Efficient from an economic perspective. See Section 6.2.6 for a discussion of this term.

in the present analysis is $0.0691/KW.hr ($19.19/GJ). This figure is obtained from B.C. Hydro [1991, 1993]. The long run marginal cost of natural gas used in the analysis is $4.9/GJ, and is obtained from B.C. Gas [Appendix D, pg. 41, 1994].

It is acknowledged that the long run marginal cost of energy does not reflect the cost of environmental externalities of energy use. Although environmental concerns related to energy use are a primary reason for undertaking this thesis, it is argued[4] that monetizing[5] environmental externalities has many difficulties. If environmental externalities are to be quantified while developing policy for energy efficiency, Multiple Attribute Utility Theory (MAUT[6]) may provide a more defensible and robust means of including environmental issues in the policy analysis.

6.2.4 Discount Rate Adjustment

The economic analysis applies an analysis in 1994 dollars. Combining the inflation rate and the discount rate results in the computed nominal discount rate. The computed nominal discount rate is 12.2% (1.10*1.02-1=0.122). In the sensitivity analysis, nominal discount rates of 9.62% (1.08*1.015-1=0.0962) and 16.5% (1.12*1.04-

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[4]See, for example, British Columbia Energy Council [1994], and the British Columbia Utilities Commission [1993].

[5]See British Columbia Utilities Commission [pg.3, 1993] for a discussion of this term.

[6]See McDaniels [1993] for a development of MAUT.

1=0.1648) are also applied.

6.2.5 Present Value Calculations

The present value (PV) of a stream of costs ($y), assuming a discount rate of r for T years may be calculated using equation (1).

$$PV = \frac{y}{r}\left(1 - \frac{1}{(1+r)^{T}}\right) \qquad (1)$$

6.2.6 Economic Efficiency, Energy Efficiency and Cost Effectiveness

The terms economic efficiency, energy efficiency and cost effectiveness deserve some elaboration. Economic efficiency implies that maximum benefits are obtained at a minimum cost. This occurs when the benefits of producing an additional unit of output (marginal benefit) equals the cost of producing an additional unit of output (marginal cost). Increased energy efficiency implies that the energy input to produce a unit of output is decreased. Improving the energy efficiency of output may increase, decrease or leave unchanged the economic efficiency of a process. Cost effectiveness implies the least cost method of achieving a goal. In the present analysis, cost effectiveness is quantified using two methods; a net present value technique, and an analysis of the incremental cost of building improvement per unit of energy saved.

The methods are explained in sections 6.5 and 6.6, respectively.

6.3 CAPITAL COST OF CASE STUDY BUILDING

The capital cost of the case study building is calculated using the materials takeoff for the building (see appendix B) in conjunction with a detailed cost database for building components[7] [Means, 1994]. This database provides cost information on construction labour, building assemblies and components. The capital cost of the base building is estimated at 5.23 million dollars, or $\$652/m^2$.

The same process is used to estimate the capital costs of the building improvements. It is assumed in the analysis that building improvements are not treated as "add-ons" by the contractor. Therefore, there are no premiums paid due to design changes associated with improvements to building performance.

The cumulative costs of successively implementing the energy conserving strategies are presented in Table 6.1. Implementing strategies 7A to 14 inclusive, the capital cost of the improved building is 5.66 million dollars. This corresponds to a cost of $\$705/m^2$, corresponding to an 8.2% increase over the capital cost of

[7]The construction cost data in Means [1994] is based on surveys of building costs across North America. The information is updated annually. Corrections are applied in the present analysis to account for cost estimates specific to Vancouver. City estimate correction factors are included in the Means database.

the base case. Improvements to the operating performance of the building lead to a continuous down-sizing of the HVAC system. The smaller HVAC system frequently offsets the increased capital cost of the building improvements.

Table 6.1. Capital Cost of Building Under Different Design Scenarios.

SIMULATION RUN	STRATEGY	CAPITAL COST, [$]	INCREMENTAL COST, [$]
7A	Base Case	5,233,000	
7B	Orientation	5,237,000	4,000
7C	Infiltration	5,250,000	13,000
7D	Infiltration	5,303,000	53,000
8A	Daylighting	5,250,000	-56,000
8B	Heat Pump	5,285,000	38,000
9	Glazing	5,592,000	307,000
10	Lighting Density	5,558,000	-33,000
11	Insulation	5,652,000	95,000
12	Elevator, Equipment	5,650,000	-2,000
14	Lighting Efficiency	5,660,000	10,000

6.4 OPERATING COSTS

The operating costs include energy, building cleaning and maintenance, administrative, and financing. To estimate the costs associated with maintenance, cleaning and financing, information published by the Building Owners and Managers Association [BOMA, 1994] is used. This material is based on survey data for private sector commercial office space. For Vancouver, the annual operating and fixed expenses, less utilities is $\$893/m^2$. This value is used in all the analyses of the case study building. To estimate the utility costs, the energy consumption of the building is obtained from the operating energy simulations of Chapter Three. This information is combined with energy price information of Section 6.2.3 to obtain annual energy costs. The annual operating cost estimates for the building are summarized in Table 6.2. In addition, the present value of the operating cost assuming 40 and 80-year lifespan is presented. The present value calculations assume a discount rate of 12.2%.

Table 6.2. Annual and Life-cycle Operating Costs.

SIMULATION RUN	STRATEGY	ANNUAL OPERATING COST [$]	PRESENT VALUE OF OPERATING COSTS [$]	
			40 Year	80 Year
7A	Base Case	845,000	6,850,000	6,920,000
7B	Orientation	845,000	6,850,000	6,920,000
7C	Infiltration	844,000	6,850,000	6,920,000
7D	Infiltration	845,000	6,860,000	6,930,000
8A	Daylighting	795,000	6,450,000	6,520,000
8B	Heat Pump	782,000	6,350,000	6,410,000
9	Glazing	791,000	6,420,000	6,480,000
10	Lighting Density	781,000	6,340,000	6,400,000
11	Insulation	780,000	6,330,000	6,390,000 ,000
12	Elevator, Equipment	771,000	6,260,000	6,320,000
14	Lighting Efficiency	761,000	6,180,000	6,240,000

For a building life of 40 years, the present value of the operating costs decreases from 6.85 million dollars to 6.18 million dollars by the cumulative adoption of strategies 7 to 14. This corresponds to a 9.8% reduction. Similarly for a lifespan of 80 years, the present value of the operating costs is reduced by 9.8%.

6.5 LIFE-CYCLE COSTS

By combining the capital and present value operating cost estimates for the building, the life-cycle building costs are determined[8]. Estimates of the building life-cycle costs are summarized in Table 6.3 for the different design configurations. Details of the analysis and graphs are presented in Appendix E.

[8]Due to the nature of present value calculations, costs incurred after 40 and are small, and after 80 years even smaller. Therefore, the cost associated with demolishing the building at the end of its service life is found to be less than the uncertainty in the economic analysis, and is not included in further analysis.

Table 6.3. Building Life-cycle Costs. Discount Rate = 12.2%.

SIMULATION RUN	STRATEGY	LIFE-CYCLE COSTS [$]	
		40 Year	80 Year
7A	Base Case	12,100,000	12,200,000
7B	Orientation	12,100,000	12,200,000
7C	Infiltration	12,100,000	12,200,000
7D	Infiltration	12,200,000	12,200,000
8A	Daylighting	11,700,000	11,800,000
8B	Heat Pump	11,600,000	11,700,000
9	Glazing	12,000,000	12,100,000
10	Lighting Density	11,900,000	12,000,000
11	Insulation	12,000,000	12,000,000
12	Elevator, Equipment	11,900,000	12,000,000
14	Lighting Efficiency	11,800,000	11,900,000

To obtain the Net Benefit (NB) associated with implementing the alternate design strategies, the life-cycle cost of each strategy is subtracted from the life-cycle cost of the base building. This information is summarized in Table 6.4.

Table 6.4. Incremental Net Benefit of Strategies. Discount Rate = 12.2%.

SIMULATION RUN	STRATEGY	NET BENEFIT [$]	
		40 Year	80 Year
8A	Daylighting	462,000	466 000
10	Lighting Density	116,000	116,000
12	Equipment, Elevator	71,700	72,400
14	Lighting Efficiency	71,000	71,800
8B	Heat Pump	67,200	68,200
7B	Orientation	-3,670	-3,670
7C	Infiltration	-9,230	-9,180
7D	Infiltration	-63,500	-63,600
11	Insulation	-86,700	-86,700
9	Glazing	-378,000	-379,000
	Total NPV	246,000	253,000

The values in Table 6.4 represent the *incremental* life-cycle net benefit of adopting the strategies. If those strategies with a positive net benefit are implemented, a savings of $0.788 million and $0.794 million ($98.18/m^2 and $98.93/$m^2$) may be achieved over

the life of the building of 40 and 80 years, respectively[9]. If all the strategies are adopted, including those that are not cost effective, the total Net Benefit (NB) is $0.246 million and $0.253 million for building lives of 40 and 80 years, respectively[10]. This implies that implementing all the strategies to reduce energy consumption will result in net savings over the life of the building with a net benefit of approximately $0.25 million. The results suggest that if one is interested in saving both energy and money, adopting all strategies may be justified. However, it should be stressed that adopting all strategies is not cost effective.

The order of the strategies in Table 6.4 reflects decreasing net benefit. Strategies dealing with orientation, infiltration, insulation and glazing have a negative life-cycle net benefit. Orientation and infiltration result in negative net benefit due to the increased use of electricity (although the total energy consumed is lower) resulting in an increased operating cost. Improved glazing and insulation are found to have negative net benefits due to the high capital costs of these improvements. In this analysis, the glazing is changed from double pane clear glass to triple pane, low-e glass. The insulation is doubled on walls and the roof. This work does not investigate whether less dramatic

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[9]Repeating this analysis using current energy prices (instead of long run marginal costs), the NB is $556,000 and $572,000 for building lives of 40 and 80 years, respectively.

[10]Repeating the analysis using current energy prices (rather than the long run marginal cost), the NB is $53,000 and $58,000 for building lives of 40 and 80 years, respectively.

design changes (for example, a 25-50% increase in insulation instead of 100% used here) might produce a positive NB for insulation and glazing strategies.

6.5.1 Sensitivity Analysis

A sensitivity analysis was performed to observe the effect on the results of the analysis due to changes in the discount rate. With a discount rate of 9.62%[11], the net benefit of the cost effective strategies is $0.98 million and $1.01 million for building lives of 40 and 80 years, respectively. Using a discount rate of 16.5%, the net benefit of implementing the cost effective strategies is $0.58 million and $0.59 million for building lives of 40 and 80 years, respectively.

6.5.2 Payback Period

An analysis was performed of those strategies with a positive net benefit to observe the payback period of investing in energy efficiency.

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[11]See Section 6.2.4 for details.

Table 6.5. Investment Payback Period for Cost-Effective Strategies.

SIMULATION RUN	STRATEGY	PAYBACK PERIOD
8A	Daylighting	Immediate
10	Lighting Density	Immediate
12	Elevator, Equip	Immediate
14	Lighting Efficiency	0.02 Yr.
8B	Heat Pump	11.3 Yr.
	All Positive NB Strategies	Immediate
7B-14	All Strategies	17.2 Yr.

Although the addition of a heat pump has a payback period of 11.3 years, if all the strategies with a positive NB are implemented together, the payback period is immediate. If all strategies investigated to improve the operating performance are implemented, the payback period is quite long, at 9 years[12].

6.6 LEVELIZED COST ANALYSIS

The analysis of section 6.5 provides information on the relative

[12] Based on a discount rate of 12.2%. Assuming a discount rate of 9.62%, the payback period is 7.5 years. With a discount rate of 16.5%, the payback period is 12.5 years.

value of the strategies used to decrease operating energy based on a net benefit analysis. An alternate methodology is to examine the incremental cost of building improvement per unit of energy saved. This value may be compared to the cost of purchasing an additional unit of energy. If the cost of saved energy is less than the cost to purchase an additional unit of energy, then it is economically attractive to implement the energy saving strategy. The levelized cost analysis provides slightly different information to the net benefit analysis of Section 6.5; this is discussed further in Section 6.6.1.

To obtain the incremental cost of building improvement per unit of energy saved, the present value of the incremental life-cycle cost is divided by the building life to obtain the levelized cost. This value is then divided by the annual energy savings in GJ. Results are summarized in Table 6.6.

Table 6.6. Levelized Cost per Unit of Energy Saved.

SIMULATION RUN	STRATEGY	LEVELIZED COST PER UNIT ENERGY SAVED [$/GJ]	
		40 Year	80 Year
7A	Base Case		
7B	Orientation	0.38	0.38
7C	Infiltration	0.72	0.72
7D	Infiltration	9.89	9.91
8A	Daylighting	-4.36	-4.40
8B	Heat Pump	-1.74	-1.77
9	Glazing	39.30	39.37
10	Lighting Density	-6.00	-6.05
11	Insulation	27.02	27.00
12	Elevator, Equipment	-3.72	-3.76
14	Lighting Efficiency	-4.42	-4.47

The levelized cost per unit of energy purchased is determined by levelizing the present value of energy costs over the 40-year and 80 year building lives. The levelized energy costs are divided by the total energy consumed over the same 40 or 80-year life. The levelized cost per unit of energy purchased is shown in Table 6.7.

Table 6.7. Levelized Cost per Unit of Energy Purchased.

SIMULATION RUN	STRATEGY	LEVELIZED COST PER UNIT ENERGY PURCHASED [$/GJ]	
		40 Year	80 Year
7A	Base Case		
7B	Orientation	3.04	1.53
7C	Infiltration	3.15	1.59
7D	Infiltration	3.24	1.63
8A	Daylighting	2.77	1.40
8B	Heat Pump	3.35	1.69
9	Glazing	3.49	1.76
10	Lighting Density	3.32	1.68
11	Insulation	3.38	1.71
12	Elevator, Equipment	3.27	1.65
14	Lighting Efficiency	2.98	1.50

Table 6.8 presents the difference between the levelized cost per unit of energy saved and the levelized cost per unit of energy purchased. A positive value indicates the investment in energy efficiency is less expensive than paying for an additional unit of energy, implying the investment is cost effective. The magnitude of

the differences indicates the relative attractiveness of the investment alternatives. Table 6.8 ranks the investment alternatives according to the attractiveness of the investment.

Table 6.8. Difference Between Levelized Cost per Unit of Energy Saved and the Levelized Cost per unit of Energy Purchased.

RANK	SIMULATION	STRATEGY	DIFFERENCE [$/GJ]	
			40 Years	80 Years
1	10	Lighting Density	9.32	7.72
2	14	Lighting Efficiency	7.40	5.97
3	8A	Daylighting	7.13	5.80
4	12	Elevator, Equipment	6.99	5.41
5	8B	Heat Pump	5.09	3.46
6	7B	Orientation	2.66	1.15
7	7C	Infiltration	2.43	0.87
8	7D	Infiltration	-6.66	-8.27
9	11	Insulation	-23.64	-25.29
10	9	Glazing	-35.81	-37.61

If only those individual strategies which are cost effective are adopted, the difference between levelized cost per unit of energy

saved and the levelized cost per unit of energy purchased is $41.02/GJ and $30.38/GJ for building lives of 40 and 80 years, respectively. If strategies 7B through 14 are all adopted, the difference between levelized cost per unit of energy saved and the levelized cost per unit of energy purchased is $1.93/GJ and $0.949/GJ for building lives of 40 and 80 years, respectively.

A sensitivity analysis was performed to observe the effect of discount rate on the difference between levelized cost per unit of energy saved and the levelized cost per unit of energy purchased. Adopting all cost effective strategies, and assuming a discount rate of 9.6%, the difference is $55.83/GJ and $41.35/GJ for building lives of 40 and 80 years, respectively. Assuming a discount rate of 16.5%, the difference is $31.91/GJ and $23.63/GJ for building lives of 40 and 80 years, respectively.

6.6.1 Comparing the Net Benefit Calculations to the Levelized Cost Analysis

The results of Table 6.8 are consistent with results of the net benefit results presented in Table 6.4. The order of strategies has changed, indicating the dependence of results on the methods used to perform the analysis. In addition, Table 6.8 suggests that changing the orientation and reducing infiltration are attractive investments. This is in contrast to the results in Table 6.4. The discrepancies are small, and may reflect characteristics of the

different calculation methods or inaccuraccies in the calculations.

Which method one uses to decide on the energy conserving strategies to be implemented depends on the priorities used in the decision making process. For example, while adopting a heat pump has a positive NB and positive levelized cost, the payback period of this strategy is 11.3 years. If one is constrained to a five-year payback period, this strategy may not be implemented if taken in isolation.

6.7 COMPARISON OF THE ENERGY ANALYSIS AND ECONOMIC ANALYSES

Comparing the results of the economic analysis of this chapter to the energy analysis of Chapters Three to Five suggests there is a correlation and dependence between the methodologies. For example, in order to obtain the operating costs over a range of building performances, the operating energy must be simulated. A consequence of this dependence is that it is not possible to perform an economic analysis without also performing (even partially) an energy analysis. Therefore, in the present analysis, economic analysis and energy analysis should be viewed as complementary.

Consistent with the notion that economic and energy analyses are based on complementary information is the observation that they provide consistent results. Many strategies used to reduce the life-cycle energy consumption of the building are also cost

effective.

The operating energy model for the building was re-run to observe the size of cost effective energy saving strategies. The order of strategy was changed to be consistent with the economic analysis based on the difference between levelized cost per unit of energy saved and the levelized cost per unit of energy purchased of Table 6.8[13]. Results of the revised operating energy analysis are presented in Table 6.9. Only those strategies that were found to be cost effective are included.

[13]As noted in Section 3.6, building sub-systems are coupled. This implies that changing the order of implementation of strategies changes the incremental reduction in operating performance.

Table 6.9. Improvements to the Operating Performance of Building Using Cost-Effective Strategies.

RANK	SIMULATION	STRATEGY	BEPI [GJ/m^2.yr]	CUMULATIVE % CHANGE
	7a	Base Case	0.96	
1	10	Lighting Density	0.86	10.6
2	14	Lighting Efficiency	0.80	16.6
3	8A	Daylighting	0.61	36.8
4	12	Elevator, Equipment	0.55	43.0
5	8B	Heat Pump	0.51	47.1
6	7B	Orientation	0.42	56.8
7	7C	Infiltration	0.38	60.0

The information in Table 6.9 suggests a 60% decrease in the operating energy of the building is possible by applying strategies that are cost effective. Alternately, the life-cycle energy of the building decreases by 50% and 48% for building lives of 40 and 80 years, respectively.

6.8 CHAPTER SUMMARY

The major findings of this chapter are listed below.

-The capital cost of improving the energy performance of the case study building is $\$53/m^2$. This corresponds to an 8.2% increase.

-If only those strategies are implemented that are cost effective, the net benefit of upgrading the building is $0.788 million, and $0.794 for building lives of 40 and 80 years, respectively.

-If only those strategies are implemented that are cost effective, the payback period is immediate.

-A second criterion for cost effectiveness used in the analysis is the difference between the unit cost of energy savings and the unit cost of energy purchases. If only those individual strategies which are cost effective are adopted, the difference between levelized cost per unit of energy saved and the levelized cost per unit of energy purchased is $41.02/GJ and $30.38/GJ for building lives of 40 and 80 years, respectively.

-Strategies used to reduce air infiltration, increase building insulation and improve the performance of fenestration systems are found to be uneconomic. The analysis of the cost effectiveness of the insulation and fenestration is incomplete. A doubling of

insulation above ASHRAE 90.1 is investigated here. Similarly, the glazing is changed from double pane to triple-pane, low-e glass. This work does not investigate whether less dramatic design changes (for example, a 25-50% increase in insulation instead of 100% used here) might produce a positive NB for insulation and glazing strategies. This deserves greater attention.

-The economic and energy analyses are based on complementary information and provide consistent results. A 60% decrease in the operating energy of the building is possible by applying strategies that are cost effective. This implies the life-cycle energy of the building may be decreased by 50% and 48% for building lives of 40 and 80 years, respectively.

CHAPTER SEVEN: ENERGY POLICY RELATED TO COMMERCIAL BUILDINGS

7.1 INTRODUCTION

Results from the previous chapters suggest there is a large potential to save energy and money by improving the performance of the case study building. Yet most offices being built today do not take advantage of the (energy and economic) savings potential found in this work. In this chapter, the focus moves away from the analysis of the case study building and considers the broader context in which decisions related to the building industry is made. The final section focuses again on the case study building to provide policy alternatives that may help to improve the performance of similar buildings.

7.2 NATURE OF THE POLICY DEBATE

Over the past twenty years, there have been hundreds of papers on the topic of energy use and energy conservation [Lutzenhiser, 1992]. What started in the 1970's as an investigation of the link between energy and the economy moved in the 1980's to an investigation of the "hard" versus the "soft" energy paths[1]. More recently, the focus has shifted to concerns about energy use leading to environmental degradation. As Sanstad and Howarth note:

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[1]See Lovins [1976] and Robinson [1982] for a discussion of these terms.

> Almost every aspect of the problem has been studied: different end uses; technologies; types of decisions; psychological, economic, social factors; and so forth. Energy analysts who call for more research typically fail to address this fact and to answer these fundamental questions: What is further research likely to uncover that has heretofore passed unrecognized in the literature? Why has all the work done to date failed to clarify debates over consumer rationality and its ties to energy efficiency? [Sanstad and Howarth, pg. 1.176, 1994, a]

It is admitted that the present chapter uncovers little that is new. Fundamental issues that were central to the energy debate twenty years ago remain unresolved. A wide diversity of opinion remains in the literature regarding the most effective policy mechanisms for achieving improved levels of energy efficiency. At one extreme is the view generally associated with economists and rooted in the concepts of consumer sovereignty and rational choice. At the other extreme is the work of behavioral researchers and technological analysts who perceive the decision making process of consumers is inconsistent with the economic concepts of rationality and utility maximization. A resolution of this debate is unlikely due to differences at the framework level between the rational choice advocates and behavioral and technology analysts. This implies that different positions in the energy policy debate are ultimately based upon a set of self-defined, self-limiting fundamental interests, and assumptions that do not result from the

debate, but guide it. In the early 80's, a similar debate occurred related to "hard" versus "soft" energy paths, prompting the following observation:

> ...underlying the factual issues apparently in dispute are differences at the framework level, that is, differences in basic presuppositions and in the patterns of thinking employed. In the main, these differences manifest themselves in differences concerning the nature of present social reality, the focus of interest of analysis and policy, and the interpretation and use of data. None of these differences, which are often inextricably intertwined, can be unambiguously resolved since the criteria in terms of which such a resolution should be made are themselves in dispute. [Robinson, pg. 24, 1982]

Although agreement is not likely between opposing views in the current energy debate, some kind of reconciliation may be explored. It is argued that disagreement over the facts and models is a central characteristic of the policy debate related to energy efficiency. As such, there is a strong argument for methodological pluralism: where no one model can describe this policy issue unambiguously and completely, combining the competing models and their solutions may provide a more robust basis for developing public policy. This issue is further explored in Section 7.4. Further, it is postulated that the concept of "bounded rationality" may provide a means for bridging the methodological and conceptual disparities between the polar views of economics, and behavioral

and engineering researchers. This is explored in Section 7.5.

7.3 VIEWS OF ENERGY

It is a premise of this work that energy is used and valued in a number of ways. How individuals and society think about energy affects the way consumers value energy and policy makers control energy. Prevalent views of energy include:

- The technologist's view of energy as a potential source of work, heat or information;

- As a strategic material, energy is viewed as having importance for military and economic security.

- In terms of a social necessity, energy supply is treated as a basic human right.

- As an ecological resource, this implies that energy is part of a natural system and must reflect the values of sustainability and frugality.

- Finally, energy can also be viewed as a commodity [Stern and Aronson, 1984].

For the purpose of this work, the first four views listed above are

collected into one conceptual model called the behavioralist/technologist's view of energy. The energy conservation literature appears to be polarized in a bimodal fashion. At one extreme is the work of behavioral analysts and technologists. At the other extreme is the work associated with neoclassical economists and consistent with the view of energy as a commodity. Proponents of the extremes are easy to identify in the literature, although many articles appear to fall somewhere in the middle. In the next section, attributes and values of the two models are compared and contrasted.

It is important to distinguish between the views of energy because policy choices are often implicitly choices among the views of energy. When a view of energy is adopted, it legitimizes certain choices and actors within the policy arena, and may marginalize or exclude others.

For example, choosing the view of energy as a commodity over the view of energy as an ecological resource may set limits or institutional barriers on what decision makers consider an appropriate energy conservation policy. These barriers and limits may be implicit or explicit. The dominance of the view of energy as a commodity is a problem in the present work, because it limits the scope of policy options aimed at energy conservation. Frequently, in order for energy conservation concerns to be addressed within a commodity framework, interested parties must argue not on their own

terms of finite resources or environmental implications, but on the basis of economic efficiency or the advantage of utilities selling energy services rather than energy as a commodity. If decision makers and consumers are to explore and be responsive to the wide range of policy options available in order to increase energy efficiency, a primary step must be a broadening of views of energy.

7.3.1 Energy as a Commodity

The model of energy as a commodity is based on the assumptions of consumer rationality[2] and utility maximization. This implies that:

> ...producers and consumers have stable preferences that they seek to satisfy through market transactions. Consumer choices thus reveal information about underlying preferences, and the acceptance or rejection of energy-efficient technologies reflects a rational evaluation of the relevant costs and benefits. Market imperfections involving imperfect information or transaction costs might impede the adoption of cost effective energy efficient technologies. But deviations from rational behaviour are ruled out by assumption and cannot, therefore, constitute an appropriate basis for policy intervention. [Sanstad and Howarth, pp. 1.176-1.177, 1994, a]

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[2]This model is based on the principles that:
1) individuals have stable and transitive preferences (if a>b and b>c, then a>c);
2) individuals are self interested; and,
3) individuals have accurate and complete information.

Consistent with the view of energy as a commodity is the argument that price provides the best signal to consumers regarding the optimal levels of consumption and conservation. "Theory would indicate that the marginal unit of consumption should be priced at the marginal price of future supply. Indeed, all units of consumption could be priced at the marginal price of future supply and consumers would be induced to use the resource efficiently from an economic stand point." [British Columbia Utilities Commission, pg. 39, 1990]

Recent examples in the literature of the view of energy as a commodity are the works by Sutherland [1992, 1994, Energy Mines and Resources Canada, 1993]. Sutherland argues that many barriers to energy efficient investments are simple characteristics of normally functioning markets. The author suggests that consumers who invest in energy efficiency require higher rates of return when the investments are illiquid, risky or possess high transactions costs. "The high discount rates required by consumers for energy efficiency investments reflect real costs in a competitive market, not artificial market barriers," [Sutherland, pg. 15, 1992].

A second argument presented in Sutherland's works is the notion that many programs designed to be energy efficient may not be economically efficient. The author argues that the legitimate role for public policy is in dealing with market failures, of which he cites issues based on externalities, the public goods nature of

energy resources and national security.

Finally, Sutherland argues that pricing and utility rate structure are the best mechanisms to promote energy efficiency among end users [Energy Mines and Resources Canada, pp. 30-31, 1993]. The author argues that energy policy should be limited to bring the consumer price of energy in line with its marginal cost.

7.3.2 The Behavioralist/Technologist Model

The incorporation of behavioral analysis in energy conservation policy provides an alternative model to the economics approach expressed by Sutherland. The works of Stern [1986], Stern and Aronson [1984], Kempton and Schipper [1994], and Robinson [1991] provide examples of this view. In general, this group perceives that consumers do not minimize the costs of obtaining energy services. In addition, this group generally does not endorse the rational choice model of consumer decision making. Therefore, behavioral/technologist analysts tend to promote the adoption of public policy to promote energy efficiency:

> Consumers are not merely ill-informed about energy technologies, but also have trouble determining how to make "correct" choices when provided with full information. Thus policies of various kinds are justified to ensure that consumers reap the benefits of energy-efficient technologies as identified by technical experts. [Sanstad and Howarth, pg. 1.177, 1994, a]

7.3.3 Behavioral Barriers to Improving Energy Efficiency

Listed in the behavioralist/technologist literature are a number of factors that create barriers to improving energy efficiency. It is beyond the scope of this work to produce an exhaustive list of these barriers, but a number of issues stand out, and are explained below.

7.3.3.1 Energy Invisibility

The invisibility of energy is frequently argued as a major obstacle to improving efficiency. Because of energy's invisibility, individuals may develop "folk calculations" to provide information on estimates of energy efficiency. These calculations may be based on running time or estimates of the amount of human labour replaced. Such calculations contribute to sub-optimal energy choices [Lutzenhiser, pg. 261, 1993].

An example of energy invisibility is common in the trend towards automating energy systems. In heating systems, one may set a single dial to control the temperature for an entire building. This invisibility comes at the cost of a loss of control, making energy conservation more difficult. In addition, evidence suggests that consumers frequently manually over-ride the automatic controls, using devices in ways they were never intended, thus exacerbating engineering attempts at improving energy efficiency [Lutzenhiser,

pg. 261, 1993].

7.3.3.2 Information

Energy information may be a barrier to behavioral changes in conservation. A major problem with energy information is that it may be presented in unfamiliar or abstract ways. Instead of there being a simple index of efficiency, information is frequently given in scientific units that may have little or no meaning to the user of the information.

A second problem with energy information is the diversity within the target audience. Because there is a great diversity among buildings and energy users, information directed towards an average building or consumer is probably going to be incorrect for any particular building or user. As an example of consumer diversity, there may be a 100% change in the consumption of energy merely by changing the occupants of a building [Stern, 1987]. This variability creates great uncertainty about the accuracy or value of information provided.

Another problem with energy information is the confusion and loss of credibility of experts created by conflicting advice and policies. An example of this may occur when utility companies promote the conversion of heating systems from electricity to gas as a means of saving on energy bills, while ignoring that

electricity powered heat pumps are highly efficient for space conditioning. Implicit in this problem is the need for credible, accurate and non-biased sources of information. People respond not only to information, but to their perceptions and evaluations about the source of information. Unfortunately, many utilities lack credibility among their customers, so it becomes a difficult task to penetrate a market with information, even if that information is correct.

7.3.3.3 Discount Rates

A common problem among consumers considering improvements to energy conservation equipment is the high discount rate many individuals implicitly place on their investments. In one study, a range from 20% to 200% was observed [Stern and Aronson, 1984]. The consequence of this is that many investments do not appear economically viable to these consumers. For example, high efficiency lighting systems have higher capital costs than regular lights, but over the life, the investment will save money. If the discount rate used by an individual is high, the investment in efficiency will not be attractive.

7.3.3.4 The Symbolic Meaning of Energy

The debate of energy supply, demand and conservation is frequently associated with control, power, and freedom. In essence, a lot of

symbolism revolves around the issues of energy consumption and conservation. Freedom and control are powerful symbols, and it is possible that energy conservation programs may be viewed as a threat to personal freedom.

7.3.3.5 Momentum of Past Behaviour

Altering the inertia of past behaviour is often difficult because people tend to commit themselves to habits that have evolved over long time spans. This problem may be confounded by fear of change and risk. An example of this occurs in the resistance to technological innovations. Heat pumps used for conditioning buildings have lower capital costs than comparable HVAC systems. In addition, they are cheaper to run. Even so, these devices are not the first choice of many building designers.

7.3.3.6 Literacy

It was estimated in Canada in 1991 that 16% of Canadian adults are functionally illiterate in either official language, and 14% are innumerate[3] [Statistics Canada, 1991, a]. If an individual cannot recognize numbers in isolation or cannot read, that individual will not be able to understand non-verbal information related to energy efficiency.

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[3]There were 16.4 million adults in Canada in 1991. This implies there were 2.6 million illiterate adults and 2.3 million innumerate adults.

7.3.3.7 Intermediaries

The presence of intermediaries such as land-lords or building contractors may have an effect on the success of efficiency programs. These individuals are responsible for the initial design and purchase of building components, but are not responsible for the operating costs. Therefore, energy efficiency may not be an important factor in the decision making process of these individuals.

7.3.4 A Third Conceptual Model

A criticism levelled at both the behavioralist/technologist's view and the economic approach is that the models focus attention and policy on aggregate effects of *typical* buildings and occupants. It has been argued that policy based on these two models exaggerates the importance of prices and technological solutions, and underestimates the importance of individual action [Lutzenhiser, 1993]. A third conceptual model of energy use that focuses primarily on the human occupants of buildings is a culturally based model. There is evidence from the social science literature that a person's energy consumption and conservation levels vary systematically on the basis of social class, ethnicity, life-cycle stage, gender, occupation, education, geographic location and local culture [Lutzenhiser, pg. 53, 1992]. In addition, a culturally based model:

> treats energy as a key variable in cultural evolution, observing that all societies require energy-conversion technologies to survive, that the amount of available energy to a culture is a function of the technology, that energy-conversion differentials influence the relative prosperity and power of societies (limiting in some cases and stimulating dramatic growth in others), that technology choices are determined primarily by political processes, and that the polity and economy are in turn shaped by cultural institutions (e.g., religious, scientific, governmental and corporate arrangements, understandings and beliefs). [Lutzenhiser, pg. 54, 1992]

An implication of the culturally based model is the assertion that there is as much inefficiency in consumers' choice of demands to be met as there is in the way those demands are provided [Kempton and Schipper, 1994]. For example, as noted in Section 7.3.3.2, there may be a 100% change in the energy consumed in a building simply by changing the occupants.

Although the cultural model does provide important insight into energy consumption and conservation at the individual level, the model poses more questions than it appears to be capable of answering at this time. Therefore, the present work will focus primarily on the behavioralist/technologist model versus the economics model for energy conservation policy[4].

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[4]The behavioralist model of energy consumption is starting to include cultural variables and issues. See for example Kempton and Schipper [1994].

7.4 ANALYSIS OF COMPETING VIEWS

As stated in the discussion on the nature of the debate between the proponents of the competing models, the behavioralist/technologist and the economic models appear to be based on a set of self-limiting assumptions. As such, there are a number of problems with the competing models. This section highlights the limits of the models presented in the last section. Due to the limitations of the economics and behavioralist models, a case is made for methodological pluralism.

There are a number of responses to the arguments presented in the economics approach expressed in Sutherland's work. A first criticism is that by assuming *a priori* that energy and conservation measures are valued only as a commodity, bought and sold in a well functioning, competitive market, the author limits the potential explanations for the low levels of energy conserving behaviour. As noted in Section 7.3, energy may be viewed and valued in a number of ways. Alternately, Sanstad and Howarth [1994, b] note there is little evidence to support the premise that energy is bought and sold in a "normal" market. A second argument is that it is difficult to distinguish between a market failure and a market barrier. Government policy may improve economic efficiency for the case of market barriers, and may reduce transactions costs or risks through a suitable choice of policy instruments. A third argument against the work of Sutherland is that the author's conclusions are

not necessarily validated by experience. The analysis of Chapter Six suggests potentially large savings over the lifecycle of buildings through the adoption of energy saving technologies. Alternately, it was found that the net present value of the benefits associated with implementing energy efficiency standards to commercial buildings in British Columbia was $\$17.32/m^2$ ($1.61/ft^2$)[5] [Energy Mines and Petroleum Resources, pg. 23, 1991].

The behavioralist/technologist model has a number of criticisms associated with it also. While this model frequently endorses the implementation of public policy as a means of resolving the perceived market barriers and market failures associated with energy consumption, this model does not address a number of key issues. First, proponents of this model have not acknowledged that the barriers that inhibit the adoption of energy efficient technologies are likely to inhibit the effectiveness of any public policy directed at solving the problems. Second, the presence of market barriers does not necessarily mean that the benefits of public policy exceed the costs. Third, the existence of behavioral barriers is frequently acknowledged in the literature, yet there is little understanding of their relative importance compared to economic criteria. Fourth, much of the information generated by behavioral analysts focuses attention on residential energy users. It is not clear if the issues and potential solutions are the same

[5]Based on the assumptions of a 10% discount rate and a 15 year study period.

for the commercial and industrial sectors. Finally, the arguments presented by behavioralists and technologists are frequently consistent with principles of economics, and may be strengthened by more thorough use of the economics literature [Sanstad and Howarth, 1994, a].

The analysis of competing views suggests that the economics and the behavioralist/technology models provide incomplete information for understanding energy conservation behaviour. This is hardly surprising, as any model is a simplification of reality, and the models are attempting to describe and predict complicated, dynamic issues. In addition, observing the debate that has occurred over the last 20 years suggests that disagreement over the facts and models is a central characteristic of the debate related to energy efficiency. As such, there is a strong argument for methodological pluralism: where no one model can describe this policy issue completely, combining the competing models and their solutions may provide a more robust basis for developing public policy than choosing one model and its solution.

7.5 CONSUMER RATIONALITY

The focal point in the debate between economists and the behavioral/technologist analysts appears to be based on different interpretations of and levels of confidence in the concept of economic rationality. At an informal level, the concept of

rationality makes sense: individuals prefer better to worse and try to make well informed, reasonable decisions. However, it seems less plausible that individuals actually make choices according to a formal optimization process expressed by rational choice theorists. As Simon notes:

> In its treatment of rationality, neoclassical economics differs from the other social sciences in three main aspects:(a) in its silence about the content of goals and values; (b) in its postulating global consistency of behaviour; and (c) in its postulating "one world"-that behaviour is objectively rational in relation to its total environment, including both present and future environment as the actor moves through time. [Simon, pg. S210, 1986]

Evidence suggests that individuals "muddle through,"[6] making imperfect decisions framed by limited time and processing capabilities, incomplete information, external constraints, and a range of non-financial motives. Simon [1986] makes the distinction between the "substantive" rationality of economics and the "procedural" or "bounded" rationality of other social sciences.

It is suggested that the concept of bounded rationality may provide more comprehensive and realistic basis for creating public policy. Further, it has been postulated that many behavioral barriers to energy efficiency create "departures from substantive rationality

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[6]See Lindblom [1959] for a discussion of this concept.

and result in the *systematic* overconsumption of energy relative to the level that would prevail given the cost-effective provision of energy services." [Sanstad and Howarth, pg. 1.178, 1994, a] There are a number of implications of adopting the concept of bounded rationality:

- it is no longer possible to label certain energy efficiency programs as economically "inefficient" based on the theoretical grounds rooted in the concept of substantive rationality;

- departures from substantive rationality may imply the systematic overconsumption of energy, resulting in a sub-optimal allocation of energy resources; and,

- the same factors which create departures from substantive rationality may create barriers to any program designed to improve energy efficiency.

The preceding sections have attempted to provide a basis for understanding the conflicting views and limited understanding surrounding the debate on energy consumption and conservation. The next step in developing a policy framework for energy conservation in commercial buildings is to define the participants in the decision making process. The next section maps the "sub-government" of this policy issue.

7.6 MAPPING THE SUB-GOVERNMENT

In developing a policy framework for improving the lifecycle energy efficiency of buildings, it is important to understand the context within which the policy is designed, implemented and enforced. The building industry is made up of a large and fragmented group of stakeholders. Interactions between these groups range from collaborative to confrontational. Frequently, however, there is little communication or co-ordination between stakeholders.

The major stakeholders involved in improving energy efficiency in buildings include:

Government:

- Federal Government;
  - Natural Resources Canada,
  - Consumer Affairs,
- British Columbia Provincial Government;
  - Energy Mines and Petroleum Resources,
  - Municipal Affairs,
  - British Columbia Utilities Commission,
  - British Columbia Energy Council (Until November 1994)
- Municipal Government
  - Planning
  - Engineering
  - Permits

Utility Companies (Private and Publicly Owned)

- Electricity
- Gas

Private Companies

- Builders
- Designers (Architects, Engineers)
- Product Manufacturers
- Performance Contractors
- Building Owners

Building Occupants

Advocacy Groups

- Consumers
- Environmental

International organizations

A number of implications result from having such a large and diverse group of stakeholders involved in the policy arena.

- Getting issues onto the policy agenda may be a simple task due to the number of access points.

- No one stakeholder can seize the policy agenda as authority and resources are diverse.

- Each stakeholder has a distinct set of priorities, and authority is diverse, therefore, the task of getting public

policy implemented is a long and difficult task [Lutzenhiser, 1994].

7.7 POLICY ALTERNATIVES

This section reviews the policy options that have been implemented in British Columbia and elsewhere to improve the energy efficiency of the building sector. The use and choice of policy instrument is discussed briefly. Further information on policy options used to regulate the energy industry may be obtained in the literature[7].

The objectives which dictate the choice of policy options include: efficiency, flexibility; distributional consequences; the ability to implement, monitor and enforce the policy; and, the philosophy of the governing agent concerning the presence of non-market forces. These factors provide a basis for comparison of the various policy options presented below. Policy options include:

- adopt utility sponsored programs in the form of Demand Side Management (DSM);

- permit a competitive market to determine the level of energy efficiency through deregulation of energy markets;

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[7] See, for example, The Energy Journal, Energy Policy, Energy Systems, and Energy.

- introduce public policy to provide information or guidelines; or,

- implement and enforce a set of regulations such as standards or pricing.

7.7.1 Utility Sponsored

There are many programs offered by utilities under the framework of Integrated Resource Planning (IRP) and Demand Side Management (DSM)[8]. Considering, for example, the electricity conservation programs for commercial buildings by B.C. Hydro, measures include:

- financial incentives in the form of grants to perform building simulation studies to examine architectural design alternatives; and,

- performance incentives based on the difference between actual building performance and building performance modelled on the ASHRAE 90.1 energy code[9].

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[8]See British Columbia Utilities Commission [1993] for an explanation of these terms. For current issues regarding IRP and DSM, see Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings.

[9]In the form of financial incentives available to designers and contractors if the building is more energy efficient than is required by the energy code.

Focusing on natural gas conservation policy by B.C. Gas, there are no DSM programs to reduce natural gas consumption by commercial users at this time. An incentive/rebate program for medium and high efficiency boilers is expected to commence shortly. In addition, incentive programs for heat pumps and natural gas powered coolers is expected to be included in the Integrated Resource Plan (IRP) for B.C. Gas in the spring of 1995 [Connally, 1995].

There are a number of points to emphasize in order to assess the value of incentives as an option in DSM programs. First, it is difficult to predict or evaluate the effectiveness of incentive programs. Because participation is voluntary, it may be difficult to design a program with enough flexibility to attract a large number of participants.

Participation rate is a critical factor affecting the success of utility sponsored DSM programs. The review by Berry [1993] suggests that participation is frequently of the order of 6%. A recent survey by Nadel et al. [1994] provides a number of strategies common to successful DSM programs. The authors list the following important attributes:

-implement programs which are easy to participate in;
-design programs which attempt to involve the entire community;
-promote personal contact between the sponsoring organization and the customer;

-provide technical assistance made readily available;
-maintain high quality of service and product;
-involve trade allies to assist in the design and marketing of the programs;
-include efficiency thresholds to create market push;
-use good marketing strategy, including,
    -marketing that targets many stakeholders in the process with information that is relevant to each stakeholder, and,
    -marketing that informs the participant of the full range of economic and noneconomic benefits of the program;
-make it possible for participation by customers, manufacturers, and distributors;
    -start programs by targeting potential participants;
-maintain consistency in program eligibility and incentives;
-provide financial incentives;
-work with other stakeholders to encourage coordination and cooperation between, for example, the utility and government regulatory bodies. [Nadel et al., pp.42-44, 1994]

A second issue of DSM programs is their cost. In the case of B.C. Hydro, the financial incentives are seen as a temporary measure to promote and publicize conservation to customers. The high cost of some DSM programs makes them a less attractive long term component of conservation strategy [Barry, 1993].

A final concern of utility sponsored conservation programs is the allocation of risk and the "principal agent problem". As noted by Sutherland [1994] and Nadel et al. [1992], the utilities (the

agent) make DSM investment decisions and are in the position to profit from the gains of successful investments. However, the customers (the principals) incur the risks and losses if the DSM investment is not successful.

Although there are uncertainties associated with the adoption of utility sponsored DSM programs, incentives, rebates and grants are a positive way of introducing the concept of efficiency and conservation to consumers. As opposed to standards or price increases, the ability to evoke a positive response towards conservation is potentially a strong attribute of these programs.

An alternative to DSM programs is performance based hook-up fees [Wirtshafter, 1994], that link building performance to the charge levied by utilities for initial connection to the grid. The attraction of this option is that such a program would force builders and designers to consider the long-term energy implications of their buildings. Another option is providing the utility with the authority to enforce building standards related to energy efficiency. Criticism of the performance based hook-up fee has centered around the notion that there is no standard method of measuring the operating performance of a building. However, the use of the Building Energy Performance Index (BEPI) may provide a solution to the criticism.

7.7.2 Competitive Markets

A second policy option is the use of deregulation and competitive markets to determine the optimal level of energy efficiency. This option has been utilized to some extent in the natural gas market, where marketing functions previously held by the British Columbia Petroleum Corporation were transferred to the private sector [Ministry of Energy Mines and Petroleum Resources, 1989]. The electricity sector is vertically integrated, resulting in a monopoly by B.C. Hydro throughout much of the province. Due to the market failure arising from a natural monopoly, deregulation of the electricity sector is difficult to justify.

7.7.3 Regulatory

Within the context of regulatory approaches to improving end use efficiency, a number of options are available to government agencies. These options range in levels of coerciveness from information, education or guidelines to imposing standards or adjusting price.

7.7.3.1 Information

Information programs are important, but information is easily forgotten. Many conservation programs rely on the process of diffusion of information for improving efficiency levels. There are a number of limitations and drawbacks to this process. For instance, it is slow. In addition, it is difficult to control and

predict where or how much effect the programs will have. Finally, the whole process relies on an individual's willingness to participate. The low rates of success that are typical of many conservation programs suggest the need for a more aggressive approach to energy conservation. In a similar way, education programs are important, but if the individuals who are being educated are not in a position to make decisions regarding consumption patterns (such as school children), the value of the programs must be questioned.

7.7.3.2 Standards

Commercial buildings constructed in Vancouver are subject to energy efficiency standards designed by the American Society for Heating Refrigeration and Air-Conditioning Engineers [ASHRAE, 1989]. This standard is used in the design of the base building in the present analysis. The National Research Council is developing a similar set of efficiency standards to be implemented nationally in 1995/96 [National Research Council, 1994].

The use of standards is widely discussed in the literature, and there are a number of issues surrounding this choice of policy instrument. The flexibility of policy instruments is an issue to be considered. Standards tend to be a relatively inflexible policy tool. However, it is not certain how much flexibility is optimal, nor is it clear whether the reduction in uncertainty derived from

standards offsets the disadvantage of lack of flexibility. A second argument against standards is that they may act as a ceiling as well as a floor since there is no incentive to surpass the requirements of a standard. However, if a ratcheting process is used, this need not be the case.

Standards are usually considered a poor choice because they may be inefficient. This may be true when the options of taxes or tradeable permits exist, but under the present circumstances, standards appear to have a number of advantages. For example, it may cost B.C. Hydro on the order of one million dollars to provide an incentive program and market that program effectively. Conversely, the Ministry of Energy, Mines and Petroleum Resources can implement a standard at a cost of approximately fifty thousand dollars [Barry, 1993]. Alternately, standards are an efficient means of overcoming the barrier discussed in section 7.5.1.7 associated with intermediaries. If those intermediaries do not have the choice to purchase inefficient devices, there is no longer a problem for the individual who must pay the operating costs. Because standards are capable of transforming entire markets, they are a potentially powerful policy instrument.

A final criticism of standards has been expressed by Conover et al. [1994] who assert that the effort needed to enforce a standard is correlated to the complexity and stringency of the standard. The authors found non-compliance rates as high as 25%.

7.7.3.3 Pricing

The role of economic rates (Through price structure and taxes) is seen by The Ministry of Energy Mines and Petroleum Resources as the most important way for energy utilities to encourage customers to conserve energy and to use it more wisely [Energy Mines and Petroleum Resources, 1989]. However, current pricing does not reflect this view, as the price for energy is less than the cost of providing additional supplies. Based on information from the Ministry of Energy Mines and Petroleum Resources [1994], the price for natural gas is approximately 2.5% less than its long run marginal cost. Similarly, the price of electricity is approximately 12% less than its long run marginal cost. Providing consumers with inaccurate price signals for energy may lead to misallocation of resources, resulting in excessive energy consumption above the economically efficient level.

In making the argument for price change as a means of reducing energy consumption, the price elasticity of demand provides useful information. The price elasticity of demand measures the percentage change in demand resulting from a 1% change in the price of a commodity, *ceteris paribus*[10].

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[10]Used to indicate that all variables except the ones specified are assumed constant.

There are a number of sources that have estimated the price elasticity for electricity and natural gas in British Columbia. In a recent rate design application, B.C. Hydro uses an aggregate coefficient for British Columbia of -0.67[11] [British Columbia Utilities Commission, pg. 38, 1990]. Alternately, Jekel-Sadlier [pg. 2, 1990] estimates the price elasticity for electricity consumption in the commercial sector of British Columbia to be -0.147, -0.489 and -0.476 for 1 year, 6 year and 16 year impact analyses, respectively.

The price elasticity for natural gas is estimated in the range of -0.046 to -0.013 by B.C. Gas [BCUC, pp 9-10, 1994, b]. Jekel-Sadlier [pg. 5, 1990] estimates the price elasticity for natural gas consumption by commercial users in British Columbia to be -0.113, -0.533, and -0.565 for 1 year, 6 year and 16 year impact analyses, respectively.

The magnitudes of price elasticity for electricity and natural gas are significantly less than unity. This implies that a change to the price of electricity and natural gas will generate less than a proportionate decrease in energy consumption. This suggests that large price increases may be required to achieve moderate

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[11] The elasticity figure includes residential, commercial, and industrial electricity users. The elasticity for the industrial sector is estimated at -0.15 to -0.25, and this sector corresponds to approximately 45% of total electricity sales by B.C. Hydro. Therefore, the elasticity for the commercial sector is probably greater than -0.67, although no figures were listed.

improvements in energy conservation levels. Therefore, it is not clear that price mechanisms alone provide the most appropriate mechanism to reduce energy consumption in the commercial sector. This is especially true in the short and medium time frames.

An alternative or supplement to uniform price increases is rate design. The British Columbia Utilities Commission has stated that "Rate design can be effective in setting rate structures that expand public awareness by sending appropriate pricing signals...rate design [is] the preferable vehicle for promoting conservation and efficient use through customer rates" [BCUC, pg. 3, 1992].

Considering for the moment electricity consumption, B.C. Hydro currently uses a declining block rate structure for commercial consumers. This implies that the more electricity a customer consumes in a month, the cheaper it becomes for a unit of consumption. The trailing block rate structure evolved from a traditional energy scenario of customers benefiting from economies of scale and declining costs in the development of new generation. However, the situation has reversed since B.C. Hydro now faces the prospect of developing higher cost resources to supply the growth in demand for electricity. Since 1992, the British Columbia Utilities Commission (BCUC) has directed utilities to move to a flat rate structure. It is anticipated in the case of B.C. Hydro, that transition to a flat rate will be complete by the 1995/96

fiscal year [British Columbia Utilities Commission, pg. 7, 1994].

It is important to assess the value of price and rate structure within the framework for evaluating policy options outlined above. The issue of efficiency is an important policy goal. The most efficient way for a commodity to be priced is through market forces. However, because the price elasticity for electricity and natural gas are significantly less than unity in the short and medium term, large price increases would be required to achieve moderate gains in energy conservation levels. this implies that a mix of policy mechanisms may provide a more appropriate solution to this policy issue. In addition, there are many externalities associated with energy supply and consumption. With the presence of multiple market failures for energy, it is impossible for the price to ever be defined optimally. However, on the basis of the alternatives, pricing must still be acknowledged as an important method of achieving policy goals efficiently.

An advantage of pricing and rate design over other options is the ease of implementation and simplicity of monitoring the effects on conservation. In addition, policy using pricing and rate design can transform entire markets, resulting in increased diffusion rates of technology. This is in contrast to the utility sponsored approach that diffuses into the market building-by-building.

7.8 RELEVANCE TO THE CURRENT STUDY

Much of what has been discussed so far in this chapter is derived from a review of the literature. The next step is to take the general information of the previous sections and draw out policy conclusions that may be utilized to improve the energy and economic performance of commercial buildings similar to the case study building.

Methodological pluralism is a central characteristic of the energy debate. Competing models and their solutions provide a number of policy alternatives based on pricing, utility sponsored DSM, and regulatory options. All strategies listed above provide options to reduce energy consumption, and should continue to form components of future policy initiatives. As noted in Section 7.4, however, the barriers that inhibit the adoption of energy conserving technologies are likely to inhibit the effectiveness of public policy solutions implemented to deal with the problems.

The price for energy does not reflect the marginal cost of adding new supply. Providing commercial energy users with the correct price signal is an important step in improving the energy and economic efficiency in the building sector. As noted in Section 7.7.3.3, the price for energy is less than the long run marginal cost of energy. However, the price elasticity for energy among commercial users is less than unity for electricity and natural gas in the short and long run. This implies that large price increases would be required to achieve moderate reductions in enery

consumption. Therefore, price changes alone may not provide the most attractive solution to improving energy efficiency.

The declining block rate structure used by B.C. Hydro does not encourage energy conservation. However, as noted in Section 7.7.3.3, a flat rate structure will be implemented by the 1995/96 fiscal year. Moving to an inclining block rate structure may provide further incentive to improve efficiency, and should be considered in future policy analysis.

The adoption of the ASHRAE 90.1 energy efficiency standards for commercial buildings in Vancouver provides a baseline performance for buildings. However, it has been shown in this work that the standards define a level of performance that is sub-optimal. More stringent performance standards, especially for lighting systems will have positive energy and economic benefits.

Utility sponsored programs are a potentially powerful option at improving energy conservation in the commercial sector. Current Demand Side Management initiatives include performance based incentives for lighting, and funding for design studies. Incentive programs to encourage medium and high efficiency boilers will commence shortly. There are a broad range of additional DSM programs available. Notably, the idea of performance-based hook-up fees deserves greater attention. In addition, daylighting and heat pumps provide viable energy conservation strategies. Future DSM

programs should target these strategies.

The current governance system may inhibit improvements in energy performance of buildings. As noted in Section 7.6, there are many stakeholders in this issue, each with a distinct set of priorities. Authority is diverse, mandates overlap, and there is little leadership or collaboration. Therefore, future policy should include mechanisms for improving the institutional arrangements in this issue.

CHAPTER EIGHT: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 SUMMARY OF FINDINGS AND CONCLUSIONS

8.1.1 Operating Energy

- The initial Building Energy Performance Index (BEPI) for the case study building is 0.96 GJ/m^2.yr. This is consistent with the case study building conforming to the ASHRAE 90.1 energy efficiency code.

- By the adoption of simple, proven technologies, the operating energy of the case study building is reduced to 0.23 GJ/m^2.yr. This corresponds to a 77% reduction in operating energy consumption.

8.1.2 Embodied Energy

- The initial embodied energy of the case study building is 4.26 GJ/m^2. Normalizing for building life, this corresponds to 0.10 GJ/m^2.yr for a building life of 40 years, and 0.053 GJ/m^2.yr for a building life of 80 years.

- Steel accounts for 38.7 % of the initial embodied energy and concrete accounts for a further 14.6% of the initial embodied energy.

- The structure accounts for approximately 32% of the initial embodied energy and the HVAC system accounts for a further 17%.

- The recurring embodied energy is 0.11 $GJ/m^2.yr$ for building lives of 40 and 80 years.

- The life-cycle embodied energy is 0.21 $GJ/m^2.yr$ and 0.16 $GJ/m^2.yr$. for building lives of 40 and 80 years, respectively. These figures are valid for all the building configurations studied in this work.

- Over the range of performances and strategies studied in this work, the operating energy and life-cycle embodied energy are nearly independent. This implies that improving the operating performance of the case study building does not change the life-cycle embodied energy of the building.

- The results of the analysis suggest that over the range of energy performances studied in this work, multiplying building price and the input-output value for non-residential construction provides sufficient accuracy to predict the initial embodied energy of the case study building.

- Options available to reduce the life-cycle embodied energy of the case study building include: materials recycling; relying

on the natural trend in the Canadian economy to reduce the embodied energy of goods and services; increasing the building life; and, materials substitution or omission of certain finishes.

8.1.3 Life-cycle Energy Analysis

- For a building life of 40 years, the life-cycle energy is reduced from 1.6 to 0.54 GJ/m^2.yr by the cumulative adoption of energy conservation strategies. This corresponding to a 66% reduction in energy consumed.

- For a building life of 80 years, the life-cycle energy is reduced from 1.55 to 0.49 GJ/m^2.yr by the cumulative adoption of energy conservation strategies. This corresponding to a 68% reduction.

- The ratio of life-cycle energy attributed to the embodied energy ranges from 13.1% to 38.9% for a building life of 40 years, and from 10.3% to 32.7% for a building life of 80 years, depending on the operating characteristics.

- Reducing the operating energy requirements of the case study building provides the largest potential energy savings.

8.1.4 Life-cycle Cost Analysis

- The capital cost of the case study building in its base configuration is $5.23 million ($652/m^2). The capital cost of improving the case study building to an energy efficient design is $53/$m^2$. This corresponds to an 8.2% increase in capital costs.

- If only those strategies are implemented that are cost effective, the net benefit of upgrading the building is $0.788 million, and $0.794 for building lives of 40 and 80 years, respectively. The analysis assumes a discount rate of 12.2%, and utilizes cost data based on the long run marginal cost of energy.

- Strategies used to reduce air infiltration, increase building insulation and improve the performance of fenestration systems are found to be uneconomic. However, the analysis of the cost effectiveness of the insulation and fenestration alternatives is incomplete, and requires further analysis.

- The life-cycle net benefit of implementing all building improvements is $0.246 million and $0.253 million for building lives of 40 and 80 years, respectively.

- If only those strategies with a positive net benefit are implemented, the payback period is immediate. Implementing all strategies has a payback period of 9 years. These results are

based on a discount rate of 12.2%.

- A second criterion for cost effectiveness used in the analysis is the difference between the unit cost of energy savings and the unit cost of energy purchases. A positive value implies it is cheaper to purchase energy savings than to purchase additional energy. If only those individual strategies that are cost effective are adopted, the difference between levelized cost per unit of energy saved and the levelized cost per unit of energy purchased is $41.02/GJ and $30.38/GJ for building lives of 40 and 80 years, respectively. If all the strategies are implemented, the difference between the unit cost of energy savings and the unit cost of energy purchases is $1.93/Gj and $0.949/Gj for building lives of 40 and 80 years, respectively.

- The economic and energy analyses are based on complementary information and provide consistent results. A 60% decrease in the operating energy of the building is possible by applying strategies that are cost effective. This implies the life-cycle energy of the building may be decreased by 50% and 48% for building lives of 40 and 80 years, respectively.

8.1.5 Policy Implications

- It has been postulated that the concept of bounded rationality

may provide a means for bridging the methodological and conceptual disparities between the polar views of economics, and behavioral and technology researchers. Further, it is argued that disagreement over the facts and models is a central characteristic of the policy debate related to energy efficiency. As such, there is a strong argument for methodological pluralism: where no one model can describe this policy issue unambiguously, combining the competing models and their solutions may provide a more robust basis for developing public policy.

- Pricing, utility sponsored DSM, and regulatory measures provide options to reduce energy consumption, and should continue to form components of future policy initiatives. However, the barriers that inhibit the adoption of energy conserving technologies are likely to inhibit the effectiveness of public policy solutions implemented to deal with the problems.

- The price for energy does not reflect the marginal cost of adding new supply. Providing commercial energy users with the correct price signal is an important step in improving energy and economic efficiency in the building sector. The price elasticity for energy among commercial users is less than unity for electricity and natural gas in the short and long run. Therefore, for price changes to be an effective policy

instrument, large price increases would be required. This suggests that a mix of policy instruments may provide a more appropriate policy choice.

- The declining block rate structure used by B.C. Hydro does not encourage energy conservation. However, a flat rate structure will be implemented by the 1995/96 fiscal year. Moving to an increasing block rate structure may provide further incentive to improve efficiency, and should be considered in future policy analysis.

- The adoption of the ASHRAE 90.1 energy efficiency standards for the case study building provides a baseline performance. However, the standards define a level of performance that is sub-optimal. More stringent performance standards, especially for lighting systems will have positive energy and economic benefits.

- Utility sponsored programs are a potentially powerful option to improve energy conservation in the commercial sector. Current Demand Side Management initiatives include performance based incentives for lighting, and funding for design studies. Incentive programs to encourage medium and high efficiency boilers will commence shortly. There are a broad range of additional DSM programs available. Notably, the idea of performance based hook-up fees deserves greater attention. In

addition, daylighting and heat pumps provide viable energy conservation strategies. Future DSM programs should target these energy conservation strategies.

- The current governance system may inhibit improvements in energy performance of buildings. There are many stakeholders in this issue, each with a distinct set of priorities. Authority is diverse, mandates overlap, and there is little leadership or collaboration. Therefore, future policy should include mechanisms for improving the institutional arrangements in this issue.

8.2 RECOMMENDATIONS

It is recommended that an economic and energy analysis, similar to the one performed here, be performed for all commercial building types and climatic regions of British Columbia. If similar performance improvements are obtainable at cost effective levels, it is recommended that the building code be modified to improve the minimum energy performance of commercial buildings in British Columbia above ASHRAE 90.1 standards.

It is recommended that future work should continue to focus on the operating performance of buildings. If the building energy performance index (BEPI) is less than 0.3 $GJ/m^2.yr$, the embodied energy will be an important component of the life-cycle energy, and

should be quantified and minimized.

Pricing, utility sponsored DSM, and regulatory measures provide options to reduce energy consumption. It is recommended that all options should continue to form components of future policy initiatives.

REFERENCES

American Society of Heating Refrigeration and Air Conditioning Engineers, ASHRAE Standard 90.1-1989: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings, Atlanta Ga., 1989.

B.C. Hydro, 1994 Electricity Plan: An Introduction to BC Hydro's Integrated Resource Plan, Vancouver, 1994 (b).

B.C. Hydro, Electricity Conservation Potential Review, 1988-2010, Phase 2: Constrained Potential, Vancouver, 1994 (d).

B.C. Hydro, The Cost of New Electricity Supply in British Columbia, Vancouver, 1994 (a).

B.C. Hydro, Resource Aquisition Policy, Vancouver, 1994 (c).

B.C. Hydro, Long Run Incremental Cost of Service Study, Vancouver, 1991.

B.C. Hydro, Electricity Conservation Potential Review, 1988-2010, Phase 1: Unconstrained Potential, Vancouver, 1993.

B.C. Gas, B.C. Gas Integrated Resource Plan, Vancouver, March 1994.

Baird, G., Aun, C.S., Energy Cost of Houses and Light Construction, School of Architecture, Victoria University of Wellington, Report o. 76, 1983.

Barry, M., Ministry of Energy Mines and Petroleum Resources, Personal Communication, Victoria, B.C., 1993.

Berry, L., "A Review of the Market Penetration of U.S. Residential and Commercial Demand Side Management Programmes", Energy Policy, Jan, 1993.

Berry, S.R., "Energy Analysis for Energy Policy", Journal of Business Administration, P.Nemetz, Ed., Vol. 10, Nos. 1&2, Vancouver, B.C., 1979.

Brand, How Buildings Learn

Brand, S., How Buildings Learn: What Happens After They're Build, Viking, New York, N.Y., 1994.

British Columbia Ministry of Energy Mines and Petroleum Resources, Supply and Requirement Forecast: 1993-2015, Victoria, B.C., 1994.

British Columbia Ministry of Energy Mines and Petroleum Resources, Energy Standards For New Low-Rise Buildings in British Columbia: Life Cycle Analysis, Victoria, B.C., Sept. 1991, a.

British Columbia Ministry of Energy Mines and Petroleum Resources, Energy Standards For New Commercial Buildings in British Columbia: Life Cycle Analysis, Victoria, B.C., Sept. 1991, b.

British Columbia Ministry of Energy Mines and Petroleum Resources, Supply and Requirement Forecast: 1990-2010, Victoria, B.C., 1991, c.

British Columbia Ministry of Energy Mines and Petroleum Resources, British Columbia Energy Policy: New Directions for the 1990's, Victoria, B.C., 1989.

British Columbia Ministry of Finance and Corporate Relations, British Columbia Economic Review and Outlook, Aug. 1994.

British Columbia Ministry of Municipal Affairs, British Columbia Building Code, Victoria, B.C., 1992.

British Columbia Utilities Commission, Annual Report, 1993, Vancouver, B.C., May 1994a.

British Columbia Utilities Commission, Decision, 1994/95 Revenue Requirements Application, Phase 2, Vancouver, B.C., Aug 1994b.

British Columbia Utilities Commission, Integrated Resource Planning Guidelines, Vancouver, B.C., 1993.

British Columbia Utilities Commission, In the Matter of a Rate Application by British Columbia Hydro and Power Authority, Vancouver, B.C., April, 1990.

British Columbia Energy Council, Planning Today for Tomorrow's Energy: An Energy Strategy for British Columbia, Vancouver, 1994.

Brown, L. Ed., State of the World, 1992, WW Norton & Co., New York, 1992.

Buchannon, A.H., Honey, B.G., "Energy and Carbon implications of Building Construction", Energy and Building, Vol. 20, pp. 205-217, 1994.

Building Owners and Managers Association (BOMA), 1994 BOMA Experience Exchange Report, Washington, DC, 1994.

Bush, M.J., "The Energy Intensity of Commodities Produced in Canada", Energy, Vol. 6, pp. 503-517, 1981.

Canada Center for Mineral and Energy Technology, (CANMET), Present and Future use of Energy in the Canadian Steel Industry, Ottawa, Ont., 1993.

Canadian Mortgage and Housing Corporation (CMHC), CMCH Research

Energy Mines and Resources Canada, Proceedings of a Workshop on the Potential for Energy Efficiency in Canada, Ottawa, 1993.

Environment and Land Use Committee Secretariat, Guidelines for Benefit Cost Analysis, Victoria, B.C., 1977.

Georgescu-Roegen, N., "Energy and Economic Myths", Southern Economic Journal, Jan., 1975.

Gilliland, M.W., Ed., Energy Analysis: A New Public Policy Tool, Westview Press, Boulder, Colo., 1978.

Gilliland, M.W., "Energy Analysis and Public Policy", Science, Vol. 189, No. 4208, pp. 1051-1056, 1975.

Houghton, D.J., "Projected and Measured Results from an Energy Efficient Small Commercial Office Building", Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, pp. 9.187-9.193, 1994.

Howard, N., Sutcliffe, H., "Precious Joules", Building, Vol. 18, pp. 48-50, March, 1992.

International Federation of Institutes of Advanced Study (IFIAS) Workshop, Energy Analyses, Workshop Report No. 6, S-17171, Solna, Sweden, 1974.

Jekel-Sadlier, S., Estimated Energy Price and Income Elasticities, Ministry of Energy, Mines and Petroleum Resources, Victoria, B.C., 1990.

Kempton, W., Schipper, L., "Expanding the Human Dimensions Research Agenda," Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, pp. 1.85-1.90, 1994.

Komor, P., Moyad, A., "How Large is the Cost-Effective Energy Savings Potential in U.S. Buildings?", Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, pp. 6.125-6.134, 1994.

Lawrence Berkeley Laboratory, DOE-2 Reference Mannual (2.1A), Simulation Researh Group, University of California, Berkely, Ca, 1987.

Lawrence Berkeley Laboratory, DOE-2 Sample Run Book, Simulation Researh Group, University of California, Berkely, Ca, 1989.

Lawrence Berkeley Laboratory, DOE-2 Supliment, Simulation Researh Group, University of California, Berkely, Ca, 1989.

Lawrence Berkeley Laboratory, DOE-2 Basics Mannual, Simulation

Project: Testing of Air Barrier Construction Details, Report No. 32173.03/1, Ottawa, 1993.

Canadian Mortgage and Housing Corporation, OPTIMIZE, A Method for Estimating the Lifecycle Energy and Environmental Impacts of a House, Ottawa, 1991.

Cole, R.J., Building Materials in the Context of Sustainable Development, Environmental Research Group, University of British Columbia, Vancouver, B.C., July, 1994.

Cole, R.J., Ed., Buildings and the Environment, Proceedings of a one day Forum held at the University of B.C., School of Architecture, University of British Columbia, Vancouver, 1991.

Cole, R.J., Rousseau, D., Energy Intensity Data Base, University of British Columbia, 1993.

Cole, R.J., Ed., Buildings and the Environment, An International Research Workshop, Environmental Research Group, University of British Columbia, Vancouver, 1992.

Common, M., "The Economics of Energy Analysis Reconsidered", Energy Policy, pp. 158-165, June, 1976.

Conally, S., B.C. Gas, Personal Communication, Vancouver, B.C., 1995.

Conover, R., Jarnagin, R.E., Shankle, D., "Commercial Building Energy Standards Implemintation: Myth vs Reality", Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, pp. 6.27-6.34, 1994.

Constanza, R., Farber, S., Maxwell, J., "Valuation and Management of Wetland Ecosystems", Ecological Economics, Vol. 1, pp. 335-361, 1989.

Costanza, R., Ed., Ecological Economics The Science and Management of Sustainability, Columbia University Press, New York, 1991.

Daly, H.E., Townsend, K.N., Ed., Valuing the Earth, Economics, Ecology, Ethics, MIT Press, Cambridge, Mass., 1993.

Daly H.E., Umana A.E., Ed., Energy, Economics and the Environment: Conflicting Views of an Essential Interrelationship, AAAS Symposium 64, Westview Press, Boulder Colo., 1981.

Danbridge, C.B., Roturier, J., Norford, L.K., "Energy Policies for Energy Efficiency in Office Equipment", Energy Policy, Vol. 22, No. 9, pp. 735-747, 1994.

Researh Group, University of California, Berkely, Ca, 1991.

Leach, G., "Net Energy Analysis-is it any use?", Energy Policy, Vol. 3, No. 4, pp. 322-344, (Dec.) 1975.

Lindblom, C.E., "The Science of Muddling Through", Public Administration Review, Vol. XIX, No. 2, pp. 79-88, Spring, 1959.

Lovins, A.B., "Expansio ad Absurdum", The Energy Journal, Vol. 2, No. 4, pp. 25-42, 1981.

Lovins, A.B., "Energy Strategy: The Road Not Taken?", Foreign Affairs, Fall, 1976.

Lutzenhiser, L., "Innovations and Organizational Networks", Energy Policy, Vol. 22, No.10, pp.867-876, 1994.

Lutzenhiser, L., "Social and Behavioral Aspects of Energy Use", Annual Review of Energy and the Environment, Vol. 18, pp.247-289, 1993.

Lutzenhiser, L., "A Cultural Model of Household Energy Consumption", Energy, Vol. 17, No. 1, pp. 47-60, 1992.

MacDonald, M.J., "Energy Efficiency Capital Requirements for Buildings in the United States," Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, pp. 1.175-1.183, 1994.

McDaniels, T., Environmental Policy Analysis: Risks and Values, A Reader, University of British Columbia, School of Community and Regional Planning, Vancouver, B.C., 1993.

Means, R.S., Means Construction Cost Data, 52th Ed., Wattford Ma., 1994.

Nadel, S., Pye, M., Jordan, J., "Achieving High Participation Rates: Lessons Taught By Successful DSM Programs", American Council for an Energy Efficient Economy, 1994.

Nadel, S.M., Reid, M.W., Wolcott, D.R., Ed., Regulatory Incentives for Demand Side Management, American Council for an Energy Efficient Economy, Washington, D.C., 1992.

National Research Council, Draft: The National Building Code of Canada Ottawa, 1994.

National Cooperative Highway Rsearch Program, Energy involved in construction materials and procedures, National research council, Washington, D.C., 1981.

Nemetz, P.N., Commerce 595 Class Notes, University of British

Columbia, Vancouver, B.C., 1993

Nemetz, P.N., Ed., Resource Policy International Perspectives, The Institute for Research on Public Policy, Montreal, Que., 1980.

Northwest Power Planning Council, Northwest Conservation and Electric Power Plan, Document 91-05, Portland, Oregon, 1991.

Odum, H.T., Environment, Power and Society, Wiley-Interscience, New York, 1971.

Oka, T., Suzuki, M., Konnya, T., "The Estimation of Energy Consumption and Amount of Pollutants due to Construction of Buildings", Energy and Buildings, Vol. 19, pp. 303-311, 1993.

Peet, M.J., "The Energy Intensity of Commodities Produced in Canada", Energy, Vol. 6, pp. 503-517, 1981.

Public Works Canada, Air Leakage Control: Guidlines for Installation of Air Leakage Control Measures in Commercial Buildings, Ottawa, 1994.

Punti, A., "Energy Accounting: Some New Proposals", Human Ecology, Vol. 16, No. 1, pp. 79-86, 1988.

Radian Canada Inc./Canada Center for Mineral and Energy Technology, Raw Materials Balances, Energy Profiles and Environmental Unit Factor Estimates for Cement and Structural Concrete Products, Oct. 1993.

Rees, W.E., "Ecological Footprints and Appropriated Carrying Capacity: What Urban Economics Leaves Out", Environment and Urbanization, Vol. 4, No.2, pp. 121-130, Aug. 1992.

Reister, D.B., "The Energy Embodied in Goods", Energy, Vol. 3, pp. 499-505, 1978.

Robinson, J.B., "Apples and Horned Toads: On the Framework-Determined Nature of the Energy Debate", Policy Sciences, Vol. 15, pp. 23-45, 1982.

Robinson, J.B., "The Proof of the Pudding: Making Energy Efficiency Work." Energy Policy, Vol. 19, No. 7, pp. 631-645, 1991.

Sanstad, A.H., Howarth, R.B., "Consumer Rationality and Energy Efficiency", Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, pp. 1.175-1.183, 1994, a.

Sanstad, A.H., Howarth, R.B., " 'Normal' Markets, market Imperfections and Energy Efficiency", Energy Policy, Vol. 22, No. 10, pp.811-818, 1994, b.

SENES Consultants, LTD., Construction and Demolition Waste in Canada, Richmond Hill, Ont, 1993.

Serber, D., "Energy Embodied in Buildings and Building Components", Energy Policy, Vol. , pp. 317-326, 1976.

Simon, H.A., "Rationality in Psychology and Economics", Journal of Business, Vol. 59, No. 4, Pt. 2, pp. S209-S224, 1986.

Smith, R., Statistics Canada, Personal communication, Otawa, Ont., 1994.

Statistics Canada, Catalogue Number 89-525E, Adult Literacy in Canada: Results of a National Survey, Ottawa, 1991, a.

Statistics Canada, Catalogue Number 57-003-IV, Quarterly Report-Energy Supply-Demand 1991-IV, Ottawa, 1991, b.

Statistics Canada, Catalogue Number 11-528E, Environmental Perspectives 1993, Ottawa, 1993.

Statistics Canada, Catalogue Number 62-001, Monthly, The Consumer Price Index, Ottawa, Aug., 1994.

Stein, R.G., Serber, D., Hannon, B., "Energy Use for Building Construction", Center for Advanced Computations, University of Illinois, 1976.

Stelco Technical Services Ltd., Raw Materials Balances, Energy Profiles and Environmental Unit Factor Estimates for Structural Steel Products, Aug. 1993.

Stern, P.C., "Blind Spots in Policy Analysis: What Economics doesn't say about Energy Use", Journal of Policy Analysis and Management, pp. 200-227, 1986.

Stern, P.C., Aronson, E., Energy Use: The Human Dimension, New York, W.H. Freeman, 1984.

Sutherland, R.J., "Market Barriers to Energy Efficiency Investments", The Energy Journal, Vol. 12, No.3, pp. 15-34, 1992.

Sutherland, R.J., "Energy Efficincy or the Efficient Use of Resources?", Energy Sources, Vol. 16, pp. 257-268, 1994.

United Nations Cenre for Human Settlements, Energy for building, Nairobi, 1991.

Webb, M., Pearce, D., "The Economics of Energy Analysis", Energy Policy, pp. 318-331, Dec. 1975.

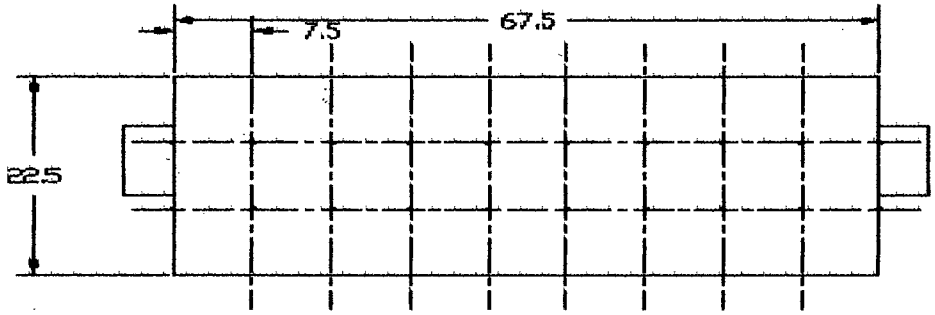
Wirtshafter, R.M., "Energy Performance-Based Hookup Fees for

Buildings", Energy Sources, Vol. 16, pp.483-501, 1994.

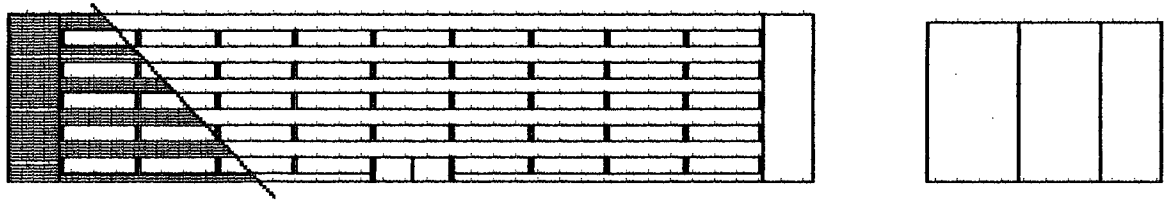
APPENDICES

Appendix A
Figure A1: Building Drawings

grid layout



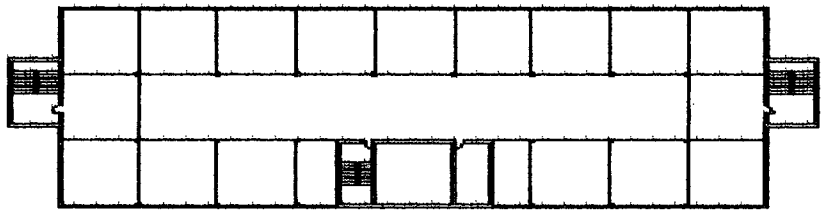
Front view



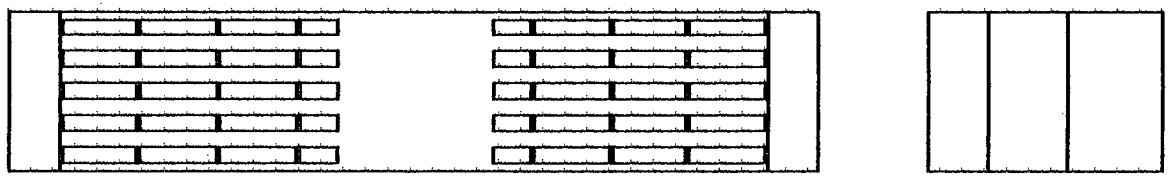
Appendix A

Figure A2: Building Drawings

Interior partitions



rear view



Appendix A

Figure A3: Building Drawings

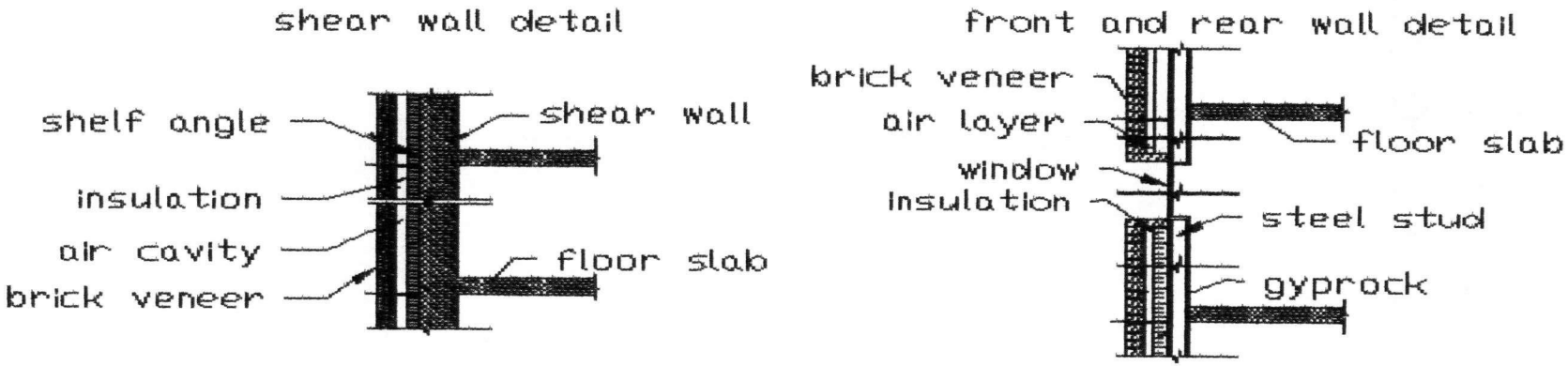


Table A1: Building Specifications						
test run	BASE BUILDING CONFIGURATION					
Schedules			Day	Hours	Factor	
	Occupancy		Mon-Fri	1,8	0	
				9,11	1	
				12	0.8	
				13	0.4	
				14	0.8	
				15,18	1	
				19	0.5	
				20	0.1	
				21	0.1	
				22,24	0	
			Weekends	1,24	0	
			and Holidays			
	Lights		Mon-Fri	1,8	0.15	
				9	0.9	
				10	0.95	
				11	1	
				12	0.95	
				13	0.8	
				14	0.9	
				15,18	1	
				19	0.6	
				20,21	0.2	
				22,24	0.15	
			Weekends	1,24	0.15	
			and Holidays			
	Equipment		Mon-Fri	1,8	0.02	
				9,20	0.8	
				21,24	0.02	
			Weekends	1,24	0.02	
			and Holidays			
	Infiltration		Mon-Fri	1,7	0.4	
				8,18	0.06	
				19,24	0.4	
			Weekends	1,24	0.4	
			and Holidays			
	Fans		Mon-Fri	1,7	0.4	
				8,18	0.06	

				19,24	0.4	
			Weekends	1,24	0.4	
			and Holidays			
Design Characteristics						
	Orientation		Major Axis Parallel to North South			
	Occupancy		13.9 sq. m/person			
	Lights		27 W/sq. m			
	Equipment		5.4 W/sq. m			
	Air Infiltration		2 ACH			
	People Heat Gain		0.47 MJ/person/hour			
	Hot Water		5000 Watts			
				Schedule= Occupancy		
	Elevator		75 KW			
				Schedule= Occupancy		
	Glazing		2 layers			
			Aluminum Frame Without Thermal Break			
			Shading coefficient		0.909	
			Thermal Conductivity		0.72	
	Office Conditions					
			Design Heat Temp		21 Deg. C	
			Design Cool Temp		23 Deg. C	
			Air Changes/Hr		4.5	
			O/A changes/Hr	0.58 cu m./person		
			Variable Air Volume System			
			Baseboard Heating			
	Underground Parking Conditions					
			Outside Air Changes/Hr		6	
			Heating, Cooling Not Supplied			

Figure B1: Monthly Energy Consumption, Build 7A

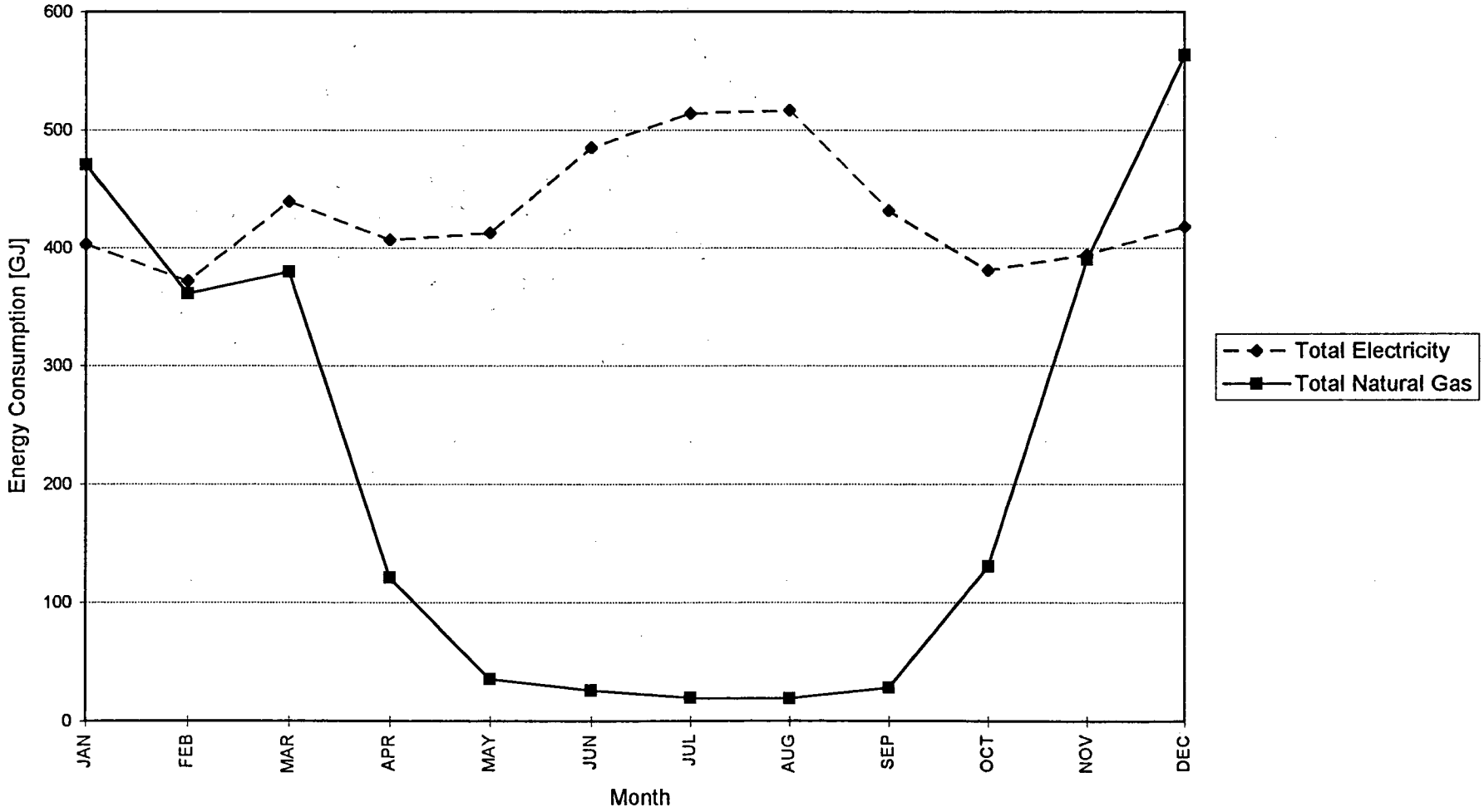


Figure B2: Monthly Heating Loads, Build 7A

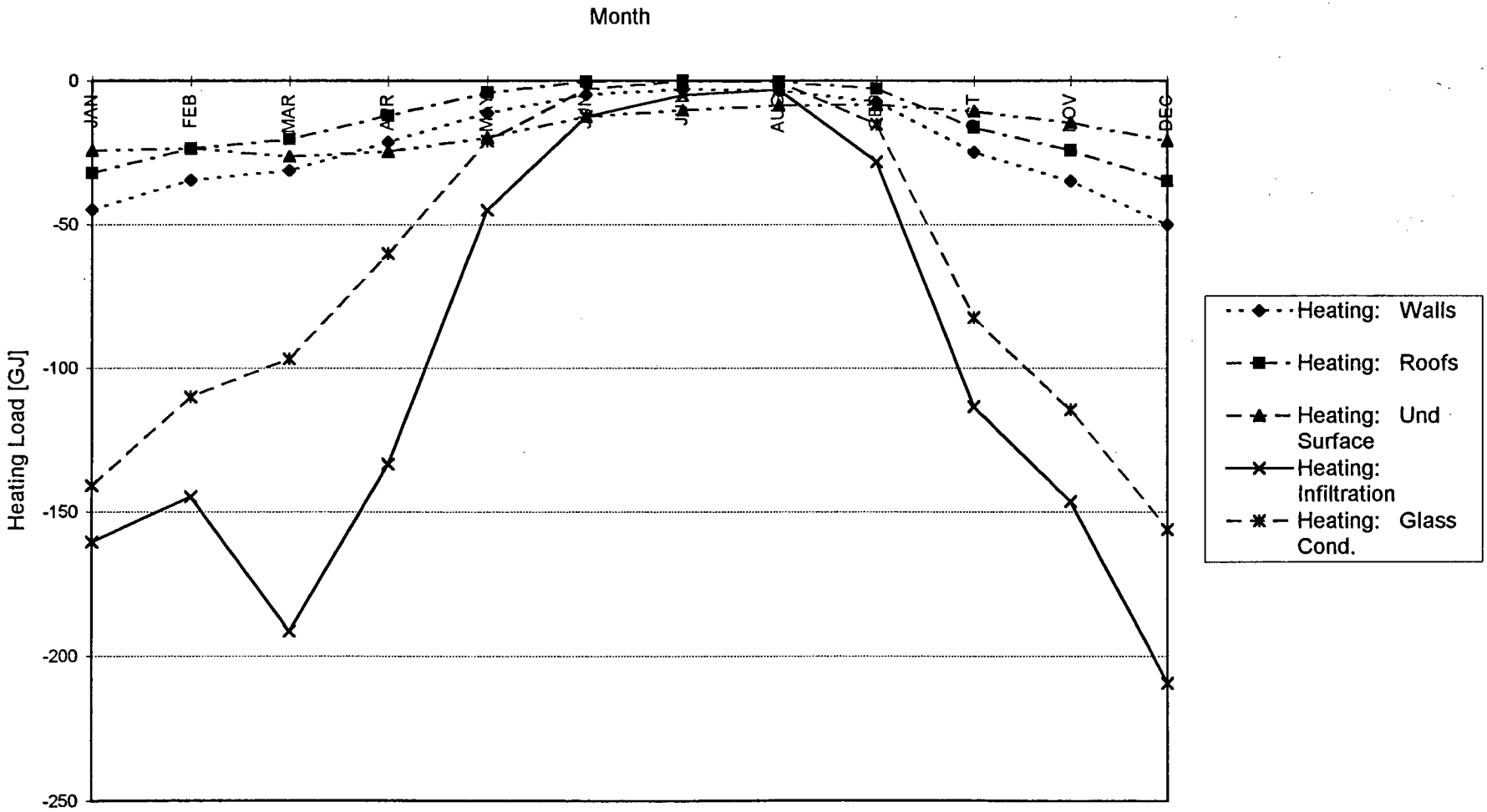


Figure B3: Building Energy Performance Index

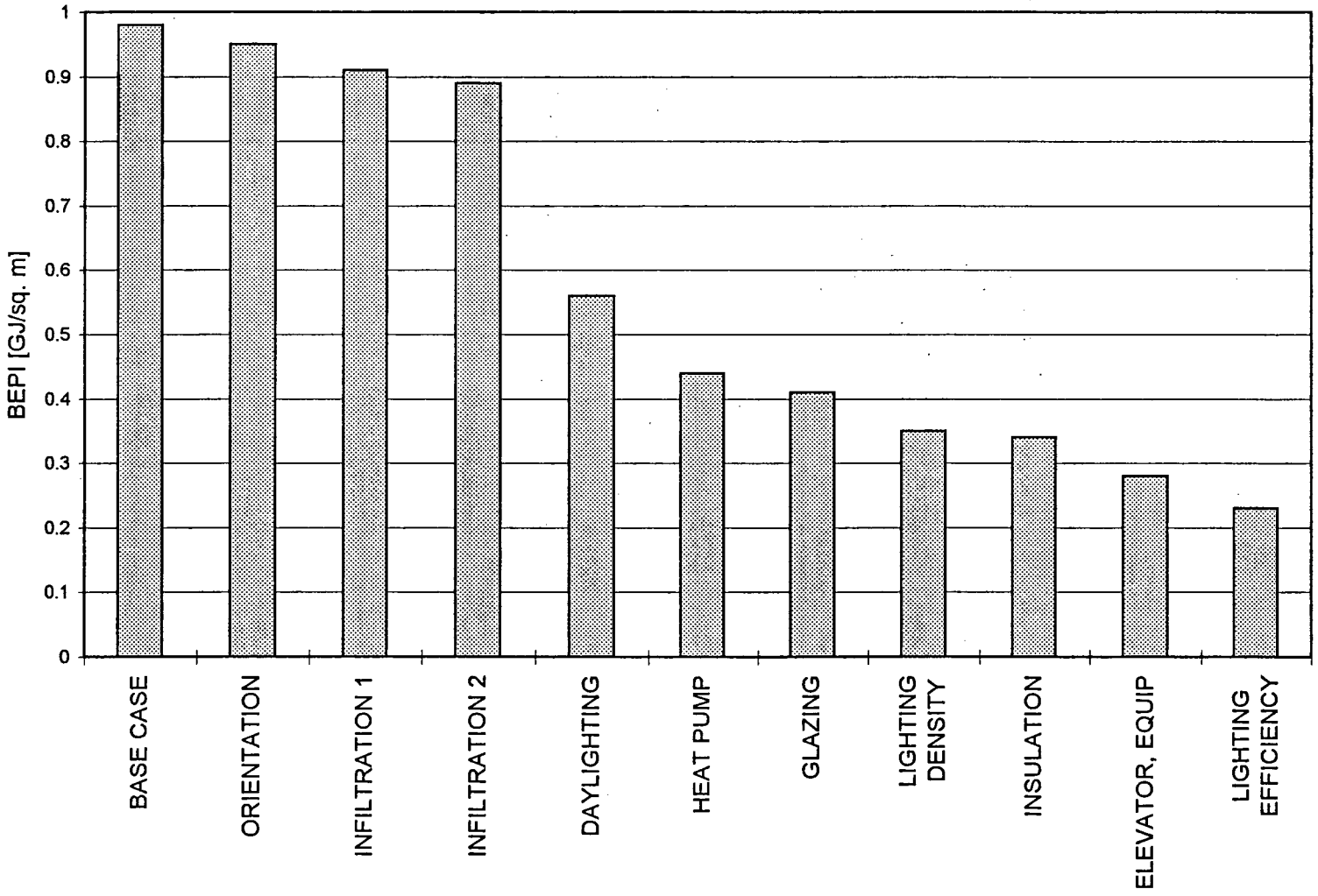


Figure B4: Energy Consumption by End Use

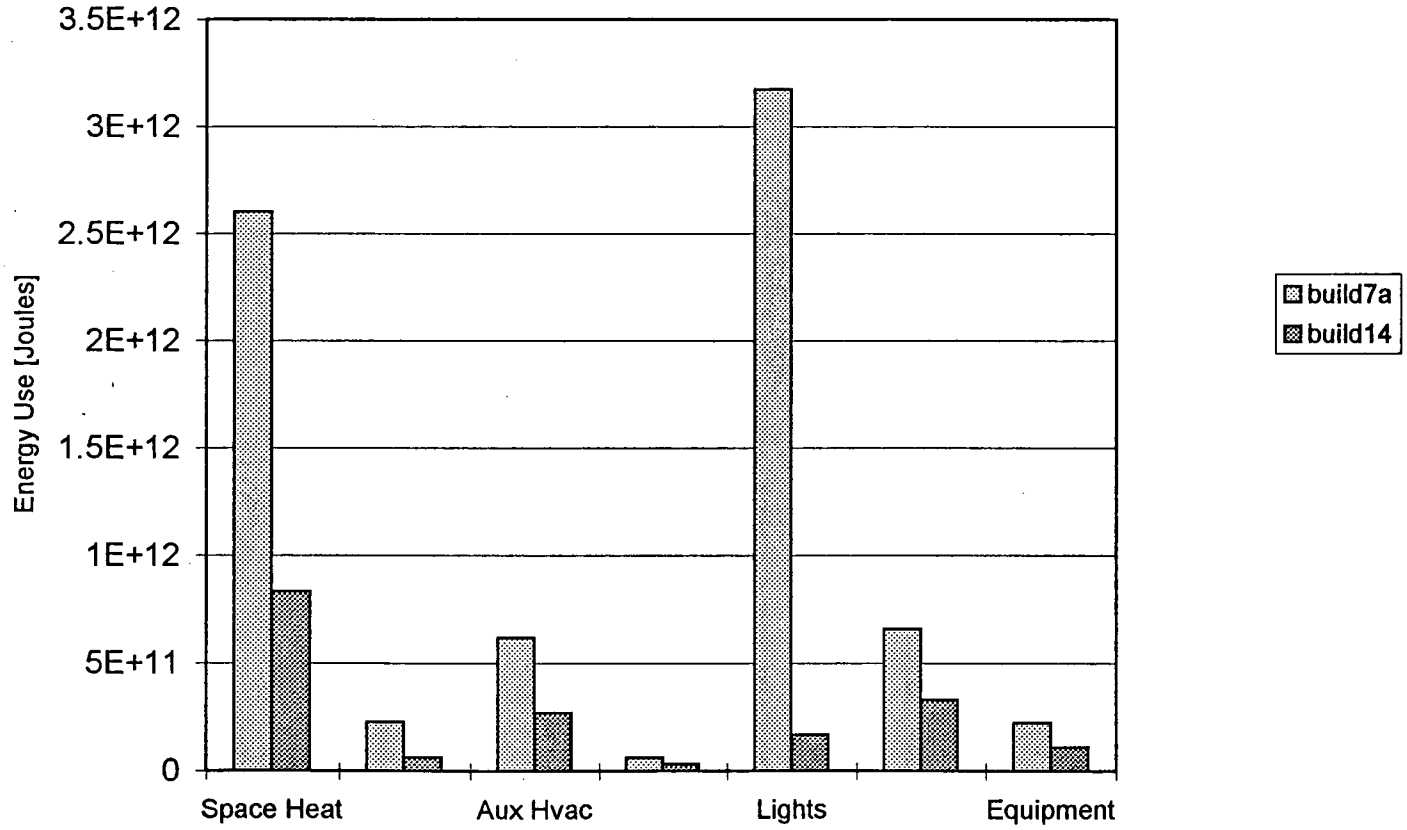


Figure B5: Energy Consumption by End Use

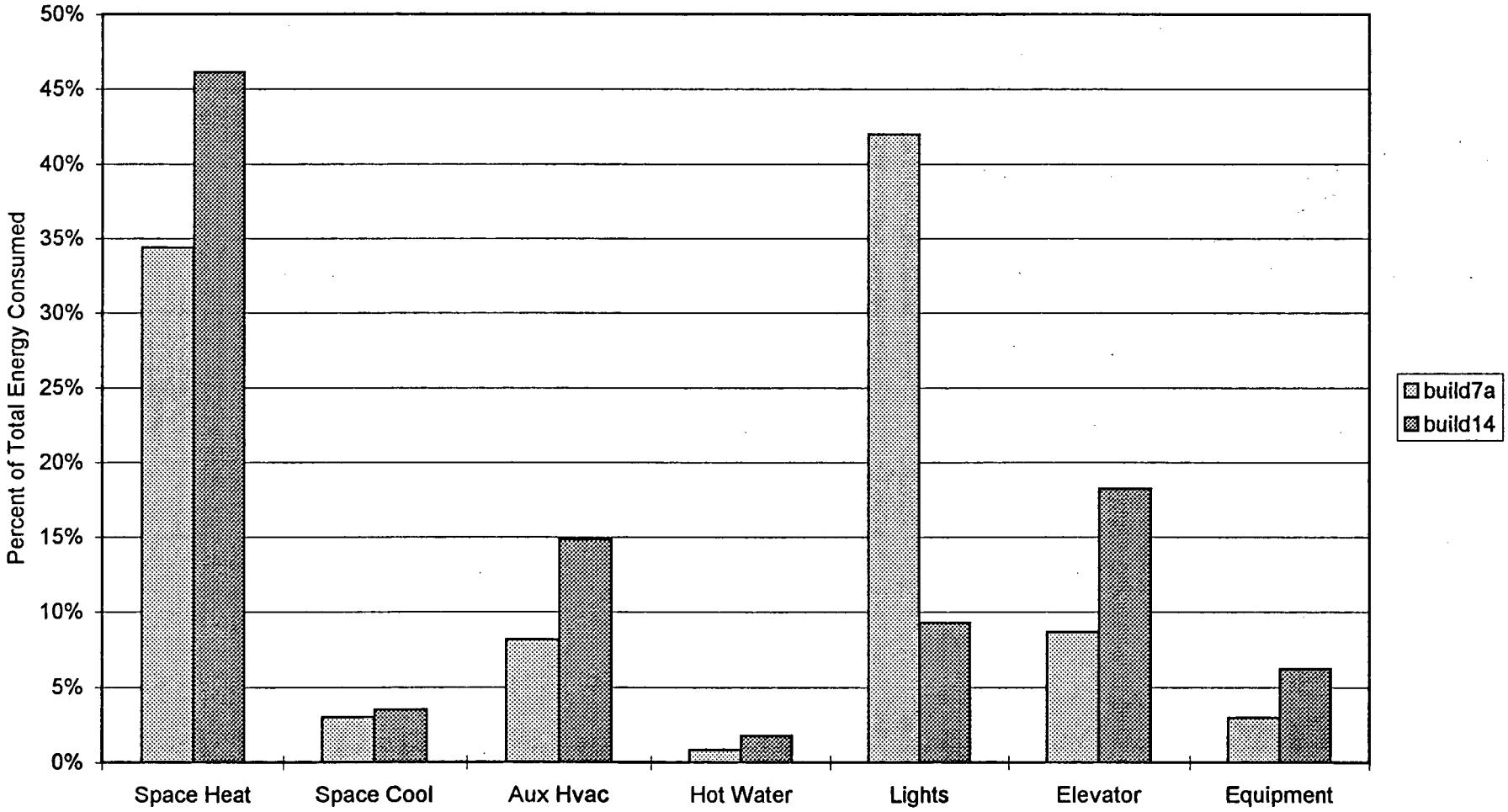


	Table B1: Energy Consumption of Case Study Building										
RUN	**BUILD7A**										
STRATEGY	base building				[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		117	2350		1.23E+11	1.6E+11	2.48E+12				
Space Cool		215			2.27E+11	2.95E+11	0		boiler	MBTU/HR	3.23
Aux Hvac		585			6.17E+11	8.02E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		chiller	MBTU/HR	2.52
Lights		3009			3.17E+12	4.13E+12	0		cooling twr	MBTU/HR	3.12
Elevator		623			6.57E+11	8.54E+11	0		supply fan	CFM	110170
Equipment		212			2.24E+11	2.91E+11	0				
Total					5.02E+12	6.53E+12	2.54E+12				
							sum	7.57E+12			
							site BEPI	**0.964468**			
							source BEPI	1.130746			
RUN	**BUILD7B**										
STRATEGY	rotate building 90 deg.				[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		99	1963		1.04E+11	1.36E+11	2.07E+12				
Space Cool		237			2.5E+11	3.25E+11	0		boiler	MBTU/HR	2.46
Aux Hvac		654			6.9E+11	8.97E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		chiller	MBTU/HR	2.59
Lights		3009			3.17E+12	4.13E+12	0		cooling twr	MBTU/HR	1.1
Elevator		623			6.57E+11	8.54E+11	0		supply fan	CFM	125840
Equipment		212			2.24E+11	2.91E+11	0				
Total					5.1E+12	6.63E+12	2.14E+12				
							sum	7.23E+12			

							site BEPI	0.922241			
							source BEPI	1.09234			
RUN	**BUILD7C**										
STRATEGY	reduce infiltration from 2 to 1				[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		83	1646		8.76E+10	1.14E+11	1.74E+12				
Space Cool		254			2.68E+11	3.48E+11	0		boiler	MBTU/HR	1.58
Aux Hvac		727			7.67E+11	9.97E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		chiller	MBTU/HR	2.73
Lights		3009			3.17E+12	4.13E+12	0		cooling twr	MBTU/HR	1.1
Elevator		623			6.57E+11	8.54E+11	0		supply fan	CFM	125840
Equipment		212			2.24E+11	2.91E+11	0				
Total					5.18E+12	6.73E+12	1.8E+12				
							sum	6.98E+12			
							site BEPI	0.889562			
							source BEPI	1.06331			
RUN	**BUILD7D**										
STRATEGY	reduce infiltration from 1 to 0.1				[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		64	1418		6.75E+10	8.78E+10	1.5E+12				
Space Cool		271			2.86E+11	3.72E+11	0		boiler	MBTU/HR	0.895
Aux Hvac		852			8.99E+11	1.17E+12	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		chiller	MBTU/HR	2.83
Lights		3009			3.17E+12	4.13E+12	0		cooling twr	MBTU/HR	1.2
Elevator		623			6.57E+11	8.54E+11	0		supply fan	CFM	125840
Equipment		212			2.24E+11	2.91E+11	0				
Total					5.31E+12	6.9E+12	1.56E+12				
							sum	6.87E+12			
							site BEPI	0.875442			
							source BEPI	1.054356			

RUN	**BUILD8A**										
STRATEGY	implement delighting				[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		73	1539		7.7E+10	1E+11	1.62E+12				
Space Cool		149			1.57E+11	2.04E+11	0		boiler	MBTU/HR	1.02
Aux Hvac		471			4.97E+11	6.46E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		chiller	MBTU/HR	1.65
Lights		1005			1.06E+12	1.38E+12	0		cooling twr	MBTU/HR	1.04
Elevator		623			6.57E+11	8.54E+11	0		supply fan	CFM	125840
Equipment		212			2.24E+11	2.91E+11	0				
Total					2.67E+12	3.47E+12	1.69E+12				
							sum	4.36E+12			
							site BEPI	**0.555781**			
							source BEPI	0.643295			
RUN	**BUILD8B**										
STRATEGY	replace the VAV system with a heat pump				[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		392	445		4.14E+11	5.38E+11	4.69E+11				
Space Cool		259			2.73E+11	3.55E+11	0		boiler	MBTU/HR	1.06
Aux Hvac		280			2.95E+11	3.84E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		cooling twr	MBTU/HR	0.783
Lights		1005			1.06E+12	1.38E+12	0		supply fan	CFM	78070
Elevator		623			6.57E+11	8.54E+11	0				
Equipment		212			2.24E+11	2.91E+11	0				
Total					2.92E+12	3.8E+12	5.34E+11				
							sum	3.46E+12			
							site BEPI	**0.440666**			
							source BEPI	0.540135			
RUN	**BUILD9**										

STRATEGY	replace double glazed windows with triple glazed/low emissivity glass										
					[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		300	367		3.17E+11	4.11E+11	3.87E+11				
Space Cool		234			2.47E+11	3.21E+11	0		boiler	MBTU/HR	0.92
Aux Hvac		255			2.69E+11	3.5E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		cooling twr	MBTU/HR	1.08
Lights		1005			1.06E+12	1.38E+12	0		supply fan	CFM	63790
Elevator		623			6.57E+11	8.54E+11	0				
Equipment		212			2.24E+11	2.91E+11	0				
Total					2.77E+12	3.61E+12	4.51E+11				
							sum	3.22E+12			
							site BEPI	**0.41108**			
							source BEPI	0.505608			
RUN	**BUILD10**										
STRATEGY	reduce lighting from 27 W/sq.m to 20 W/sq. m										
					[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		341	458		3.6E+11	4.68E+11	4.83E+11				
Space Cool		205			2.16E+11	2.81E+11	0		boiler	MBTU/HR	0.95
Aux Hvac		254			2.68E+11	3.48E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		cooling twr	MBTU/HR	1.02
Lights		466			4.92E+11	6.39E+11	0		supply fan	CFM	63790
Elevator		623			6.57E+11	8.54E+11	0				
Equipment		212			2.24E+11	2.91E+11	0				
Total					2.22E+12	2.88E+12	5.47E+11				
							sum	2.76E+12			
							site BEPI	**0.352312**			
							source BEPI	0.427325			
RUN	**BUILD11**										

STRATEGY	double the insulation in the roof, walls, and underground surfaces										
					[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		305	382		3.22E+11	4.18E+11	4.03E+11				
Space Cool		219			2.31E+11	3E+11	0		boiler	MBTU/HR	0.907
Aux Hvac		254			2.68E+11	3.48E+11	0		DHW	MBTU/HR	0.017
Hot Water		0	60.8		0	0	6.41E+10		cooling twr	MBTU/HR	1.04
Lights		466			4.92E+11	6.39E+11	0		supply fan	CFM	63790
Elevator		623			6.57E+11	8.54E+11	0				
Equipment		212			2.24E+11	2.91E+11	0				
Total					2.19E+12	2.85E+12	4.67E+11				
							sum	2.66E+12			
							site BEPI	**0.339133**			
							source BEPI	0.413572			
RUN	**BUILD12**										
STRATEGY	halve elevator and equipment loads										
					[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		323	421		3.41E+11	4.43E+11	4.44E+11				
Space Cool		194			2.05E+11	2.66E+11	0		boiler	MBTU/HR	0.92
Aux Hvac		254			2.68E+11	3.48E+11	0		DHW	MBTU/HR	0.009
Hot Water		0	30.4		0	0	3.21E+10		cooling twr	MBTU/HR	0.984
Lights		466			4.92E+11	6.39E+11	0		supply fan	CFM	63790
Elevator		311			3.28E+11	4.27E+11	0				
Equipment		106			1.12E+11	1.45E+11	0				
Total					1.74E+12	2.27E+12	4.76E+11				
							sum	2.22E+12			
							site BEPI	**0.283135**			
							source BEPI	0.34206			
RUN	**BUILD14**										

STRATEGY	reduce lighting from 20 W/sq.m to 6 W/sq. m										
					[joules]						
		[MBTU]			ELEC						
		ELEC	N.G.		site	source	N.G.		EQUIPMENT SIZE		
Space Heat		291	497		3.07E+11	3.99E+11	5.24E+11				
Space Cool		60			6.33E+10	8.23E+10	0		boiler	MBTU/HR	0.92
Aux Hvac		254			2.68E+11	3.48E+11	0		DHW	MBTU/HR	0.009
Hot Water		0	30.4		0	0	3.21E+10		cooling twr	MBTU/HR	0.984
Lights		159			1.68E+11	2.18E+11	0		supply fan	CFM	63790
Elevator		311			3.28E+11	4.27E+11	0				
Equipment		106			1.12E+11	1.45E+11	0				
Total					1.25E+12	1.62E+12	5.56E+11				
							sum	1.8E+12			
							site BEPI	**0.229747**			
							source BEPI	0.271205			
ADDITIONAL STRATEGIES TESTED, BUT FOUND TO HAVE MINIMAL OR NEGATIVE IMPACT											
RUN	BUILD13										
STRATEGY:	night venting of the building if the interior temperature is greater than 20 deg. C										
RUN	BUILD15										
STRATEGY:	alter (increase and decrease) the window to wall ratio										
RUN	BUILD16										
STRATEGY:	increase the thermal comfort zone										
RUN	BUILD17										
STRATEGY:	add interior SUNSPACE										

Table C1: Energy Intensity of Building Materials								
Conversion factors								
1 Btu	0.001055 mj				1 lb/ft3	16.028 kg/m3		
1 Btu	251.98 cal				1 kg/m3	0.0639 lb/ft3		
1 mj	947.87 Btu				1 lb/ft3	16.0283 kg/m3		
1 lb	0.4536 kg				1 lb/ft	1.488 kg/m		
1 kg	2.2046 lb				1 Btu/lb	0.0023258 mj/kg		
1 ft	0.3048 m				1 Btu/ft	0.00346 mj/m		
1 m	3.2808 ft				1 Btu/yd3	1.0066 mj/m3		
1 ft2	0.0929 m2				1 Btu/ft3	0.03728 mj/m3		
1 m2	10.76 ft2				1 Btu/gal	.0002787 mj/L		
1 ft3	0.0283 m3				1 lb/ft2	4.881 kg/m2		
1 m3	35.3357 ft3				1 Btu/ft2	0.0113518 mj/m2		
1 gal (US)	3.78541 L							
		Density	**Source**	**Units**	**Density**	**Intensity**	**Intensity**	**Source**
		kg/m3			**kg/unit**	**mj/kg**	**mj/unit**	
Division 1	**Preliminaries**							
Preliminaries				$			39.50	h
Administration				$			22.50	h
Division 2	**Sitework**							
Earthwork				**m3**			**100.00**	h
Conc. pipe, non-reinforced				kg		4.14		a
	250mm			**m**	**75.888**		**314.18**	a
PVC pipe				kg		108.382		a

Table C1: Energy Intensity of Building Materials								
ABS and PVC pipe and fittings				kg		190		e
	75mm			**m**	**1.726**		**187.07**	a
	100mm			**m**	**2.842**		**308.02**	a
	150mm			**m**	**6.86**		**743.50**	a
	250mm			**m**	**14.91**		**1615.98**	a
Earthwork								
Uncrushed sand		1600		m3	1600	0.01743	27.89	b
		1900		m3	1900		33.12	b
Uncrushed gravel				m3		0.01743		b
Granite		2645	I	m3	2645	0.05113	135.24	b
Sand aggregate		1763	I	m3	1763	0.03	52.89	c
	to	1763	I	m3	1763	0.3	528.90	c
Sand and gravel		1763	I	m3	1763	0.051	89.91	e
Stone, crude		2404	I	m3	2404	0.14	336.56	e
Paving								
100mm 150x150 no.5 wm				m2			499.48	a
150mm 150x150 no.5 wm				m2			681.11	a
Concrete								
Bituminous paving						2.4		e
38mm wearing surface only				m2			619.81	a
65mm wearing surface only				*m2*			*1060.20*	*a*
				m3			*16310.79*	*a*
Paving brick				No.			27.01	a
Division 3	**Concrete**							
Cast in place concrete								

Table C1: Energy Intensity of Building Materials								
Ready mix concrete		2345	I	m3		1.49	3582.53	a
				m3			3582.53	a
Concrete		2345	I	m3		0.96	2251.20	d
	to	2345	I	m3		2.41	5651.45	d
Concrete		2345	I	m3		0.5	1172.50	e
	to	2345	I	m3		0.8	1876.00	e
Concrete		2345	I	m3		0.96	2251.20	k
Concrete		2345	I	m3		1.2	2814.00	f
Concrete		2345	I	m3		0.9	2110.50	m
Cement						5.9		f
Concrete		2345	I	m3	Incl. trans.	1.6	3752.00	c
	to	2345	I	m3		2.2	5159.00	c
Concrete	15 mPa	2345	I	m3		1.36	3189.20	g1
	20 mPa	2345	I	m3		1.5	3517.50	g1
	30 mPa	2345	I	m3		1.99	4666.55	g1
Cement						4.96		g1
Cement						4.9		m
Cement						4.9		n
Division 4	Masonry							
Mortar				kg		13.19		a
Brick (56x90x190mm)				No.			15.09	a
Brick wall incl. mortar				m2	*195.23*		*1487.09*	a
Brick wall 100mm				m2			1191.98	k

Table C1: Energy Intensity of Building Materials								
Common brick UK						1.2		c
	to					1.8		c
Brick						2.1		e
Brick and mortar						4.5		f
Brick						4.9		f
Mortar						2.2		f
Mortar						1.4		m
Brick						3.1		m
Brick						2.8		n
Division 5	**Metals**							
Steel								
Carbon steel		7854						a
Sheet steel plain						39.0734		a
Sheet steel galvanized						64.6572		a
Structural shapes						52.7957		a
Pipes (hss)						60.0056		a
Steel						39		e
Steel						32.1		k
Finished steel UK						35.9		c
Galvanized steel US						64.5		c
Alloy steel structural shapes						62.564		a
Steel								d
Steel						27.2		m

Table C1: Energy Intensity of Building Materials								
Nails						43.80		g3
Wire mesh						46.20		g3
Screws nuts bolts						48.10		g3
Heavy trusses						41.60		g3
OWSJ						38.50		g3
Rebar						36.00		g3
HSS						28.40		g3
Tubing						28.70		g3
Hot rolled sheet						25.80		g3
Cold rolled sheet						28.80		g3
Galvanized sheet						28.50		g3
Galvanized decking						29.30		g3
Galvanized studs						29.20		g3
Stainless steel								
	Sheets (cold)					320.96		a
	Sheets (hot)					208.86		a
	Plates					369.8		a
	Bars (cold)					448.88		a
	Bars (hot)					365.15		a
Stainless		8174				235		d
Aluminum								
Structural shapes		2644				214.44		a
Plates and sheets						269.79		a
Sheet (Germany)						261		c
Finished products (UK)						270		c
Plate and sheet (US)						270		c

Table C1: Energy Intensity of Building Materials								
100% recycled aluminum						10.5		d
Sheet, bar						59.9		d
	to					371		d
Aluminum						236.3		f
Aluminum anodized						273.9		f
Aluminum						261.7		m
Aluminum						189		n
Aluminum						95.36		k
Copper								
Cast or rolled copper		8912	l					
Structural shapes						108.85		
Sheets, strips						162.11		
Pipe						170.02		
Wire, extrusions						29		e
Copper						93.03		k
Metal fasteners						60.47		a
						11		e
Division 6	**Wood and Plastics**							
Softwood framing				bd ft			*8.04*	a
Lumber				bd ft			8.02	k
	to			bd ft			10.23	k
Finished tomber		512.91	*d*	m3		3.3		d
	to					6.4		d
Softwood, kiln dried, planed						3.12		f
Plywood, exterior grade								

Table C1: Energy Intensity of Building Materials								
	6mm			m2			43.82	a
	9mm			m2			65.73	a
	12mm		d	m2	7.32		87.52	a
	16mm			m2			109.43	a
	19mm			m2			131.68	a
Plywood and veneer						15		e
Lumber and timber						7.4		e
Millwork						10		e
Timber, rough				m3			848.00	h
Timber, air dry, treated				m3			1200.00	h
Timber glulam				m3			4500.00	h
Timber, kiln dry, treated				m3			4690.00	h
Timber, formwork				m3			283.00	h
Hardboard				m3			20600.00	h
Softwood				m3			15470.00	h
Particle board				m3			12900.00	h
Plywood				m3			9440.00	h
Veneer				m3			11200.00	h
Plywood 12mm				m2			87.47	k
Plywood				m2			94.22	k
	to			m2			192.98	k
Softwood plywood						12.4		f
Softwoof plywood prod.						9.69		f
Low density fibre board						8.84		f
Softwood, kiln dried						5.6		g2
Sheathing plywood						9.66		g2
Strand board						6.03		g2

Table C1: Energy Intensity of Building Materials								
Plastics								
General plastics				kg		160		h
Polymers						8.5		d
	to					159		d
Polyethylene						44		d
	to					163		d
Polyethylene				kg		112		h
PVC						69		d
	to					96		d
PVC				kg		96		h
Polypropylene						126		d
	to					171		d
Polypropylene				kg		175		h
Polystyrene						96		d
	to					152		d
Polystyrene				kg		100		h
Polyolefin				kg		97		f
Polyolefin, prod.				kg		36		f
Poltethylene				kg		87		f
Polyethylene, prod.				kg		24		f
Poltethylene				kg		49.3		m
Polystyrene insulation						105		f
Polystyrene ins., prod.						28		f
Adhesives						97		e
Division 7	Thermal and Moisture Protection							
Kraft paper						26.8		f

Table C1: Energy Intensity of Building Materials								
Polyolefin						97		f
Polyolefin, prod.						36		f
Asphalt coating				L			2.926	a
Building paper				kg		24.42		a
Building paper, 1 ply				m2			5.96	a
Building paper				kg		12		e
Building paper				m2			7.46	h
Polystyrene insulation				kg		177.69		a
25mm Polystyrene		38.47	*a*	m2			173.68	a
64mm Mineral wool batt				m2			64.71	a
				kg		18		e
Fibreglass insulation				kg		22.3		f
Polystyrene						96		d
	to					152		d
Polystyrene insulation						105		f
Polystyrene ins., prod.						28		f
Loose fibre insulation		48.08	*a*	m2		14,9	*72.88*	a
Rigid fibreglass insulation							29.7	f
	production						24.5	f
Sprayed cellulose insulatio							13.7	f
	production						4.17	f
Rolled asphalt roofing				m2			88.09	a
Asphalt felts				kg		31.1		h
Bituminous felts				kg		38		h

Table C1: Energy Intensity of Building Materials								
Fibreglass batts				kg		150		h
Polystyrene				kg		100		h
Polystyrene				kg		122.8		m
Polystyrene				kg		118.8		n
Division 8	**Doors and windows**							
Glass		2539	I	kg		14		d
	to					29.3		d
Glass				kg		29.31		k
						22		e
Glass						10.2		f
6mm Glass (plate & float)		2539	I	m2			545	a
Tempered glass				m2			824	a
Laminated plate glass				m2			2418	a
Laminated sheet glass				m2			1283	a
Sheet glass UK				kg		11.9		c
Glass (sheet)				kg		21.6		m
Glass (sheet)				kg		16.5		n
Division 9	**Finishes**							
Steel studs 25ga				kg		43.5		a
	90mm			m	0.58		25.22	a
	100mm			m	0.62		27.16	a
	150mm			m	0.82		35.64	a
Gypsum board				kg		8.12		a

Table C1: Energy Intensity of Building Materials								
	12mm			m2	9.76		79.24	a
	16mm			m2	12.2		99.1	a
Gypsum UK				kg		0.8		c
	to			kg		1		c
Gypsum				kg		4.5		e
Gypsum				kg		1.4		m
Gypsum bd. int.				kg		7.4		f
Dry wall				kg		5.02		k
Vinyl flooring				kg		116.29		a
Vinyl flooring 3mm				m2	6.35		612	a
Vinyl tile				kg		18.61		k
Rubber, plastic, tiling				kg		32		e
Carpet				kg		74		e
Carpet				m2			257.3	f
Tiles				m2	14.64	2.1	30.75	e
Painting								
Exterior oil base				L			136.01	a
Exterior wate base				L			136.28	a
Interior oil base				L			141.86	a
Interior water base				L			121.79	a
Paint				L	1.2		1.5	d
	to			L			158	d
Paint water base, dry				kg		76.7		n

Table C1: Energy Intensity of Building Materials								
Sources								
						Date	Location	Analysis
a)	Stein et al.							
	Handbook of Energy Use for Building construction							
	National technical information service							
	U.S. Dept. of Commerce					1981	US	
b)	National Cooperative Highway Research Program							
	Energy involved in Construction materials and Proceedures							
	National Research Council, Washington DC					1981	US	
c)	United Nations Centre for Human Settlements							
	Energy for Building							
	Nairobi					1991	Kenya	
d)	Baird and Chan							
	Energy Cost of Houses and Light Construction Buildings							
	School of Architecture, Univ. of Wellington							

Table C1: Energy Intensity of Building Materials								
	Victoria New Zealand					1983	New Zealand	
e)	Canadian Housing and Mortgauge Corporation							
	Optimize					1993	Canada	
f)	Cole and Rousseau							
	Environmental Research Group, UBC, Vancouver BC					1991	Canada	
g)	Forintek Canada Inc.							
	Building Materials in the Context of Sustainable Development							
	Raw Material Balances,							
	Energy Profiles and Environmental Unit Factor Estimates for:							
g1)	Cement and Structural Concret Products					1993	Canada	
g2)	Structural Wood Products					1993	Canada	
g3)	Structural Steel Products					1993	Canada	
h)	Buchanan and Honey					1993	New Zealand	
j)	Howard and Sutciffe							
	BRE						UK	
k)	American Institute of Architects							
	The Energy Design Handbook, Ed. Donald Watson					1993	US	
l)	Graphic Standards							
m)	Kohler					Early 1980	Switzerland	
n)	Salokangas					Early 1980	Finland	

Table C2: Energy Intensity Trends for Building Materials in Canada, 1976-1990.

Code	Commodity	1976 (IN 1971 $) see note (a	in 1986$ ee note (b)	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	% change beween 1971& 1990
42	SAND (EXCL SILICA) & GRAVEL	83.30	24.64	16.52	19.75	16.76	15.85	14.76	15.14	17.11	19.51	19.27	15.52	48.05%
43	STONE, CRUDE	100.38	29.70	20.27	24.44	21.25	19.30	17.60	17.66	19.14	20.17	20.27	16.69	68.45%
128	POLYAMIDE RESINS, INCL NYLON	111.81	33.08	27.64	25.00	26.57	23.72	22.35	20.44	20.65	21.03	20.10	18.36	77.47%
136	TEXTILE FLOOR COVERING	70.99	21.00	14.10	15.08	12.79	12.92	11.08	10.21	10.55	11.58	12.13	11.37	50.69%
150	LUMBER & TREATED WOOD	50.63	14.98	13.94	13.66	12.90	12.10	11.65	11.80	13.24	12.86	12.92	11.17	20.07%
152	CUSTOM WOOD WORK & MILLWORK	52.61	15.57	12.10	12.28	11.50	11.04	10.18	9.85	10.76	10.77	10.61	9.57	31.54%
153	PLYWOOD & VENEER	50.35	14.90	14.19	14.00	13.01	12.32	11.81	11.97	12.46	11.80	12.05	11.88	15.85%
154	WOOD CONST. PROD.,EXCL PREFAB. BUILD	50.43	14.92	8.35	8.85	8.55	7.97	8.05	7.93	8.87	9.02	8.65	8.03	36.26%
155	WOOD PREFAB. BUILDINGS	49.60	14.67	8.29	8.76	8.47	7.92	7.97	7.77	8.70	8.83	8.44	7.91	35.62%
156	WOOD CONTAINERS	43.81	12.96	9.27	8.67	9.28	8.81	8.85	8.82	9.82	9.16	9.17	9.49	18.25%
158	OTHER WOOD PRODUCTS	74.45	22.03	16.14	16.22	16.74	15.28	13.51	13.10	14.76	13.76	13.19	12.23	51.57%
159	HOUSEHOLD FURNITURE	46.21	13.67	8.21	9.05	8.46	7.99	7.93	7.74	8.48	8.76	8.54	7.75	31.14%
160	OFFICE FURNITURE	50.99	15.09	8.68	10.13	10.16	8.43	8.28	8.03	8.68	9.29	9.18	7.92	37.72%
161	COMMERCIAL, INSTIT. & OTH FURNITURE	54.93	16.25	9.45	10.01	10.83	9.60	8.93	9.03	9.65	10.42	10.40	8.91	38.62%
169	BUILDING BOARD & ASPHALT BUILD. PROD	119.95	35.49	26.81	21.56	25.20	23.63	22.51	21.22	21.40	20.84	21.83	22.50	68.33%
173	VINYL FLOOR & WALL COVERING	77.84	23.03	14.97	14.90	14.39	13.78	13.12	13.06	12.99	13.48	13.87	12.39	56.01%
187	FERRO-ALLOYS	202.20	59.82	44.80	51.13	50.36	42.82	45.50	45.19	46.65	45.11	44.24	38.84	110.44%
188	IRON & STEEL INGOTS, BILLETS, ETC	172.00	50.89	44.66	49.80	49.29	41.89	43.95	43.27	43.12	43.18	43.06	39.40	60.46%
189	STEEL CASTINGS	198.55	58.74	42.58	48.41	47.79	41.35	44.37	43.02	44.74	44.71	43.60	38.68	105.59%
190	STEEL BARS & RODS	192.99	57.10	40.80	45.61	45.77	40.20	42.61	41.80	41.88	39.76	38.37	33.24	125.58%
191	FLAT IRON&STEEL,INCL GALV,TINPLATE	210.36	62.24	44.85	50.66	50.13	42.91	45.72	45.41	47.04	45.07	43.55	38.50	124.94%
193	TAR & PITCH	167.76	49.63	27.58	32.76	42.08	35.64	37.02	34.86	38.01	36.22	34.96	25.76	125.67%
197	OTHER IRON & STEEL PIPES & TUBES	141.34	41.82	26.15	26.78	31.04	27.10	27.14	24.89	26.02	21.20	18.83	15.25	139.81%
198	OTHER CAST IRON PRODUCTS	89.47	26.47	17.82	19.81	16.69	18.89	13.58	13.06	16.52	16.88	17.24	27.26	-4.14%
199	IRON & STEEL PIPE FITTINGS	78.19	23.13	15.63	16.87	16.00	18.80	14.60	13.99	16.72	17.06	17.19	17.86	27.75%
210	ALUMINUM & ALUM.ALLOY FABRICATED MAT.	115.21	34.09	21.38	21.55	19.81	18.61	18.72	16.80	17.29	17.79	15.42	14.25	104.38%
211	COPPER FABRICATED MATERIALS	90.09	26.65	25.56	23.35	23.04	21.37	22.69	20.23	21.39	22.96	21.91	19.95	35.27%
212	COPPER ALLOY FABRICATED MATERIALS	88.99	26.33	24.87	22.49	22.53	21.38	23.05	20.82	22.05	22.76	21.59	19.15	37.78%
213	LEAD & LEAD ALLOY FABRICATED MAT.	76.80	22.72	15.70	19.90	16.68	15.74	16.55	15.79	15.80	16.13	15.73	13.94	46.24%
214	NICKEL & NICKEL ALLOY FABRICATED MAT.	107.35	31.76	36.55	35.31	36.64	34.15	33.11	32.73	32.76	33.21	35.03	38.62	-36.10%
217	FABRICATED STEEL PLATE	70.11	20.74	12.57	13.35	14.11	13.39	13.87	12.98	14.02	14.18	14.10	11.71	47.56%
218	TANKS	72.39	21.42	12.42	12.78	13.54	12.61	13.64	12.62	13.77	13.71	14.08	11.55	51.92%

	Table C2: Energy Intensity Trends for Building Materials in Canada, 1976-1990.													
219	POWER BOILERS	69.79	20.65	12.14	12.88	13.77	13.03	14.09	13.08	14.09	13.75	13.05	10.41	53.88%
220	IRON & STEEL STRUCTURAL MATERIALS	147.88	43.75	36.38	30.85	32.95	29.92	30.12	28.65	29.02	29.57	28.43	23.38	107.20%
221	PREFAB. METAL BLDGS & STRUCTURES	69.92	20.69	12.36	12.96	13.98	13.12	13.97	13.02	14.02	14.11	14.15	11.80	46.75%
222	OTHER METAL BUILDING PRODUCTS	76.36	22.59	12.85	13.77	14.45	13.14	13.09	12.72	13.02	13.21	12.32	10.47	63.79%
223	FLAT IRON & STEEL, ALLOY, OTH COATED	174.95	51.76	40.75	44.47	43.32	37.86	29.44	28.83	30.57	38.92	36.46	31.24	108.00%
224	CORRUGATED METAL CULVERT PIPE	86.80	25.68	13.76	14.44	18.19	15.96	14.03	13.14	14.82	16.65	15.08	12.26	70.61%
226	METAL ROOFING, SIDING, DUCTS, ETC	84.17	24.90	13.85	14.22	16.94	15.24	13.65	12.90	14.12	15.20	13.94	11.47	70.70%
233	HARDWARE	54.99	16.27	14.81	16.14	17.03	15.00	14.61	14.22	15.59	14.53	13.82	12.11	21.89%
238	OTHER HEATING EQUIPMENT	64.24	19.01	10.93	11.45	12.02	11.68	12.27	11.39	12.54	11.79	10.89	8.64	54.56%
239	NON-ELECT. FURNACES & HEAT EQUIP	64.23	19.00	10.09	10.29	10.74	9.75	9.69	9.27	9.89	9.89	9.61	8.29	56.40%
240	OIL & GAS BURNERS, ETC	55.99	16.57	10.07	10.40	11.16	10.30	10.10	9.75	10.43	9.24	9.08	7.83	45.96%
243	IRON & STEEL FORGINGS	81.24	24.04	14.16	15.01	15.46	14.19	13.44	14.40	15.19	15.45	15.38	12.48	60.83%
244	VALVES	74.96	22.18	14.12	15.13	15.57	15.11	13.90	14.65	15.29	15.47	15.59	12.81	49.31%
245	PLUMBING FIXTURES & FITTINGS	77.99	23.07	14.22	15.41	15.45	14.59	13.45	15.28	14.73	14.60	14.61	12.51	55.61%
246	GAS & WATER METERS	77.54	22.94	6.70	6.26	7.22	6.73	6.49	6.70	6.74	6.45	6.00	6.08	88.72%
248	CONTROL PANELS, REGULATORS, ETC	72.54	21.46	9.24	8.31	9.91	9.44	8.49	7.91	6.93	6.77	5.00	6.07	80.99%
253	PUMPS, COMPRESSORS & BLOWERS	52.68	15.59	8.07	8.71	8.66	8.21	7.96	7.43	8.50	8.34	8.28	7.60	42.02%
256	FANS & AIR CIRC. UNITS, NOT INDUST.	53.97	15.97	8.39	8.81	8.66	8.09	8.05	7.69	8.57	8.86	8.51	7.53	44.42%
257	PKG., AIR PUR. & OTH GEN.PURP.MACH	57.17	16.91	9.68	10.09	9.87	8.96	8.81	8.18	9.34	9.39	8.85	8.14	46.16%
261	REFRIGERATION & AIR COND. EQUIP	53.79	15.91	8.90	8.88	8.69	7.58	8.56	8.17	9.10	8.94	9.12	8.19	40.65%
264	COMPUTERS,OFFICE MACH.EXCL PHOTO.&FAX	19.84	5.87	6.27	6.05	5.61	3.92	3.43	2.94	2.36	2.14	1.78	1.61	22.44%
287	ELECTRIC FURNACE&OTH ELECT.HEAT.EQUIP	50.62	14.98	10.11	11.00	11.19	10.25	9.95	9.76	10.43	8.76	8.57	7.53	39.20%
298	TRANSFORMERS, BALLAST & CONVERTERS	45.93	13.59	9.13	10.17	9.30	9.18	9.23	8.99	9.28	8.11	7.46	6.89	35.25%
299	INDUSTRIAL ELECTRIC EQUIPMENT	45.56	13.48	8.71	9.68	8.86	8.65	8.78	8.58	8.85	8.25	7.76	7.03	33.96%
301	WIRE & CABLE, INSULATED, EXCL ALUM.	74.28	21.98	14.88	15.20	15.04	14.03	14.01	12.83	13.36	13.37	12.95	12.77	48.45%
302	ALUMINUM WIRE & CABLE	87.52	25.89	16.08	16.21	16.60	15.44	15.97	14.84	15.39	16.10	14.67	13.92	63.00%
303	WIRING MAT. & ELECTRICAL METERS	57.59	17.04	9.48	10.91	9.34	9.13	9.33	9.07	9.36	8.68	7.53	7.07	52.49%
304	LIGHTING FIXTURES, BULBS & TUBES	58.41	17.28	9.31	10.27	9.30	8.95	9.29	9.00	9.28	8.51	7.93	7.25	52.78%
305	CEMENT	332.46	98.36	64.52	65.57	59.46	63.68	52.04	62.91	73.79	77.00	81.11	70.74	145.35%
307	CONCRETE PRODUCTS, INCL SAND & LIME	96.01	28.41	19.87	19.72	19.06	18.11	16.02	18.31	20.91	21.71	21.03	20.10	43.69%
308	READY-MIX CONCRETE	144.75	42.83	29.23	29.52	26.30	26.11	21.72	24.14	29.79	31.61	31.23	29.44	70.42%
309	BRICKS & OTHER CLAY BLDG. PRODUCTS	148.19	43.84	29.56	33.75	34.57	35.19	34.86	31.52	29.87	33.32	37.20	35.22	45.40%
312	REFRACTORY PRODUCTS	112.96	33.42	31.45	33.12	31.70	29.85	26.51	25.25	24.64	24.94	25.36	22.66	56.65%
313	NATURAL STONE BUILDING PRODUCTS	76.35	22.59	31.53	32.75	31.68	30.38	26.41	25.10	24.05	24.57	25.35	22.89	-1.57%
314	GYPSUM BUILDING PRODUCTS	90.89	26.89	31.13	33.56	31.72	30.39	26.78	25.54	24.37	24.78	25.59	23.01	20.44%
315	MINERAL WOOL BUILDING PRODUCTS	90.27	26.71	31.41	33.63	31.72	30.39	26.81	25.54	24.37	24.79	25.62	23.01	19.47%
318	GLASS & GLASS PRODUCTS	103.58	30.64	25.44	26.03	23.63	21.64	20.18	19.72	19.03	20.25	18.78	17.99	66.59%
328	ASPHALT & PRODUCTS	214.89	63.58	26.79	29.25	30.83	32.29	31.66	32.13	35.50	34.23	35.18	34.04	155.47%

	Table C2: Energy Intensity Trends for Building Materials in Canada, 1976-1990.														
331	POLYMERS	171.49	50.74	33.28	35.84	32.20	29.98	28.60	27.26	26.68	26.65	26.98	24.95	135.72%	
335	PAINTS & RELATED PRODUCTS	94.56	27.98	13.91	15.41	16.58	15.29	14.83	14.59	14.92	12.89	12.71	11.80	85.12%	
379	ADHESIVES	93.08	27.54	13.70	13.39	28.46	24.81	24.42	24.92	28.77	27.27	29.30	21.22	33.28%	
396	FLOOR & WALL COVERING, EXCL VINYL	78.83	23.32	14.97	14.98	14.32	13.45	12.84	12.87	12.88	13.02	13.35	11.89	60.20%	
406	REPAIR CONSTRUCTION	39.72	11.75	6.96	6.73	7.10	6.93	6.52	6.35	7.03	6.88	6.66	5.83	31.16%	
407	RESIDENTIAL CONSTRUCTION	42.71	12.64	7.87	7.38	7.69	7.54	7.15	6.80	7.54	7.69	7.38	6.53	32.13%	
408	NON-RESIDENTIAL BUILDING CONSTRUCTION	38.42	11.37	7.20	7.01	6.88	6.56	6.29	6.26	6.85	6.86	6.74	5.79	29.34%	
458	SERVICES TO BUILDINGS & DWELLINGS	24.81	7.34	5.42	5.67	5.76	6.18	6.17	6.33	6.51	6.13	6.03	5.62	9.07%	
464	SPARE PARTS&MAINT.SUPPL.MACH&EQUIP	59.62	17.64	7.42	7.79	7.72	7.25	6.76	6.23	6.45	6.22	5.65	5.43	64.24%	
														56.29%	average
Notes															
(a)	Ref.: Bush, 1981														
(b)	based on Stats Can Consumer price index.														
(c)	Ref.: Smith, 1994.														

Table C3.1. Initial Embodied Energy of Case Study Building.

5 STOREY CONCRETE-FRAMED OFFICE BUILDING WITH UNDERGROUND PARKING

																						Costs adjusted for Van.		
											mj/unit	units	qty.	mj	%	mat.	lab.	equip.	total	total $	%	Conv.	$ Cdn.	%
GENERAL CONDITIONS (Overhead, profit and contingencies)																								
SITE PREP.																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj total														
Excavation		m3	0.9	7.25				7	5	7							9.35	5.81	15.2					
SITE SERVICES ASSEMBLIES																								
Watermain																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj total														
Excavation		m3	0.9	7.25				7	5	7							9.35	5.81						
Bedding sand		m3	0.225	90				20	5	21						0.79	1.25							
Backfilling		m3	0.675	7.25				5	5	5														
150mm dia. pvc pipe		m	1	459				459	5	482						19	14.5							
Tracer wire (14ga stranded copper)		m	1	20				20	5	21														
Total mj per m of component								511		536	m	78	41824	0.13	19.8	25.1	5.81	50.7	3,953	0.07	113.1	4,471	0.08
Water supply accessories																								
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Hydrants		no.	1	3800				3800	5	3990														
Valve boxes		no.	4	1000				4000	5	4200														
Valves		no.	4	500				2000	5	2100														
Conc. thrust blocks (6no. 20mpa)		m3	2.4	3462				8309	4	8641														
Water meter		no.	1	2000				2000	5	2100														
Total mj								20109		21031	no.	1	21031	0.06					5,000	0.09	113.1	5,655	0.10
Gas pipe																								
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Excavation		m3	0.44	7.25				3	5	3							7.28	4.2						
Bedding sand		m3	0.14	90				13	5	13						0.79	1.25							
Backfilling		m3	0.3	7.25				2	5	2														
60mm dia. polyethylene pipe		m	1	*300*				300	5	315						4.2	7.25							
Tracer wire (14ga stranded copper)		m	1	20				20	5	21														
Total mj per m of component								338		355	m	54	19163	0.06	4.99	16.8	4.2	25	1,348	0.02	113.1	1,525	0.03
Gas supply accessories																								
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Gas meter		no.	1	2000				2000	0	2000														
Valve boxes		no.	3	1000				3000	4	3120														
Valves		no.	3	200				600	0	600														
Total mj								5600		5720	no.	1	5720	0.02					3,000	0.05	113.1	3,393	0.06
Electricity and telephone supply																								
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Excavation		m3	1.1	7.25				8	5	8							11.5	8.53						
Bedding sand		m3	0.325	90				29	5	31						4.63	6.96							
Backfilling		m3	0.78	7.25				6	5	6														

Table C3.1. Initial Embodied Energy of Case Study Building.

100mm dia. pvc pipe conduit		m	2	188				376	5	395					18.8	26.1							
75mm dia. pvc pipe conduit		m	3	116				348	5	365					11.9	31.3							
Incoming electrical service		m	1	100				100	2	102					50								
Incoming telephone service		m	1	100				100	2	102					40								
Total mj per m of component								967		1009	m	77	77710	0.23	125	75.8	8.53	210	16,139	0.29	113.1	18,253	0.31
Electricity and telephone supply accessories																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Pull box (concrete)		no.	1	4500				4500	5	4725													
Total mj								4500		4725	no.	1	4725	0.01				1175	1,175	0.02	113.1	1,329	0.02
Storm sewer																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Excavation		m3	0.78	7.25				6	5	6						7.28	4.2						
Bedding sand		m3	0.33	90				30	5	31					1.8	2.72							
Backfilling		m3	0.45	7.25				3	5	3													
250mm dia. concrete pipe		m	1	316				316	5	332					13	20.2							
Tracer wire (14ga stranded copper)		m	1	20				20	5	21													
Total mj per m of component								375		393	m	182	71589	0.21	14.8	30.2	4.2	49.2	8,949	0.16	113.1	10,121	0.17
Sanitary sewer																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Excavation		m3	0.78	7.25				6	5	6						7.28	4.2						
Bedding sand		m3	0.33	90				30	5	31					1.8	2.72							
Backfilling		m3	0.45	7.25				3	5	3													
250mm dia. abs pipe		m	1	996				996	5	1046					13.7	10.7							
Tracer wire (14ga stranded copper)		m	1	20				20	5	21													
Total mj per m of component								1055		1107	m	119	131774	0.40	15.5	20.7	4.2	40.3	4,800	0.09	113.1	5,429	0.09
Manhole																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Excavation		m3	4	7.25				29	5	30													
Backfilling		m3	2	7.25				15	5	15													
Concret base 20mpa		m3	0.34	3462				1177	4	1224													
Rebar, no.4		m	14		0.99	14	36.00	499	5	524													
Benching		m3	0.2	3462				692	4	720													
Concrete shaft		m3	0.52	3462				1800	4	1872													
Reinforcing mesh		m2	5		7	35	36.00	1260	4	1310													
Concrete lid		m3	0.22	3462				762	4	792													
Rebar, no.4		m	8		0.99	8	36.00	285	5	299													
Brick		no.	42	214.2	2.04	86	2.50	214	8	231													
Mortar		kg	20	1.8				36	5	38													
Cast iron cover and frame		no.	1	2000	100	100	20.00	2000	0	2000													
Ladder rungs		no.	3	202.5	1.5	5	45.00	203	1	205													
Total mj per component								8972		9262	no.	7	64831	0.19	1125	1225		2350	16,450	0.30	113.1	18,605	0.31
Road gullies																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
		no.	1	1000				1000	2	1020													
Total mj per component								1000		1020	no.	6	6120	0.02				*400*	2,400	0.04	113.1	2,714	0.05

Table C3.1. Initial Embodied Energy of Case Study Building.

Site lighting																							
Light standards																							
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Concrete base	m3	0.1	3746				375	4	390														
Rebar	kg	5.5				36.00	198	5	208														
Steel base plate	kg	14.4				28.00	403	5	423														
Anchor bolts	no.	4		1.5	6	45.00	270	5	284														
HSS shaft 150x150mm	m	5		6	25	28.00	700	5	735														
Light fixture	no.	1	300				300	0	300														
Total mj per component							2246		2339	no.	8	18715	0.06	1575	725		2300	18,400	0.33	113.1	20,810	0.35
Site lighting electricity supply																							
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Excavation	m3	1.1	7.25				8	5	8						3.76	2.69							
Bedding sand	m3	0.325	90				29	5	31					1.77	2.66								
Backfilling	m3	0.78	7.25				6	5	6														
75mm dia. pvc pipe conduit	m	3	116				348	5	365					11.9	31.3								
Incoming electrical service	m	1	20				20	2	20					10									
Total mj per component							411		431	m	60	21641	0.06	23.7	37.7	2.69	64.1	3,205	0.06	113.1	3,624	0.06
						% of total																	
	Embodied energy			gj	485	1.45%																	
TOTAL FOR SITE SERVICES ASSEMBLIES				$US	84820																		
Vancouver costs		112.6		$Cdn.	95507	1.83%																	
PAVING ASSEMBLIES																							
Parking areas																							
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Excavation	m3	0.25	7.25				2	5	2														
200mm sub base <75mm gravel	m3	0.2	550				110	5	116														
100mm base >38mm sand/gravel	m3	0.1	300				30	5	32														
64mm asphaltic concrete	m3	0.065	1375				89	5	94														
Asphalt primer	L	1.8	2.5				5	5	5				0.00										
Total mj per m2 of assembly							236		247	m2	290	71767	0.22	8	5.75		13.8	3,988	0.07	113.1	4,510	0.08
Sidewalks																							
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Excavation	m3	0.25	7.25				2	5	2														
100mm sub base <75mm gravel	m3	0.1	550				55	5	58														
100mm base >38mm sand/gravel	m3	0.1	300				30	5	32														
100mm concrete (30mpa)	m3	0.1	4593				459	5	482														
150x150mm reinforcing mesh	kg	1.8	36				65	4	67														
Total mj per m2 of assembly							611		641	m2	549	351805	1.06	11.6	20.2		31.8	17,463	0.32	113.1	19,739	0.33
Concrete curb																							
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Concrete curb (30mpa)	m3	0.045	4593				207	5	217														
200mm base <75mm gravel	m3	0.04	550				22	5	23														
Total mj per m of assembly							229		240	m	75	18009	0.05	11.2	11.6		22.7	1,706	0.03	113.1	1,929	0.03

Table C3.1. Initial Embodied Energy of Case Study Building.

TOTAL FOR PAVING ASSEMBLIES			Embodied energy			gj	442	1.32%																
						$US	23146																	
		Vancouver costs		112.6		$Cdn.	26062	0.50%		0.00														
Building excavation																								
			Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Excavation																								
Excavation			m3	1	7.25				7	5	8													
Total mj per m3 of assembly									7	5	8	m3	8400	63945	0.19				4.5	37,800	0.69	113.1	42,752	0.72
			Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Backfilling																								
Backfilling			m3	1	7.25				7	5	8													
Total mj per m3 of assembly									7	5	8	m3	1440	10962	0.03				7.5	10,800	0.20	113.1	12,215	0.21
Perimeter drain and dampproofing																								
			Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
100mm pvc pipe			m	1	188				188	5	197					10.2	9.36							
Bedding sand			m3	0.25	90				23	5	24													
Bituminous asphalt			m2	3	20				60	5	63					4.33	30.5							
Total mj per m of assembly									271		284	m	210	59645	0.18	14.5	39.9		54.4	11,416	0.21	113.1	12,911	0.22
TOTAL BUILDING EXCAVATION			Embodied energy			gj	135	0.40%																
						$US	60016																	
		Vancouver costs		112.6		$Cdn.	67678	1.29%		0.00														
STRUCTURE																								
All structural concrete 20MPa			Units	Qty.	Qty.	conv.	kg	mj/kg	mj	Waste	mj													
Below grade horizontal																								
Wall footings (basement walls)			m3	10.65		2276	24239	0.60	14544	1	14689	m	177.5			25.6	72.2		97.8	17,360	0.32	111.0	19,269	0.33
Rebar			kg		586.8	1	586	38.20	22376	4	23271													
Wall footings (east & west stairs)			m3	5.22		2276	11881	0.60	7128	1	7200	m	87			25.6	72.2		97.8	8,509	0.15	111.0	9,445	0.16
Rebar			kg		287.1	1	287	38.20	10967	4	11406													
Column footings			m3	61.73		2276	140497	0.60	84298	1	86141	no.	16			445	555		1000	16,000	0.29	111.0	17,760	0.30
Rebar			kg		1173	1	1173	38.20	44807	4	46599													
Pilaster footings			m3	18		2276	40968	0.60	24581	1	24827	no.	16			98.5	162		261	4,168	0.08	111.0	4,626	0.08
Rebar			kg		342	1	342	38.20	13064	4	13587													
Elevator footings			m3	3.2		2276	7283	0.60	4370	1	4414	no.	4			98.5	163		262	1,046	0.02	111.0	1,161	0.02
Rebar			kg		60.8	1	61	38.20	2323	4	2415													
Basement slab on grade			m3	150.1		2276	341682	0.60	204949	1	206999	m2	1550			17.1	34.1		51.2	79,360	1.44	111.0	88,090	1.49
Rebar			kg		7354	1	7354	38.20	280918	1	283727													
Ground floor suspended slab												m2	1519			37.6	79.6		117	178,027	3.24	108.7	193,515	3.27
Slab bands			m3	127.2		2276	289563	0.60	173732	1	175469													
Rebar			kg		5725	1	5725	38.20	218684	4	227432													
254mm slabs			m3	212.8		2276	484310	0.60	290586	1	293492													
Rebar			kg		4681	1	4681	38.20	178826	4	185979													
178mm slabs			m3	61.09		2276	139041	0.60	83425	1	84259													
Rebar			kg		1955	1	1955	38.20	74683	4	77670													
East and west stairs slab on grade																								
Slabs			m3	4.61		2276	10492	0.60	6295	1	6358	m2	46.1			17.1	34.1		51.2	2,360	0.04	111.0	2,620	0.04

Table C3.1. Initial Embodied Energy of Case Study Building.

Slabs			m3	1.02		2276	2322	0.60	1393	1	1407	m2	10.2			17.1	34.1		51.2	522	0.01	111.0	580	0.01
Rebar			kg		275.8	1	276	38.20	10534	1	10640													
Sub total									1762483		1786979			1786979	5.36									
			Units	Qty.	Qty.	conv.	kg	mj/kg	mj	Waste	mj													
Below-grade vertical																								
Basement walls			m3	131.2		2276	298679	0.60	179208	1	181000	m	244.5			82	213		295	72,128	1.31	111.0	80,062	1.35
Rebar			kg		6562	1	6562	38.20	250649	4	260675													
Foundation wall to west stair			m3	2.42		2276	5508	0.60	3305	1	3338	m	22			20	51		71	1,562	0.03	111.0	1,734	0.03
Rebar			kg		179.1	1	179	38.20	6841	4	7114													
Elevator pit and walls to u/s slab			m3	9.12		2276	20757	0.60	12454	1	12579	m	13			115	315		430	5,590	0.10	111.0	6,205	0.10
Rebar			kg		674.9	1	675	38.20	25780	4	26812													
Columns below basement slab			m3	0.58		2276	1320	0.60	792	1	800	no.	16			12.2	41.5		53.7	859	0.02	111.0	954	0.02
Rebar			kg		65.09	1	65	38.20	2486	4	2586													
Pilasters below basement slab			m3	0.38		2276	865	0.60	519	1	524	no.	16			10	36.5		46.5	744	0.01	111.0	826	0.01
Rebar			kg		43.39	1	43	38.20	1657	4	1724													
Columns to u/s slab band			m3	6.77		2276	15409	0.60	9245	1	9338	no.	16			128	436		564	8,022	0.16	108.7	8,807	0.17
Rebar			kg		764.8	1	765	38.20	29215	4	30383													
Pilasters to u/s slab band			m3	2.45		2276	5576	0.60	3346	1	3379	no.	16			105	383		488	7,813	0.14	108.7	8,493	0.14
Rebar			kg		276.6	1	277	38.20	10567	4	10990													
Sub total									536065		551241			551241	1.65									
			Units	Qty.	Qty.	conv.	kg	mj/kg	mj	Waste	mj													
Above-grade horizontal																								
Upper floors (4no.)												m2	6076			37.6	79.6		117	712,107	12.96	108.7	774,061	13.09
1200mm slab bands			m3	264.4		2276	579105	0.60	347463	1	350938													
2400mm slab bands			m3	512.9		2276	######	0.60	700362	1	707365													
Rebar			kg		34628	1	34628	38.20	1318982	4	1371741													
228mm slabs			m3	620.9		2276	######	0.60	847846	1	856325													
Rebar			kg		15521	1	15521	38.20	592913	4	616629													
178mm slabs			m3	244.4		2276	556209	0.60	333725	1	337063													
Rebar			kg		7820	1	7820	38.20	298730	4	310679													
Roof												m2	1619			37.6	79.6		117	178,027	3.24	108.7	193,515	3.27
1200mm slab bands			m3	64.61		2276	147052	0.60	88231	1	89114													
2400mm slab bands			m3	129.2		2276	294105	0.60	176463	1	178227													
Rebar			kg		8722	1	8722	38.20	333183	4	346611													
228mm slabs			m3	156.5		2276	356217	0.60	213730	1	215867													
Rebar			kg		3913	1	3913	38.20	149470	4	155449													
178mm slabs			m3	61.09		2276	139041	0.60	83425	1	84259													
Rebar			kg		1955	1	1955	38.20	74683	4	77670													
Roof slab to east and west stairs																								
Slab			m3	10.94		2276	24899	0.60	14940	1	15089	m2	54.7			29.3	59.2		88.5	4,841	0.09	108.7	5,262	0.09
Slab			m3	2.24		2276	5098	0.60	3059	1	3090	m2	11.2			29.3	59.2		88.5	991	0.02	108.7	1,077	0.02
Rebar			kg		421.9	1	422	38.20	16116	4	16761													
Sub total									5593321		5732776			5732776	17.19									
			Units	Qty.	Qty.	conv.	kg	mj/kg	mj	Waste	mj													
Above-grade vertical																								
Shear walls			m3	150.1		2276	341628	0.60	204977	1	207026	m2	408.6			37.8	99.5		137	56,101	1.02	108.7	60,982	1.03

Table C3.1. Initial Embodied Energy of Case Study Building.

Rebar			kg		22141	1	22141	38.20	845776	4	879607												
Interior walls to north stair & washrm.			m3	94.03		2276	214012	0.60	128407	1	129691	m2	631			37.8	99.5		137	72,806	1.33	108.7	79,249	1.34
Rebar			kg		3329	1	3329	38.20	127159	4	132246												
Elevator shaft			m3	44.3		2276	100827	0.60	60496	1	61101	m2	234			37.8	99.5		137	32,128	0.68	108.7	34,923	0.59
Rebar			kg		1568	1	1568	38.20	59906	4	62302												
East and west stair walls			m3	162.9		2276	370760	0.60	222456	1	224681	m2	428.4			37.8	99.5		137	58,819	1.07	108.7	63,937	1.08
Rebar			kg		5766	1	5766	38.20	220277	4	229088												
Interior columns upper floors			m3	36.86		2276	83893	0.60	50336	1	50839	no.	32			128	436		564	18,045	0.33	108.7	19,615	0.33
Perimeter columns upper floors			m3	24.58		2276	55944	0.60	33566	1	33902	no.	32			105	383		488	15,626	0.28	108.7	16,985	0.29
Rebar			kg		6943	1	6943	38.20	265212	4	276820												
Interior columns roof			m3	9.22		2276	20985	0.60	12591	1	12717	no.	32			128	436		564	18,045	0.33	108.7	19,615	0.33
Perimeter columns roof			m3	6.14		2276	13975	0.60	8385	1	8469	no.	32			105	383		488	15,626	0.28	108.7	16,985	0.29
Rebar			kg		1736	1	1736	38.20	66303	4	68955												
Sub total									2305848		2376445			2376445	7.13								
			Units	Qty.	Qty.	conv.	kg	mj/kg	mj	Waste	mj												
Miscellaneous																							
Landings			m3	19.2		2276	43699	0.60	26220	1	26482												
Half-landings			m3	9.6		2276	21850	0.60	13110	1	13241												
Stair flights			m3	58.84		2276	136196	0.60	81718	1	82536	no.	28			628	1498		2126	59,528	1.08	108.7	64,707	1.09
Rebar			kg		5752	1	5752	38.20	219726	4	228515												
Sub total									340773		350773			350773	1.05								
	Steel - 7854kg/m3																						
form plywood									267000					267000									
TOTAL STRUCTURAL ASSEMBLIES			Embodied energy			gj	10798	32.36%																
						$US	######																
		Vancouver costs		112.7		$Cdn.	######	36.49%															
											0												
ENVELOPE ASSEMBLIES																							
Exterior wall assembly (framed walls)												m2											
Brick																							
			Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	total mj												
100mm clay brick (210x75mm face)			no.	64		2.04	131	2.50	326	10	343												
Mortar			kg	32.4	1.8				58	5	61												
Stainless steel ties			No.	3.5		0.057	0	45.00	9	5	9												
Nails			No.	14		0.005	0	45.00	3	5	3												
Steel angle			m	0.3		7.97	2	28.00	67	5	70												
Bolts			no.	1		0.5	1	45.00	23	5	24												
Caulk (polyurethane)			m	0.3	6.7				2	5	2												
Backer rod (polyethylene foam)			m	0.3	6.7				2	5	2												
Total mj per m2 of component									490		515												
Insulation																							
			Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj												
75mm extruded polystyrene board			m2	1		2.75	3	105.00	289	5	303												
Plastic clips (pvc)			no.	3.5		0.02	0	67.00	5	5	5												
Adhesive			m2	1		1	1	97.00	97	5	102												

Table C3.1. Initial Embodied Energy of Case Study Building.

Total mj per m2 of component								390		410																				
Air barrier (peel and stick)																														
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj																					
Rubber based liquid primer	m2	1	18				18	5	19																					
1mm rubberized asphalt membrane	m2	1.05	90				95	5	99																					
Caulking (at ties)	m	0.4	5.7				2	5	2																					
Total mj per m2 of component							115		121																					
Exterior sheathing (Densgold)																														
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj																					
12mm reinforced gypsum board	m2	1		10	10	75.00	750	10	825																					
Screws, self tapping, bulge head 25mm	no.	21		0.005	0	45.00	5	5	5																					
Total mj per m2 of component							755		830																					
Steel studs																														
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj																					
92mm steel studs	m	2.5		0.74	2	28.00	54	5	56																					
Steel stud track	m	0.55		0.74	0	28.00	12	5	13																					
Blocking	m	0.55		0.74	0	28.00	12	5	13																					
Screws	no.	10		0.005	0	45.00	2	5	2																					
Fasteners	no.	2.5		0.007	0	45.00	1	5	1																					
Total mj per m2 of component							81		85																					
Vapour barrier																														
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj																					
Polyethylene sheet	m2	1.1	12				13	5	14																					
Sealant	m	0.3	5.7				2	5	2																					
Total mj per m2 of component							15		16																					
Interior Finish (Gwb)																														
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj																					
12mm gypsum board	m2	1	60				60	10	66																					
Gwb tape	m	1.1	0.28				0	5	0																					
Gwb compound	kg	0.23	2				0	5	0																					
Screws	no.	9		0.0013	0	45.00	1	5	1																					
Metal beads	m	0.3		0.18	0	28.00	2	5	2																					
Sealant	m	0.3	5.7				2	5	2																					
Paint (3 coats)	m2	1	10				10	1	10																					
Total mj per m2 of component							75		81																					
Total mj per m2 of assembly							1920		2056	m2	1172	2409951	7.23	57.5	105		162	189,864	3.46	114.0	216,445	3.66
Exterior wall assembly (shear walls)										m2																				
Brick																														
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	total mj																					
100mm clay brick (210x75mm face)	no.	64		2.04	131	2.50	326	10	343																					
Mortar	kg	32.4	1.8				58	5	61																					
Stainless steel ties	No.	3.5		0.057	0	45.00	9	5	9																					
Nails	No.	14		0.005	0	45.00	3	5	3																					
Steel angle	m	0.3		7.97	2	28.00	67	5	70																					

Table C3.1. Initial Embodied Energy of Case Study Building.

Bolts		no.	1		0.5	1	45.00	23	5	24														
Caulk (polyurethane)		m	0.3	5.7				2	5	2														
Backer rod (polyethylene foam)		m	0.3	6.7				2	5	2														
Total mj per m2 of component								490		515														
Insulation																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
75mm extruded polystyrene board		m2	1		2.75	3	105.00	289	5	303														
Plastic clips (pvc)		no.	3.5		0.02	0	67.00	5	5	5														
Adhesive		m2	1		1	1	97.00	97	5	102														
Total mj per m2 of component								390		410														
Air barrier (peel and stick)																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Rubber based liquid primer		m2	1	18				18	5	19														
1mm rubberized asphalt membrane		m2	1.05	90				95	5	99														
Caulking (at ties)		m	0.4	5.7				2	5	2														
Total mj per m2 of component								115		121														
Total mj per m2 of assembly								995		1045	m2	1478	1544506	4.63	42.5	83.3		126	185,832	3.39	114.0	211,963	3.58	
TOTAL EXTERIOR WALL ASSEMBLIES		Embodied energy			gj	3954	11.85%																	
					$US	376796																		
	Vancouver costs		112.6		$Cdn.	423147	8.09%																	
Windows and entry doors																								
Glazing																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Glass layer 1		m2	1	300				300	5	315														
Glass layer 2		m2	1	300				300	5	315														
Fill		m3																						
Total mj per m2 of component								600		630	m2	1072	675360	2.03	129	129		258	276,576	5.04	114.0	315,297	5.33	
Frame																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Aluminum frame		m	1		1.75	2	274.00	480	5	503														
Spacer		m	1		0.5	1	235.00	118	5	123														
Fasteners		no.	3		0.007	0	45.00	1	5	1														
Glazing tape		m	2	5				10	5	11														
Total mj per m of component								608		638	m	2787	1779060	5.34										
Deflection head section																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Deflection head section		m	1		2	2	274.00	548	5	575														
Total mj per m of component								548		575	m	569	327403	0.98										
Window hardware																								
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Per operable window		no.	1	250				250	1	253														
Total mj per component								250		253	no.	158	39895	0.12										

Table C3.1. Initial Embodied Energy of Case Study Building.																								
Aluminum door hardware																								
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Per door	no.	1	760				760	1	768															
Total mj per component							760		768	no.	4	3030	0.01											
TOTAL GLAZING ASSEMBLIES	Embodied energy			gj	2825	8.46%																		
				$US	276576																			
Vancouver costs		114.7		$Cdn.	317233	8.06%																		
		114.7																						
Roof assembly																								
Membrane																								
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Granular finish SBS top sheet	m2	1.2	318				382	5	401															
SBS base sheet	m2	1.2	248				298	5	312															
Asphalt (2 layers)	kg	2.7	2.5				7	5	7															
Total mj per m2 of component							686		720					9.7	11.7		21.4							
Insulation																								
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
75mm rigid fibreglass board	m2	1		5.4	5	29.70	160	5	168															
Screws and stress plates	no.	3.5		0.05	0	45.00	8	5	8															
Tapered fibreglass crickets 50mm ave.	m2	1		3.6	4	29.70	107	5	112															
Screws and stress plates	no.	3.5		0.05	0	45.00	8	5	8															
Total mj per m2 of component							283		297					16.8	3.9		20.7							
Vapour retarder																								
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Membrane	m2	1.07	100				107	5	112															
Asphalt	kg	0.7	2.5				2	5	2															
Primer	m2	1	18				18	5	19															
Total mj per m2 of component							127		133					1.6	4.4		6							
Total mj per m2 of assembly							1096		1151	m2	1551	1784484	5.35	28.1	20		48.1	74,603	1.36	109.7	81,840	1.38		
Parapet																								
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Flashing and counter-flashing (18ga)	m2	0.75		3.17	2	236.00	561	5	589															
Membrane	m2	1.2	#####				823	5	864															
12mm plywood blocking	m2	0.6	67				40	5	42															
11mm Asphalt impregnated fibreboard	m2	0.4					0	5	0															
38x89mm cant and blocking	m	3	13.2				40	5	42															
Vapour retarder membrane	m2	0.6	#####				76	5	80															
Total mj per m of component							1640		1617	m	210	339588	1.02	15	15		30	6,300	0.11	109.7	6,811	0.12		
Roof access hatch																								
	Units	Qty	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Hatch		1	4000				4000	0	4000															
Total mj per component							4000		4000	no.	1	4000	0.01	820	175		995	995	0.02	109.7	1,092	0.02		
TOTAL ROOFING ASSEMBLIES	Embodied energy			gj	2128	6.38%																		
				$US	81898																			

Table C3.1. Initial Embodied Energy of Case Study Building.																								
	Vancouver costs		114.7		$Cdn.	93937	1.80%																	
			114.7																					
INTERIOR ASSEMBLIES																								
Ceiling assemblies																								
Acoustic tile and t-bar																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
1200x600mm tile		m2	1		3.87	4	8.80	34	5	36														
T-bar		m	3		0.75	2	30.00	68	5	71														
12ga suspension wire @ 600mm oc		m	2		0.1	0	29.00	6	5	6														
Fasteners		no.	1.25		0.006	0	45.00	0	5	0														
Total mj per m2 of component								108		113	m2	6847	774246	2.32	15.9	15.9		31.8	217,736	3.96	111.2	242,121	4.09	
Gwb ceiling																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
12mm gypsum board		m2	1	60				60	10	66														
Gwb tape		m	1.1	0.28				0	5	0														
Gwb compound		kg	0.23	2				0	5	0														
Screws		no.	9		0.0013	0	45.00	1	5	1														
21mm furring channels @600 oc		m	2.25		0.52	1	29.00	34	5	36														
38mm channels @ 600 oc		m	2.25		0.75	2	29.00	48	5	51														
12ga suspension wire @ 600mm oc		m	1.8		0.1	0	29.00	5	5	5														
Fasteners		no.	2		0.006	0	45.00	1	5	1														
Metal beads		m	0.3		0.18	0	29.00	2	5	2														
Sealant		m	0.3	6.7				2	5	2														
Paint (3 coats)		m2	3	10				30	1	30														
Total mj per m2 of component								183		194	m2	333	64655	0.19	6.8	18.7		25.5	8,492	0.15	111.2	9,443	0.16	
TOTAL CEILING ASSEMBLIES		Embodied energy			gj	839	2.51%																	
					$US	226226																		
	Vancouver costs		109.2		$Cdn.	247039	4.72%																	
Interior partition, no rating, 2700mm high																								
Partition to u/s ceiling																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
12mm gypsum board		m2	2	60				120	10	132														
Gwb tape		m	2.2	0.28				1	5	1														
Gwb compound		kg	0.46	2				1	5	1														
Screws		no.	22		0.0013	0	45.00	1	5	1														
Metal beads		m	0.6		0.18	0	29.00	3	5	3														
Sealant		m	1.5	6.7				9	5	9														
64mm steel studs @ 400mm oc		m	2.75		0.63	2	29.00	50	5	53														
Steel stud track		m	0.74		0.63	0	29.00	14	5	14														
Fasteners/screws		no.	27		0.006	0	45.00	7	5	8														
64mm acoustic insulation		m2	1		0.76	1	22.30	17	5	18														
100mm rubber base		m	0.74	12.8				9	5	10														
Adhesive		m2	0.07		0.75	0	97.00	5	5	5														
Paint (3 coats)		m2	6	10				60	1	61														
Total mj per m2 of component								297		316	m2	3315	1045960	3.14	10.8	21.5		32.3	106,942	1.95	111.2	118,919	2.01	

Table C3.1. Initial Embodied Energy of Case Study Building.																								
Interior partition, 2hr. rating, 3400mm high																								
Partition to u/s floor																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
16mm gypsum board		m2	4	80				320	10	352														
Gwb tape		m	2.2	0.28				1	5	1														
Gwb compound		kg	0.92	2				2	5	2														
Screws 25mm		no.	22		0.0013	0	45.00	1	5	1														
Screws 41mm		no.	22		0.002	0	45.00	2	5	2														
Metal beads		m	0.6		0.18	0	29.00	3	5	3														
Sealant		m	1.5	5.7				9	5	9														
64mm steel studs @ 400mm oc		m	2.75		0.63	2	29.00	50	5	53														
Steel stud track		m	0.59		0.63	0	29.00	11	5	11														
Fasteners		no.	27		0.006	0	45.00	7	5	8														
64mm acoustic insulation		m2	1		0.76	1	22.30	17	5	18														
100mm rubber base		m	0.74	12.8				9	5	10														
Adhesive		m2	0.07		0.76	0	97.00	5	5	5														
Paint (3 coats)		m2	6	10				60	1	61														
Total mj per m2 of component								497		536	m2	585	313379	0.94	19.8	31.6		51.4	30,069	0.55	111.2	33,437	0.57	
Furring																								
Column furring																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
12mm gypsum board		m2	1	60				61	10	67														
Gwb tape		m	1.1	0.28				1	5	1														
Gwb compound		kg	0.23	2				2	5	2														
Screws		no.	9		0.0013	0	45.00	1	5	1														
Metal beads		m	0.3		0.18	0	29.00	2	5	2														
Sealant		m	0.75	5.7				6	5	7														
64mm steel studs @ 400mm oc		m	4.5		0.63	3	29.00	82	5	86														
Steel stud track		m	0.74		0.63	0	29.00	14	5	14														
21mm furring channels @ 600mm oc		m	4		0.52	2	29.00	60	5	63														
Fasteners		no.	14		0.006	0	45.00	4	5	4														
100mm rubber base		m	0.37	12.8				13	5	14														
Adhesive		m2	0.035		0.76	0	97.00	3	5	3														
Paint (3 coats)		m2	3	10				13	1	13														
Total mj per m2 of component								262		277	m2	826	229065	0.69	10.3	20.2		30.5	25,193	0.46	111.2	28,015	0.47	
Wall furring																								
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
12mm gypsum board		m2	1	60				60	10	66														
Gwb tape		m	1.1	0.28				0	5	0														
Gwb compound		kg	0.23	2				0	5	0														
Screws		no.	9		0.0013	0	45.00	1	5	1														
Metal beads		m	0.3		0.18	0	29.00	2	5	2														
Sealant		m	0.75	5.7				4	5	4														
21mm furring channels @ 600mm oc		m	4		0.52	2	29.00	60	5	63														
Fasteners		no.	14		0.006	0	45.00	4	5	4														
100mm rubber base		m	0.37	12.8				5	5	5														
Adhesive		m2	0.035		0.76	0	97.00	3	5	3														

Appendiix C3:

Table C3.1. Initial Embodied Energy of Case Study Building.																								
Paint (3 coats)	m2	3	10				30	1	30															
Total mj per m2 of component							169		179	m2	900	160869	0.48	10.3	20.2		30.5	27,450	0.50	111.2	30,624	0.52
Doors assemblies																								
Solid core non rated (2100x900mm)																								
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Door	no.	1	200				200	1	202					236	124									
18ga pressed metal frame	m	5.2		3.13	16	29.00	472	1	477															
Frame anchors	no.	6		0.25	2	45.00	68	1	68															
Butts	no.	3		0.4	1	45.00	54	1	55					69										
Lockset	no.	1		1.5	2	60.00	90	1	91					67.5	23.5									
Closer	no.	1		2.2	2	60.00	132	1	133					100	49									
Stop	no.	1		0.4	0	45.00	18	1	18															
Additional studs	m	5.4		0.63	3	29.00	99	5	104															
Less 2 sq m of non rated partition		2	-297				-594	5	-624															
Total mj per component							538		524	no.	145	75920	0.23	473	203		675	97,875	1.78	111.2	108,837	1.84
Steel 1hr. rated (2100x900mm)																								
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Door	no.	1	400				400	1	404					355	174									
18ga pressed metal frame	m	5.2		3.13	16	29.00	472	1	477															
Frame anchors	no.	6		0.25	2	45.00	68	1	68															
Butts	no.	3		0.4	1	45.00	54	1	55					69										
Panic set	no.	1		5	5	60.00	300	1	303					500	75									
Closer	no.	1		2.2	2	60.00	132	1	133					100	49									
Stop	no.	1		0.4	0	45.00	18	1	18															
Additional studs	m	5.4		0.74	4	29.00	116	5	122															
Less 2 sq m of 1hr. rated partition		2	-497				-994	5	-1044															
Total mj per component							565		535	no.	15	8032	0.02	1024	298		1322	19,830	0.36	111.2	22,051	0.37
Pair solid core 1hr. rated (2x2100x900mm)																								
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
Door	no.	2	600				1200	1	1212					630	274									
18ga pressed metal frame	m	6.1		3.13	19	29.00	554	1	559															
Frame anchors	no.	6		0.25	2	45.00	68	1	68															
Butts	no.	6		0.4	2	56.00	134	1	136					69										
Panic sets	no.	2		5	10	56.00	560	1	566					1000	150									
Coordinator	no.	1		1	1	56.00	56	1	57															
Astragal (steel)	m	2.1		1.5	3	29.00	91	1	92															
Closer	no.	2		2.2	4	56.00	246	1	249					200	98									
Stop	no.	2		0.4	1	56.00	45	1	46															
Additional studs 92mm	m	5.4		0.74	4	29.00	116	5	122															
Less 4 sq m of 1hr. rated partition	m2	4	-497				-1989	5	-2088															
Total mj per component							1081		1017	no.	10	10170	0.03	1899	522		2421	24,210	0.44	111.2	26,922	0.46
Rubberbase																								
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj															
100mm rubber base	m	1	12.8				13	5	13															
Adhesive	m2	0.1		0.39	0	97.00	4	5	4															
Total mj per m of component							17		17	m	2858	49764	0.15	1.8	1.9		3.7	10,575	0.19	111.2	11,759	0.20

Table C3.1. Initial Embodied Energy of Case Study Building.

Ceramic wall tile																							
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Ceramic tile	m2	1	*33*				33	5	35														
Thinset adhesive	m2	1		0.75	1	97.00	73	5	76														
Total mj per m2 of component							106		111	m2	545	60515	0.18	23.5	28.2		51.7	28,177	0.51	111.2	31,332	0.53	
TOTAL INTERIOR PARTITION ASSEMBLIES	Embodied energy			gj	1954	5.85%																	
				$US	370320																		
Vancouver costs		109.2		$Cdn.	404389	7.73%																	
FLOOR FINISH ASSEMBLIES																							
Carpet																							
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Nylon face (.87kg/m2)	m2	1		0.87	1	80.00	70	5	73														
Polypropylene backing (1.35kg/m2)	m2	1		1.35	1	80.00	108	5	113														
Adhesive	m2	1		0.1	0	97.00	10	5	10														
Total mj per m2 of component							187		197	m2	6400	1258656	3.77	40	6.7		46.7	298,880	5.44	111.2	332,355	5.62	
Resiliant flooring																							
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
3.2mm Linoleum	m2	1	40				40	5	42														
Adhesive	m2	1		0.39	0	97.00	38	5	40														
Total mj per m2 of component							78		82	m2	335	27377	0.08	28	12.9		40.9	13,702	0.26	111.2	15,236	0.26	
Ceramic tile flooring																							
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Ceramic tile	m2	1	50				50	5	53														
Thin-set adhesive	m2	1		1	1	97.00	97	5	102														
Total mj per m2 of component							147		154	m2	116	17905	0.05	37.4	29.3		66.7	7,737	0.14	111.2	8,604	0.15	
Granite tile flooring																							
	Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Granite tile	m2	1	*20*				20	5	21														
Thin-set adhesive	m2	1		1	1	97.00	97	5	102														
Total mj per m2 of component							117		123	m2	120	14742	0.04	68.9	89.3		158	18,984	0.35	111.2	21,110	0.36	
TOTAL FLOOR FINISH ASSEMBLIES	Embodied energy			gj	1319	3.95%																	
				$US	339303																		
Vancouver costs		104.9		$Cdn.	355929	6.80%																	
MISCELLANEOUS ASSEMBLIES																							
Garage door and opener																							
	Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj														
Door	no.	1		118	118	60.00	7080	1	7151														
Opener	no.	1		40	40	60.00	2400	1	2424														
Total mj per component							9480		9575	no.	1	9575	0.03	1425	755		2180	2,180	0.04	114.0	2,485	0.04	
Stair assemblies																							
Stair flight accessories																							

Table C3.1. Initial Embodied Energy of Case Study Building.

		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Stair nosings		m	18		1	18	274.00	4932	5	5179													
Guard rail 40mm steel tube		m	11		2.74	30	28.00	844	1	862													
Vertical supports 40mm steel tube		m	4		2.74	11	28.00	307	1	310													
Fixing plates and studs		no.	4		2	8	28.00	224	1	226													
Hand rail 40mm steel tube		m	3.9		2.74	11	28.00	299	1	302													
Brackets		no.	4		0.75	3	45.00	135	1	136													
Paint (3 coats, 0.125m2 per m)		m2	2.36	10				24	1	24													
Total mj per stair flight								6765		7030	no.	22	154660	0.46	293	221		514	11,308	0.21	111.2	12,574	0.21
Stair landing accessories																							
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Guard rail 40mm steel tube		m	4.5		2.74	12	28.00	345	1	349													
Vertical supports 40mm steel tube		m	2		2.74	5	28.00	153	1	155													
Fixing plates and studs		no.	2		2	4	28.00	112	1	113													
Paint (3 coats, 0.125m2 per m)		m2	0.81	10				8	1	8													
Total mj per landing								619		626	no.	3	1875	0.01	Costs incl. above								
Washrooms																							
Plumbing fixtures																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
WC		no.	1		40	40	29.40	1176	1	1188	no.	30	35633	0.11	515	350		865	25,950	0.47	100.6	26,080	0.44
Urinal (wall hung)		no.	1		25	25	29.40	735	1	742	no.	10	7424	0.02	480	410		890	8,900	0.16	100.6	8,945	0.15
Lav.		no.	1		20	20	29.40	588	1	594	no.	30	17816	0.05	237	353		590	17,700	0.32	100.6	17,789	0.30
Janitors sink		no.	1		30	30	29.40	882	1	891	no.	5	4454	0.01	440	380		820	4,100	0.07	100.6	4,121	0.07
Drinking fountain		no.	1		20	20	29.40	588	1	594	no.	5	2969	0.01	395	233		628	3,140	0.06	100.6	3,156	0.05
Total																							
Washroom accessories																							
		Units	Qty.	mj/unit	conv.	kg	mj/kg	mj	Waste	mj													
Electric dryer		no.	1		5	5	80.00	400	1	404	no.	20	8080	0.02	380	46		426	8,520	0.16	105.6	8,989	0.15
Toilet paper holder		no.	1		1.5	2	60.00	90	1	81	no.	30	2727	0.01	25.8	7.6		33.4	1,002	0.02	103.3	1,035	0.02
Soap dispenser		no.	1		1	1	60.00	60	1	61	no.	30	1818	0.01	45	9.2		54.2	1,626	0.03	103.3	1,680	0.03
Grab bars		no.	1		3	3	45.00	135	1	136	no.	20	2727	0.01	30	9.2		39.2	784	0.01	103.3	810	0.01
Toilet partitions and doors		no.	1	400				400	1	404	no.	30	12120	0.04	770	147		917	27,510	0.60	103.3	28,418	0.48
Total																							
TOTAL MISCELLANEOUS ASSEMBLIES		Embodied energy			gj	262	0.78%																
					$US	112720																	
	Vancouver costs		104.9		$Cdn.	118243	2.26%																
MECHANICAL																							
		Units	Qty./m	mj/unit	conv.	kg	mj/kg	mj/sq m	Waste	mj													
		m2	1	350				350	5	350	m2	8026	2809100	8.42				35.2	282,515	5.14	100.6	283,928	4.80
		m2	1	250				250	5	250	m2	8026	2006500	6.02				10	80,260	1.46	100.6	80,661	1.36
		m2	1	50				50	5	75	m2	8026	601950	1.81				27	216,702	3.95	100.6	217,786	3.68
		m2	1	0.035				35	0	35		8026	380000	1.14					80,000	1.46	102.4	81,920	1.39
																			0				
ELECTRICAL																			0				

Appendiix C3:

Table C3.1. Initial Embodied Energy of Case Study Building.																								
General			m2	1	300				270	0	270	m2	8026	2167020	6.50				69.9	561,017	10.21	105.6	591,873	10.01
	% embodied E	% $							Total initial embodied energy in mj					33371058	99		Total cost US$			#######	88			
HVAC	8.42%	4.80															Total cost Cdn.$						#######	
Plumbing	6.01%	1.36							Initial embodied energy in mj perm2					4158			Cost per m2 in US$			600.45				
Fire safety	1.80%	3.68															Cost per ft2 in US$			55.80				
Conveyance	1.14%	1.39																						
ELECTRICAL	6.50%	10.01							Total initial embodied energy in mj					25406488			Cost per m2 in Cdn.$						651.94	
									for building only								Cost per ft2 in Cdn.$						60.59	
									Initial embodied energy in mj perm2					3166										
									for building only															

Table C3.2. Mechanical Takeoff.											
Note: Takeoff is for Jack Davis Building.											
Use floor area multiplier to get embodied energy figures for											
case study building.											
										material	
part	description		number		weight		embodied energy			cost	
					[kg]		Mj/kg	total	% of total	$	
boilers	950 kW each		2		30000		**51.6**	1548000	**15.0%**	39600	
									0.0%		
automatic	19 valves,	sizes:	number						0.0%		
		150 mm	3	120.8728	362.6183		76.4	27704.04	0.3%		
		75 mm	15	15.1091	226.6365		76.4	17315.03	0.2%		
									0.0%		
pumps		size [kw]	number						0.0%		
		7.5	4		194		76.4	59286.4	0.6%		
		3.75	1		133		76.4	10161.2	0.1%		
		2.25	1		133		76.4	10161.2	0.1%		
		1.5	2		77		76.4	11765.6	0.1%		
		0.5	1		55		76.4	4202	0.0%		
		0.35	10		55		76.4	42020	0.4%		
		0.25	1		55		76.4	4202	0.0%		
		0.15	2		55		76.4	8404	0.1%		
water pump			1		194		76.4	14821.6	0.1%		
air compressor			1		194		76.4	14821.6	0.1%		
									0.0%		
air filters		size	number		Mj/sq m				0.0%		
		4.5	12		176			9504	0.1%		
									0.0%		
diffusers			720		1		**28.5**	20520	0.2%		
VAV boxes			192		13.4		**28.5**	73324.8	0.7%		
									0.0%		
fans		size [kw]	number	size[hp]					0.0%		
		5.5	1	7.37	133		76.4	10161.2	0.1%		

Table C3.2. Mechanical Takeoff.											
		3.75	5	5.025	133		76.4	50806	0.5%		
		2.25	3	3.015	77		76.4	17648.4	0.2%		
		0.75	32	1.005	55		76.4	134464	1.3%		
		0.6	3	0.804	55		76.4	12606	0.1%		
		0.375	1	0.5025	55		76.4	4202	0.0%		
		0.2	1	0.268	55		76.4	4202	0.0%		
		0.1	3	0.134	55		76.4	12606	0.1%		
			49						0.0%		
									0.0%		
heat exchange		size	number						0.0%		
		5.2 l/sec	1		2522		51.6	130135.2	1.3%		
									0.0%		
expansion tanks			number						0.0%		
			2		150		51.6	15480	0.2%		
hot water tanks			2		150		51.6	15480	0.2%		
									0.0%		
									0.0%		
silencers		size	number		Mj/sq m				0.0%		
		0.488	1		176			85.888	0.0%		
		6.95	30		176			36696	0.4%		
		11.5	15		176			30360	0.3%		
									0.0%		
cooling tower		size	number						0.0%		
		18.75 kw	1	~5 ton	442		51.6	22807.2	0.2%		
									0.0%		
chillers		300 ton	1		8000		51.6	412800	4.0%		
									0.0%		
air handling units		size	number						0.0%		
		11.25 kw	8		350		51.6	144480	1.4%		
									0.0%		
ducting		see sheet 1 for wt calculations			37590		64	2405760	23.3%		
									0.0%		

Table C3.2. Mechanical Takeoff.												
hangers for ducting			lenght [m]						0.0%		
	6mm dia steel		5800		5584		48.1	268590.4	**2.6%**		
									0.0%		
insulation for ducting			area [sq.m]				Mj/sq m		0.0%		
			7450				176	1311200	**12.7%**		
copper piping									0.0%		
	size[mm]		lenght [m]	wt [lb/ft]					0.0%		
	18		3330	0.78	3870.126				0.0%	1.28	4262.4
	25		1180	0.99	1738.86				0.0%	2.02	2383.6
	32		2092	1.50	4675.62				0.0%	2.56	5355.52
	50		300	1.83	818.01				0.0%	5.9	1770
	75		14	3.45	71.967				0.0%	12	168
	100		40.5	5.72	345.1734				0.0%	19.95	807.975
	150		14	10.00	208.6	total wt.			0.0%	41.5	581
						11728.36	169.9	1992648	**19.3%**		
valves									0.0%		
	size[mm]								0.0%		
	18		128	0.244596	31.30824				0.0%	5.3	678.4
	25			0.655317	0				0.0%	10.2	0
	32			1.374299	0				0.0%	25	0
	50		45	5.242533	235.914	total wt, brass			0.0%	25	1125
	75		7	15.1091	105.7637	**267.2222**	169.9	45401.05	0.4%	184	1288
	100		18	35.81416	644.6548				0.0%	195	3510
	150		22	120.8728	2659.201	total wt.			0.0%	250	5500
					steel valv	**3409.62**	60	204577.2	**2.0%**		
ABS/PVC piping									0.0%		
	size[mm]			wt [lb/ft]					0.0%		
	18								0.0%		
	25								0.0%		
	32		40	0.305	18.178				0.0%	1.6	64
	50								0.0%		

Table C3.2. Mechanical Takeoff.											
	75		246	1.38	505.8252				0.0%	3.18	782.28
	100		484	1.97	1420.685				0.0%	4.14	2003.76
	150		550	3	2458.5	total wt.			0.0%	8.05	4427.5
						4403.188	80	352255.1	**3.4%**		
steel piping									0.0%		
	size[mm]			wt [lb/ft]					0.0%		
	18								0.0%		
	25		960	1.68	2403.072				0.0%	1.96	1881.6
	32				0				0.0%		
	50		428	3.65	2327.678				0.0%	3.57	1527.96
	75		440	7.58	4969.448				0.0%	7.5	3300
	100		40	10.79	643.084				0.0%	12	480
	150		76	18.97	2148.163	total wt.			0.0%	24.5	1862
						12491.44	**60**	749486.7	**7.3%**		43759
									0.0%		
pipe hangers			1000		0.88	880	**48.1**	42328	0.4%		
										100.0%	
								10303479	**Mj**		
								0.696181	**Gj/sq. m.**		
								as % of embodied energy			12.73%
								as % of cost			15.00%

Table C3.3. Electrical takeoff																
Note: Electrical takeoff is for Jack Davis building																
Use floor area multiplier to obtain figures for																
case stuty building.					cost calculations				embodied energy calculations							
parking level P2 (assume the same for P1)																
					unit	total		total								
item			**number**	**unit**	**cost**	**cost**		**material**	**wt/unit**	**wt [lb]**	**energy/wt**	**energy[Mj]**			**% of total**	
hid luminaries			32													
flourescent			49		282	13818				10	26.8	5836.44444			0.18%	
	ballast									10	20	4355.55556			0.13%	
recepticles			24		55.5	1332									0.00%	
speakers			15												0.00%	
conduit	12 mm		375	m	4.28	5264.4			0.6	738	60	19680			0.60%	
	32 mm		235	m	6.3	4856.04			1.5	1156.2	60	30832			0.94%	
	100 mm		240	m	25.5	20073.6			6.38	5022.336	60	133928.96			4.07%	
															0.00%	
wire	2*#12		450	m	440	12988.8			0.033	97.416	160	6927.36			0.21%	
	1*#3		75		700	1722				205	160	14577.7778			0.44%	
	3*#10 MI cable		85												0.00%	
															0.00%	
panel boards															0.00%	
			22950	watts	2000	2000			alum	185	250	20555.5556			0.62%	
			24500	watts	2000	2000			alum	185	250	20555.5556			0.62%	
			13000	watts	1275	1275			alum	50	250	5555.55556			0.17%	
															0.00%	
transformer		t1	30KVA			1950				310	20	2755.55556			0.08%	
		t2	30KVA			1950				310	20	2755.55556			0.08%	
								69229.84						**268315.9**	0.00%	
															0.00%	
typical floor															0.00%	
															0.00%	
item			**number**	**unit**											0.00%	
flourescent			164		282	46248				10	26.8	19534.2222			4.75%	
	ballast									10	20	14577.7778			3.55%	
incandescent			7												0.00%	
cable tray	1/2 m		182	m	17.5	10446.8			10	5969.6	26.8	159985.28			38.91%	

Table C3.3. Electrical takeoff																
conduit	12 mm		1070	m	4.28	15021.09			0.6	2105.76	60	56153.6			13.66%	
	25 mm		382	m	6.3	7893.648			1.16	1453.434	60	38758.2293			9.43%	
wire	#18		6600	m	66.5	3598.98			5	108.24	160	7697.06667			1.87%	
wall recepticles			18		55.5	999									0.00%	
speakers			15												0.00%	
															0.00%	
															0.00%	
panel boards			26100	watts		2425			alum	185	250	20555.5556			5.00%	
			2600	W					alum	50	250	5555.55556			1.35%	
			4600	W		995			alum	50	250	5555.55556			1.35%	
Transformer			30kVA			1950	for 8 floors			310	20	2755.55556	per floor	total	0.67%	
							89577.52	**716620.13**					331128.4	**2649027**	0.00%	
															0.00%	
verticle risers															0.00%	
	conduit	50m	700	m	9.85	22615.6			2.42	5556.32	60	148168.533			4.50%	
		100	168	m	25.5	14051.52			6.38	3515.635	60	93750.272			2.85%	
	wire	#3	2100	m	700	48216			0.205	1412.04	160	100411.733			3.05%	
		insulation								310	96	29760			0.90%	
								84883.12						**372090.5**		
														3289434	**total [Mj]**	
							total electrical	**870733.09**						**269.6257**	**Mj/sq. m**	
							total/S.F.	**6.4980081**								
							means S.F data	**5.86**	includes city multiplyer, size factor							

Table C4. Recurring Embodied Energy of Base Building																		
year	age	energy intensity		Mainenance costs														
				Assume 2%/yr inflation														
			MJ/$	$/yr														
1994	1	6.958	6.105791	1.26E+05	769329.7													
1995	2	6.727	6.044733	128520	776869.1													
1996	3	7.095	5.984286	131090.4	784482.4													
1997	4	6.927	5.924443	133712.2	792170.4													
1998	5	6.52	5.865199	136386.5	799933.6													
1999	6	6.35	5.806547	139114.2	807773													
2000	7	7.031	5.748481	141896.5	815689.2													
2001	8	6.883	5.690996	144734.4	823682.9													
2002	9	6.664	5.634087	147629.1	831755													
2003	10	5.831	5.577746	150581.7	839906.2													
2004	11		5.521968	153593.3	848137.3													
2005	12		5.466749	156665.2	856449													
2006	13		5.412081	159798.5	864842.2													
2007	14		5.35796	162994.4	873317.7													
2008	15		5.304381	166254.3	881876.2													
2009	16		5.251337	169579.4	890518.6													
2010	17		5.198823	172971	899245.7													
2011	18		5.146835	176430.4	908058.3													
2012	19		5.095367	179959	916957.3													
2013	20		5.044413	183558.2	925943.4													
2014	21		4.993969	187229.4	935017.7													
2015	22		4.944029	190974	944180.9													
2016	23		4.894589	194793.4	953433.8													
2017	24		4.845643	198689.3	962777.5													
2018	25		4.797187	202663.1	972212.7													
2019	26		4.749215	206716.4	981740.4													
2020	27		4.701723	210850.7	991361.4													
2021	28		4.654705	215067.7	1001077													
2022	29		4.608158	219369	1010887													
2023	30		4.562077	223756.4	1020794													
2024	31		4.516456	228231.6	1030798													
2025	32		4.471292	232796.2	1040900													
2026	33		4.426579	237452.1	1051100													
2027	34		4.382313	242201.2	1061401													
2028	35		4.33849	247045.2	1071803													
2029	36		4.295105	251986.1	1082307													
2030	37		4.252154	257025.8	1092913													
2031	38		4.209632	262166.3	1103624													
2032	39		4.167536	267409.6	1114439													
2033	40		4.125861	272757.8	1125361	37455066												
2034	41		4.084602	278213	1136389	4667.88												

Table C4. Recurring Embodied Energy of Base Building																	
2035	42		4.043756	283777.3	1147526												
2036	43		4.003318	289452.8	1158772												
2037	44		3.963285	295241.9	1170128												
2038	45		3.923652	301146.7	1181595												
2039	46		3.884416	307169.6	1193175												
2040	47		3.845572	313313	1204868												
2041	48		3.807116	319579.3	1216675												
2042	49		3.769045	325970.9	1228599												
2043	50		3.731354	332490.3	1240639												
2044	51		3.694041	339140.1	1252797												
2045	52		3.6571	345922.9	1265075												
2046	53		3.620529	352841.4	1277472												
2047	54		3.584324	359898.2	1289992												
2048	55		3.548481	367096.1	1302634												
2049	56		3.512996	374438.1	1315399												
2050	57		3.477866	381926.8	1328290												
2051	58		3.443087	389565.4	1341308												
2052	59		3.408657	397356.7	1354452												
2053	60		3.37457	405303.8	1367726												
2054	61		3.340824	413409.9	1381130												
2055	62		3.307416	421678.1	1394665												
2056	63		3.274342	430111.6	1408333												
2057	64		3.241598	438713.9	1422134												
2058	65		3.209182	447488.1	1436071												
2059	66		3.177091	456437.9	1450145												
2060	67		3.14532	465566.7	1464356												
2061	68		3.113867	474878	1478707												
2062	69		3.082728	484375.6	1493198												
2063	70		3.051901	494063.1	1507831												
2064	71		3.021382	503944.3	1522608												
2065	72		2.991168	514023.2	1537530												
2066	73		2.961256	524303.7	1552597												
2067	74		2.931644	534789.8	1567813												
2068	75		2.902327	545485.6	1583178												
2069	76		2.873304	556395.3	1598693												
2070	77		2.844571	567523.2	1614360												
2071	78		2.816125	578873.6	1630181												
2072	79		2.787964	590451.1	1646156												
2073	80		2.760084	602260.1	1662289	92780550											
2074	81		2.732483	614305.3		11562.88											
2075	82		2.705159	626591.4													
2076	83		2.678107	639123.3													
2077	84		2.651326	651905.7													
2078	85		2.624813	664943.8													

Table C4. Recurring Embodied Energy of Base Building

life-cycle embodied energy based on replacement information

year	age	energy intensity factor 0.01	20 yr site	80 yr structure	20%@25y envelope	15yr Windows	15yr Roof	10 yr Int. walls	10yr Flooring	10 yrs Bathrooms	20 yrs HVAC	40 yrs plumb	30 yrs Elevator	30 yrs Elec.
1994	1	1												
1995	2	0.99												
1996	3	0.9801												
1997	4	0.970299												
1998	5	0.960596	102.7838			302.5877	209.4099	187.3162	633.9934	24.9755	537.9338			208.4493
1999	6	0.95099												
2000	7	0.94148												
2001	8	0.932065												
2002	9	0.922745												
2003	10	0.913517	97.74635			287.7579	199.1468	1785.013	1204.929	239.3415	511.5697		17.35683	198.2332
2004	11	0.904382												
2005	12	0.895338												
2006	13	0.886385												
2007	14	0.877521												
2008	15	0.868746	92.9558			2736.549	1848.691	169.4054	573.3722	22.58739	486.4977			188.5178
2009	16	0.860058												
2010	17	0.851458												
2011	18	0.842943												
2012	19	0.834514												
2013	20	0.826169	877.3911			260.2431	180.1048	1614.333	1089.716	216.4562	4626.544		15.6972	179.2786
2014	21	0.817907												
2015	22	0.809728												
2016	23	0.801631												
2017	24	0.793614												
2018	25	0.785678	84.06756		989.9545	247.4886	171.2778	153.2072	518.5476	205.8477	439.9798			170.4922
2019	26	0.777821												
2020	27	0.770043												
2021	28	0.762343												
2022	29	0.754719												
2023	30	0.747172	79.94741			2353.592	1589.982	1459.974	985.52	195.7591	418.4164		283.9254	1621.363
2024	31	0.7397												
2025	32	0.732303												
2026	33	0.72498												
2027	34	0.717731												
2028	35	0.710553	76.0292			223.8243	154.9006	138.5579	468.9651	18.47438	397.9098			154.1901
2029	36	0.703448												

Table C4. Recurring Embodied Energy of Base Building																	
	2030	37	0.696413														
	2031	38	0.689449														
	2032	39	0.682555														
	2033	40	0.675729	716.2728			212.8547	147.3089	1320.375	891.2866	177.041	3784.083		12.83885	146.6332		
	2034	41	0.668972														
	2035	42	0.662282														
	2036	43	0.655659														
	2037	44	0.649103														
	2038	45	0.642612	68.75944			2024.227	1367.477	125.3093	424.1237	16.7079	359.8625			139.4467		
	2039	46	0.636185														
	2040	47	0.629824														
	2041	48	0.623525														
	2042	49	0.61729														
	2043	50	0.611117	65.38954		770.0077	192.5019	133.2236	1194.123	806.0636	160.1127	342.2257		11.61123	132.6124		
	2044	51	0.605006														
	2045	52	0.598956														
	2046	53	0.592966														
	2047	54	0.587037														
	2048	55	0.581166	62.18481			183.0674	126.6943	113.3275	383.5698	15.11033	325.4532			126.1131		
	2049	56	0.575355														
	2050	57	0.569601														
	2051	58	0.563905														
	2052	59	0.558266														
	2053	60	0.552683	585.8445			1740.953	1176.11	1079.944	728.9895	144.8031	3095.027		210.0197	1153.45		
	2054	61	0.547157														
	2055	62	0.541685														
	2056	63	0.536268														
	2057	64	0.530906														
	2058	65	0.525596	56.23882			165.5629	114.58	102.4913	346.8937	13.66551	294.334			114.0544		
	2059	66	0.520341														
	2060	67	0.515137														
	2061	68	0.509986														
	2062	69	0.504886														
	2063	70	0.499837	53.48256			157.4487	108.9645	976.6816	659.285	130.9573	279.9087		9.496904	108.4646		
	2064	71	0.494839														
	2065	72	0.48989														
	2066	73	0.484991														
	2067	74	0.480141														
	2068	75	0.47534	50.86138			1497.321	1011.524	92.69131	313.7244	12.35884	266.1904			103.1488		
	2069	76	0.470587														
	2070	77	0.465881														
	2071	78	0.461222														
	2072	79	0.45661														
	2073	80	0.452044	0													

Table C4. Recurring Embodied Energy of Base Building																	
			sub-total	3069.955	0	1759.962	12585.98	8539.396	10512.75	10028.98	1594.198	16165.94	0	560.9461	4744.448		
			total	4083.04	0	2340.75	16739.35	11357.4	13981.96	13338.54	2120.284	21500.69	0	746.0584	6310.116		
															total		
															92518.19	for 80 yr life	
															8.8		
			sub-total	1308.137	0	989.9545	6109.455	4144.103	5320.491	4841.051	898.4662	6880.918	0	316.9794	2512.075		
			total	1739.823	0	1316.639	8125.576	5511.657	7076.253	6438.597	1194.96	9151.62	0	421.5826	3341.06		
															total		
															44317.77	for 40 yr life	
															4.2		

Figure D1. Life-cycle Energy, Building Life = 40 Years

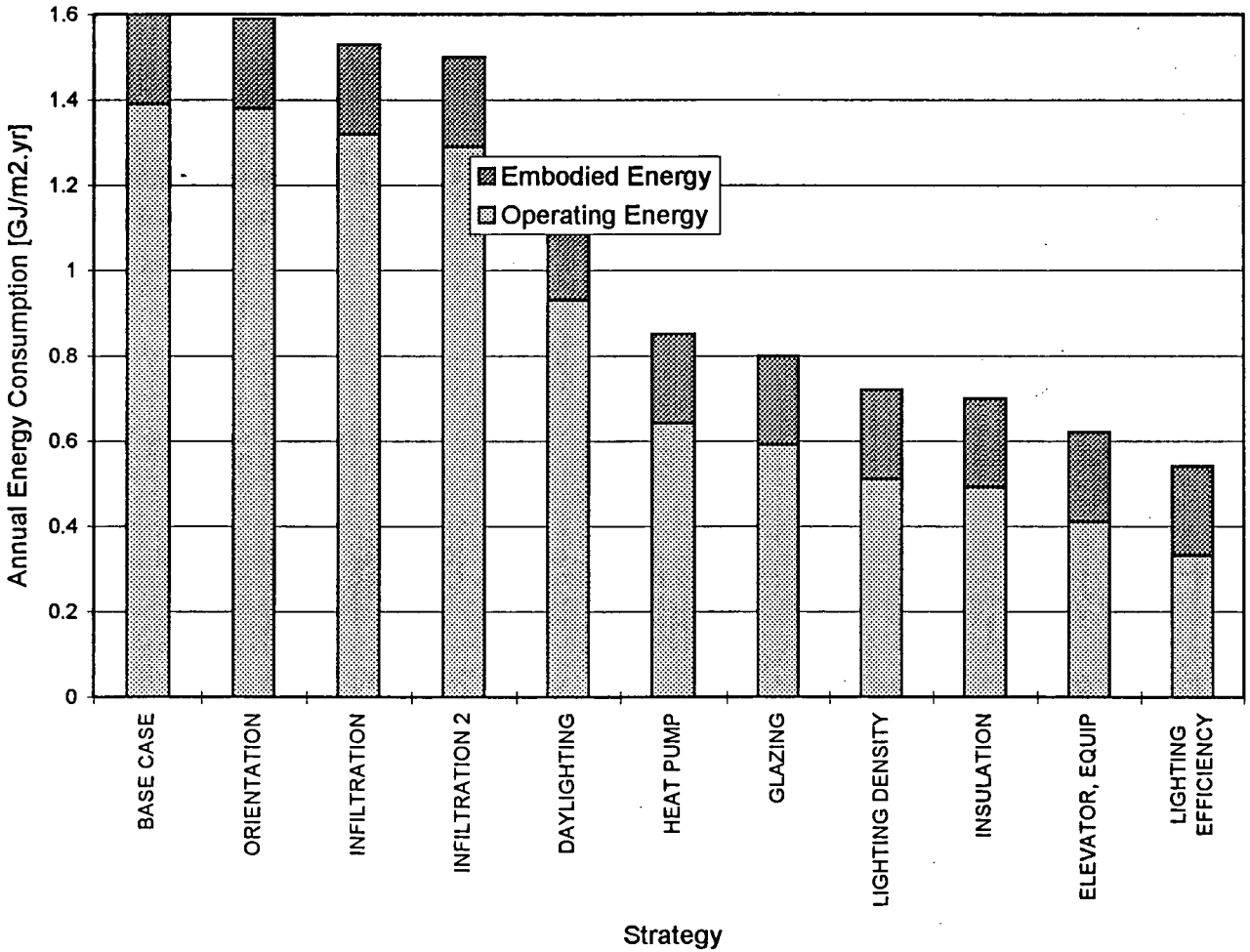


Figure D2. Life-cycle Energy, Building Life = 80 Years

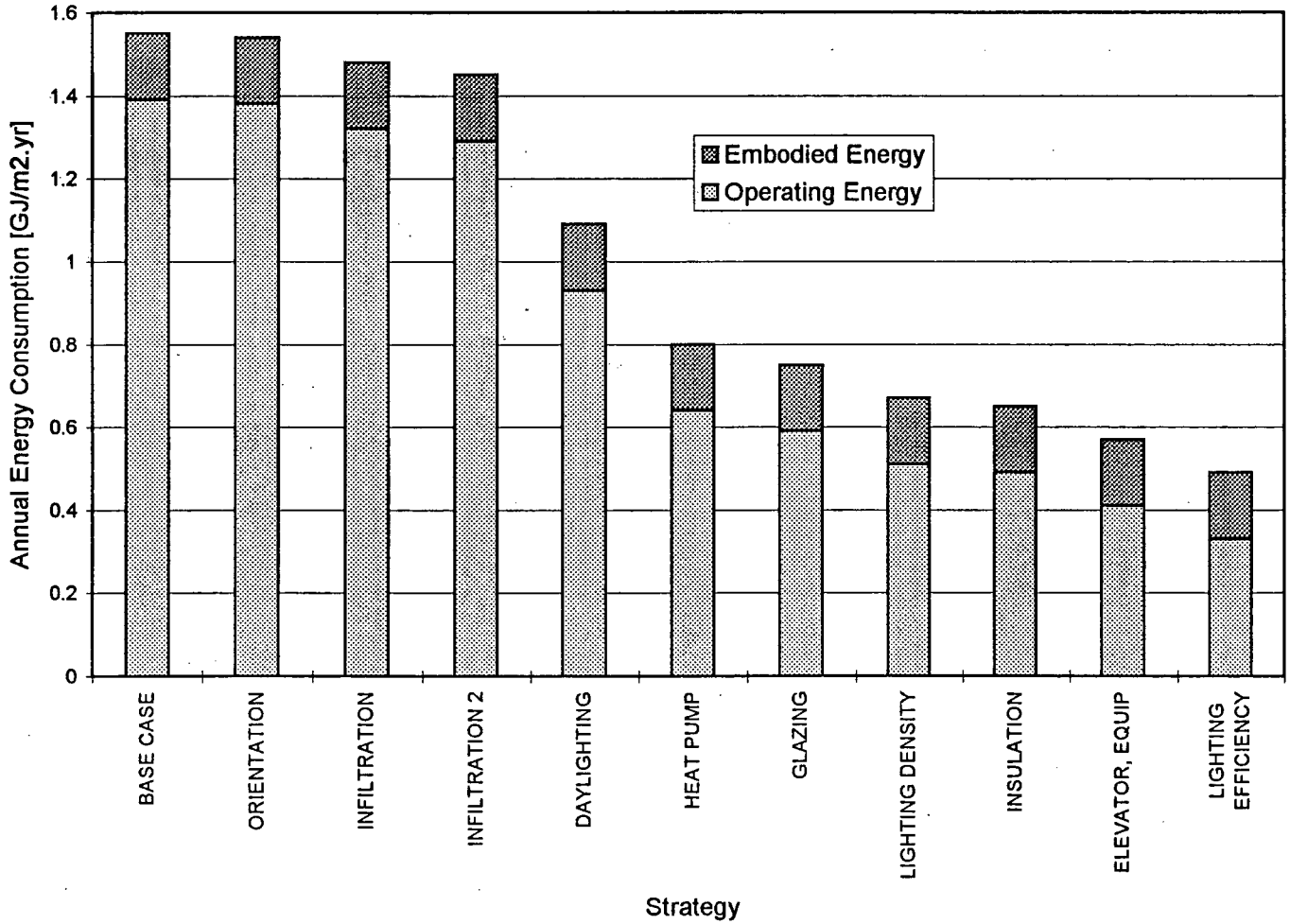


Figure E1: Net Present Value of Strategies

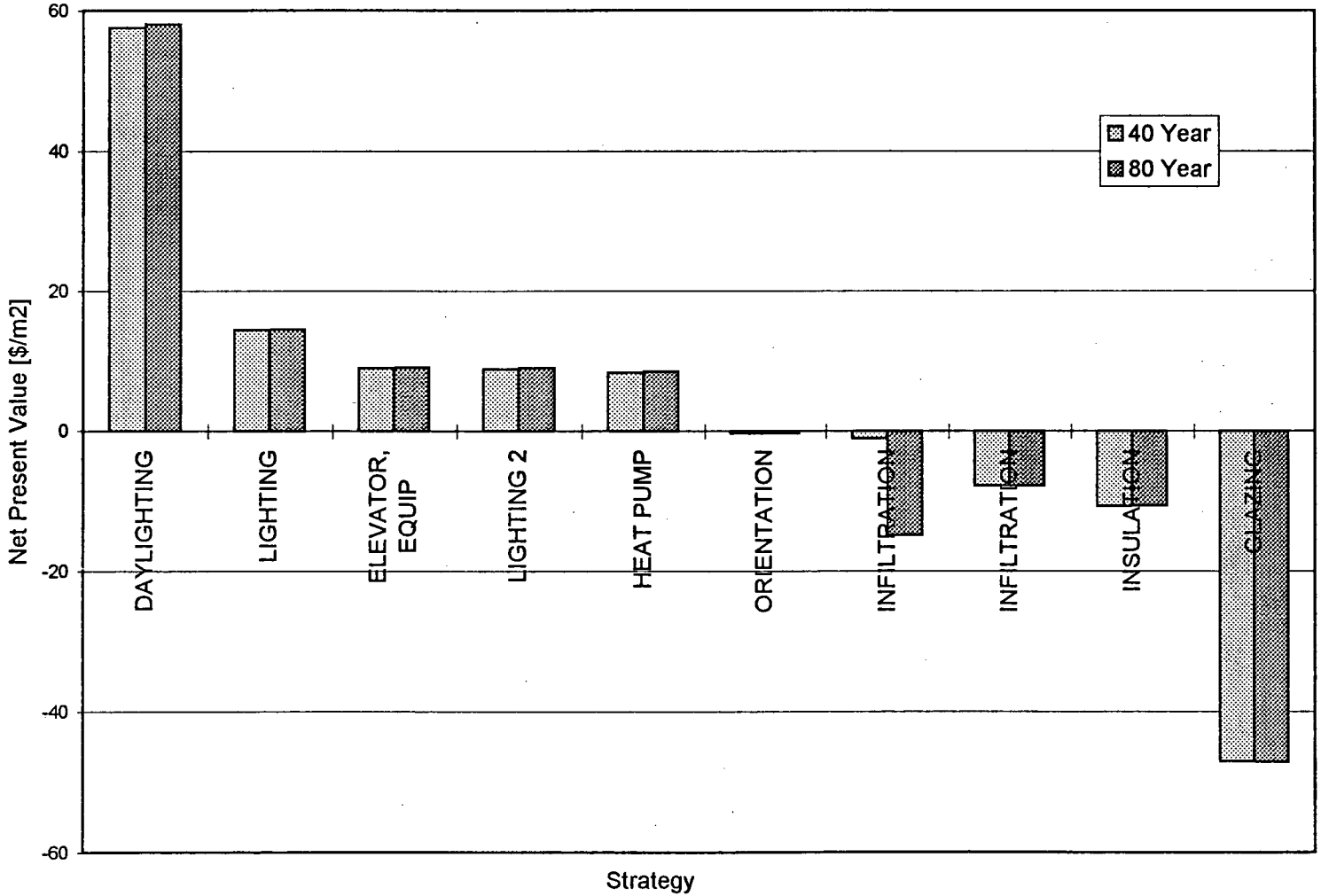
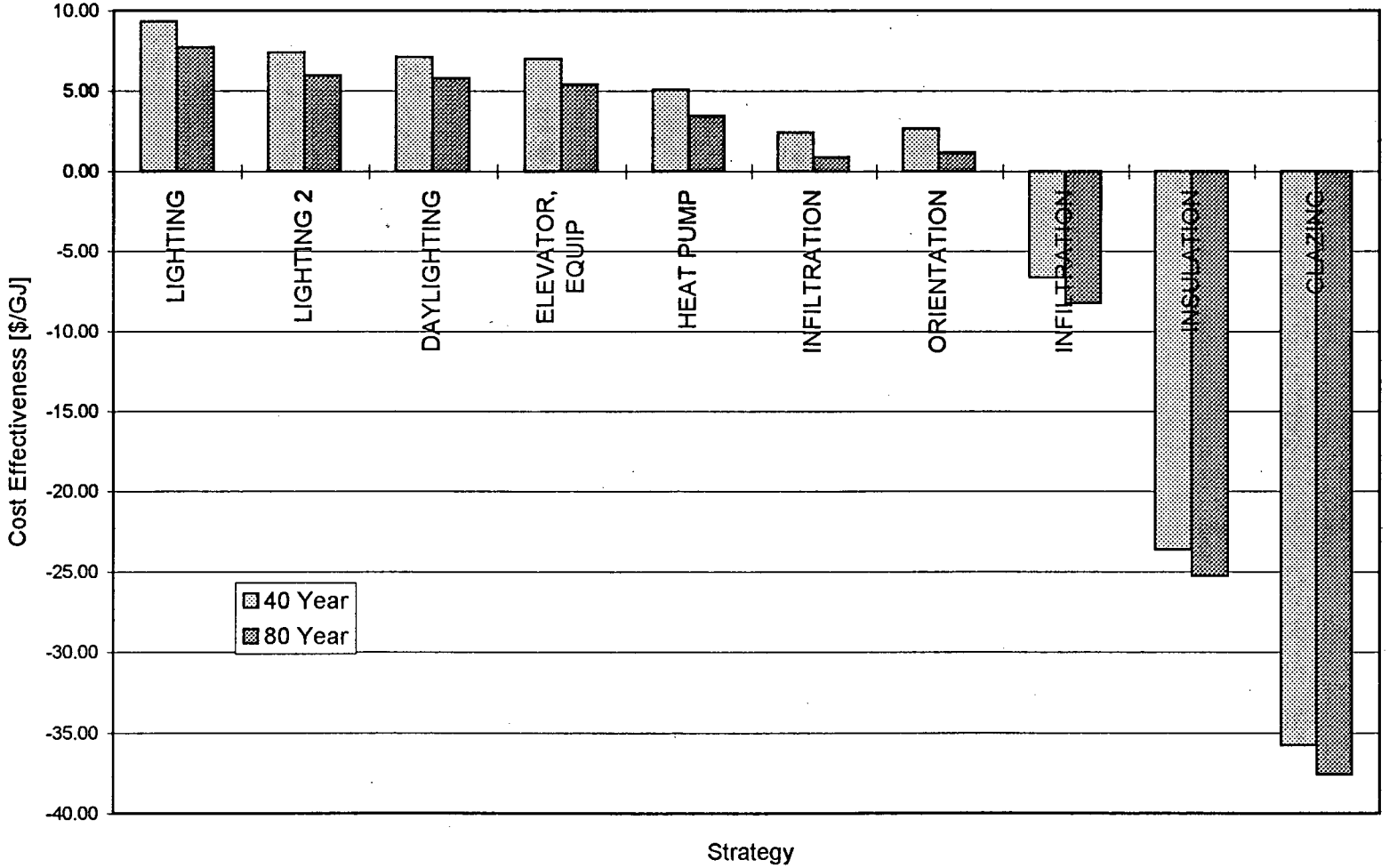



Figure E2. Ranking Cost Effective Strategies