COGENERATION AND COMMUNITY DESIGN:

PERFORMANCE BASED MODEL FOR OPTIMIZATION OF THE DESIGN OF U.S. RESIDENTIAL COMMUNITIES UTILIZING COGENERATION SYSTEMS IN COLD CLIMATES

A Dissertation

by

HAZEM MOHAMED RASHED ALI ATTA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2006

Major Subject: Architecture

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Approved by:

Chair of Committee,	Phillip J. Tabb
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ABSTRACT

Cogeneration and Community Design: Performance Based Model for Optimization of the Design of U.S. Residential Communities Utilizing Cogeneration Systems in Cold Climates. (August 2006)

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Chair of Advisory Committee: Dr. Phillip J. Tabb

The integration of cogeneration technologies in residential communities has the potential of reducing energy demand and harmful emissions. This study investigated the impact of selected design parameters on the environmental and economic performances of cogeneration systems integrated into residential communities in cold U.S. climates following a centralized or a decentralized integration approach. Parameters investigated include: 1) density, 2) use mix, 3) street configuration, 4) housing typology, 5) envelope and building systems' efficiencies, 6) renewable energy utilization, 7) cogeneration system type, 8) size, and 9) operation strategy. Based on this, combinations of design characteristics achieving an optimum system performance were identified.

The study followed a two-phased mixed research model: first, studies of residential community design and three case studies of sustainable residential communities were analyzed to identify key design parameters; subsequently, simulation tools were utilized to assess the impact of each parameter on cogeneration system performance and to optimize the community design to improve that performance. Assessment procedures included: developing a base-line model representing typical design characteristics of U.S. residential communities; assessing the system performance within this model, for each integration approach, using three performance indicators: reduction in primary energy use, reduction in CO_2 emissions; and internal rate of return; assessing the impact of each parameter on the system performance through developing 46 design variations of the base-line model representing changes in these parameters and calculating the three indicators for each variation; using a multi-attribute decision analysis methodology to evaluate the relative impact of each parameter on the system performance; and finally, developing two design optimization scenarios for each integration approach.

Results show that, through design optimization, existing cogeneration technologies can be economically feasible and cause reductions of up to 18% in primary energy use and up to 42% in CO_2 emissions, with the centralized approach offering a higher potential for performance improvements. A significant correlation also existed between design characteristics identified as favorable for cogeneration system performance and those of sustainable residential communities. These include high densities, high mix of uses, interconnected street networks, and mixing of housing typologies. This indicates the higher potential for integrating cogeneration systems in sustainable residential communities.

DEDICATION

To my mother, I wish you were here.

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I would like to express my sincerest appreciation to all the members of my dissertation committee for their support, guidance, and thoughtful comments, without which this research would not have been possible. My deepest gratitude goes to Dr. Phillip Tabb, the chair of my dissertation committee, whose on-going support, knowledge, and expertise guided me throughout all the phases of my Ph.D.; to Dr. Jeff Haberl, for his deep knowledge of building simulation and building systems, and for his thoughtful suggestions for developing the methodology of this research; to Dr. Michael Neuman, for introducing me to the various aspects of planning and for his insightful reviews and comments throughout the research; and finally to Dr. Robert Johnson, for his very helpful comments and suggestions and in particular for his guidance with regard to the economical assessments parts of the research.

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LIST OF ACRONYMS

AIA	American Institute of Architects
APA	American Planning Association
ASHRAE	American Society of Heating, Ventilation and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
BCHP	Buildings Cooling, Heating and Power
BEES	Building for Environmental and Economic Sustainability
BEQUEST	Building Environmental Quality for Sustainability Through Time
BESTEST	Building Energy Simulation Test and Diagnostic Method
BREEAM	Building Research Establishment Environmental Assessment Method
BTU	British Thermal Unit
CBECS	Commercial Buildings Energy Consumption Survey
CEADS	Community Energy Assessment and Design Support
CDD	Cooling Degree Days
CHB	Combined Heat and Power
CIBSE	Chartered Institution of Building Services Engineers
CNU	Congress for the New Urbanism
CO_2	Carbon Dioxide
DG	Distributed Generation
DHC	District Heating and Cooling
DHN	District Heating Network
DHW	Domestic Hot Water
DoD	Department of Defense
DOE	Department of Energy
eGRID	The Emissions & Generation Resource Integrated Database
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EUI	Energy Use Intensity
FRP	Fiberglass-Reinforced Plastic
GHG	Greenhouse Gases

GRI	Gas Research institute
H/P	Heat to Power Ratio
HDD	Heating Degree Days
HERS	Home Energy Rating Standards
HGV	Highlands' Garden Village
HUD	Department of Housing and Urban Development
ICC	International Code Council
IDHA	International District Heating Association
IEA	International Energy Agency
IEEC	International Energy Efficiency Code
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
IUCN	The World Conservation Union
LBNL	Lawrence Berkeley National Laboratories
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life Cycle Costs Analysis
LEED	Leadership in Energy and Environmental Development
LTHW	Low Temperature Hot Water
MADA	Multi-Attribute Decisions Analysis
MMBtu	Million British Thermal Units
NAHB	National Association of Home Builders
NASEO	National Association of State Energy Officials
NIST	National Institute for Standards and Technology
NPV	Net Present Value
NREL	National Renewable Energy Laboratories
O&M	Operation and Maintenance
ORNL	Oak Ridge National Laboratory
PEMFC	Proton-Exchange Membrane Fuel Cell
R&D	Research and development
RECS	Residential Energy Consumption Survey
RESNET	Residential Energy Services Network

SCN	Sustainable Communities Network
SFH	Single Family House
SOFC	Solid Oxide Fuel Cell
TMY	Typical Meteorological Year
TND	Traditional Neighborhood Development
TOD	Transit Oriented Development
ULI	Urban Land Institute
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
US GBC	United States Green Building Council
WCED	World Commission on Environment and Development
WWF	World Wide Fund for Nature

DEFINITIONS

Centralized cogeneration:	The integration of a central cogeneration plant in the residential community to provide electricity and thermal energy to its buildings.
Cogeneration:	The combined production of electrical power & useful thermal energy. Also known as Combined Heat and Power.
Community design optimization:	The identification of a combination of community design characteristics that achieves an optimum performance.
Community design parameter:	A variable quantity determining a certain facet of the design of the community.
Decentralized cogeneration:	The integration of several small, building-integrated, cogeneration systems into each of the residential buildings of the community.
Distributed generation:	Production of power on a local site or at a local distribution utility that directly supplies the local distribution network.
District heating network:	A network of pipes conveying heat from a central plant to the community's buildings by means of hot water or steam.
Electrical base-loading:	The design of a cogeneration system to meet the minimum amount of power required by the building/community thus resulting in the operation of the system at a constant rate.
Electrical load-matching:	The design of a cogeneration system with a capacity exceeding the minimum requirements of the building/ community and operating it so that the power output increases or decreases in response to the electrical demand.
Environmental sustainability:	A multi-dimensional concept that aims to address a variety of environmental challenges arising from both development and industrialization as well as from underdevelopment and poverty including: global warming, natural resource depletion, pollution, and ecosystem destruction.
Heat to power ratio:	The ratio of thermal energy to electrical power needs of a facility. Also, the ratio of thermal energy to electrical power output of a cogeneration system.
High mix of uses:	A mix of residential and non-residential uses which corresponds with a town or neighborhood center and which is anchored by a grocery store or supermarket.
Internal rate of return:	A method of economic evaluation in which the earning rate of

	a project is determined by converting all the cash flows to present values that equal the initial investment.
Life cycle assessment:	An assessment methodology that considers all the significant monetary and non-monetary costs and benefits associated with a project over a specific time period.
Life cycle costing:	An economic assessment methodology that considers all the significant monetary costs of ownership over a project's economic life expressed in terms of equivalent dollars.
Life cycle costs analysis:	A cost-centered economic analysis aimed at determining the costs attributed to each of the alternative courses of action over a specific time period.
Low mix of uses:	A mix of uses which corresponds with low density residential areas and includes a small community center, a child care center, and a corner store.
Medium mix of uses:	A mix of uses which corresponds with a main street grouping and which is anchored by a convenience/food store.
Micro-cogeneration Systems:	Systems that simultaneously produce heat and power for a residence, and therefore work as a household appliance that can provide various residential energy needs such as space and water heating, electricity, and, potentially, cooling.
Mix of uses:	The mixing of residential and non-residential (commercial and civic) uses and buildings within a residential community.
Mixed research methods:	An emerging direction in research methodologies used to expand understanding from one method to another, to neutralize the inherent biases of any single method, and/or to confirm or converge findings from multiple data sources.
Multi-attribute decisions analysis:	Methods used to choose or rank a finite number of alternatives measured by two or more attributes, and which can combine attributes not measurable in the same units or attributes that are impractical, impossible, or too costly to measure.
Optimized mix of uses:	A variation of the high mix of uses in which changes are made to building types and operation schedules to improve the performance of the cogeneration system.
Sustainability indicators:	Measures aiming to evaluate progress towards increasing sustainability and which aim to integrate environmental, social and economic factors.
Sustainable development:	Meeting the needs of the present without compromising the ability of future generations to meet their own needs.

CHAPTER I
INTRODUCTION

1.1 SUSTAINABILITY, THE BUILT ENVIRONMENT, AND COGENERATION

In the past three decades, the need for adopting the principles and practices of sustainability has been clearly established through research activities as well as political conventions and protocols. While a lack of consensus still exists over the definition of sustainable development and the issues it should address, existing schools of thought agree over the need for balancing its three main components: environmental, social, and economic sustainability. The need for environmental sustainability stems from the growing sense of responsibility motivated by the realization of the serious environmental problems facing world communities (e.g. global warming, resources depletion, increased pollution, etc.) on the local, regional, and global levels. Such problems clearly pose an evident and increasing threat to both current and future generations (IEA, 1997).

Energy is a central issue in the sustainability debate affecting all three of its components (see IEA, 1998; Reddy, 1997; Johansson & Goldemberg, 2002 & 2004). This wide impact of energy indicates that energy efficiency, while perhaps not a sufficient condition for sustainability, is certainly a necessary one. The United Nations Development Program (UNDP, 1996) argues, however, that energy efficiency is not an end of itself, but rather the means to achieve the goal of sustainable development. Projected increases in global energy demand, caused by a combination of population and economic growth, combined with the continued dominance of fossil fuels and the issues posed by the centralized structure of the current energy system indicate that problems caused by this current energy system will continue to increase and that efforts are therefore needed to further investigate methods of reducing these problems.

Accounting for 20 to 30% of the world energy consumption (IEA, 1996), and 38.7% of U.S. energy consumption (EIA, 2005b), the built environment plays a major role within the world energy system. Subsequently, increasing energy efficiency in the built environment can

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This dissertation follows the style of *Building Research & Information.*

have an impact on achieving further sustainability. Studies conducted on the relations among sustainability, urban form, and building design (e.g. Breheny, 1992; Owens, 1986; Rickaby, 1985; Tabb, 1990; Williams et al., 2000) indicate a clear potential for achieving significant reductions in energy consumption through intelligent and sustainable planning and architecture.

In the U.S., energy consumption in the residential sector accounts for about 21% of the total U.S. energy consumption. This consumption is projected to grow by 23% by 2025 with 68% of that growth resulting from increased use of electricity (EIA, 2005a). While significant opportunities exist for more energy efficiency in both existing and new residential communities, the potential for applying the principles of sustainability from the early stages of the design process is considerably higher in the case of new communities. Projected increases in U.S. population and in the percentage of urban population as well as increases in housing stock all add to the potential impact that increasing the energy efficiency of new residential communities can have on the energy use, environmental impact, and overall sustainability of the sector. Statistics, however, show that the majority of the new U.S. housing stock are detached single family houses (almost 83% of new houses in 2004 (U.S. Census Bureau, 2005)); and that these new houses are typically larger in size, and therefore consume more energy, than the current average of U.S. homes. Such trends would further increase the energy use and environmental impact of the residential sector. A clear need, therefore, exists for research activities that aim to explore alternative strategies, design characteristics, systems, and technologies that aim to increase the energy efficiency and reduce the energy demand of the residential sector and to demonstrate the potential environmental and economic benefits that could result from that.

Electricity production resulted in 39% of energy-related CO_2 emissions in the U.S. in 2003 (EIA, 2004a). The electricity sector's centralized structure, with its inherent production, transmission, and transportation losses, as well as its continued reliance on fossil fuels, is projected to result in an increase in the sector's CO_2 emissions by 1.7% annually and in its share of total emissions to 41% by 2025. Distributed generation (DG) is an established, more efficient, alternative that can fundamentally alter existing centralized power systems (IEA, 2002) and, through increasing conversion efficiency and reducing transmission and transportation losses, can result in considerable economic benefits and significant reductions in harmful emissions (see ORNL (2003a, b) for a quantitative assessment of these benefits). The use of cogeneration, a technology that produces electricity locally and utilizes the, otherwise wasted, thermal energy byproduct of the electricity generation process in thermal end uses such as space and water heating, further increases the efficiency and subsequently the potential benefits of DG. Combined with energy conservation measures, cogeneration technologies offer the potential of meeting most or all of the energy needs of residential communities in a more efficient, economic, and environmentally friendly manner. Consequently, integrating cogeneration technologies into new residential communities has the potential of reducing the energy consumption and subsequent harmful emissions of these communities thus mitigating the expected increase in the environmental impact of the residential sector. However, while cogeneration technologies are well established in many market sectors with large energy needs, e.g. the industrial and educational sectors, and their potential economic and environmental benefits in these sectors are well known; their use in the residential sector, especially in the U.S., is still limited. This issue will be discussed in the following section.

1.2 COGENERATION AND COMMUNITY DESIGN

The growing number of sustainable communities and green building programs (listings of which can be found in Barton (2000); NAHB (2002c); SCN (2005); and SCN (2005a)) as well as the increased use of environmental rating systems such as "*Leadership in Energy and Environmental Development (LEED)"* (US GBC 2003, 2005) in the past few years indicate an increase in the sense of environmental responsibility in the built environment professions. However, several studies (e.g. Garde-Bentaleb et al., 2002, Morbitzer, 2003; Shaviv et al., 1996) suggest that the integration of environmental considerations into the design process is still lacking especially in the early design stages in which, typically, a large number of design alternatives need to be considered in a small period of time making it difficult to conduct detailed environmental analyses of each alternative. Design decisions taken in these early stages, however, have a significant impact on environmental performance and are difficult to change in later design stages (Grumman, 2003), making it important for environmental consideration to be integrated into these stages. Design decisions in these early stages are typically based on expert rules of thumb and/or design guidelines, developed based on field experiences, precedents, or specialized research (Morbitzer, 2003 & Shaviv et al., 1996). Such guidelines, however, are typically general in nature and need to be adapted to specific project conditions. The increased power of building simulation tools offers the potential for developing more accurate guidelines that take into consideration the interrelationships between various design parameters. Such guidelines can provide designers with a sound knowledge-base for these critical design decisions through determining both optimum values and acceptable ranges for relevant design parameters.

Cogeneration technologies can typically be integrated into residential communities in one of two methods, to be henceforth described as integration approaches. The first is the centralized approach, used in a number of European communities, which involves supplying the electrical and thermal requirement of the community from a centralized plant through a distribution network (typically called a district heating or district energy network); while the second is the decentralized approach, made possible through recent development of smaller, building-integrated, cogeneration systems (also called micro-cogeneration) and which can thus provide electricity and heat to each building individually. For both approaches, cogeneration systems can be sized to meet all the electricity demands of the community thus becoming grid-independent (also called stand-alone systems). However, such systems typically have very high initial cost which negatively affects their economic feasibility. Grid-connected systems, on the other hand, only meet part of those demands while relying on the grid to meet the rest of them as well as a backup in emergencies and in system maintenance periods (Caton, 2003). While established in other market sectors, the use of cogeneration systems in the U.S. residential sector, so far, has been minimal. This is indicated by a survey of U.S. district energy systems (ORNL, 2003) which showed that only 1.9% of the over 6,000 systems operational at that time were located in residential communities. However, recent technological advances in medium and small sized (micro) cogeneration systems have increased the potential of using cogeneration in both the residential and the commercial sectors. The availability of these smaller systems, combined with the increased awareness of the environmental implications of the current energy system and the potential impact of residential cogeneration systems on the sustainability of the residential sector, have all resulted in increased research activities which aim to investigate this potential, explore its benefits, and determine the optimum conditions under which these systems can be utilized in residential communities. This study represents one of these activities.

In spite of the limited use of residential cogeneration in the U.S., a number of studies have indicated that their use could result in significant energy and emissions reductions (e.g. Phetteplace, 1995b; Ellis, 2002; Fischer, 2003; Gunes & Ellis, 2003; Braun et al., 2004; White et al., 2004). These studies, however, have also identified certain obstacles that limit that use mostly in relation to the economic feasibility of using cogeneration instead of conventional systems (i.e. grid electricity and conventional residential HVAC systems). For the decentralized approach, these obstacles include the currently high initial costs of the systems, while for the centralized approach, which uses more established technologies with less initial cost, the obstacles relate to the high cost of the piping network required. Both approaches are also negatively impacted by the current typical characteristics of U.S. residential energy use including high annual consumption and large daily variations. However, studies mentioned here have almost exclusively dealt with the issues at the scale of individual buildings and not that of the community. The majority of them also did not investigate the impact that improving the energy consumption characteristics of buildings, communities, or both can have on the energy use, and consequently the economic performance of the cogeneration system. Additionally, few studies have been conducted that aim to identify suitable markets for residential cogeneration systems.

Economic feasibility plays a critical role in achieving wider adoption and market acceptance for energy efficiency measures, emergent technologies, and systems such as residential cogeneration. In these cases, the main obstacle is usually the high initial cost of the technology, which is impacted by the high research and development (R&D) costs and the low production volume of these emergent technologies and systems thus making them economically feasible only in selected markets whose characteristics are favorable to the most efficient use of the technology. As the production volume increases, these initial costs tend to decrease thus improving the economics of the technology and increasing its potential markets.

Throughout the U.S., a number of new, sustainable, residential communities are being developed, which attempt to integrate the principles of sustainability and energy efficiency from the early stages of their design. The design characteristics of these communities are consequently different from those of conventional ones thus resulting in improved energy consumption characteristics. These communities are also widely used by different manufacturers and research institutions to demonstrate the performance of various emergent, energy efficient, technologies and systems. While their number is still limited, these communities represent a potential market for the integration of cogeneration systems. The utilization of cogeneration systems in these communities can result in further reductions in the energy use and environmental impact of the communities as well as to a wider acceptance of the technology and to improvements in its economic performance making it suitable for other markets.

From the previous discussion, it is clear that a potential exists to explore the integration of cogeneration technologies in sustainable residential communities and to investigate the impact that the different design characteristics of these communities, from those of conventional ones, can have on the energy, environmental, and economic performances of the cogenerations systems as a means of developing design guidelines to inform designers of these communities, particularly in the early community design stages.

1.3 RESEARCH AIMS AND OBJECTIVES

The design of residential communities utilizing cogeneration systems involves a large number of parameters on the planning, architecture, and cogeneration system scales. Examples of these parameters include density, mix of uses, street configuration, housing typology, envelope and building systems' efficiencies, cogeneration system type, and size. This study aims to identify the combination of design characteristics, on the three scales, resulting in the optimum environmental and economic performances of the cogeneration system, as will as those characteristics resulting in a minimum acceptable performance for the system. This optimization is based on an assessment of the individual impact of selected planning, architectural, and system parameters on the performance of the cogeneration system, followed by an integration of the results of these individual assessments, or sensitivity analyses, that takes into consideration the inter-relationships between these parameters, the potential conflicts between their impacts on the system performance, as well the typical design considerations of sustainable residential communities as identified from the literature and the selected case studies. To accomplish its purpose, the study aims to achieve the following objectives:

1) To identify the key planning and architectural design parameters of sustainable residential communities as well as those of residential cogeneration systems through a review of the literature and an analysis of three case studies of sustainable residential communities.

2) To develop a base-line model of a residential community representing typical program and design characteristics of these communities in the U.S., as well as prototypes for a number of residential and small commercial building typologies, which can possibly be integrated in a mixed-used sustainable residential community.

3) To determine the impact of variations in each of the selected planning, architectural, and cogeneration system parameters on the environmental and economic performances of a

cogeneration system integrated into the developed community model in a cold climate as compared to the system performance in the base-line community.

4) To determine the combination of community and system design characteristics resulting in the optimum cogeneration system performance, as well as those resulting in a minimum acceptable system performance for each of the two integration approaches: the centralized one and the decentralized, building-integrated, one.

5) To determine the potential environmental and economic benefits resulting from the integration of cogeneration systems in residential communities for both the centralized and decentralized cogeneration integration approaches.

6) To investigate the potential for utilizing cogeneration systems is sustainable residential communities in the U.S. based on the design characteristics of these communities.

1.4 RESEARCH SIGNIFICANCE

Achieving sustainable development requires addressing a wide range of interrelated and interacting issues that span across many scales and disciplines. It also requires professionals from all these disciplines to actively contribute towards promoting and applying the goals of sustainable development in their respective fields. Building on that, this study investigates the design characteristics of residential communities in a cross-disciplinary manner which aims to identify the relative impact of each of these disciplines and scales (i.e. planning, architecture, and technology), on the performance of an emergent technology such as cogeneration, which has the potential of achieving significant reductions in the energy use and environmental impact of these residential communities. By focusing on the design characteristics of the community, the study also explores the impact that planners and architects can have, through the design decisions they make determining issues such as density, mix of uses, housing typology, building form, etc., on the performance of this emergent technology.

The results of the study can assist designers of residential communities who wish to integrate cogeneration technologies in their communities in making informed decisions that can potentially improve the environmental and economic performance of the cogeneration system thus resulting in larger reduction in the energy use and environmental impacts for the community. This is achieved by informing these designers of the combination of community design characteristics that would result in an optimum system performance as well as those resulting in a minimum acceptable one. As such combinations may not always be possible to achieve in all design situations, the study, by investigating the individual impacts of each of the major design parameters on the cogeneration system performance, also provides designers with the acceptable ranges for each of those parameters and their relative impacts on the cogeneration system performance. Additionally, the study can assist in identifying residential communities with suitable characteristics in which cogeneration technologies can be integrated, thus providing these technologies with potential market entry points which can result in their wider acceptance therefore increasing their potential benefits for the residential sector. Through the comparison of the two cogeneration integration approaches, the study can also assist in identifying the feasibility of each approach as well as its potential markets.

In summary, the study aims to demonstrate the effective role that intelligent planning, design, and use of technology can have on reducing the energy use and environmental impact of residential communities through increasing the feasibility of cogeneration technologies. These communities, which make use of the basic principles of sustainability while in the same time utilizing the latest and most energy-efficient technologies, can play an effective role in promoting sustainability principles and practices by providing people with efficient, motivating, and sustainable physical environments that can assist in achieving the changes in people's values, life styles, and behavior, which are necessary for achieving sustainable development.

1.5 RESEARCH SCOPE AND LIMITATIONS

While sustainability studies, in general, can address a wide range of issues covering the three main components of sustainable development: environmental, social, and economic sustainability, this study focuses on energy as a central issue in the sustainability debate and investigates the integration of cogeneration systems in residential communities as a means of reducing the energy use, and subsequent environmental impacts, of these communities. Although cogeneration systems can have other impacts on the social and economic sustainability of residential communities, such as the potential impact of centralized cogeneration systems on increasing the sense of community and providing local employment opportunities (Barton, 2000), these impacts are not addressed in this study nor are other factors impacting sustainability such as user behavior patterns.

Studies of energy use in residential communities vary in complexity depending on the planning scale the issue is addressed on, the size of the community, and the energy end-uses being considered. As this study is only interested in energy uses that the cogeneration system can meet and therefore can impact its performance, the study is limited to energy use within small residential communities and does not address issues of energy use in larger residential communities, requiring very large or multiple cogeneration systems, or energy use between communities. For the same reason, the scope of the study is limited to energy end-uses within the community buildings and does not extend to energy use outside these buildings, such as transportation. However, the study acknowledges that these energy uses are also impacted by the variations of the community design characteristics and can have a considerable impact on the overall energy use of the community.

Opportunities for improving the energy performance of residential communities and cogeneration systems can be found in all the life cycle stages of the community's buildings including early and detailed building and system design stages as well as their operation and maintenance. While extensive studies have been conducted on the impact of detailed design and operation stages on the energy performance of the community and the cogeneration system, early design stages have not been studied as much, although many studies (e.g. Grumman, 2003; CIBSE, 1998) contend that applying the principles of sustainability and energy efficiency in these early design stages can increase the potential of achieving larger reductions in energy use. To address this gap, this study focuses on design decisions typically decided by designers in these early design stages. The study does not address detailed design consideration of either the community or the cogeneration system.

Even with a scope limited to early design stages, a large number of community and cogeneration system design parameters can still be identified. The complexity of these parameters necessitated limiting this study to a selected number of them. The selected design parameters represent community design characteristics that have a potentially large impact the performance of the cogenerations system, and in the same time have wider impacts on the overall sustainability of the community. These parameters include: density of urban form, mix of uses, and street configuration, on the planning scale; housing typology, envelope and building systems' efficiencies, and utilization of renewable energy, on the building scale; and cogeneration system type, size and operation strategy, on the cogeneration system scale. The study acknowledges that the list of parameters addressed here is not exhaustive and that other design parameters can also impact the energy use of the community and the performance of the cogeneration system. The study also does not address the impact of these selected parameters on other energy end-uses within the community, such as transportation, or their impact on other sustainability considerations.

With regard to the selected climate zone for the study, limiting the scope of the study to cold U.S. climates was based on the results of previous studies (e.g. Fischer, 2003), which identified these climates as having a higher potential for achieving a good cogeneration system performance. The study, however, acknowledges that the design characteristics, configuration, and performance of the cogeneration systems being investigated are strongly influenced by climatic conditions as well as by other local factors such as energy prices, rate structures, and emission rates. While the large time requirements of investigating the performance of the cogeneration systems in multiple climate zones required this study to focus only on cold climates, more detailed studies are required to identify the potential for residential cogeneration systems in other climate zones as well as on the state and county levels.

While this study deals primarily with cogeneration as an emergent technology with potential environmental benefits, it does not investigate the technical details of the cogeneration systems or their interconnections with buildings. For the purposes of the study, system details are considered a controlled variable, and the cogeneration systems performance characteristics used in this study, e.g. electrical and thermal full and part load efficiencies, represent average values indicated by current literature. While future improvements in system details and/or its connection with buildings, resulting in improved performance characteristics, can affect the overall energy use of the system, these variations will not affect the relative impact of the various design parameters investigated in this study on the performance of the system.

Finally, the study was also limited by the capabilities of the simulation tools utilized in it. For example, the limitations of the tool used to simulate the performance of the cogeneration system prevented the evaluation of the impact of thermal storage, a cogeneration system component identified in previous studies as beneficial for the system performance especially in the case of the decentralized approach. However, as the inclusion of thermal storage would have caused improvements in the cogeneration system performance for all the community design alternatives investigated in the study, not including it does not significantly affect the relative impact of the design parameters investigated on the system performance, and therefore, the conclusions of the study, with regard to the optimization of the community design, remain valid.

Other limitation for this study include the uncertainty of the cogeneration systems' initial and maintenance costs, which result from the fact that many of these systems are in their early stages of commercialization. To address this issue, efforts have been made to compare different sources for this data and, in most cases, average values identified in recent literature as typical for such system were used. As variation in costs can have major impacts on the economic performance of the cogeneration system, sensitivity analyses of the impact of changes in these costs were conducted when possible.

1.6 ORGANIZATION OF THE DISSERTATION

This dissertation is divided into seven chapters. An outline of each of these chapters is presented next:

Chapter I introduces the research through discussing its context and background and describing the problems it seeks to address. The chapter also presents the aims and objectives of the research and outlines its significance, scope, and limitations.

Chapter II presents a review of relevant literature. The topics reviewed include: 1) a discussion of the general principles of sustainability, development, the environment, and energy; 2) sustainability as it relates to the built environment; 3) sustainability in residential communities, including efforts to increase the energy efficiency of these communities and examples of sustainable communities; 4) distributed generation and cogeneration technologies; and 5) assessment of sustainability, including sustainability indicators, building energy modeling and simulation, simulation of cogeneration systems' performance, estimation of emission levels, economic performance assessment, and Multi-Attribute Decision Analysis Methodologies.

Chapter III discusses the research methodology. The chapter describes the research design and the tasks performed in it including: 1) identification of community design parameters; 2) development of a base-line community model; 3) assessment of the performance of the cogeneration system within the base-line community model for both the centralized and decentralized integration approaches; 4) assessment of the impact of the selected design parameters on the performance of the cogeneration system for both approaches; and 5) optimization of the community design based on the relative impact of each parameter. The chapter also describes the different methods and tools used in each research task.

Chapter IV discusses each of the selected design parameters on the planning, architecture, and cogeneration system scales. For each parameter, the discussion includes: 1) the significance of the parameter; 2) its potential impact on the performance of the cogeneration system; 3) its wider impact on other sustainability issues within the residential community; 4) an analysis of the case studies with regard to this design parameter; and 5) the selected assessment values for each parameters, which constitute the design alternatives investigated to determine the impact of the parameter on the cogeneration system performance.

Chapter V presents the results of assessing the impact of variations in each of the selected design parameter on the performance of the cogeneration system as compared to the performance of the system within the base-line community for both integration approaches (centralized and decentralized). The assessment is based on the following performance indicators: percentage of reduction in annual community primary energy consumption due to the use of cogeneration, subsequent percentage of reduction in annual community CO_2 emissions, and the internal rate of return (IRR) of the cogeneration system.

Chapter VI describes the optimization of the community design, for each cogeneration integration approach, based on the individual impact of each parameter. Two optimization scenarios are identified for each approach. For the centralized approach, the scenarios include an optimum design scenario, and a minimum acceptable design scenario; while for the decentralized approach, the scenarios include a high-density scenario and low-density scenario.

Chapter VII summarizes the objectives, methodology, and results of the study, discusses its conclusions, and offers recommendation for future directions of research.

CHAPTER II
LITERATURE REVIEW

2.1 INTRODUCTION

Because of the cross-disciplinary nature of the issues addressed in this research, the following literature review covers a wide range of issues from different disciplines linked by their relationship to the overall context of sustainability. The review aims first to introduce sustainability as defined in relevant literature both as a general concept and then as it relates to the built environment. It then aims to offer both justification for the conducted research and support for its various components through a general, yet thorough, review of relevant literature in the different topics on which the research is based and which impacted its design.

To achieve those aims, a review of the definitions of sustainability and their relationship to development, the environment, and energy is presented, followed by a focus on sustainability in the built environment, including both planning and architecture, which highlights the significance of sustainable residential communities in this regard. Several directions and programs related to the sustainability of residential communities, which were used in developing the methodology of this study, are then reviewed. Distributed generation and cogeneration technologies are then presented focusing on their residential applications. Finally, the current state of the art in sustainability assessment and simulation of building and cogeneration systems energy performance is discussed, including a general background to the different tools used in the research. While this review focuses on general issues, additional references indicating data sources, and specific methods and techniques are included in following chapters.

The literature review presented here draws from multiple sources of sustainability related journals, reports, and books by leading researchers in planning, architecture and technology. Publications by U.S. and international organizations and research centers are also used including: the Department of Energy (DOE), Energy Information Agency (EIA), Environmental Protection Agency (EPA), U.S. Census Bureau, the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), National Renewable Energy Laboratories (NREL), Lawrence Berkeley National Laboratories (LBNL), Oak Ridge National Laboratories (ORNL), International Energy Agency (IEA), as well as other relevant sources.

2.2 SUSTAINABILITY

Although the majority of researchers now accept sustainability as a concept, there is little agreement in the literature over what it actually means or how it could be achieved. The following sections review the various definitions of sustainability and its relationship to development. The significance of the environment, the focus of this research, within the overall sustainability debate is then discussed and the role of energy systems in this regard emphasized.

2.2.1 Sustainability and Development

Historically, the literature on sustainability can be traced back to 19th century writings which questioned the ability of industrialization to satisfy mankind's needs (Edwards & Du Blessis, 2001). However, the term "*sustainable development*", which aims to reconcile the two seemingly conflicting intellectual human traditions of natural limits and material development (Mitchell, May, & McDonald, 1995), was first introduced in the influential Bruntland Report "*Our common Future*" (WCED, 1987), in which the term was defined as *"meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs"* (Steele, 1997, p.5). A number of other definitions of sustainability can also be found in the literature including one by the World Conservation Union (IUCN/UNEP/WWF, 1991) which stresses the need for improving quality of life within the carrying capacity of supporting eco-systems. While varying in details, these definitions emphasize the main issues dominating the sustainability debate, namely the need for balancing environmental, economic and social considerations while maintaining a good quality of life (Barton, 2000; Mitchell et al., 1995).

The lack of consensus indicated by the various definitions of sustainability is a reflection of the varying schools of thought involved in the ongoing sustainability debate. Although most of these schools acknowledge the three main components of sustainable development: the environmental, including protection of eco-systems and natural resources; the economical, including economic vitality and growth; and the social, including issues of equity and participation; they vary considerably in the importance they attach to each component (Cooper, 2002). Rothenberg (1989) classified the approaches to sustainable development into two main groups: *eco-centrists*, who are motivated by a lack of faith in modern technology and a belief in dematerialization; and *techno-centrists*, who believe in economic growth and the ability of technology to overcome all impediments. A different approach is presented by Sachs et al. (1996); Sachs (1999 & 2000), & Neuman (2005)) who suggest that sustainability is mainly a dialogue between how we live and how we should live and therefore achieving it requires changes in the life styles and even the value systems of people. Additionally, Beatly (1995) argues that sustainable development needs to be considered in a holistic and integrative way, in which methods of combining policies, programs and design solutions are sought with the aim of achieving multiple objectives, and both Barton et al. (2003) and Hart (1999) also argue that sustainable development policies should address all three main components: environmental sustainability, social sustainability, and economic vitality. Finally, Mitchell et al. (1995) and Curwell & Cooper (1998) identify 4 principles of sustainable development: environment, futurity, equity, and public participation.

2.2.2 Sustainability, the Environment, and Energy

The environmental dimension of sustainability stems from the growing realization of the increasing and potentially irreversible damage facing the environment, (WCED, 1987; Naess, 1989; IPCC, 1995, 2001; IEA, 1997). The Inter-governmental Panel on Climate Change (IPCC, 1995) concludes that this damage is, at least partially, caused by human utilization of nature, depletion of natural resources, and resulting increases in harmful emissions; and lists numerous environmental problems resulting from this including acid rain, pollution, desertification, deforestation, pollution of environmental sinks, decline in biodiversity, and global warming. In its third assessment report, the IPCC (2001, p 4) asserts that*" there is new and stronger evidence that most of the warming observed over the last fifty years is attributable to human activities".* Furthermore, Socolow et al. (2004) argue that continuing on currently predicted paths, which relegate significant action on global carbon emissions to a later time, is likely to cause the doubling of global CO_2 emissions relative to today's levels, and that this is likely to be accompanied by significant global warming, rising sea level, increased threats to human health, more frequent extreme weather events, and serious ecological disruption.

A strong and direct link exists between environmental sustainability: including issues of mitigation of existing environmental problems, protection of eco-systems, more efficient use of natural resources, and protection of natural processes and biodiversity; and between energy and energy systems. Reddy et al. (1997) contends that energy is not a sectoral issue but one that it is related to numerous dimensions of development, while Johansson & Goldemberg (2002, 2004) describe conventional sources of and approaches to providing and using energy as unsustainable and link them to significant environmental, social, and health problems both currently and in the future. Many other studies have linked environmental problems, either directly or indirectly, to current problems in the world energy system (e.g. IEA, 1998 & 2002; Borbely & Kreider, 2001; and Wuppertal Institute, 2002). These problems include dominance of fossil fuels, inefficient use of energy, and the inherent inefficiencies of the centralized system structure. A number of studies suggest different strategies to achieve a more sustainable energy system (IEA, 1998 & 2002; Borbely & Kreider, 2001; Johansson & Glodemberg, 2002 & 2004) including: more efficient use of energy especially at the point of end-use; increased use of renewable energy resources; accelerated development and deployment of new energy technologies; and decentralization of the world energy systems.

2.3 SUSTAINABILITY AND THE BUILT ENVIRONMENT

Increasing the sustainability of the built environment, through more efficient use of resources and reduced environmental impact, is a major component of sustainable development. Consequently, increasing energy efficiency in the built environment is a necessary, though perhaps not sufficient, requirement for achieving that purpose. Many studies conducted on the relations among sustainability, urban form, and building design indicate a clear potential for achieving significant reductions in energy consumption through intelligent, and sustainable planning and architecture (Breheny, 1992; Owens, 1986; Rickaby, 1985; Tabb, 1990; Williams et al., 2000). Grumman (2003) further argues that this potential is considerably larger when sustainability principles are applied in the early stages of the design process.

The following sections focus on sustainability as it relates to the built environment both on the planning and the architecture scales. The role of residential communities in this regard is then discussed, and different methods of reducing their energy consumption and increasing their sustainability, which will form the basis for developing the methodology of this study, are introduced. Finally, three case studies of sustainable residential communities, two in the U.S. and on in Europe, are also presented and discussed.

2.3.1 Sustainability and Planning

2.3.1.1 Sustainability, planning, and urban form

The concepts of sustainability in planning can be traced back to Howard's Garden City at the turn of the 20th century (Barton, 2000). More recently, many researchers argued for a strong relationship between sustainability and urban form (Breheny, 1992, 1996; Jenks et al.,

1996) and many of them criticized sprawl for being highly inefficient and unsustainable (Southworth, 1997; Ewing, 1997; Neuman, 2005). Burchell et al. (2002) lists many of the costs of sprawl including loss of resource land, increased energy consumption, increased infra-structure, increased travel, and negative social consequences.

Despite agreeing that sprawl is unsustainable, little agreement exists between researchers on which urban forms are sustainable and a strong debate continues between two sides defined by Breheny (1996) as *"Centrists",* who believe in high density, and advocate urban infill and revitalization; and *" De-centrists"*, who call for urban decentralization as a reaction to problems of industrialized cities. Jenks et al. (1996) contends that there are strong arguments for both sides of the debate, while Breheny (1996), Rickaby (1985), and Williams et al. (2000) all call for alternative solutions that make use of the advantages of both sides including some form of compactness, mix of uses, interconnected street configuration, strong public transportation, environmental controls and urban management.

Owens (1986, 1992) argued for a reciprocal relationship between energy and spatial structures and showed that changes in these structures can lead to up to 200% reduction in energy demand. Owens, Rickaby (1985), and Tabb & Gee (1990) also argue that while certain factors, such as transportation and certain energy applications, favor increased densities, and others, such as utilization of solar energy, favor more dispersed forms, these two factors are not mutually exclusive. A possible alternative suggested by Rickaby is a polycentric pattern consisting of small to medium size settlement clusters. Other proposed alternatives include eco-neighborhoods (Barton, 2000); smart growth strategies (O'Neill, 1999), and New Urbanism's "*neo-traditional*" communities, characterized by somewhat higher densities, a greater mix of uses, provision of public transit, accommodation of the pedestrian, and an interconnected street pattern (Southworth & Ben Joseph, 1997). These proposed alternatives will be discussed next.

2.3.1.2 New Urbanism

New Urbanism refers to a design-oriented approach to planned urban development, which emerged as an alternative to prevailing patterns of low-density, auto-dependent land development in the U.S. (Ellis, 2002; Fainstein, 2000). New Urbanism calls for well-structured cities, towns, and neighborhoods with identifiable centers and edges; compact development; infill development to revitalize city centers; pedestrian-friendly, interconnected streets; mixed land uses; avoiding auto-dominated landscapes; transit-oriented development; and intermingling of housing typologies (Duany & Plater-Zyberk, 1994; Katz, 1994; CNU, 2000; Ellis, 2002).

The fundamental organizing element of New Urbanism is the neighborhood. The charter of New Urbanism (CNU, 2000) asserts that the neighborhood should be compact, pedestrian friendly, with a mix of activities and a broad range of housing types, which aim to strengthen the social bonds of the community. Duany et al. (2000) identifies the optimal size of a neighborhood as a quarter mile from center to edge. This size aims to gather the neighborhood's population within walking distances of many of their daily needs, including a transit stop (Hebbert, 2003).

While a relationship can be seen between the principles of New Urbanism and those of sustainable development, the issue of New Urbanism's ability to provide a model for sustainable urban development is still being debated. Day (2003) argues that New Urbanism seeks to foster environmental sustainability yet notes that it emphasizes urban livability but gives limited attention to other dimensions of development. Similarly, Ellis (2002) argues that new urbanism holds the potential for significant environmental benefits but concedes that more research is needed on this topic; while Berke (2002) argues that new urbanism focuses much more on physical design characteristics than issues of ecology and social sustainability. Finally, Southworth (2003) contends that the future success of new urbanism, as a model for sustainable urban growth, will depend on whether it can integrate social and economic consideration into its models, currently dominated by physical characteristics.

2.3.1.3 Smart growth

Smart growth is a term that encompasses various planning strategies and practices that aim to accommodate the inevitable and continuing need for urban growth in the U.S. in an intelligent and sustainable manner. O'Neill (1999) defines smart growth as *"ensuring that neighborhoods, towns and regions accommodate growth in ways that are economically sound, environmentally responsible, and supportive of community livability".* Promoted by institutions such as the American Planning Association (APA, 1999), the Urban Land Institute (ULI) (O'Neill, 1999 & Corriagn et al., 2004) and the National Association of Home Builders (NAHB, 2002b), smart growth principles and strategies include: revitalization of cities and inner suburbs; mixing of land uses & concentrated centers; protecting environmental systems and conserving resources; creating a range of housing choices; enhancing connectivity and providing a variety of sustainable transportation choices; creating walkable communities; and compact designs.

While smart growth advocates urban infill development as the responsible, resource-conscious first choice to meet urban growth needs, it recognizes that a large proportion of those needs must be accommodated on the urban fringe (Corrigan et al., 2004). Smart growth aims to increase the attractiveness, accessibility, efficiency, environmental sensitivity, livability, and profitability of this new urban fringe development through integrating a mix of land uses, preserving open space, fiscal responsibility, and providing transportation options (O'Neill, 1999). A study by the Natural Resources Defense Council (NRDC, 2003), which aimed to measure the environmental benefits of smart growth by comparing two existing neighborhoods in Nashville, TN, concluded that the "*smarter*" neighborhood, on a per capita basis, occupies only two-thirds as much land; consumes 13% less water; emits 25% less CO_2; and has half the average annual rates of storm water runoff and associated water pollution.

A more radical approach of controlling urban growth and reducing sprawl, thus mitigating its negative impacts, is the establishment of urban growth boundaries (UGB). UGB's are invisible lines beyond which urban development can not extend into rural areas. Aven & Bayer (2003) report 146 examples of U.S. counties or cities with UGB. They however concluded that there is no empirically based substantiated method to determine the optimum size for UGB's which makes establishing them a rather difficult process.

2.3.2 Sustainability and Architecture

2.3.2.1 The climatic design tradition

Environmental issues and technologies have always played a role in shaping many buildings, sometimes quite profoundly (Cole, 2004). Impact of the environment on recent architecture can be traced back to the interest in climatic design, as seen in the early works of Olgyay (1963) and Givoni (1969, 1976). In his book *"Design with Climate",* Olgyay advocated a regional approach to architecture, which aimed to achieve thermal comfort through adapting to local climatic conditions. He also developed the *"Bioclimatic Charts",* which indicated the conditions under which different climate control strategy are effective in achieving comfort. Givoni, addressing similar issues, further improved the charts which he later used to develop the widely referenced and used Givoni-Milne charts and design strategies (Milne & Givoni, 1979). These strategies were later used in many studies dealing with climatic design (e.g. Lechner, 2001; Tabb, 1984). Other studies dealing with climatic design include the later work of Givoni (1981, 1994, 1998), which discussed passive and low energy cooling techniques; as well as

Watson and Labs' "*Climatic Design*" (1983), which suggested 50 climatic design practices and techniques, falling under seven climate control strategies to reduce the need for energy. Climatic design strategies also had an energy efficiency dimension as indicated by Watson and Labs, who contended that *"climatic design is the one approach by which to reduce the energy costs of the building comprehensively"* (p.3),

2.3.2.2 The energy crises and passive architecture

The early 1970's witnessed a widening of the environmental debate to address issues of resource depletion, population growth, and environmental impacts as exemplified by Meadows' "*the Limits to Growth*" (1972). However, the 1973 oil crises led to the focusing of this debate solely on energy supply and efficiency issues. Cole (2004) argued that this crisis added a "*survivalist*" emphasis to the environmental debate. The crises also had an impact on architecture and buildings as interest rose in reducing building energy consumption and the resulting subsidies programs caused an increase in research activities in the area. Two directions can be identified in this period: the first was aimed at providing energy autonomy and self-reliance to buildings and communities through reducing energy use using passive solar design strategies and the utilization of available site resources (e.g. rainwater harvesting); while the second direction focused on controlling indoor environments through mechanical systems and building envelopes. Cole (2004) contended that while the former direction, which required greater integration and collaboration between different disciplines, had more of an impact on building form, it was largely pursued at the small residential scale (skin-dominated buildings); while the latter direction, dealing mostly with larger load-dominated buildings, represented the main stream of the profession and was dominated by conventional mechanical environmental controls.

Interest in all of these directions has continued. In the case of passive design strategies, this included developing passive strategies based on historical precedents (Fathy, 1986; Lechner, 2001), thermodynamic calculations (Santamouris et al., 1998), and case study analysis (Hyde, 2000; IEA, 1994; Roaf et al., 2001); while in the case of renewable energy resources, it included active solar heating and photovoltaics as exemplified by the work of Duffie & Beckman (1991), Gordon (2001), Kreith & Kreider (1978), Lechner (2001), and Sick & Erge (1996). Interest in increasing the efficiency of building envelops and mechanical systems includes the work of Anderson et al. (2000); ASHRAE (2000; 2003); and Kreider & Rabl (1994). Although having different strategies, the goals and activities within these directions frequently overlapped.

2.3.2.3 Architecture, sustainability, and the environment

Cole (2004) argued that the mid 1980's was a formative point in which a comprehensive view of environmental concerns and an elevated sense of environmental responsibility were re-established and the "*survivalist*" emphasis of the debate was replaced by an emphasis on "*environmental responsibility*". This period also witnessed increasing appreciation of the social, economical, environmental, and technological dimensions of energy and paid more attention to the capacity of eco-system to support human activities. Emphasis was also placed of the impact of buildings on occupants' health and well-being. Consequently, a wider movement towards a more sustainable architecture emerged, which encompasses several schools of thought. Guy & Farmer (2001) identified six of these schools of though, which they described as "*competing logics*", and which differ in their emphasis, their relationship with technology, and their images of buildings and spaces. The two prominent logics are those emphasizing technology, believing in its ability to mitigate environmental problems; and those emphasizing ecology, focusing on protecting ecosystems and natural capital. The other logics identified emphasize health, aesthetics, social considerations, and culture respectively. While acknowledging the, sometimes substantial, differences between these logics, Guy & Farmer emphasized the need for constructing consensus between them in order to achieve the goals of sustainable architecture.

2.2.2.4 Environmental considerations and the design process

While interest in green and sustainable architecture continues to grow, Mazouz & Zerouala (2001) argue that environmental considerations still tend to be overlooked in the architectural design process mainly because of methodological obstacles. They further argue that such consideration should not be limited to the evaluation stage but should be integrated in the early stages of the design process in a way that contributes to the process of form generation with the aim of developing environmentally and climatically sound solutions. The need therefore exists to continue to develop effective methods of integrating environmental consideration in the various stages of the design process.

Garde-Bentaleb et al. (2002) identifies three types of design tools available to architects and engineers in different project design stages: 1) expert rules, mostly used by architects in the schematic design stage and take the form of simple general expression that need to be adapted to specific building types and climates; 2) simplified computer programs, which are typically user friendly allowing easy application by architects during the iterative stage of building architecture yet are fairly generalized and not adaptive to detail ; and 3) specialized computer programs mostly used by engineers in the detailed design stages and are typically not user friendly, has specialized user interface, and are mostly used for verification and evaluation purposes. Shaviv et al. (1996) also presents three approaches for computer-aided and simulation design tools: 1) comprehensive procedural simulations derived from first principles; 2) simplified procedural methods not derived from first principles; and 3) rules of thumb and acquired experience. Shaviv et al. however argue for the need for a knowledge-based evaluation model to be applied at the early formative stages of the design process, where the impact of design choices on the energy performance of the building is more significant and describe the development of such a model.

2.3.3 Sustainability and the Residential Sector

2.3.3.1 Significance of residential sector

According the EIA, the U.S. residential sector accounts for about 21% of the total U.S. energy consumption (compared to 18% for the commercial sector) (EIA, 2005a). The EIA (2005b) also projects U.S. residential delivered energy to increase by 23% between 2003 and 2025 (9% by 2010) and that 68% of that increase will be due to increased use of electricity. As a result, in 2004, almost 46% of the total residential energy use was lost in the generation, transmission, and transportation of electricity (EIA, 2005a), a percentage that would likely increase in light of the projected increased share of electricity. With regard to CO_2 emissions, the EIA (2004a) estimates the share of the residential sector to be about 21% of the total U.S. emission in 2003. This represented an increase of 1.7% from 2002 levels compared to the national average of 0.8%. This increase was due to: a 1.1% increase in housing stock; an increase in the share of electricity, accounting for more than two thirds of residential emissions; as well as the fact that new homes are, on average, 13% larger than existing housing stock, thus having higher energy demands. All of these statistics indicate the significance of the residential sector with regard to the goal of reducing energy consumption and emissions levels, and therefore, the significance of this study, which investigates the use of cogeneration as a potential method of achieving these goals.

The U.S. Census Bureau (2005) reports that in 2004, more than 1.5 million one-family houses were completed, an increase of 10.5% from 2003 and 23.3% from 2000. In comparison, only 0.31 million multifamily units were completed in 2004, an increase of 6.2% from 2003 and a decrease of 6.6% from 2000. The median size for one-family houses in 2004 was 2,140 ft^2, an increase of 4% from 2000, 10.3% from 1994, and 25% from the overall median for all housing units (US Census Bureau, 2004). In comparison, the median size of new multifamily units was in the range from 1,000 to 1,199 ft^2. This again shows the importance of investigating the potential for reducing the dominance of detached single family houses in the U.S. residential sector as a means of reducing the energy consumption and subsequent environmental impact of this sector.

2.3.3.2 Residential energy use characteristics

The EIA's Residential Energy Consumption Survey (RECS) (EIA, 2004b) reports the national average annual consumption of houses to be about 92 MMBtu/household/year, or about 43.2 kBtu/ft/year. This energy is typically used for space heating, cooling, domestic hot water (DHW), lighting, and equipment (including self-contained refrigeration, cooking, washing & drying, and other plug equipment). Residential energy consumption is characterized by large daily and seasonal load variations, with daily electrical load profiles typically ranging from 0.5 kW to over 15 kW for large houses (Anderson, 2003). Anderson (2004, per. comm.) contends that these large variations adversely affect the feasibility of some emergent technologies, such as on-site power generation. Research efforts in the area of residential energy efficiency are extensive and most of the studies cited in section 2.3.2.2 address this issue. Other notable studies in this area include Mazria's *"The passive solar energy book"* (1979), and Vale & Vale's *"The new autonomous house"* (2000). The following sections discuss a number of the programs aimed at increasing the energy efficiency, and subsequently the sustainability, of the residential sector on the local and national levels. While some of these programs only address the energy consumption of individual houses (e.g. Building America program, Home Energy Rating Standards (HERS), and Energy Star Program), others address a wider range of issues related to both buildings and their sites (e.g. Green Building Programs), while others address overall community energy efficiency (e.g. Community Energy Assessment and Design Support (CEADS)). These programs will be used in the following chapters in developing the methodology of this study, as a basis for identifying the community design parameters investigated in it, as well as in determining the values to be evaluated for each parameter.

2.3.3.3 Building America Program

Building America is an industry-driven research program sponsored by the U.S. DOE that applies systems engineering approaches to accelerate the development and adoption of advanced building energy technologies in new and existing residential buildings (Anderson et al., 2004; & Hendron et al., 2004). The multi-year goals of the program include the development of cost-effective, production-ready systems that will reduce whole-house energy use by 40-70% and increase onsite power production by up to 30%. The program also aims to improve indoor air-quality; encourage the adoption of a systems engineering approach in the design of new homes; and accelerate the development and adoption of high-performance residential energy systems. Measuring the progress towards achieving these goals is achieved through evaluating cost and performance trade-offs using a series of controlled field and laboratory experiments supported by energy analysis techniques using test data to "calibrate" simulation models.

As part of the program, a set of residential performance analysis procedures were developed including the definition of a research benchmark to be used as a fixed reference point to estimate the whole-house energy savings of prototype houses and subsequently progress towards achieving the goals of the program (Hendron et al., 2004; Hendron, 2005). In general, the benchmark is consistent with the 1999 HERS Reference Home, as defined by the National Association of State Energy Officials/Residential Energy Services Network (NASEO/RESNET, 2002), with additions that allow for the evaluation of all home energy uses including estimated annual consumption and detailed hourly energy usage and load profiles for different end-uses. This benchmark, and specifically the energy usage and load profiles developed within it, will be utilized in developing the residential prototypes used in this study.

2.3.3.4 Home Energy Rating Standards (HERS)

Efforts to develop national Home Energy Rating Standards (HERS) can be traced to 1991 when the U.S. DOE, in collaboration with the Department of Housing and Urban Development (HUD) initiated a collaborative process to define a residential home energy rating program linked with energy efficiency mortgage (EEM) financing (Judkoff & Neymark, 1995b). Following the 1992 Energy Policy Act, which called for creating guidelines for Home Energy rating Systems (HERS), a HERS council was incorporated, which worked in collaboration with NREL towards the development of such guidelines.

As a result of these efforts, HERS accreditation standards were published in 2002 (NASEO/RESNET, 2002), which aimed to ensure that accurate and consistent home energy ratings are performed by accredited home energy rating systems nationwide. HERS rate homes on an annual purchased energy consumption basis compared to a fixed reference home, the characteristics of which were based on the requirements of the 1993 Model Energy Code (MEC).

HERS included both a 0 to 100 point score and a one to five star rating. On the point score, the reference home achieves 80 points, then each 5% increase or decrease in the energy efficiency potential of the rated home compared to the reference home constitute a one-point increase or decrease in the score (from 80). Similarly, the star rating, which is based on the numerical score, awarded homes matching or exceeding the performance of the reference home a rating of 4 stars or above. A five star rating is achieved with a HERS score of 86 or above. Although intended to address whole-house energy efficiency, the 2002 HERS standards only took into consideration the heating, cooling, and hot water end-uses in the home. The HERS score is used by several green building programs as a basis for determining their required energy efficiency levels (NAHB, 2002c) as will be discussed in section 3.3.3.6. This score will be used in this study as a basis for determining the assessment values for the architecture scale design parameters.

In 2004, a number of enhancements to HERS were approved by RESNET (2004), which aimed to solve many known issues with the previous standards. The two major technical changes in these enhancements are: 1) changing the reference home to make it consistent with the requirements of the new 2004 supplement to the IECC (ICC, 2005); 2) introducing an “Expanded HERS score”, which accounts for lighting, appliances, and on-site energy production, in addition to space heating, cooling, and domestic hot water. The previous HERS score was maintained and renamed the “Classic HERS score”. The standards gave program providers the option of reporting either the two scores or only the classic score.

2.3.3.5 Energy Star Program

Energy Star is a program administered by the EPA, which establishes high energy efficiency standards which equipment and homes need to meet to be awarded the government-backed Energy Star label. The label can then be used by manufacturers and builders for marketing purposes. The program works in partnership with manufacturers, retailers, home builders, state and local programs, and other businesses and institutions to encourage greater investment in energy efficiency on a cost effective basis (EPA, 2005). The EPA reports that the Energy Star label can be found on 40 different types of products and 32,000 individual product models and that, in 2004, 1.5 billion Energy Star products have been purchased. Efficient new homes became eligible for the Energy Star label in 1995 and the EPA reports that 360,000 Energy Star homes are now in place, saving 125 billion kWhs of energy and preventing 30 million metric tons of green house gases (GHG) emissions (EPA, 2005). Energy Star building systems and appliances efficiencies will be used in developing several of the design alternatives investigated in this study.

Homes can qualify for the Energy Star label in different ways depending on their method of construction. Homes constructed on site can qualify either by achieving a HERS score of 86 or by using one of the "*Builder Option Packages*" (BOP), which are a set of construction specifications, each for a specific climate zone which specify performance levels for the thermal envelop. The EPA (2005) contends that Energy Star homes provide comfort, value, and savings to home owners and increased profits to home builders, while protecting the environment.

2.3.3.6 Green building programs

Aiming to increase the overall sustainability of the residential sector, local green building programs, many of which are in various stages of development throughout the U.S., offer a more comprehensive approach that addresses a wider range of issues compared to the previous two programs. These issues include, among others, site considerations, energy use, water conservation, materials selection, and waste management (NAHB, 2002a & c). NAHB (2002c) gives a summary of 26 green building programs currently active in the U.S. and reports that, as of 2002, more than 18,000 homes have been built in compliance with them mostly in the Built Green Colorado Program in Denver and the Austin Energy Green Building Program, both recognized by NAHB as having the largest and most established programs in the country. Although some of these programs are mandatory (e.g. Boulder, CO's Green Points Program), most are voluntary and builders are motivated to participate through market recognition.

Green building programs can have an impact on improving the performance of buildings, reducing their environmental impact, and preserving natural resources. They also help in educating builders and home buyers about more efficient systems, materials, and building techniques that can result in considerable environmental benefits, and can demonstrate the economic feasibility of these systems and materials on a life-cycle cost basis. Additionally, these programs can provide a suitable way of demonstrating emergent technologies and systems and can offer them a niche market which can then be used as a basis for wider distribution. On these bases, such programs can form a suitable market for cogeneration systems. However, while having a more comprehensive approach than those focusing only on building energy consumption; green building programs, with some exceptions such as the Built Green Colorado Communities Program, do not address community level issues such as density and mix of uses.

With regard to energy, most green building programs require houses to achieve a minimum level of energy efficiency, and then award extra points for lower energy use and/or higher component efficiencies. While some programs require homes to meet state energy efficiency codes (e.g. Florida Green Building Coalition) or to exceed it (Wisconsin Green Built Homes); others require them to achieve a minimum HERS score (e.g. Built Green Colorado) and then award extra points for achieving higher HERS scores. Other programs require homes to achieve either the national or the state equivalent of the Energy Star rating (e.g. Seattle Built Green), while others (e.g. Austin's Green Building) award points on a component performance basis. In its guidelines for Green Building Programs, NAHB suggests a minimum efficiency level that meets the 2003 IECC code (ICC, 2003) requirements, and then three achievement levels corresponding to reductions of 15%, 30%, and 40% from that level.

On the national level, the U.S. Green Building Council (USGBC) is currently developing a homes component of its LEED program as a voluntary initiative aiming to promote more sustainable practices in the mainstream home building industry (USGBC, 2005). While still under development, "*LEED for homes*" adopts a comprehensive approach addressing a wide range of issues on the building, site, and community levels. The program currently requires homes to achieve an Energy Star rating and awards extra points for higher HERS score.

2.3.3.7 Community-wide energy efficiency programs

Compared to the numerous studies and programs dealing with residential energy efficiency on the individual home scale, the complexities involved with addressing this issue on the community scale reduced the number of studies attempting to achieve that. Sung (2004) provides a review of one of these activities, the Comprehensive Community Energy Management Planning (CCEMP), developed by Hittman and Associates Inc. and adopted to reduce energy consumption in the City of Boulder, CO. CCEMP aimed to measure current community energy usage and to develop energy conservation methods on the community level. CCEMP methodology accounted for energy use in the residential, commercial, industrial, municipal, and transportation sectors of a community, based on each sector's fuel mix, and using a blend of user input and default procedures. CCEMP methodology was used by Sung (2004) as a starting point for developing a methodology for calculating NOx emissions reduction from energy conservation strategies.

The Community Energy Assessment and Design Support (CEADS) tool is another attempt to address energy efficiency issues on the community scale. CEADS, developed by the Joint Center for Energy Management (JCEM) and the Vesica Group Architects (VGA) for the Japan Research Institute (JRI), is a software designed to aid the decision making process for the planning of sustainable communities which is focused on energy conservation and renewable energy resources (Sung, 2004). Tabb & Krieder (2000), in a study of the use of CEADS to design a prototype sustainable community in southern Japan, discussed the conceptual design elements of the prototype and the basic quantitative mechanism and functions of community-scale energy use. The inputs needed for the CEADS analysis included community size, density, mix of building typologies, building thermal properties, integration of solar technologies, transportation options, destination efficiencies and infrastructure configurations.

The previous studies, and the scarcity of similar ones, indicate the complexities involved in addressing community-scale energy efficiency. They also indicate that finding an optimum solution on that scale requires analyzing the impact of multiple parameters, and that while some of these impacts are positive and additive, others, while individually having a positive affect, are not additive (e.g. density and the utilization of renewable energy sources).

2.3.4 Sustainable Residential Communities

2.3.4.1 Defining sustainable residential communities

The difficulties in defining what a sustainable residential community is stems from the various definition of and approaches to sustainability as discussed earlier. Sustainable communities therefore generally aim to address one or more of the issues involved in the sustainability debate. These issues, however, are not mutually exclusive and a number of attempts have been made, including the examples discussed later, which aim to comprehensively address the various components of sustainability (i.e. environmental, social, and economical) with varying degrees of success.

Many sustainable communities are currently in different stages of development throughout the U.S. and Europe. Barton (2000) argues that developing such communities can change the prevailing culture of local decision makers, professionals, and development companies. Kleiner & Barton (2000) cite many difficulties in both establishing selection criteria and collecting information about new sustainable communities. They however offer a survey of

60 world-wide communities including 10 U.S. ones. Corbett & Corbett (2000) propose that new developments take the form of garden city units, made up of garden village neighborhoods, and offer an analysis of four case studies of new U.S. “Garden Cities”. Other listings of sustainable communities include Jackson & Svensson (2002); the DOE’s Smart Communities Network (SCN) (2005b); and the Sustainable Communities Network (SCN) (2005). These communities offer a large opportunity for achieving better energy performance as well as demonstrating some emergent technologies, such as cogeneration, under more favorable conditions.

2.3.4.2 Traditional neighborhood development & transit oriented communities

New Urbanist communities form a type of residential communities that, among other goals, aims to address some of the issues of sustainable development. These communities exist both in the form of urban & suburban infill, encouraged by the CNU charter (CNU, 2000) over peripheral expansion; as well as urban extensions when infill is insufficient to meet the needed growth. New Urbanism, however, argues that urban extension should be organized as neighborhoods and districts and developed with a mix of activities and with homes for a mix of incomes (CNU, 2000; Hebbert, 2003). Two directions can be identified within new urbanism with regard to the form of new communities; the first is Duany’s Traditional Neighborhood Development (TND), while the second is Calthorpe’s Transit Oriented Development (TOD) (Grant, 2002). TND (Duany et al., 1994, 2000) calls for intensification and mixing of uses in a fine grain and promotes residential units over stores in a diverse but low rise town center (Grant, 2002). TOD, on the other hand, concentrates development in nodes associated with transit station with a density gradient starting from next to the transit lines and decreasing towards the neighborhood edges (Calthrope, 1994). Duany et al. (1994) agues that there is general agreement regarding the physical composition of the neighborhood between the TND and the TOD, as they both offer a balanced mix of dwellings, workplaces, shops, civic buildings and parks; while Grant (2002) claims that those committed to urban sustainability prefer the TOD because of its more efficient use of infra structure, and reduced environmental impact.

The following sections present a brief and general description of three sustainable residential communities, two in the U.S. and one in Europe. A more detailed analysis of the main design characteristics of these case studies is included in chapter IV where they are used as one of the bases for identifying the community design parameters addressed in this study as well as the assessment values for each parameter. The U.S. case studies presented here represent the two types of urban growth discussed earlier, urban infill and expansion. They also represent two contrasting U.S. climates, cold and hot dry. The European case study is included as an example of a residential community which actually utilizes cogeneration technologies.

2.3.4.3 Community of Civano, Tucson, AZ

Originally named the "*Tucson Solar Village*", Civano is an 818 acres master planned community within the city limits of Tucson, which is designed to offer a unique sustainable and livable community based on principles of long-term sustainability and New Urbanism including a respect for, and integration with, the natural environment and the creation of a pedestrian-friendly community (City of Tucson, 2005). History of Civano dates back to the 1980's, while its first master plan was approved in 1992. The first stage of the community, Neighborhood I Planned Area Development (PAD) was approved in 1997 and revised in 1998 (Community Design Associates, 1998). Many parts of this neighborhood are now either complete or under construction and master plans for the remaining stages of the community are under development.

The environmental performance of Civano is governed by its "*IMPACT*" system, initially approved in 1995 and revised in 2003. The IMPACT standards describe the principal areas of resource conservation, and required and suggested performance targets for Civano (City of Tucson, 2005). These targets include reducing residential energy consumption by 65% from Tucson's 1990 levels and 50% from 1995 levels; reducing commercial energy consumption by 55% from 1990 levels; reducing domestic water consumption by 65%; reducing internal vehicle miles by 40%; and creating one job on-site for every two residences (City of Tucson, 2003). Based on this, both a model energy code (MEC) and a set of sustainable energy standards (SES) were prepared for Civano. Al Nichols Engineering inc. (ANE) (2004) reports that, in 2003-2004, energy consumption in Civano homes ranged from 30 to 130 kBtu/ft^2/year of source energy with the average consumption being 74.75 source kBtu/ft^2/year per home, and that approximately 4.6 kBtu/ft^2/year reduction (per home) at Civano resulted from the use of solar hot water heating. ANE (2003) also found the average total energy use at Civano homes to be 66% that of Tucson at-large homes, and 70% that of Tucson 1998/99 homes.

Civano homes were used as demonstration projects by the Building America program for a number of technologies including integrating solar-assisted DHW systems in 18 Civano homes, which achieved a solar fraction (i.e. the percentage of the DHW loads met by solar energy) of 0.48 & 0.66 (Rittelmann, 2004); as well as the design and construction of seven prototype homes in collaboration with one of Civano's local builders, which aim to achieve the energy consumptions reductions required by Civano's SES (IBACOS Consortium, 2003). This indicates that the improved energy consumption characteristics of such sustainable residential communities make them suitable for demonstrating emergent building technologies, which is one of the premises of this study.

2.3.4.4 Highlands Garden Village, Denver, CO

Highlands Garden Village (HGV) is a 27 acre residential mixed-use urban infill project built on the site of the Elitch Gardens amusement park in Denver, Colorado. The master plan for HGV was designed by Peter Calthorpe, and the project is being developed by Jonathan Rose & Co. When complete, HGV will include 346 living units, including single family, town homes, live/work, lofts, apartments, senior housing, and a "co-housing" area, in addition to 90,000 ft^2 of commercial space, including retail, office, community buildings, and a small private school (Calthorpe & Fulton, 2001; NAHB, 2002b). Calthorpe and Fulton describe HGV as an example of Greyfield redevelopment that reflects the pattern of its surrounding neighborhood; while Haughey (2005) presents it as an example of smart growth, describing it as a walkable, transit-linked community and a financially viable model for environmentally responsible development.

With regard to energy use, NAHB (2002b) reports that HGV home will aim to meet the requirements of two programs: the Colorado Built Green Program (the local green building program in Denver), and the Colorado E Star Program (the local home energy rating system). Other green building features in HGV are: energy efficient mechanical systems; energy efficient water heaters and home appliances; reconstituted or recycled interior doors; insulated exterior doors; fly ash concrete using waste from coal-fired power plants.

2.3.4.5 Community of Kronsberg, Hannover, Germany

The Kronsberg community is a new sustainable suburb of Hannover, Germany located adjacent to the EXPO2000 location. Kronsberg was initially built to house visitors to the expo with the intention of being a long-term residential project (City of Hannover, 2004). When fully completed, Kronsberg will include 6,000 residential units grouped around neighborhood parks and housing about 15,000 people. The district also includes a number of mixed uses such as day care centers, schools, health centers, and some office spaces (City of Hannover, 2000). The main objectives for Kronsberg were achieving optimal sustainable planning and construction on all levels (environmental, social, and economic). The environmental dimension is exemplified by the "*Ecological Optimization*" project, which included: energy efficiency optimization; a rainwater conservation concept; as well as waste management and soil management concepts.

With regard to energy, Kronsberg homes aimed to achieve a heating energy demand of 50 kWh/m^2/year (compared to the national German standards of about 96 kWh/m^2/year). Kronsberg energy planning also gives priority to district heating and waste heat utilization (cogeneration). The target for Kronsberg was to reduce CO_2 emissions by 60%, with no extra cost, compared to normal German levels. 23% of this reduction would result from the district heating. A further 20% reduction was also planned through the use of wind power. Monitoring of Kronsberg homes showed them to have an average energy index of 56 kWh/m^2/year in 2001 representing a saving of 42% compared to national standards.

The district energy concept in Kronsberg was achieved using two operational centralized cogeneration plants, each with its own district heating network. The first plant, serving about 2,300 dwellings and other facilities through 6 km of pipelines, contains two 5 MW boilers and a cogeneration unit delivering 1,250 kW of electricity and 1.65 MW of thermal energy. The second plant serves about 742 dwellings through 2.5 km of pipelines and consists of two gas boilers, 1.65 MW each; and 2 cogeneration modules each delivering 110 kW of electricity and 220 kW of thermal energy. Monitoring showed that the district heating network in Kronsberg has resulted in a reduction of CO_2 emission of 45% compared to the reference scenario.

Because of its characteristics, Kronsberg homes and other buildings have been used for various demonstration projects of emergent technologies and design concepts including, among others, low-energy and passive solar homes; solar thermal collectors and thermal storage; photovoltaic systems; a housing development project with a micro-climate zone, as well as a number of sustainable construction techniques.

2.4 DISTRIBUTED GENERATION AND COGENERATION

Previous sections have discussed some of the problems associated with the current structure of the world energy system including the dominance of fossil fuels, the considerable energy losses associated with centralized generation, transmission and distribution of electricity, the subsequent CO_2 emissions resulting from that, as well as the concerns about the vulnerability of the system. The following sections discuss the concept of distributed generation (DG) as a possible alternative for the existing centralized system, which has the potential of reducing these problems. The discussion includes the possible advantages of DG, its available technologies, and the obstacles facing their wider use in the U.S. Cogeneration is then presented as a potential technology which can further increase the advantages of distributed generation, and the possible technologies and typical components of cogeneration systems are discussed. Residential applications of cogeneration are then presented including possible integration approaches, available technologies, and a review of residential cogeneration performance assessment studies in the U.S.

2.4.1 Distributed Generation

2.4.1.1 Definition and advantages of distributed generation

DG is an alternative to centralized power production involving the deployment of relatively small generators on-site to meet some or all of a facility's power needs (Caton, 2003) and can also be used to provide support to a utility's distribution network (IEA, 2002). Typical DG technologies include engines, small and micro turbines, fuel cells, and photovoltaic systems. The IEA (2002), in a study of DG, contends that it has the potential of positively changing the current structure of the world energy system, while Braun et al. (2004) argue that deregulation of the electric utility industry, already proceeding in several states, as well as technological advances in smaller power generation technologies and end-user equipments will all act as strong market forces, which will result in increased use of DG technologies.

DG offers several potential advantages compared to centralized systems. WADE (2003) identifies several of these advantages including: 1) lower CO_2 emission; 2) lower costs; 3) lower transmission and distribution losses; 4) greater power quality; and 5) less system vulnerability. In addition, a study by ORNL (2003b) aiming to quantify the benefits of distributed energy resources shows net benefits for DG in the following: 1) cost; 2) reliability; 3) emissions reductions; 4) ancillary services; and 5) postponement of transmission and distribution expansion. Another ORNL study (2003a) of the emissions benefits of DG in Texas concludes that, while DG will produce emissions on the local level, the power it displaces might have produced more emissions and that the emissions reduction from other sources can be over 20 times as much as the production from DG. Reducing the vulnerability of power systems through decentralization also gains further importance in light of current homeland security concerns.

A suggested concept based on the DG principle is that of *microgrids*. *Microgrids* consist of multiple generation devices, either serving one customer or an aggregation of customers, which are viewed by the traditional power system, or *macrogrid*, as a single, controllable system (Firestoen & Marnay, 2005). Research in microgrids is currently being conducted in LBNL using both modeling and demonstration projects and a number of assessment tools have been developed for that purpose (Siddiqui et al., 2003; Bailey et al., 2003). Other studies of distributed generation include Borbely & Kreider (2001); Chambers et al. (2001); and Willis et al. (2000). The DOE is also involved in a large research and development effort to promote DG (IEA, 2002; EERE, 2005).

2.4.1.2 Distributed generation & sustainable development

From the point of view of overall sustainable development, in addition to the environmental benefits of energy use and emissions reductions, Houghton (2000) suggested the establishment of *"community energy utilities"* as a vital element of new sustainable settlements and argued for the social and economic benefits of DG and contended that developing small scale, locally-based, community energy utilities can have many societal benefits including increasing awareness of the consequences of energy use, increasing social responsibility, and improving local economy through lowering energy costs and providing local employment. Houghton concluded that *"a successful community energy utility has the potential to bring together the three main strands of sustainable development - environmental and social responsibility within a sound economy"*.

2.4.1.3 Obstacles facing distributed generation in the U.S.

The IEA (2002) identified a number of obstacles facing DG in U.S. markets, which include: low cost of electricity and spikes in natural gad prices, which negatively impact the economics of DG projects; decentralization of the permitting process, which hinders approval of these projects; variable interconnection standards between DG and the grid; incomplete regulatory reform in many states; as well as local environmental standards, which sometimes prohibit the use of certain systems.

2.4.2 Cogeneration Systems

2.4.2.1 Cogeneration definition, advantages, and current obstacles

The use of cogeneration, also known as combined heat and power (CHP) and defined as the combined production of electrical power & useful thermal energy (Caton, 2003), increases the efficiency and potential benefits of distributed generation through the utilization of the otherwise wasted heat resulting from electricity generation (ORNL 2003a, b). This utilization, which is not possible in the case of centralized generation, typically results in increased system efficiencies, reduction in harmful emissions, as well as potential reductions in energy cost.

Aiming to benefit from the potential advantage of cogeneration, a number of DOE and EPA programs and initiatives currently exist to promote their use in the U.S. These programs include the Cooling, Heating, and Power for Buildings Program (BCHP, 2004) and the EPA-Combined Heat and Power Partnership (EPA, 2004). These programs aim to develop different cogeneration technologies and to promote their use in different market sectors with the goal of increasing U.S. cogeneration capacity from 46 MW to 92 MW by 2010 (Trouche, 2003). On the other hand, and similar to distributed generation in general, Caton (2003) identified a number of obstacles that hinder the wider use of cogeneration in the U.S. including: 1) high cost of capital investment, 2) local environmental concerns due to increased local emissions, 3) low cost of electricity, 4) restricted revenue from electricity sale, and 5) high utility back-up rates. Caton, however, maintained that these obstacles can be either minimized or eliminated.

2.4.2.2 Typical components of cogeneration systems

Cogeneration systems mainly consist of a prime mover, a heat recovery unit and may include other thermally activated technologies. The following review of existing technologies is based on Borbely & Kreider (2001); ONSITE (1999); Orlando, (1996, 1997); and BCHP (2004). Different prime mover technologies currently exist ranging in sizes from a few kW's to several MW's. Prime mover technologies for buildings include gas turbines, reciprocating engines, microturbines, and fuel cells. Engines offer higher electrical efficiencies and more size flexibility but have a lower thermal output and higher maintenance costs. Turbines, on the other hand, have higher heat to power ratios and lower maintenance costs but have lower electrical efficiencies and a minimum size of about 500 kW. Microturbines come in smaller sizes and have lower maintenance costs but are still less commercially established than gas turbines. Fuel cells, on the other hand, are a very promising, emergent, technology offering a wide range of sizes, high efficiencies, very low maintenance, and no byproducts. Fuel cell technologies are now in different stages of development although some of them are commercially available. Different sizes of fuel cells are now being developed for various applications including stationary power generation, motor vehicle power, as well as smaller, portable, units ranging in size from 5 W or smaller to 100 W power levels that could be used as a *"personal"* power source (Hirschenhofer et al., 1998). A summary prepared by ONSITE (2000) of the technical characteristics of currently available cogeneration technologies is included in table 2-1.

In most cogeneration applications, exhaust gasses from electric generation are ducted to a heat exchanger and the resulting hot water or steam is then either used directly, or used to run thermally activated technologies such as absorption chillers or desiccant dehumidifiers (BCHP, 2004). Absorption chillers use almost no electricity, are more environmentally friendly and quieter than electric chillers (BCHP, 2004). They are particularly useful when the heating loads are highly seasonal (space and water heating) since they can level the annual thermal load and increase the overall efficiency (Orlando, 1997). To reduce the initial design and engineering costs of cogeneration systems, pre-engineered, factory-assembled, *"packaged"* systems have been developed, which are characterized by lower design costs, factory testing, and reduced installation time (Caton, 2003). However, these packaged systems can not be customized to the specific needs of a facility.

2.4.2.3 Cogeneration systems design strategies

Caton (2003) identified four operating points for sizing cogeneration systems based on the electrical and thermal needs of the project. These are: 1) matching the thermal needs while maintaining the power supply low and purchasing supplementary power from the local utility; 2) matching electrical power needs and having excess thermal energy; 3) matching electrical power needs while not satisfying thermal needs, in which case a supplementary boiler is usually used; and 4) matching thermal needs and having excess electrical power, in which case this power can be sold back to the utility. Caton contended that the first strategy offers the best economic and operational choice for cogeneration projects. Grumman (2003) recommended sizing cogeneration systems based on the lesser of the thermal and electrical needs. The ratio of thermal energy to electrical power needs of a facility, known as the heat to power (H/P) ratio, is also an important factor in selecting the prime mover type. Gas turbines are typically more suitable than engines for higher H/P ratios (Caton, 2003) and vice versa.

Table 2-1 Description of the Technical Characteristics of Currently Available Cogeneration Technologies (Source: ONSITE, 2000)

	Diesel Engine	**Natural Gas Engine**	**Steam Turbine**	**Gas Turbine**	**Microturbine**	**Fuel Cells**
Electric Efficiency (LHV)	30-50%	25-45%	15-35%	25-40% (simple)40-60% (combined)	20-30%	40-70%
Size (MW)	0.05-5	0.05-5	Any	0.5 -200	0.025-0.25	0.2-2
Footprint (ft^2/kW)	0.22	0.22-0.31	<0.1	0.02-0.61	0.15-1.5	0.6-4
CHP installed cost ($/kW)	800-1500	800-1500	800-1,000	700-900	500-1300	>3000
O&M Cost ($/kWh)	0.005-0.008	0.007-0.015	0.004	0.002-0.008	0.002-0.01	0.003-0.015
Availability	90-95%	92-97%	Near 100%	90-98%	90-98%	>95%
Hours between overhauls	25,000-30,000	24,000-60,000	>50,000	30,000-50,000	5,000-40,000	10,000-40,000
Start-up Time	10 sec	10 sec	1 hr-1 day	10 min –1 hr	60 sec	3 hrs-2 days
Fuel pressure (psi)	<5	1-45	n/a	120-500 (may require compressor)	40-100 (may require compressor)	0.5-45
Fuels	diesel and residual oil	natural gas, biogas, propane	all	natural gas, biogas, propane, distillate oil	natural gas, biogas, propane, distillate oil	hydrogen, natural gas, propane
Noise	moderate to high (requires building enclosure)			moderate (enclosure supplied with unit)		low (no enclosure required)
NOx Emissions (lb/MWh)	3-33	2.2-28	1.8	0.3-4	0.4-2.2	<0.02
Uses for Heat Recovery	hot water, LP steam, district heating	hot water, LP steam, district heating	LP-HP steam, district heating	direct heat, hot water, LP-HP steam, district heating	direct heat, hot water, LP steam	hot water, LP-HP steam
CHP Output (Btu/kWh)	3,400	1,000-5,000	n/a	3,400-12,000	4,000-15,000	500-3,700
Useable Temp for CHP (°F)	180-900	300-500	n/a	500-1,000	400-650	140-700

2.4.2.4 Feasibility and potential applications of cogeneration systems

The feasibility of a cogeneration system is conventionally assessed based on the economic return on invested capital. Caton (2003) argued that the economic performance of a cogeneration system is highly affected by its initial capital cost as well as by the magnitude and profile of the building loads. He also argued that this performance is sensitive to the cost of electricity and fuel and especially the utility rate structure, which may include demand (peak) charges and/or back-up or standby-power charges.

Cogeneration systems are proven to be economically successful in industrial plants and large building complexes such as hospitals, and universities (Orlando, 1997). A DOE study (RDC, 2002) puts the potential building sector market for cogeneration at almost 17 GW in 2010, growing to over 35 GW by 2020. The same study shows that many cogeneration system options provide paybacks periods of much lower than 10 years, with a significant portion of them having payback periods under 4 years. The study shows that most cogeneration systems are concentrated in education and health care applications. With regard to district heating networks, a national census conducted by ORNL in 1993 (ORNL, 1993) indicates that the U.S. has about 6,000 operating networks providing about 1.3% of all U.S. energy use. The study also shows that the majority of these networks are located in colleges and hospitals (more than 30% each), while only 1.9% of them are located in residential communities. The reviewed studies, however, show that the potential exists for cogeneration systems in other building sectors, one of which is the residential sector as will be discussed in the following section.

2.4.3 Cogeneration and Residential Applications

2.4.3.1 Residential cogeneration & integration approaches

Although cogeneration is less established in the residential sector especially in the U.S., efforts have recently been conducted to promote its use in that sector. HUD has a program for cogeneration in multi-family residential applications (Groberg, 2003). Micro-cogeneration systems have also been addressed in a 2003 DOE workshop held to explore solutions to barriers facing these applications. A DOE roadmap (DOE, 2003) resulted from the workshop and concluded that micro-cogeneration offers potential benefits to homeowners, utilities, manufacturers, and society at large and that certain available technologies are currently able to meet the energy needs of some markets. The Department of Defense (DoD) also has an active program for demonstrating the performance of residential fuel cell based systems, most of which utilize cogeneration, as part of a larger fuel cell demonstration program (White et al., 2004).

Two approaches can be identified for integrating cogeneration systems in residential communities, the centralized and the decentralized. Centralized integration involves a central plant supplying electricity, heating and possibly cooling to a number of buildings through electrical distribution and district heating/cooling (DHC) networks. However, as discussed previously, few of these community energy networks currently exist in the U.S. While the centralized integration approach can utilize larger sized and more established technologies, the overall system efficiency is negatively impacted by losses in the DHC network. The ASHRAE Systems and Equipment Handbook (ASHRAE, 2000) recommends using DHC systems in high-density building clusters but cites some successful stories for low-density residential areas. Phetteplace (1995b), while emphasizing DHC systems' potential for energy conservation and reduced environmental impacts, identified the high cost of piping as a major barrier for their widespread use in the U.S. Figure 2-1 shows an image of a central cogeneration plant in the community of Kronsberg in Hanover, Germany.

Decentralized integration, on the other hand, is a new alternative, in which smaller-sized micro-cogeneration systems are integrated in individual homes. This option is becoming more feasible with the technological advances in micro-cogeneration technologies. While not having the penalty of network losses, micro-cogeneration systems, because of their relative novelty, are still lower in efficiency and higher in initial cost than their larger-sized counterparts. Knight and Ugursal (2005) report that the use of cogeneration for residential buildings has yet to become commercially viable though several manufacturers have developed, or are developing, products suitable for residential use. One of these products, a 1 kW SOFC fuel cell, is shown in figure 2-2.

Figure 2-1 Central Cogeneration plant – Kronsberg Community, Hannover, Germany (Photo by Researcher)

Figure 2-2 The 1-kW HXS 1000 SOFC Micro Cogeneration System (Source: Knight & Ugursal, 2005)

2.4.3.2 Residential cogeneration available technologies

Available technologies for residential cogeneration applications vary depending on the selected integration approach. Centralized integration typically requires meeting relatively large loads and can therefore utilize the more established technologies shown previously in table 2-1 such as medium sized reciprocating engines, fuel cells, and microturbines. Decentralized integration, on the other hand, requires the use of the newer micro-cogeneration technologies. The DOE (2003) lists 4 possible residential technologies including: 1) Stirling engines, 2) reciprocating engines, 3) fuel cells, and 4) Rankine cycle generators. Knight & Ugursal (2005) provide an up-to-date review of the various cogeneration technologies suitable for residential applications, including reciprocating engine, fuel cell, and Stirling engine based systems and offer a review of currently available commercial models as well as those under development. They conclude that commercially available small reciprocating engine, fuel cell, and Stirling engine based systems are suitable for single- and multi- family residential applications (1 - 10kW), and that, technologically, fuel cell and Stirling engine cogeneration systems seem promising for residential applications; although they still require significant reliability and affordability improvements to see wider acceptance.

On the other hand, residential and small-scale commercial systems based on reciprocating engines are currently well proven, robust, and have reasonable costs. Knight and Ugursal (2005) also conclude that reciprocating engines have a higher electrical efficiency than Stirling engines, while fuel cells promise to have the highest electrical efficiency. Reciprocating engines, however, have higher maintenance requirements, as well as CO, NO_x, and particulars emissions than other competing technologies. On the other hand, fuel cells have the lowest NO_x & CO emission levels. A summary of the typical properties of single and multi-family residential cogeneration systems prepared by Knight and Ugursal (2005) is included in table 2-2.

Table 2-2 Summary Table of Properties – Single and Multi-Family Residential Cogeneration Systems (Source: Knight & Ugursal, 2005)

Parameter range	ICE	Fuel Cell	Stirling
Electrical Capacity (kWe)	1-100	0.5-100	1-55
Electrical Efficiency* (HHV)	20%-40%	30%-50% PEMFC 40%-50% SOFC	20%-35% Current 35%-50% Possible
Heat Recovery Efficiency (HHV)	50%-60%	40%-60%	40%-60%
Temperature of heat available (°C)	85-110	80-100 PEMFC 950-1000 SOFC	200
Overall Efficiency** (HHV)	80%-90%	70%-90% PEMFC 70%-95% SOFC	65%-95%
Thermal Output (kWth)	3-300	1-300	3-150
Availability	85%-98%	95%	85%-90%
Part Load performance efficiency	Good	Best	Better
Maintenance – cost (US$/kWh)	0.01-0.015	0.008-0.012	0.02-0.03
Emissions – NOx, SOx, COx, Particulates	Low	Lowest	Lower
Cost (US$/kWe)	1,000-2,800		

* Electrical efficiency = electrical output (kW)/ fuel input (kW) based on Higher Heating Value or Gross Calorific Value.

** Overall efficiency = useful heat recovered (kW) + electrical output (kW)/ fuel input (kW) based on Higher Heating Value or Gross Calorific Value

2.4.3.2 Residential cogeneration strategies

Ellis (2002) contends that selection of a cogeneration strategy affects the size of the cogeneration plant, the requirements for reliability, the utility interface, and the economic merits of the application. Selection of a strategy for residential systems is based on the same analysis of possible operating points discussed in section 2.4.2.3 for cogeneration systems in general. Consequently, Ellis suggests four basic residential cogeneration strategies: 1) electrical load tracking; 2) thermal load tracking; 3) electrical base load; and 4) thermal base load; and argues that base load strategies make the most use of a system's investment because energy is provided at a constant rate which allows the system to operate at peak efficiencies. Braun et al. (2004), on the other hand, also suggest four strategies for fuel cell based residential cogeneration systems corresponding with different system configurations including: 1) net metering; 2) thermal energy storage using a hot water storage tank system; 3) using excess electrical energy for electric water heating; and 4) integration with heat pump systems. A more detailed discussion of these strategies is included in the chapter IV where they will be used as a starting point for the selection of the cogeneration system design parameters addressed in this study.

2.4.3.3 Residential cogeneration performance assessment studies

Several studies can be found in the literature, which aim to assess the performance of residential cogeneration systems in the U.S. While most of these studies rely on simulation, some are based on the performance of prototype demonstration systems. The following paragraphs present a summary of the main studies reviewed:

Gunes & Ellis (2003) used simulation to assess the performance of a fuel cell based cogeneration system compared to that of the conventional systems it is replacing. The study first established the energy needs of a typical U.S. single-family home (SFH) in two locations, then the energy use and emissions of the cogeneration system were compared to those of the conventional one. Finally, life cycle costs for the cogeneration system were compared to costs of conventional systems. Results of the study showed cogeneration system efficiencies of 65.8% in Atlanta and 73.5% in Syracuse resulting in reductions of 34 to 55% in energy use and 38 to 61% in CO_2 emissions compared to conventional systems. Economically, the study showed that for cogeneration systems to have life-cycle costs comparable to conventional ones, its initial costs need to be \$500/kW$_e$ or less. The study concluded, therefore, that cogeneration systems can provide substantial energy and environmental benefits but require considerable initial cost reductions to be economically justified.

Oyarza´bal et al. (2004) developed thermodynamic, geometric, and economic models for use in the optimal synthesis/design of fuel cell cogeneration systems for multi-unit residential applications. The results of the study indicate that the optimal system life cycle costs are significantly impacted by the number of residences (i.e. the system size). The system efficiency, however, did not change significantly with the change in size. The study concluded that the energy and economic characteristics of the most promising syntheses/designs are presented for fuel cell cogeneration systems serving 50 residences. These systems were found to have an electrical efficiency of 39%. The study also concluded that fuel cell cogeneration systems are likely to be economical in clusters of homes or apartment complexes first and then be applicable in SFHs as the manufacturing volume increases.

Fischer (2003) investigated the economic viability of three micro-cogeneration technologies (Stirling Engines, Fuel Cells, and Steam Generator Topping Cycles) for SFHs in all U.S. states aiming to identify the potential states/markets in which current economics offer the greatest potential for these technologies. Models for the three technologies were developed and used to determine the fuel consumption of the system based on EIA average residential loads. The study identified some markets where micro-cogeneration appears viable. These markets were generally characterized by high electricity rates and high heating loads.

Ellis (2002) also reviewed the market potential of fuel cell cogeneration systems in U.S. residential applications on the basis of the match between residential load profiles and system characteristics as well as system economics. Ellis concluded that residential systems will likely require some type of thermal storage to be economical and that fuel cell system costs have to drop to roughly below $1,000/kWe before they can compete with utility power in most locations.

The DoD Residential Fuel Cell Demonstration Project (White et al., 2004) is an active program, which began in 2001 and which aims to demonstrate domestically-produced residential fuel cells at military facilities. Fuel cell systems were installed and operated in a variety of US locations, with the aim of documenting and analyzing the results and assessing the performance of the technology and its possible impact in supporting sustainability and increasing efficiency in military installations. While many are still on-going, a number of the demonstrations have been concluded and some final reports are now published (LOGANEnergy Corp., 2004; SwRI, 2004; Plug Power, Inc., 2004). White et al. (2004) reports that the first sites to complete the 1-year program either met or surpassed the minimum 90% availability requirement assumed to be necessary to demonstrate the viability of the technology for various building applications.

While the results of the previous studies vary, several communalities can be identified. First, most studies address the energy, environmental, and economic performance of the technologies. Second, while mostly showing significant energy and environmental benefits from residential cogeneration, studies generally agree that the economics of the technology are still uncompetitive with conventional systems because of the higher initial cost as well as the low cost of electricity. All studies, however, were based on typical U.S. residential loads and most of them only dealt with individual buildings (mainly SFHs). While this study uses a similar methodology in assessing the cogeneration system performance that considers both the environmental and the economic components of this performance, it aims to address the issue on the community scale and to investigate the potential improvement in system performance that can result from improving the community's energy consumption characteristics through design.

2.5 SUSTAINABILITY ASSESSMENT

The different components of sustainability and the complex relationships between the factors affecting it increase the difficulty of assessing sustainability. Various methodologies and tools for sustainability assessment, however, have been developed. While some of these methodologies and tools offer a comprehensive assessment of sustainability, others focus on one or more of the issues involved. The following sections present a review of the concept of sustainability indicators and the sustainability assessment frameworks based on them. They then focus on the assessment of energy consumption in buildings, the different tools used for that, and some of the issues involved. Tools used in assessing the performance of cogeneration systems are then reviewed followed by a review of the assessment of emissions levels. The issue of economic performance evaluation is then addressed and a number of relevant methodologies are presented. Finally, the concept of life cycle assessment is discussed including the use of Multi-Attribute Decision Analysis methodologies (MADA). The different methodologies and tools discussed in the following section will form the basis for the study methodology presented later in chapter III.

2.5.1 Sustainability Indicators and Assessment Frameworks

The complex relationships between the factors affecting sustainability require the identification of sustainability indicators, which aim to integrate environmental, social and economic factors and to measure progress towards increasing sustainability (Guy & Kibert, 1998). Various listings of indicators are found in the literature. The DOE's Smart Communities Network (SCN, 2005a) provides a list of U.S. sustainability indicators and systems, while the EC funded Network on Construction & City Related Sustainability Indicators (CRISP, 2004) offers a similar list of international ones. Sustainability assessment frameworks typically integrate several indicators, which are then used to assess the sustainability of buildings and/or communities. The relative weight of each of the indicators within the framework depends on the importance that the framework attaches to each of the different components of sustainability.

Generally, two types of frameworks can be identified: the first are rating systems that assign values to different aspects of the design and then evaluate it based on an overall score, while the second are performance improvement programs that aim to encourage sustainable design by offering guidelines for different design stages and aspects without assigning a specific rating to them (Grumman, 2003). The current leading rating systems are: "*Leadership in Energy and Environmental Design (LEED)"* (USGBC, 2003) in the U.S., and *"Building Research Establishment Environmental Assessment Method (BREEAM)"* in the UK. Many performance improvement programs also exist including the GBTool (Cole & Larsen, 2002) in Canada and The ASHRAE Green Guide (Grumman, 2003) in the U.S.

Selecting a suitable assessment framework or tool for a project is a complex task that depends on a number of factors including the type of project and the sustainability issue/s that need to be addressed. To assist in this selection, the European Commission developed the *"Building Environmental Quality for Sustainability through Time (BEQUEST)"* toolkit (Cooper, 2002; BEQUEST, 2004)". BEQUEST is a decision support toolkit for selecting sustainability assessment methods, which consists of a database of assessment methods and tools categorized according to development activity (e.g. planning, design, construction, etc), spatial level (from the building component level to the national and global levels), and sustainability issue (including environmental, social, economical, and institutional ones). For each method or tool, BEQUEST provides information about the tool, its data requirements, the activities, spatial levels, time frame, and issues it addresses, as well as references for further information. A comprehensive listing of assessment methods is also found in a survey by Annex 31 of the IEA (2004). Generally, most of these methods and tools take the form of a weighted rating or scoring system and may depend on other building simulation tools to provide the required inputs such as energy consumption and emissions values. These tools will be discussed next

2.5.2 Building Energy Modeling and Simulation

2.5.2.1 Whole-building energy simulation software

In the U.S., full scale computer applications for HVAC related problems started in the early '60s (Kusuda, 1999). The development of building simulation tools went through many stages from the early manual calculation methods to the state of the art dynamic simulation tools as detailed in Ayres & Stamper (1995). Clarke (2001) categorized the evolution of building simulation tools into four generations as follows: 1) first generation tools, which include simplified computer tools providing general indications of certain performance criteria; 2) second generation tools, which attempt to imitate real physical condition and dynamics of buildings, yet still decoupling the treatment of air movement and HVAC; 3) third generation tools, which treat all system parameters, except for time and space, as dependent; and 4) fourth generation tools, which consider issues of program interoperability and include new developments such as more accessible user interfaces, application quality control and user training. Currently, numerous tools exist both dealing with whole building analysis as well as with simulation of specific building components, equipments, and systems. An extensive listing of energy-related building software can be found in the DOE's *"Tools Directory"* (DOE*,* 2004).

At the forefront of whole -building energy simulation software currently available are BLAST (BLAST Support Office, 1992), DOE-2 (Winkelmann, 1993), ECOTECT (Marsk and Raines, 1998), ENERGY-10 (Balcomb and Beeler, 1998), EnergyPlus (Crawley et al., 2000), and eQUEST (Hirsch, 2003). Out of these programs, DOE-2, developed by the U.S. Department of Energy, is currently the most accepted and most widely used. The EnergyPlus program is currently being developed by the DOE as the new generation of building simulation software (Crawly et al., 2001); however, it still does not have the acceptability of DOE-2.

Available versions of DOE-2 include: DOE-2.1e (Winkelmann, 1993) and DOE-2.2 (LBNL & J. J. Hirsch Associates, 2004). Both versions use a Building Description Language (BDL) to input instructions, assignments and control operations. However, DOE-2.1e consists of four sub-programs: LOADS, SYSTEMS, PLANT, and ECONOMICS, in addition to a REPORT sub-program used to generate output reports (York & Tucker, 1980); while DOE-2.2, on the other hand, incorporates the SYSTEM and PLANT sub-programs into a new HVAC sub-program and introduces the concept of CIRCULATION-LOOP. DOE-2 also includes a set of weather analysis programs to manipulate, summarize and plot weather data. The Quick Energy Simulation Tool (e-QUEST) is a software consisting of a DOE-2.2 engine, combined with a building creation wizard, an energy efficiency measures wizard, industry standard input defaults, and a graphical results display module (Hirsch, 2003), and which can be used to perform detailed analysis of building energy performance. A number of other commercial versions of DOE-2 are also available including EZ-DOE, DOE-Plus, and VisualDOE3.1. These programs also use the DOE-2 engine while adding a user interface to simplify data input procedures. While this study uses e-QUEST for the modeling and simulation of all building prototypes, it acknowledges a number of issues involved with this selection. A detailed discussion of these issues as well as the main differences between e-QUEST & DOE-2.2, on the one hand, and DOE-2.1e, on the other hand, is included in appendix A.

2.5.2.2 Software comparison and validation

Because of the wide range of simulation software currently available, selecting a suitable tool depends on a number of factors including, among others, the tasks and level of detail required as compared to the capabilities of the software, as well as issues of availability, validation, and technical support. A recent report issued by the DOE, the University of Strathclyde, and the University of Wisconsin, Madison (Crawley et al., 2005) contrasts the capabilities of 20 major building energy simulation programs in eighteen assessment categories based on information provided by developers. Results take the form of 14 tables each contrasting the 20 tools in one or more of these categories. While this report offers valuable insight on the different capabilities of each of the software being compared, it does not give an indication the validity of the result reached by them.

One method of assessing this validity, however, is by using the Building Energy Simulation Test (BESTEST), which consists of set of tests developed by Task 12 of the IEA's Solar Heating and Cooling (SHC) Program in collaboration with NREL, which aimed to systematically test whole-building energy simulation programs and diagnose the source of predictive disagreement (Judkoff & Neymark, 1995a). The objectives of BESTEST include quality assurance during development of building energy simulation computer programs, as well as certification of software used for performance-based code compliance in energy standards (Neymark & Judkoff, 2004). BESTEST was originally developed to test building thermal fabric (envelope), and this procedure was adopted with some refinements by ASHRAE and the American National Standards Institute (ANSI), and now forms the basis for ANSI/ASHRAE Standard 140: Method of Test for the Evaluation of Building Energy Analysis Computer Programs. HVAC BESTEST (Neymark & Judkoff, 2004) extended the original BESTEST by adding the capability to test and diagnose mechanical system models. Two groups of HVAC tests have been developed, the first, Volume 1, (Neymark & Judkoff, 2002) consist of steady-state analytical verification tests; while the second, Volume 2, (Neymark & Judkoff, 2004) tests a program's modeling capabilities in an hourly dynamic context. Tests from volume 1 have already been added to ANSI/ASHRAE Standard 140, while those from volume 2 are in the process of being added to the standard as well.

Tools assessed in HVAC BESTEST Volume 2 (Neymark & Judkoff, 2004) include both DOE-2.1e & DOE-2.2 along with CODYRUN, TRNSYS, EnergyPlus, and HOT3000. For both DOE-2.1e & DOE-2.2, the authors conclude that the annual summed or averaged results for system performance and zone conditions appear satisfactory when compared with other programs. Some disagreements between both software and the other programs are reported with regard to hourly extreme values and some other hourly estimates. These disagreements are linked by the authors to DOE's inability to iterate systems and loads calculations within a time step. In the case of DOE-2.2, however, the authors report that the code authors are planning to examine the remaining disagreements and revise their software if necessary.

2.5.2.3 Climate classification and weather data

Climatic conditions are a major variable affecting energy consumption in buildings. Briggs et al. (2003a) discuss the history of climate classification dating it back to Aristotle in the 4th Century B.C. Modern climate classifications date back to the work of Köppen in the early 20th Century who established a classification system consisting of major climate groups subdivided into climate type and subtypes. Olgyay (1963) (based on Köppen's work) divided the U.S. into four climate categories: cool, temperate, hot-arid, and hot-humid. Watson (1983) used a classification developed by the American Institute of Architects (AIA) dividing the U.S. into 15 climatic regions, while Lechner (2001) used material from the AIA's Research Corporation's "*Regional Guidelines for Building Passive Energy Conserving Homes*" to divide the U.S. into 17 climatic regions. Recently, Briggs et al. (2003a, b) developed a new climate classification to help improve building energy standards in the U.S. This classification includes 17 climate zones and suggests representative cities for each of them. This classification is now the basis for the new International Energy Efficiency Code (IECC) 2004 supplement (ICC, 2005), and it will be used for the purposes of this research.

With regard to weather data, several sets of weather data are available for energy simulation including Test Reference Year (TRY); Typical Meteorological Year (TMY & TMY2); California Thermal Zone (CTZ & CTZ2); Weather Year for Energy Calculation (WYEC & WYEC2); and Canadian Weather for Energy Calculation (CWEC). Haberl et al. (1995) evaluated the impact of using measured weather data vs. TMY data and found that energy consumption values predicted using DOE-2 & TMY data are consistently higher than measured energy consumption. Huang & Crawley (1996) also compared the energy consumption of a case study building using six types of weather data and found a ± 5% variation in energy consumption due to weather variations. Huang & Crawley concluded that the use of TMY2 of WYEC2 data will result in predicted energy consumption that is closer to the long term average. This research uses TMY2 data, which include typical values of solar radiation and meteorological elements for a one year period for 239 stations in the U.S. (Marion & Urban. 1995).

2.5.3 Simulation of Cogeneration Systems and District Heating Networks

2.5.3.1 Simulation of cogeneration systems

Performance models for mechanical equipment, e.g. cogeneration systems, include *"Mechanistic Models",* which use thermodynamic principles and equipment parameters; and *"Empirical Models"* which use parameters derived from measured data (Beasley, 1999). Baxter (1997) categorizes computer programs used for cogeneration evaluation into: detailed engineering analysis models; combined thermodynamic and economic analysis models; financial analysis models; and forecasting models. While a relatively large number of these tools exist, only a few deal with building cogeneration applications. A recent survey by ORNL (Hudson, 2003) presents nine of these software packages including both screening and design tools. The majority of these, however, are commercial programs aimed at specific building types or market sectors. More recently, the IEA (2003) started a new research annex (Annex 42), which aims to develop models to simulate the performance of residential fuel cells and other micro-cogeneration systems. These models, once developed, will be integrated into existing whole building simulation software including ESP-r & Energy Plus. Capabilities for simulating cogeneration systems also exist in the DOE-2 program. A study by GARD Analytics (2000) concluded that DOE-2.1E has the capability to model all of the power generation, heating, cooling, thermal storage, and ventilation/ IAQ equipment, and system controls appropriate for cogeneration systems, whether commercially available or an emerging technology. LBNL & Hirsch (2003) describes similar capabilities in DOE-2.2.

A number of public domain software are also available that assess distributed generation and cogeneration projects. The Distributed Energy Resources Customer Adoption Model (DER-CAM), developed at LBNL, is an optimization model, which identifies the energy bill minimizing combination of on-site generation and heat recovery equipment for sites (Siddiqui et al., 2003; Siddiqui et al., 2004). DER-CAM uses the site's five load profiles (electricity-only, cooling and refrigeration, space heating, water heating, and natural gas only), tariff structure, and values from a database of technology costs and performance to generate a set of installed DER technologies that minimize energy annual costs, an operating schedule of each technology, as well as utility energy purchases. RETScreen CHP (NRCan, 2005), on the other hand, is one of the modules of RETScreen, a decision support tool for renewable and clean energy sources developed by Natural Resources Canada. The RETScreen CHP model is a Microsoft Excel workbook, which contains sheets for energy models, loads, equipment selection, costs, GHG analysis, financial summary, and sensitivity analysis. Like other RETScreen models, RETScreen CHP includes product, weather, and cost databases; an online manual; an engineering textbook; project case studies; and a training course.

Another distributed energy and cogeneration analysis tool is “HOMER”, a tool, developed by NREL, that simplifies the task of evaluating designs of off-grid and grid-connected distributed power systems for a variety of applications (NREL, 2003; Lambert et al., 2006). It simulates the performance of a system by making energy balance calculations for each of the 8,760 hours of the year. For each hour, HOMER compares the electrical and thermal demand with the energy each component of the system can supply. HOMER can also be used to optimize different possible system configurations based on net present costs and to conduct sensitivity analysis of different design parameters. This research uses HOMER to assess the performance of cogeneration systems for both the centralized and decentralized integration approaches.

2.5.3.2 Simulation of district heating networks

Modeling of the thermodynamic and economic behavior of district heating and cooling (DHC) networks is a difficult task because of the complex interactions between the different system components (Fleming, 1997). Factors affecting the performance of an energy network include length of pipes, soil properties, insulation, and construction methods. These factors affect the energy losses in the network, which include heat losses to the ground as well as pumping and piping costs (ASHRAE, 2000; Phetteplace, 1995b). Few studies have dealt with the design of DHC networks. Phetteplace (1995b) developed a design method for the optimal sizing of pipes that takes into consideration all major network costs; while the International District Heating Association (IDHA) also published a “*District Heating Handbook*” (IDHA, 1983), which analyses various topics related to DHC networks including system consideration, distribution systems, metering, and economic and financial analyses.

To calculate thermal losses in district heating networks, ASHRAE (2000) includes steady-state models for heat transfer analysis in several DHC network designs including: single pipe (insulated, uninsulated, and in conduit), and two pipes (separate, in conduit, in trench, or tunnel). ASHRAE contends that "*steady-state calculations are appropriate for determining the annual heat loss/gain from a buried system if average annual temperatures are used".* This research will utilize these ASHRAE equations in assessing the energy losses from the different district heating network alternatives addressed.

2.5.4 Estimation of Emissions Levels

The estimations of emission levels resulting from the production and use of electricity is a vital part of the evaluation of the environmental impact of various energy efficiency projects. The Emissions & Generation Resource Integrated Database (eGRID) is a comprehensive data base of environmental attributes for electric power systems developed by the EPA, which provides emissions and resource mix data for every power plant, electric generation company, state, and region of the U.S. power grid (EPA, 2003). Data reported by eGRID includes generation, resource mix, emissions of NOx, SO_2, and CO_2, and mercury, emission rates, heat input, and capacity. eGRID reports this information on an annual basis for different levels of aggregation including: boiler, generator, power plant, electric generating company, parent company, state, NERC region, Power Control Area (PCA), eGRID sub-region, and U.S. total.

Three formats of eGRID 2002 are available: 1) spreadsheet files; (2) a user-friendly data browser; and (3) a web-based version (under development) (EPA, 2003). Using either of these formats, the reduction in CO_2 (or other) emissions resulting from a reduction in electricity consumption, in turn resulting from an energy efficiency measure, or in the case of this research the integration of a cogeneration system, can be estimated. Haberl et al. (2003) used eGRID to calculate the reduction in NOx emissions resulting from the adoption of the International Energy Conservation Code (ICC, 2003) in non-attainment Texas counties. eGRID will be used to estimate the reduction in CO_2 emissions for the purposes of this research.

2.5.5 Economic Performance Assessment

As discussed in chapter I, economic performance assessment is a basic component of the evaluation of energy efficiency technologies, equipment, and systems. Methodologies of assessing economic performance typically take into consideration all the costs incurred by the project over an estimated project life cycle. This concept is generally known as Life Cycle Costing (LCC) and is defined by Kirk & Dell'isola (1995) as "*an economic assessment ..... that considers all the significant costs of ownership over its economic life expressed in terms of equivalent dollars*" (p. 8). ASHRAE Applications Handbook (ASHRAE, 2003) lists the different costs of ownership as: 1) initial cost; 2) periodic costs (e.g. taxes, insurance, and rent); 3) replacement costs; and 4) salvage value. It also lists the costs of operation as: 1) annual utility costs (e.g. utilities, fuel. water, and on-site power generation); 2) annual maintenance costs; and 3) annual administration costs. Kirk & Dell'isola (1995) also list other factors impacting life cycle costs including: 1) the time value of money; 2) inflation, and 3) discount rates.

Various methodologies are used for economic assessment. Kirk & Dell'isola divide these methodologies into: "*economic analysis methods"*, defined as an examination of the costs and benefits resulting from a certain course of action, and including payback period, return on investment, and savings to investment ration; and "*life cycle costs analysis" (LCCA) methods*, defined as a cost-centered economic analysis aimed at determining the costs attributed to each of the alternative courses of action over a specific time period, and include present worth methods, and annualized costs methods. On the other hand, ASHRAE Handbook identifies and provides equations for a number of economic analysis methods including: 1) simple payback; 2) present worth analysis; 3) single payment present value analysis; 4) improved payback analysis; 5) savings to investment ration; 6) life cycle costs; 7) internal rate of return; 8) uniform annualized cost method; and 9) cash flow analysis method.

With regard to the economic analysis of cogeneration projects, Caton (2003) suggested using one of the following methods: 1) simple payback period; 2) investor's rate of return; 3) annualized costs; 4) annualized worth; 5) net present value; and 6) internal rate of return. He however recommended the use of either the net present worth or the internal rate of return methods. Ellis (2002), on the other hand, suggested two approaches for the economic analysis of building applications of cogeneration, the first is a simple cost of electricity analysis which compares the cost of electricity generated from the cogeneration system to that purchased from the utility; while the second is an hourly system modeling which determines, for every hour of the year, the electricity generated by the cogeneration system and that purchased from the utility, and accounts for part-load performance of cogeneration systems and the utility rate structure. Ellis identifies two major drawbacks of the simplified method. The first is the inclusion of a number of constants estimated by experience, and the second is that it does not account for variations in the utility rate structure.

2.5.6 Life Cycle Assessment & Multi-attribute Decision Analysis

Life cycle assessment (LCA) methodologies follow the same principle of life cycle costing (LCC) methodologies but extend the concept of monetary costs and benefits to include all monetary and non-monetary costs and benefits associated with the project. The LCA process is a systematic, phased approach that typically consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation. Environmental LCA is defined by the EPA (2001) as a "*cradle-to-grave*" approach for assessing systems beginning with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. Environmental LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses. Including both environmental and economic impacts in the decision making process is made difficult by the fact that these impacts are typically measured in non-commensurate units. Several approaches have been developed to address this issue that aim to either assign monetary values to environmental impacts; or to develop methodologies that allow for the combined consideration of both monetary and non-monetary impacts (including both quantitative and qualitative ones).

Dixon et al. (1997) presented a variety of approaches for assigning monetary values, or "*valuing*", of environmental impacts, thus making it possible to analyze them using traditional economic evaluation methodologies. These approaches are categorized into "*objective valuation approaches*" such as measuring changes in productivity, costs of illness, replacement and restoration costs, and human capital (mortality rate); and "*subjective valuation approaches*" including hedonic approaches and contingent valuation. While Dixon et al. (1997) acknowledge several limitations to these approaches, such as the uncertainty associated with many of them, the ethical considerations of assigning monetary values to human life and health; and the failure of these approaches to fully capture certain impacts on the environment; they still argue that such approaches can provide a more accurate estimate of environmental impacts.

An alternative approach is offered by methodologies developed to combine both monetary and non-monetary impacts into a single decision making process. One of these methodologies is Multi-attribute Decision Analysis (MADA) (Norris & Marshall, 1995). MADA methods apply to problems where a decision maker is choosing or ranking a finite number of alternatives measured by two or more relevant attributes (Norris & Marshall, 1995). MADA methodologies can combine attributes not measurable in the same units or attributes that may be either impractical, impossible, or too costly to measure. Norris & Marshall (1995, p. 7) describes 14 classes of MADA methods used for screening, ranking, or choosing between a set of alternatives and usually involves assigning weights to the various attributes being considered. Two MADA methods, that have a higher potential in the evaluation of buildings and building systems, are then described in detail: the Analytical Hierarchy Process (AHP) and the Non-Traditional Capital Investment Criteria (NCIC) method.

One application of MADA with regard to building components is the Building for Environmental and Economic Sustainability (BEES) software developed by the U.S. National Institute for Standards and Technology (NIST) to assist in selecting building products based on a combined environmental and economic performance assessment (Lippiatt, 2002). BEES measures the environmental performance of building products using the environmental LCA approach specified in the International Standards Organization (ISO) standard 14040. BEES analyzes all stages of a product's life including: raw material acquisition, manufacture, transportation, installation, use, and waste management. Economic performance is then measured using the American Society for Testing and Materials (ASTM) standard life-cycle cost method, covering initial investment, replacement, operation, maintenance and repair, and disposal costs. Environmental and economic performances are then combined into an overall performance using the ASTM standard for Multi-attribute Decision Analysis (NIST, 2002). This study adapts the MADA methodology used in the BEES software and uses it to synthesize the environmental and economic performances of residential cogeneration systems into an overall combined performance, which is then used as a basis for comparing the relative impacts of the various design parameters on the performance of the cogeneration systems, as well as in the community design optimization process within this study.

2.6 SUMMARY

The literature review presented in this chapter established the significant need for sustainability, the need for environmental sustainability, and the role of energy efficiency in increasing it. The review also established the importance of increasing sustainability generally and in the built environment specifically and showed the large and growing impact of the U.S. residential sector on national energy consumption and CO_2 emissions and therefore the role that reducing energy consumption in the residential sector can play in increasing the sustainability of this sector and of the building sector in general. A review of efforts to increase sustainability in planning and architecture generally, and in the residential sector specifically, was then presented including new directions in the planning of residential communities, such as New Urbanism and smart growth, as well as several programs aiming to increase the energy efficiency of residential buildings and communities, including the Building America program, Home Energy Rating Standards (HERS), the Energy Star Program, and green building programs. This review aimed to establish the common planning and architectural characteristics of sustainable residential communities, which will subsequently be used for the identification and selection of the design parameters investigated in this study as well as the assessment values of each parameter. These characteristics include compact urban form, moderate to high density, high mix of land uses, mix of housing typologies, and low building energy consumption through increased efficiency standards. A review of three case studies of sustainable communities in the U.S. and Europe also reinforced these common characteristics and established the potential for using these sustainable residential communities for the demonstration of emergent sustainable technologies.

The chapter then presented a review of distributed generation and cogeneration concepts and technologies which illustrated their existing environmental and economic benefits in several market sectors, as well as their potential benefits in the residential sector. The chapter then reviewed the state of the art in cogeneration technologies, which will be used in the cogeneration systems' performance assessment conducted in later sections of this study. Two approaches for the integration of cogeneration system in residential communities, the conventional centralized approach and the emerging decentralized, or building integrated, one, were then presented. This showed the need for a comparative assessment of the performances of each integration approach in U.S. residential communities, and the lack of existing studies addressing this issue. Several residential cogeneration performance assessment studies were then reviewed. This review showed that the majority of the studies addressed both the economic and the environmental performances of the cogeneration system, an approach also adopted within this study. Additionally, as few of the reviewed studies addressed the issue on the community scale or took into consideration the impact of changing the typical energy consumption characteristics of buildings and communities on the performance of the cogeneration system, a need subsequently exists, which this study addresses, for investigating these issues.

Finally, the chapter presented the concept of sustainability indicators and several assessment frameworks, such as LEED, BREEAM, and BEQUEST, utilizing these indicators. Different methodologies and tools used in the performance assessment procedures within this study were then reviewed. First, methodologies and tools of modeling and simulating the energy use of buildings were presented, including the software eQUEST, which will be used for the simulation of building energy consumption within this study, and various issues related to building energy simulation, such as climate data and verification, were also discussed. This was followed by a review of methodologies and tools of simulating the performance of cogeneration systems including the software HOMER, which will also be used for this purpose within this study. The review then covered a number of specific performance assessment tools and methods including the estimation of energy losses within district heating networks, the estimation of emissions levels, the assessment of economic performance, life-cycle assessment, and multi-attribute decision analysis. All of these methodologies will form parts of the procedures developed within this study to assess the performance of the residential cogeneration system being investigated.

CHAPTER III
METHODOLOGY AND METHODS

3.1 INTRODUCTION

The purpose of this chapter is to describe the research methodology and the different methods and tools utilized in this study to assess the impact of changes in the design characteristics of residential communities on the environmental and economic performances of residential cogeneration systems as a means of optimizing the design of these communities. The chapter starts by describing the design of the research including the underlying methodologies, the study variables, as well as a general description of the assessment procedures and the tools utilized in the study. A detailed description of the different research tasks performed within the study is then presented in which the data sources and specific methods and tools used in each of them are detailed, justified, and referenced.

3.2 RESEARCH DESIGN

3.2.1 Background & Research Strategy

As discussed in chapter I, this study aims to investigate the impact of the design characteristics of residential communities on the environmental and economic performance of residential cogeneration systems. While issues of system performance, both environmental and economic, are best expressed using quantitative measures, and therefore lend themselves to the use of quantitative research methodologies; this is not always the case with regard to community design issues. In the case of this study, the identification of which design parameters to investigate represented an issue not easily resolved using quantitative research methods. Therefore, achieving the goals of this study required utilizing a mixed-methods approach, in which both qualitative and quantitative data are collected and analyzed within a single study (Creswell, 2003; Tashakkori & Tiddlie, 1998 & 2003). Creswell (2003) contends that the use of mixed methods is an emerging direction in research methodologies which is used to expand understanding from one method to another, to neutralize the inherent biases of any single research method, and/or to confirm or converge findings from multiple data sources (i.e. triangulation). In this study, the utilization of mixed research methods aimed to use the results from one method, qualitative, to inform the other, quantitative (Tashakkori & Tiddlie, 2003).

Subsequently, this study utilizes a sequential exploratory research design model (Creswell, 2003) the first phase of which involves the collection and analysis of qualitative data, including both document and case study analysis, to identify the design parameters to be investigated within the study. A quantitative research method, modeling and simulation, is then utilized to investigate the impact of these parameters on the performance of the cogeneration systems. In this study, qualitative and quantitative data are collected and analyzed separately, however, the final discussion and interpretations draws on both of the research phases. A visual model of the research strategy is presented in figure 3-1.

While utilizing both qualitative and quantitative research methods, the quantitative part of the study, i.e. modeling and simulation, is much more dominant. Groat and Wang (2003) argue that the use of modeling and simulation in research allows for dealing with complex issues especially when utilizing current computer technologies. This is especially the case with regard to the analysis and performance assessment of complex building systems and Morbitzer (2003, p. 10) argues that, currently, the most powerful technique available for this purpose is building simulation, and quotes Clarke's contention that the advantages of building simulation lie in the fact that a simulation tool: "*permits an evaluation of building performance in a manner that corresponds to reality [...] and enables integrated performance assessment in which no single issue is unduly prominent*.". A schematic diagram of the overall design of the study is shown in figure 3-2, while a diagram of the simulation procedures is included in section 3.2.2.

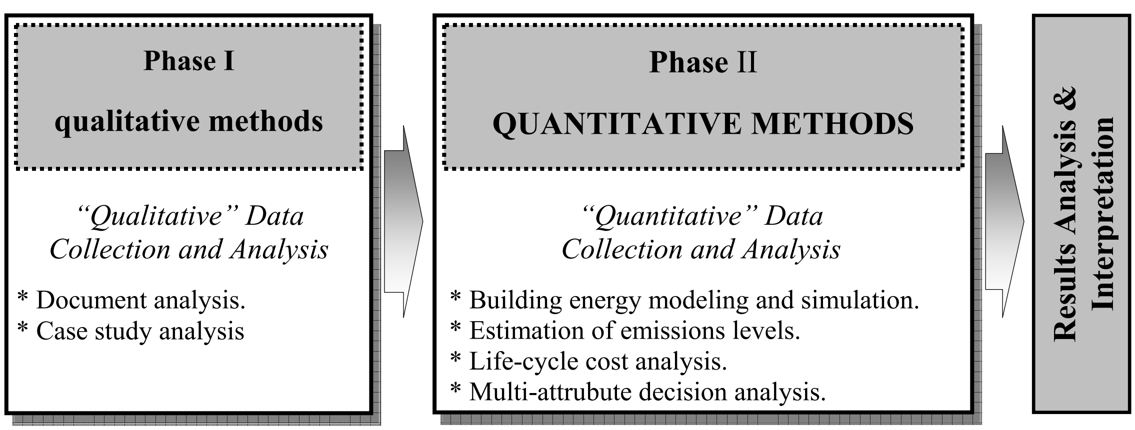


Figure 3-1 Visual Model of Sequential Research Strategy (adapted from Creswell (2003))

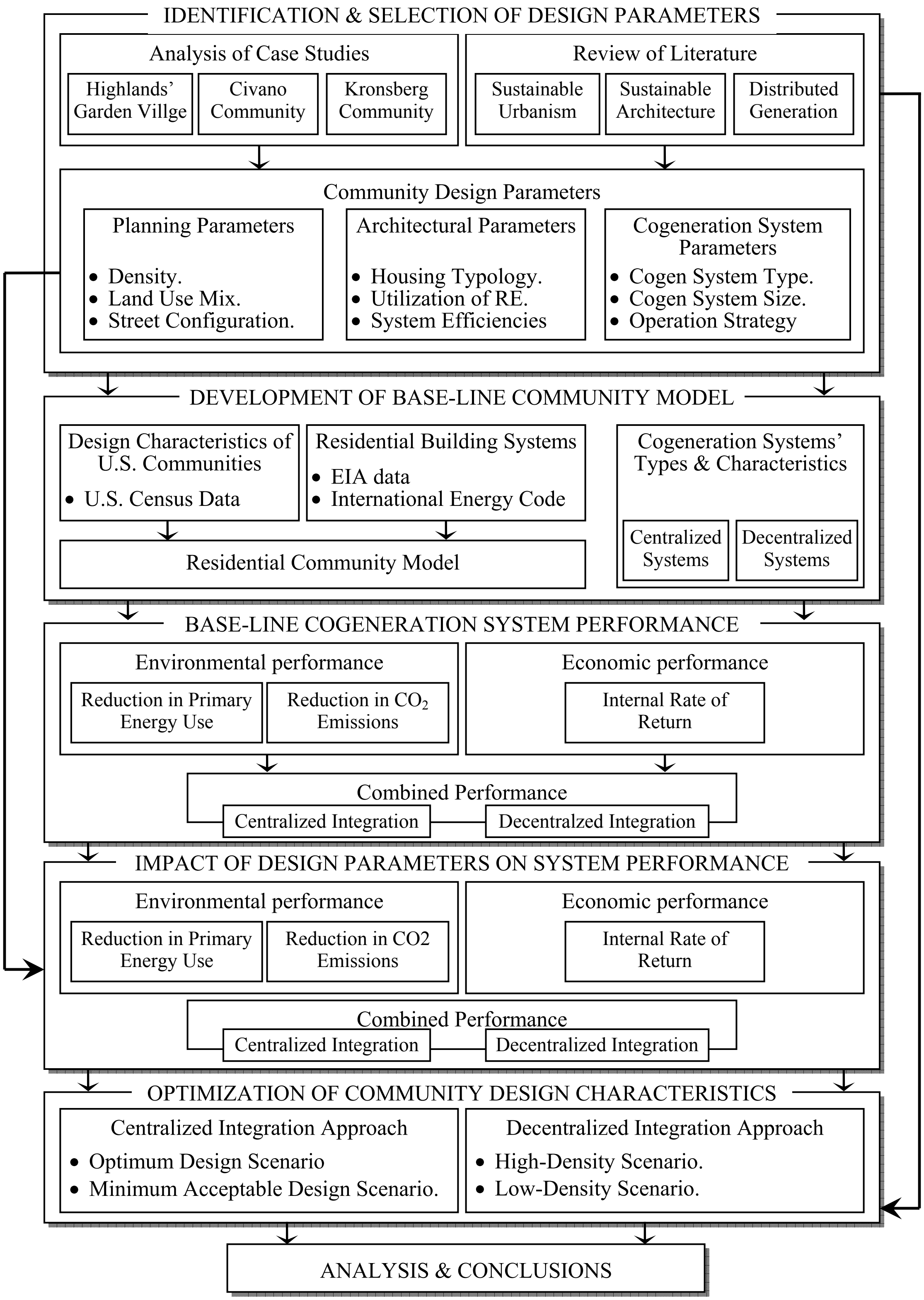


Figure 3-2 Schematic Diagram of Research Design

3.2.2 Cogeneration System Performance Indicators

Studies dealing with assessing the performance of cogeneration systems (e.g. Spiewak & Weiss, 1994; Baxter, 1997; Ellis, 2002; Caton, 2003; Fischer, 2003) typically focus only on their economic feasibility, i.e. they aim to identify the optimum design characteristics of the cogeneration system (e.g. system type, size, operation strategy, components, configuration, etc.), which would achieve the maximum possible internal rate of return for the project over its life cycle. However, as discussed previously in chapter II, the assessment of sustainability requires adopting a more comprehensive approach that incorporates both environmental and economic consideration, and if possible, social considerations as well. Consequently, sustainability assessment methodologies of the built environment, on the community, buildings, or building components scales (e.g. Cole & Larsen, 2002; BEQUEST, 2004; Lippiatt, 2002) aim to assess both environmental and economic impacts usually using the concept of indicators; and a number of more recent cogeneration systems' performance assessment studies also adopt this approach (e.g. Gunes & Ellis, 2002; Braun et al., 2004). Consequently, this study aims to assess both the environmental and the economic performances of the residential cogeneration systems using a selected number of performance indicators as will be discussed next.

Methodologies of assessing the environmental impact of buildings, building components and systems typically involve a large number of performance indicators. For example, the BEES methodology developed by the National Institute of Standards and Technology (NIST) assesses the environmental impact of building components based on their impact on 12 environmental problems and assesses this impact using a number of indicators ranging between three and 24 per problem. As conducting such a comprehensive environmental impact assessment is beyond the scope of this study, the study focuses on two of the major environmental problems identified in the literature: global warming and fossil fuel depletion, and assesses the environmental performance of the cogeneration system based on its impact on these two problems as expressed by two major performance indicators, reduction in CO_2 emissions, in the case of global warming, and reduction in primary energy use, in the case of fossil fuel depletion.

With regard to assessing economic performance, while all the reviewed cogeneration systems' performance assessment studies utilized a life cycle cost (LCC) approach to assess the economic performance of the systems, they used a variety of economic measures to express this performance. Caton (2003) reviewed a number of measures including discounted payback, annualized costs, annualized savings, net present value (NPV), and internal rate of return (IRR), but recommended using either the NPV or the IRR. Spiewak & Weiss (1994) also used both NPV and IRR, while Ellis (2002) and NREL-GRI (2003), measured economic performance based on the Levelized Cost of Electricity (COE). Out of these measures, this study assesses the economic performance of the cogeneration systems using the Internal Rate of Return (IRR). This is primarily because the calculation of the IRR does not involve the selection of a discount rate, which can be a very subjective decision, but instead calculates the expected annual rate of return for the project over a certain life cycle period.

As the indicators used to assess the environmental and economic performances of the cogeneration systems are denominated in different units, they can not be simply added to reach an overall performance. However, a number of approaches exist, which aim to overcome this problem including assigning monetary values to environmental impacts (Dixon et al., 1997), and using Multi-attribute Decision Analysis (MADA) methodologies (Lippiatt, 2002). Based on the MADA methodology, the BEES tool (Lippiatt, 2002) calculates a combined, environmental and economic, performance by rescaling each of the two performances, and placing them on the same relative scale from 0 to 100, then combining both of them into an overall score by weighting environmental and economic performances by their relative importance and taking a weighted average. This study uses this MADA-based methodology in calculating a combined, environmental and economic, performance for the cogeneration system in each of the different community design variations investigated in the study, as detailed in section 3.3.4.2, compared to their performance in the base-line community. Details of the calculation procedures for this combined performance are included in section 3.3.3.11. This combined performance however, as discussed in Lippiatt (2002), does not represent an absolute overall performance, but rather represents the proportional differences in performance, or relative performance, among competing alternatives and can change if more alternatives are added to or removed from the group of alternatives being considered. For the purposes of this study, the combined performance aims to assess the performance of the cogeneration system in each of the design variations being considered relative to the performance of the system in the base-line community.

3.2.3 Performance Assessment Procedures

3.2.3.1 Assessment model and tools

The cogeneration systems performance assessment procedures carried out in this study involved several steps that utilized a number of existing software and databases presented in chapter II and discussed in detail in the following sections. This section summarizes these procedures and presents a visual model for them, while a detailed description of them is included in section 3.3. For each of the community design variations investigated in the study, assessing the performance of the cogeneration system involved the development of building prototypes, either residential only or a mix or residential and commercial according to the design variation in question. In total, seven residential prototypes and 21 commercial prototypes, of different building typologies and sizes, were developed for this study using the simulation software eQUEST (Hirsch, 2003). While all prototypes utilized the design development wizard tool in eQUEST for initial model development, subsequent editing using the detailed mode of eQUEST was required for all prototypes to achieve the desired characteristics. A majority of the prototypes also required editing the text input file of the DOE-2.2 engine of eQUEST. The annual electrical and thermal energy consumption of the models, without the cogeneration system, was then simulated using eQUEST and the results of the simulation were validated by comparing them to EIA energy use surveys as discussed in section 3.2.3.3.

Following this, the procedures were divided into three subdivisions: first, the annual primary energy use and annual CO_2 emission of the community, without the cogeneration system, were calculated. Second, in the case of the decentralized cogeneration approach, the electrical and thermal loads of the cogeneration system were calculated for each building and the annual site electrical and thermal energy use each prototype, with the cogeneration system, was simulated using the HOMER software (Lambert et al., 2006). The annual primary energy use and annul CO_2 emission for the whole community were then calculated similar to the first step. The same procedure was also used for the centralized cogeneration approach with the addition that calculating the annual thermal system loads involved designing a district heating network, calculating the thermal energy losses within this network, and adjusting the cogeneration system thermal loads accordingly. The percentage of reduction in annual primary energy use and annual CO_2 emission for the community was then calculated for both the centralized and decentralized cogeneration approaches. A life cycle cost analysis was then conducted for each approach and the internal rate of return for each of them was calculated. These three cogeneration system performance indicators were subsequently used to calculate an environmental and an economic performance for the cogeneration system, and the two performances were integrated into a combined performance. A summary diagram of the procedure is included in figure 3-3.

3.2.3.2 Selected climate

This study is conducted in the cold dry climate zone (zone 6b) as defined by the climate classification developed by Briggs et al. (2003a & b) for use in energy codes and standards, design guidelines, and building energy analysis. The selection of the cold climate zone was based on previous studies (e.g. Gunes & Ellis, 2003; Fischer, 2003), which identified it as more favorable for cogeneration systems. To facilitate the use of this climate classification, Briggs et al. (2003b) identified a representative city for each of the climate zones so that code criteria or design guidelines could be developed for a given climate zone based on simulation performed using the climate of its representative city. Following this approach, this study used the climate data for Helena, MT, which was identified by Briggs et al. as the representative city for zone 6b.

3.2.3.3 Validation of simulation results

Validating the results of this study is derived from two bases; the first is the validation of the simulation tool used in the assessment process, while the second is the validation of the prototypes developed for the study. Methodologies of validating the predictive accuracy of a simulation tool include comparison with measurements from buildings in use, inter-program comparison, and diagnostic tests (Clarke, 2001). One of the major sets of diagnostic tests developed for this purpose are the BESTEST (Neymark & Judkoff, 2002 & 2004). With regard to DOE-2.2, Neymark and Judkoff (2004) concluded that, in general, it exhibits a good level of agreement with the other programs tested in the study (including DOE2.1e, TRNSYS, Energy Plus, CODYRUN, and HOT3000) with regard to assessment of annual energy use, loads, and other annual average results. Further discussion of this issue is included in Appendix A.

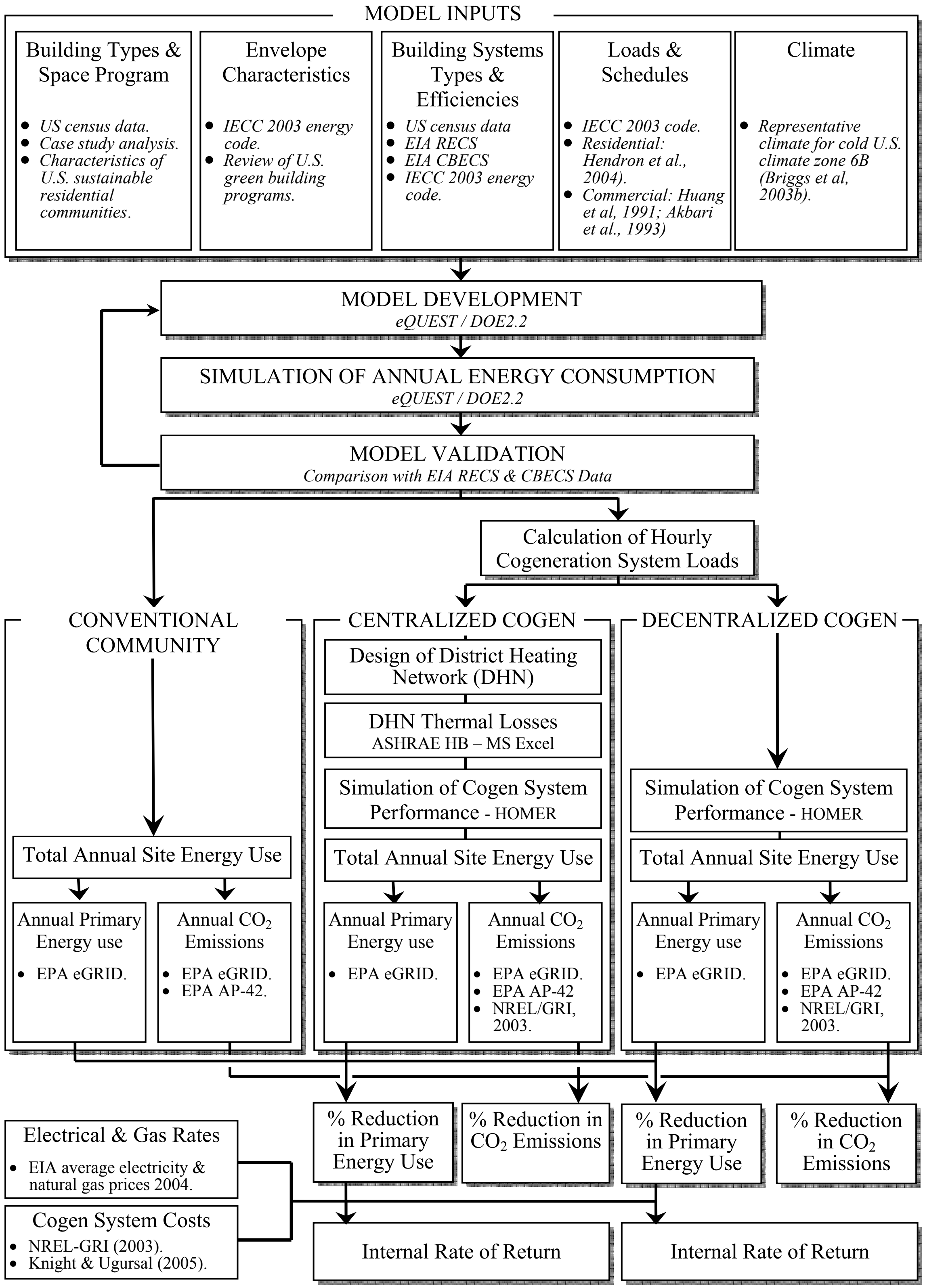


Figure 3-3 Detailed Model of Simulation Procedures

To validate the prototypes, the annual energy use of the residential and commercial prototypes was compared to annual energy use values in the Residential Energy Consumption Survey (RECS) (EIA, 2004b) and Commercial Buildings Energy Consumption Survey (CBECS) (EIA, 2002) performed by the Energy Information Association (EIA) in 2001 and 1999 respectively. U.S. average survey values were adjusted to account for building area, climate zone, year of construction, and heating fuel. The use of EIA data for model validation was also used in several studies of cogeneration systems' performance assessment (e.g. Gunes & Ellis, 2002 & Braun et al., 2004). The validation process and results for the base-line model (the single-family house) are included in section 3.3.2.2, while those for the other residential and commercial prototypes are included in section 3.3.5.2 and appendix B.

3.3 RESEARCH TASKS

3.3.1 Selection of Community Design Parameters

The first task of this study involved the identification and selection of the key community design parameters to be investigated in later tasks. Two information sources were utilized for this purpose. The first source was a review of relevant literature in the areas of urban sustainability (e.g. Calthorpe, 1993, 1994; Barton, 2000; Barton et al., 2003; & Steuteville & Langdon, 2003), sustainable residential architecture (e.g. Haughey, 2003, 2005; NAHB, 2000a, 2000b, 2000c, 2004; & Vale & Vale, 2000), and cogeneration systems (e.g. Spiewak & Weiss, 1994; Ellis, 2002; Gunes & Ellis, 2002; & Caton, 2003), while the second source was the analysis of three selected case studies of sustainable residential communities. Two of those case studies were located in the U.S., representing a cold and a hot climate, and the third was located in Germany, representing an example of a residential community with two operational residential cogeneration systems. The selection of the case studies was based on a number of surveys of U.S. and international sustainable residential communities (e.g. Kleiner & Barton, 2000; Smart Communities Network, 2005b; Sustainable Communities network, 2005). These three selected case studies are:

1) The Civano Community, in Tucson, Arizona.

2) Highlands Garden Village (HGV), in Denver, Colorado.

3) Kronsberg Community, in Hannover, Germany.

The analysis of these case studies was mainly based on published material relating to the design aims, characteristics, and performance of each of the selected communities with regard to the parameters addressed in this study. In the case of the Kronsberg Community, a site visit was also conducted.

As the design of residential communities, even in its initial stages, involves a large number of parameters, a set of criteria were developed for selecting those parameters that are relevant for the purposes of this study on each of the three previously identified scales: community, buildings, and cogeneration system, which correspond to the planning, architectural design, and cogeneration system design phases of the community design process. Consequently, the selected parameters needed to meet the following criteria as indicated by the studies analyzed for each parameter and detailed in the following sections:

1) To represent issues typically considered in the early stages of the design process for each of the three scales being investigated (i.e. early planning stages on the community scale; early architectural design stages on the building scale; and early system design stages for the cogeneration system scale).

2) To have a major impact on the design of residential communities on one of these three scales taking into consideration the limited details typically available in early design stages.

3) To have a potential impact on the environmental and economic performance of the cogeneration systems utilized in the community.

4) To have wider implications on other aspects of the overall sustainability of the residential community (e.g. transportation energy consumption, social sustainability, and economic sustainability).

5) To represent major design differences between sustainable residential communities and their conventional counterparts as indicated by the analysis of case studies of sustainable communities.

6) In the case of cogeneration system parameters, to represent issues typically considered in preliminary feasibility studies of cogeneration systems.

Based on the previous criteria, the following community design parameters were selected: on the community scale: 1) density of urban form, 2) mix of uses, and 3) street configurations; on the building scale: 1) housing typologies, 2) envelope and building systems' efficiencies, and 3) utilization of renewable energy resources; and on the cogeneration system scale: 1) cogeneration system type & efficiency, 2) cogeneration system size, and 3) operation strategy. For the purposes of this study, these selected design parameters formed the independent study variables, while the cogeneration system performance indicators, discussed in section 3.2.2, formed the dependent variables. The literature review and case study analysis was then used to identify the range of alternatives for each of these selected parameters, the impact of which on the performance of the residential cogeneration system will be investigated in later stages of the study.

3.3.2 Development of Base-Line Community Model

3.3.2.1 Model characteristics and information sources

The goal of this task was to develop a model of a conventional residential community representing the typical program and design characteristics of new U.S. residential communities on the planning, architecture, and building systems scales. This model then becomes a base-line for the design variation to be investigated in later stages of the study. The development of this base-line community model was informed by a number of sources including U.S. census data, EIA energy use surveys, building energy conservation codes, and other relevant literature as will be discussed in subsequent sections.

As sizes of residential communities vary considerably, the selection of the size of the base-line community was not a straightforward decision. Available surveys of sustainable U.S. residential communities (e.g. Smart Communities Network, 2005b; Sustainable Communities network, 2005) report community sizes ranging from as small as 35 dwelling units (du) to as large as 2000 du. However, a majority of these communities were in the range of 200 du to 500 du. Additionally, selecting the size of the residential community was based on the size of the two U.S. case studies investigated within the study, Civano Community and HGV. As HGV includes 300 du and Civano's neighborhood center includes approximately 350 du, the size of the base-line community was selected as 300 du. This size also conforms with the average range of sustainable community sizes mentioned previously and can either represent a medium size residential community or a part (e.g. center or edge) of a larger community. This community size was fixed for all the community design variations investigated in this study.

With regard to the planning characteristics of the base-line community, the community was assumed to be a single-use residential community consisting of only single-family detached houses. The base-line community has a gross density of 4 dwellings/acre (du/ac), which is based on Burchell et al.'s study of "*The Costs of Sprawl – 2000*" (Burchell et al., 2002, p. 184) in which the average U.S. single-family housing density is reported as 4.19 du/a. The street configuration for the base-line community followed the interconnected network, or grid, configuration described by both Southworth and Owens (1993) and Teed & Condon (2002). A layout of the base-line community is shown in figure 3-4.

On the building scale, a base-line prototype of a single-family house (SFH) was developed using the simulation software eQUEST version 3.55, which utilizes a DOE-2.2 version 44c3 engine. The floor area of the SFH prototype was set as 2130 ft^2 (1800 ft^2 conditioned area and 330 ft^2 garage), which is equal to the median floor area of new U.S. SFHs (US Census Bureau, 2005). The prototype consists of a single-story square house facing west with pitched roofs, with glazing distributed equally on its four sides, two exterior doors (front and back), and a slab on grade foundation. The garage is 15 ft x 22 ft and is attached to the south side of the house. There are no exterior shading devices, moveable windows shades or adjacent buildings or shade trees. With regard to envelope characteristics, the prototype was assumed to comply with the requirements of the 2003 International Energy Conservation Code (ICC, 2003). Compliance was determined using the prescriptive method (ICC, 2003, Chapter 5), assuming a window area of 18% of the gross external wall area and climate zone 15 of the climate classification used in IEEC 2003 (7000 to 8499 heating degree days) and in which Helena, MT is located. These requirements include R-25 external walls, R-49 ceilings, R-14 slab perimeter insulation (4 ft deep), and a glazing U-factor of 0.33. Windows were modeled using the windows library method of DOE-2.2 and utilized a glass type code of 2634 with aluminum-flush frames and no dividers. The edge of glass U-factor was not accounted for. External wall absorbance was 0.6 & roof absorbance was 0.45. An image of the model is showed in figure 3-5.

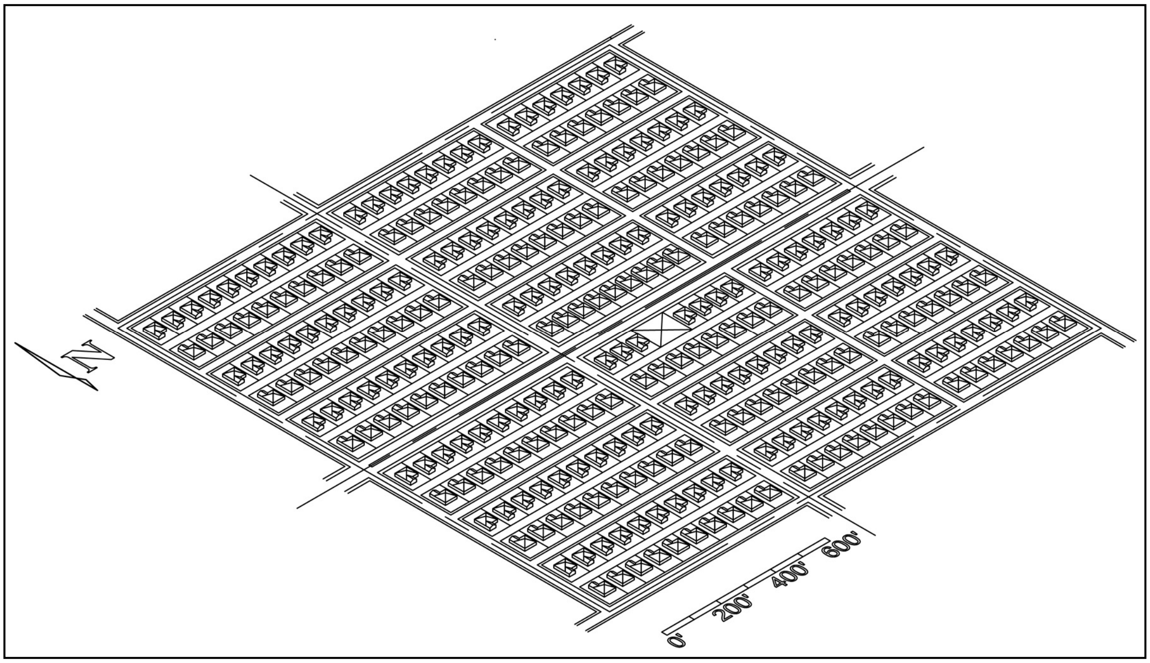


Figure 3-4 Layout View of Base-Line Residential Community

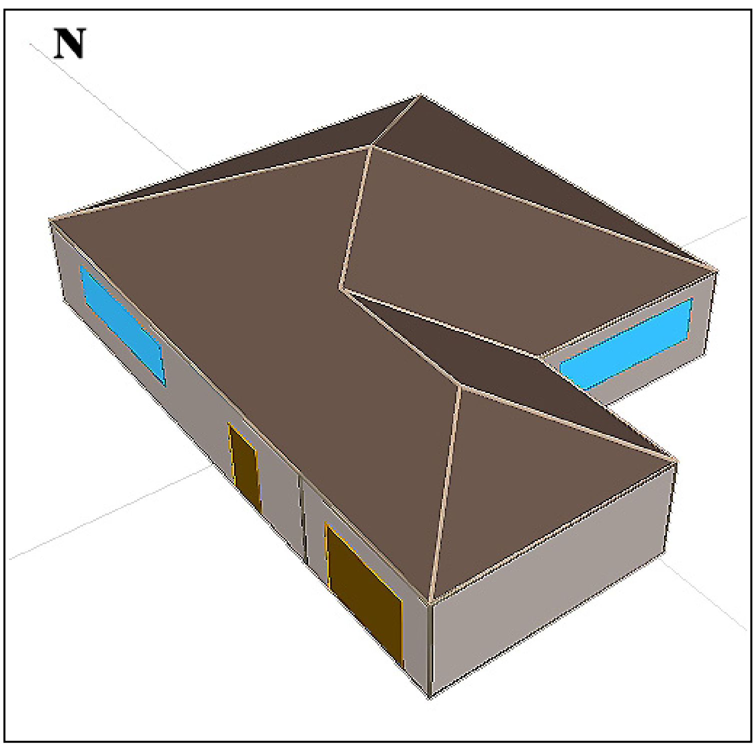


Figure 3-5 A 3-D View of the Base-Line Single Family House eQUEST Model

According to IECC 2003 requirements, daily hot water usage was 60 gal/day (based on a three-bedroom house). Other internal loads, not available in IECC, were based on the performance analysis procedure and research benchmark definition developed for U.S. single family homes by the Building America program (Herndon et al., 2004; Herndon, 2005). This benchmark represents the typical standard practice in the mid-1990s and is generally consistent with the HERS Technical Guidelines established by NASEO/RESNET in 1999 with additional specifications for end uses not addressed by HERS (Hendron et al., 2004). The benchmark gives average annual energy consumption for lighting and other kitchen and plug appliances. Based on this, an average daily energy use per unit area is calculated and used in the simulation combined with annual average normalized daily load profiles (i.e. profiles adding to a daily total of 1.0). These profiles, along with average occupancy schedules, were also developed by the Building America program (EERE, 2006). Values of annual energy use for various end-uses and appliances are included in table 3-1, while the occupancy and load schedules are included in the prototype input files, which is part of appendix E. The performance analysis procedure also includes a formula for calculating the mains water temperature for a specific location and time of year based on TMY2 data. This formula was used to calculate the monthly mains water temperature for Helena, MT, which was used for this study for calculating domestic hot water energy usage and to calculate the losses in the district heating network in later tasks.

3.3.2.2 Model validation

The annual electric and thermal energy uses of the prototype were simulated using eQUEST. These results were validated by comparing them with energy use values for heating, hot water, cooling, and lighting & appliances listed in the 2001 Residential Energy Consumption Surveys (RECS) performed by the EIA (EIA, 2004b). In order to determine an appropriate value for comparison with the simulation results, RECS average U.S. values for new construction (1990 – 1999) were adjusted to account for housing type and size (single-family detached with three bedrooms), climate zone (> 7000 HDD), heating fuel (natural gas), and range of heated floor space (1600 to 1999 ft^2). The resulting values were then compared to the outcome of the simulation and the results of the comparison are shown in figure 3-6.

Table 3-1 Design Characteristics of Base-Line Community Model

Design Characteristics	**Value**	**Information Source**
Community Design Characteristics:		
Community size	300 du	
Gross density	4 du/ac	Burchell et al. (2002)
Land-use mix	Single use residential	U.S. Industry standards
Street configuration	Interconnected network / grid	Southworth & Owens (1993)
		Teed & Condon (2002)
Housing typology	Single-family detached	U.S. Industry standards
Single Family House Model Characteristics:		
Floor area	2130 ft^2 (1800 CFA + 330 garage)	US Census Bureau (2005)
Building form	Single-story, square, glazing distributed equally on four sides, slab on grade foundation.	
Envelope characteristics		
Wall R-value	R-25	IECC 2003 (ICC, 2003)
Ceiling R-value	R-49	IECC 2003 (ICC, 2003)
Slab perimeter insulation	R-14, 4 ft deep	IECC 2003 (ICC, 2003)
Window U-factor	0.33	IECC 2003 (ICC, 2003)
Building systems' efficiencies		
Air-conditioning system	SEER 10	IECC 2003 (ICC, 2003)
Furnace	AFUE = 78%	IECC 2003 (ICC, 2003)
Domestic Hot Water System	EF = 0.594	Federal efficiency regulations
Internal Loads:		
DHW usage	60 gallons/day	IECC 2003
Interior lighting	0.8 * CFA + 455 = 1893.4 kWh/yr	Hendron et al. (2004)
Garage lighting	100 kWh/yr	Hendron et al. (2004)
Exterior lighting	250 kWh/yr	Hendron et al. (2004)
Refrigerator energy use	669 kWh/yr	Hendron et al. (2004)
Washer energy use	52.5+17.5 * BR = 105 kWh/yr	Hendron et al. (2004)
Dryer energy use	418+139 * BR = 835 kWh/yr	Hendron et al. (2004)
Dishwasher energy use	103+34.3*BR = 205.9 kWh/yr	Hendron et al. (2004)
Range energy use	604 kWh/yr	Hendron et al. (2004)
Plug appliances	1.67 * FFA= 3554 kWh/yr	Hendron et al. (2004)

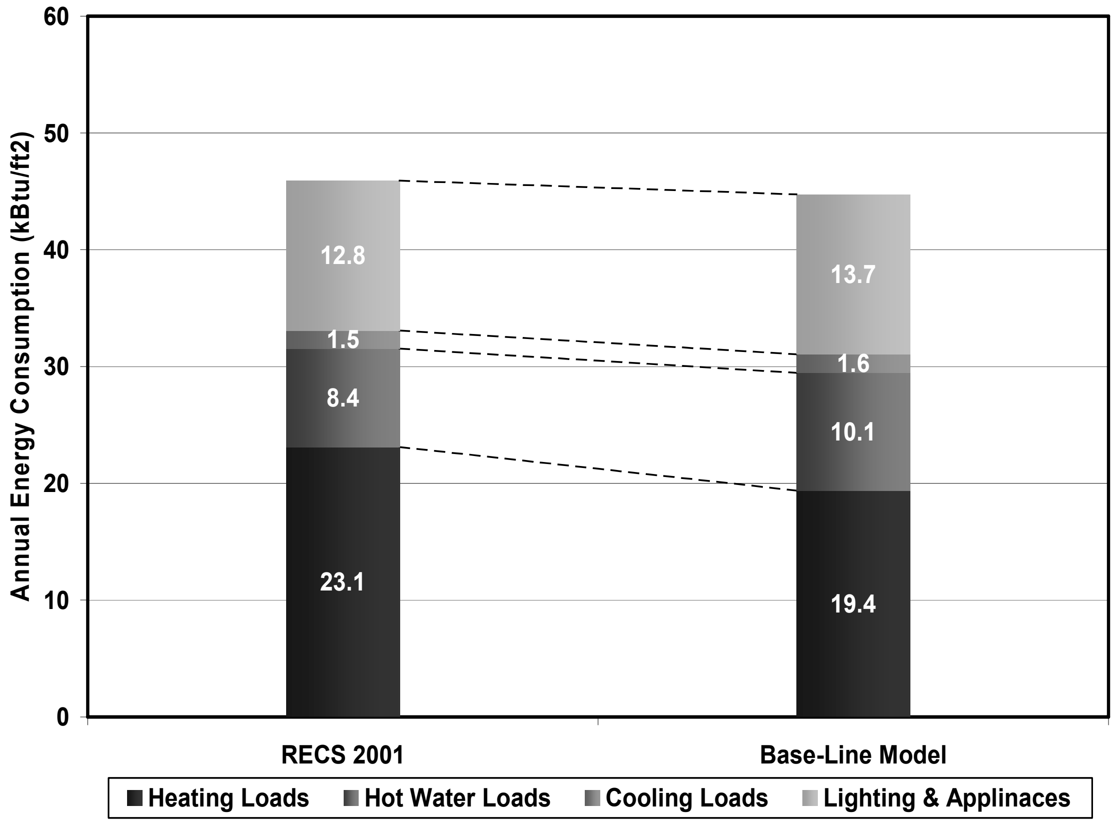


Figure 3-6 Annual Loads of Base-Line SFH Model vs. Average EIA RECS Data

Figure 3-6 demonstrates that the results of the simulation are in general agreement with the RECS 2001 energy use values. While the annual energy consumption of the model is about 6% less than that of the RECS values, more than half of that difference is due to the lighting and appliances end use, which were determined by IECC requirements and the Building America benchmark definition. On the other hand, the total annual thermal energy use of the prototype (heating and domestic hot water) is within 2% of RECS values. Therefore, it can be concluded that the model results are within a reasonable margin of the survey results and consequently, the model can be used to represent a single-family residence typical for this climate region of the United States.

3.3.3 Assessment of Base-Line Cogeneration System Performance

3.3.3.1 Introduction – centralized & decentralized cogeneration approaches

In this task, the environmental and economic performances of the cogeneration systems were assessed using the three selected indicators: reduction in annual community primary energy use, reduction in annual community CO_2 emissions, and internal rate of return. The performance of the cogeneration system was assessed for each of the two cogeneration integration approaches being investigated: the centralized approach (using one central system to serve the whole community), and the decentralized approach (using several micro-cogeneration systems integrated into each individual residential building); and the assessment procedures, detailed in the following sections, were applied to both approaches unless otherwise indicated. Three excel workbooks were developed for the purposes of this performance assessment, the first was used to calculate the sizes of the district heating network pipes as well as the thermal energy losses within the network; the second was used to generate seasonal and annual electrical and thermal average daily load profiles for the prototype SFH and the whole community, while the third was used to calculate the reductions in primary energy use and CO_2 emissions as well as the IRR of the cogeneration system. All excel workbooks utilized hourly energy use data extracted from eQUEST and HOMER as will be described in more details in subsequent sections.

3.3.3.2 Community annual primary energy consumption – without cogeneration

In the previous task, the annual site electrical and thermal energy consumption for the SFH prototype was simulated using eQUEST. In this task the community annual primary energy use, including both the natural gas use and the energy consumption in electric utilities, was calculated. The calculation procedures, performed using an excel workbook, were as follows:

1) Hourly total electrical and thermal end-use energy data from the prototype simulation were extracted using the “formatted” hourly data save option in eQUEST’s “detailed data edit mode”. This option exports the hourly data to a fixed field width formatted text file with no headers or pagination. This hourly data was then used to calculate the total community monthly site electrical and thermal energy consumption.

2) A natural gas pipeline and distribution loss fraction of 2.68%, representing average U.S. pipeline and distribution use in 2004 (EIA, 2005d), was added to the site thermal energy use to calculate the total community primary natural gas use (in MMBtu).

3) To calculate the community electricity generation requirements at the utility plants, the site electric energy use was adjusted to account for transmission and distribution losses. These losses were estimated based on an ORNL report (Mulholland et al., 2003), which includes an analysis of the U.S. electrical system losses. Mulholland et al. report a U.S. total average energy losses percentage of 7.62% of the total electricity generation, as well as a power or demand loss of 10.84%. As this study only deals with average annual energy use, the 7.62% value was used to calculate the utility electricity generation.

4) The utility electricity generation was divided by the average utility generation efficiency to calculate the energy input to the electric utilities. Utility generation efficiency values were extracted from the EPA database eGRID (EPA, 2003) by dividing the electricity generation values by the heat input values. While eGRID offers the potential for determining these values on a number of aggregation levels ranging from individual power plants to U.S. averages, for the purposes of this study, the average state aggregation level was considered suitable to achieve a balance between specificity and generalizability of the study results. A more detailed discussion of the generalizability of the results is included in chapter VII. As the selected cold-climate case study, Highlands' Gardens Village, is located in Colorado, average eGRID data for Colorado were used within this study. In this case, the average utility electric generation efficiency for Colorado was 32.86%, however, chapter VI includes an assessment of the sensitivity of the resulting cogeneration system performance, for the four design optimization scenarios, to changes in this generation efficiency.

5) The total annual community primary energy use (in MMBtu) was then calculated by adding the community primary natural gas use to the electric utility heat input.

3.3.3.3 Community annual CO_2 emissions – without cogeneration

The methodology for calculating the annual community CO_2 emissions was adapted from a methodology developed by Haberl et al. (2003) & Sung (2004) to calculate community-wide NO_x emissions reductions. Based on this methodology, community CO_2 emissions were divided into two major components: 1) on-site CO_2 emissions, typically resulting form the direct combustion of fossil fuels within the community; and 2) remote CO_2 emissions, typically resulting from energy delivered within the community, yet the generation of this energy produces CO_2 emissions in a location outside the community. For the purposes of this study, on-site CO_2 emissions will be limited to the combustion of natural gas within heating furnaces and domestic water heaters; while remote CO_2 emissions will be limited to emissions resulting from the generation of electricity in remote utility power plants. In both of these cases the CO_2 emissions were calculated by multiplying the energy use in question by an appropriate CO_2 emissions rate (or emission factor), which varies according to the type of fuel used. The EPA (1995) defines emissions rates as "*a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant*". Emission rates used in this study were derived from two main sources: 1) the EPA's AP-42 (EPA, 1995), in the case of natural gas consumption; and 2) the EPA's eGRID database (EPA, 2003), in the case of electric utility emissions. The procedures for calculating the total annual CO_2 emissions were as follows:

1) The on-site CO_2 emissions resulting from the combustion of natural gas in furnaces and domestic water heaters were calculated using emissions rates from the EPA's AP-42 (EPA, 1995). AP-42 is an inventory of emissions rates for various fuels and pollutants. In the case of CO_2 emissions resulting from natural gas consumption, AP-42 reports an emissions rate of 120,000 lb/10^6 scf, where scf = standard cubic foot of natural gas. Therefore, on-site CO_2 emissions were calculated based on the following equation (EPA, 1995):

$$CO_2 \text{ emissions (lb)} = \frac{\text{thermal energy use (MMBtu)} \times 10^6 \times (120{,}000/10^6) \text{ (lb/scf)}}{1020 \text{ (Btu/scf)}} \qquad (3.1)$$

2) The remote electric utility CO_2 emissions were calculated by multiplying the electricity generation at the utility plant, calculated in step 3 of the previous section, by the corresponding output CO_2 emissions rate in the eGRID data base. As explained previously, the average utility output emissions rates for Colorado, of 2013.7 lb/MWh, was used in this calculation.

3) The total annual community CO_2 emissions were calculated by adding the on-site emissions to the remote utility emissions.

3.3.3.4 Cogeneration system loads – centralized approach

Calculation procedures of the cogeneration system loads for the centralized approach varied in complexity between the electrical and thermal loads. The hourly total electric end-use energy consumption values of the SFH prototype were multiplied by 300 to get the hourly total community electrical energy consumption, which in turn is equal to the electrical loads of the centralized cogeneration system. Calculation procedures for the cogeneration system thermal loads, on the other hand, were more complex and involved the design of a district energy network and the calculation of the thermal energy losses within this network. These procedures included the following:

1) A diagram of the district heating network for the community, shown in figure 3-7, was developed based on the community layout. This diagram was subsequently used to calculate the approximate lengths of the various pipe segments within the network.

2) A variable flow design for the district heating network was then developed. ASHRAE (2000) contended that this design can improve energy use and expand the capacity of the distribution system piping. The heat-carrying medium for the network was assumed to be low-temperature hot water (LTHW), defined by Phetteplace (1995a) as having supply temperatures less than 250ºF. While LTHW systems are less widely used in the U.S. compared to medium and high temperature hot water (MTHW & HTHW) and steam systems, their use can result in considerable reductions in heat losses. Phetteplace (1995a) reports the results of measurements for several hot water systems which show that heat losses for LTHW systems are about 35% of those for HTHW systems, and performs even better when compared to steam systems, in which losses can exceed 50%. Phetteplace also reported other benefits for LTHW systems including reduced capital cost; reduced leakage; lower maintenance; increased possibility of serving lower load densities; and increased cogeneration potential. Phetteplace argues that these benefits outweigh the advantage of the larger temperature difference (ΔT) between supply and return, which is typically achieved with HTHW systems. LTHW systems also allow for the use of certain high-efficiency thermal insulation materials, such as urethane, which can not be used at high temperatures. With regard to ΔT, ASHRAE (2000) contends that a high ΔT is most cost effective because it allows for smaller pipe sizes in the distribution system, and recommends a ΔT of 40ºF or greater, while Phetteplace argues that well designed LTHW systems can achieve a ΔT of up to 100ºF similar to MTHW and HTHW systems. For the purposes of this study, the supply water temperature was assumed to be 205ºF (similar to the outlet water temperature of several commercially available cogeneration systems), while ΔT was assumed to be 65ºF, similar to the ΔT of two experimental LTHW systems described by Phetteplace.

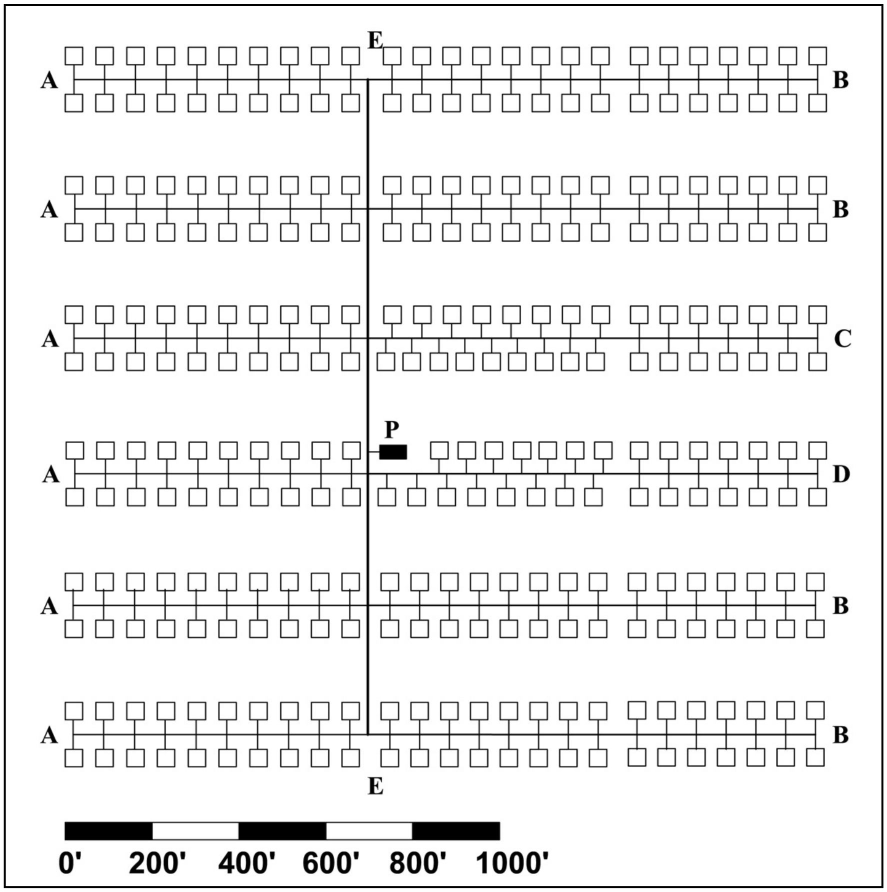


Figure 3-7 Diagram of District Heating Network for Base-Line Community

3) Subsequently, the size of the various pipe segments within the network was determined. To achieve this, the maximum hourly thermal load for the prototype SFH was calculated by multiplying the maximum hourly thermal energy consumption by 0.8 to account for the thermal efficiency of the heating system. The thermal load for each of the pipe segments was then calculated based on the number of houses served by the pipe segment and assuming a demand diversity factor of 0.8 (ASHRAE, 2000). The design load, in gallons per minute (gpm), for each pipe segments was then calculated according to the following equation:

$$Q = (q_{max} \times v \times 7.48137) / ((h_{supply} - h_{return}) \times 60) \qquad (3.2)$$

Where Q is the design flow rate (gpm); q_{max} is the design load (Btu/hr); v is the specific volume of water (ft^3/lbm); h_{supply} & h_{return} are the enthalpy of water at the supply and return temperatures respectively (Btu/lbm); and 7.48137/60 is a conversion factor from ft^3/hr to gpm. The design flow rate for each of the segments was then used to determine its size based on the velocity and head loss pipe sizing criteria described by McQuiston et al. (2005). While typical criteria for pipe sizing are a maximum velocity of 4 ft/sec, for pipe sizes 2 in. and smaller, and a maximum head loss of 4 ft per 100 ft of pipe, for larger pipe sizes, McQuiston et al. (2005) recommend relaxing these criteria in locations where noise is not critical to a maximum velocity of 5 ft/sec or a maximum head loss of 7 ft per 100 ft respectively. These relaxed criteria were used for pipe sizing within this study. Suitable fittings were then assumed for each pipe segment (including valves, elbows, bends, and tees as required) and the equivalent length of these fittings was calculated based on the equations in McQuiston et al. (2005). This equivalent length was then added to the pipe length and multiplied by the head loss rate per 100 ft for the selected pipe size to calculate the total head loss within the pipe segment. A summary of the results of the calculations for the district heating network within the base-line community is included in table 3-2.

Table 3-2 Calculated Pipe Segment Sizes and Head Losses for Base-Line Community District Heating Network

Pipe segment	**No. of SFH**	**Length (ft)**	**Total length (ft)**	**No. of SFH**	**Design load (kBtu/hr)**	**Design flow rate (gpm)**	**Pipe Size (in.)**	**Head loss (ft)**
SFH - NW	300	34	10200	1	41.1	1.3	0.5	176.6
A-EE	6	667	4001	20	658.2	21.0	1.25	283.2
B-EE	4	1043	4171	30	987.3	31.5	2.0	94.9
C-EE	1	1043	1043	31	1020.2	32.6	2.0	26.3
D-EE	1	1043	1043	29	954.3	30.5	1.5	73.6
EE	1	1507	1507	300	9872.5	315.2	4.0	75.4
EE-Plant	1	45	45	300	9872.5	315.2	4.0	9.1
Total			22009.8					739.0

4) Thermal losses within the network piping were then calculated using the heat transfer analysis equations reported in ASHRAE (2000) for district heating networks. The piping system was assumed to consist of two pipes (supply and return) buried separately at a horizontal centerline distance of 2 ft and a depth of 6 ft (see figure 3-8). The pipes were insulated with a polyurethane foam insulation and each insulated pipe was encased in a fiberglass-reinforced plastic (FRP) jacket, approximately 0.1 in. thick with no air-space between the insulation and the inside of the jacket (Phetteplace, 1995a). Insulation thickness was calculated for each pipe size based on IECC minimum pipe insulation thickness requirements for low temperature heating systems (ICC, 2003, p. 40) adjusted to account for the increased thermal conductivity of the polyurethane (0.014 Btu/h·ft·°F according to ASHRAE (2000)) from the conductivity used in the energy code (4.6 h·ft·°F/Btu/in. or 0.018 0.014 Btu/h·ft·°F) as allowed by the code. Calculated thicknesses were rounded up to the nearest possible insulation thickness.

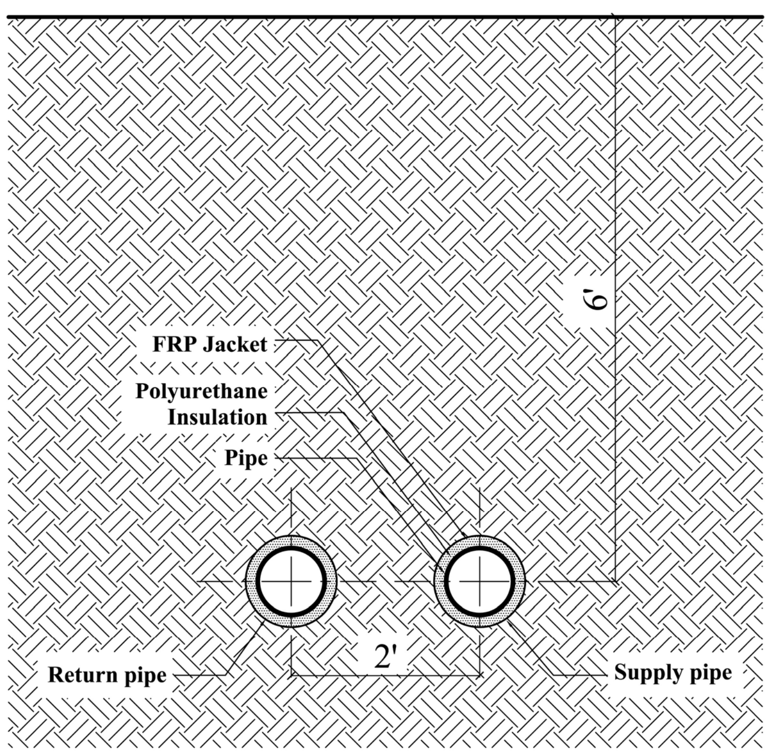


Figure 3-8 Diagram of District Heating Supply and Return Pipes

The heat loss calculations involved calculating the thermal resistance of each of the supply and return pipes including the resistance of the insulation, FRP jacket, and soil, which were added up to form the total thermal resistance of each pipe segment. The thermal resistance of the pipe itself was not taken into consideration. Soil thermal resistance was based on the pipe depth, outside diameter, and the thermal conductivity of the soil, assumed to be 1.0 Btu/h·ft·°F, while the thermal resistance of the insulation and the jacket was based on the inside and outside diameter and the thermal conductivity of each of them. Thermal and geometric/material correction factors, which account for the proximity of the two pipes (supply and return), were then used to calculate the effective thermal resistance of each pipe within the two-pipe system. Heat flow from the pipes was then calculated based on the difference between the water and soil temperatures and the effective pipe resistance based on the following equation:

$$q = (t_p - t_s)/R_e \qquad \text{(ASHRAE, 2000) (3.3)}$$

Where q is the heat flow from the pipe (Btu/hr.ft); t_p is the water temperature (°F); t_s is the soil temperature (°F); and R_e is the effective resistance of the pipe (h· ft ·°F/Btu). An excel work book was developed to perform the heat loss calculations for each pipe segment. The calculations were based on hourly thermal energy consumption data for the SFH prototype multiplied by 0.8 to account for the efficiency of the heating system. The calculations utilized average monthly ground temperatures based on the formula developed by NREL for the Building America Program (Hendron et al., 2004), previously discussed in section 3.3.2.1. Hourly heat losses were added sequentially to each pipe segment according to its diameter, length, and insulation thickness. Total hourly heat losses, from all pipe segments, were calculated and added to the hourly thermal demand for all the community buildings, and these values represented the hourly thermal load of the centralized cogeneration system. The heat loss calculation results showed a total loss percentage of 14.7% of the total required heat production, which is higher than values reported by Phetteplce (1995a) for European LTHW systems, in which losses range from 4.9% to 7.7% of the total heat production. However, this can be attributed to the lower density of the base-line community compared to densities of residential communities in Europe.

3.3.3.5 Cogeneration system loads – decentralized approach

Calculations of the cogeneration system loads for the decentralized, building integrated, approach were more straightforward than those for the centralized approach as they did not involve district heating network calculations. In this case, the hourly total electric end-use energy consumption of the SFH prototype directly represented the hourly electrical loads of the cogeneration system, while the hourly total thermal end-use energy consumption of the prototype were multiplied by an average furnace thermal efficiency of 0.8 to obtain the hourly thermal loads of the cogeneration system.

3.3.3.6 Simulation of cogeneration system energy consumption

The energy consumption of the cogeneration system, for both the centralized and the decentralized approaches, was simulated using the HOMER software (NREL, 2003; Lambert et al., 2006). The simulation utilized the hourly electrical and thermal loads generated for the centralized and decentralized systems in sections 3.3.3.4 & 3.3.3.5 respectively. The size of the cogeneration system used in the simulation was assessed through the development of average daily seasonal and annual load profiles for both the SFH prototype and the community as a whole assuming an electrical base-load operation strategy. To generate the load profiles, the software tool COLROW3D (Matson et al., 1991) was used to process the hourly energy consumption data, extracted from eQUEST, and produce a new file containing a spread sheet compatible data matrix in which each day's worth of data is compressed into one row in the matrix. Output files from COLROW3D were then imported into an MS excel workbook, which was used to generate the load profiles. Other system characteristics for the centralized approach (e.g. system type, configuration, full and part-load efficiencies) were based on a cogeneration technology characterization report prepared jointly by NREL and the Gas Research Institute (GRI) for the U.S. DOE (NREL & GRI, 2003). System characteristics for the decentralized approach were similarly based on a review of current residential cogeneration technologies prepared by Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme (Knight & Ugursal, 2005). While thermal storage has been identified by several previous studies as having a positive impact on the performance of cogeneration systems, it was not included in the configuration of the system in this study because of the limitations of the HOMER simulation tool. However, as any improvements resulting from thermal storage will apply to all the scenarios assessed in this study, the relative performance of the systems will not be significantly changed. A more detailed discussion of this issue and its potential impact on the results of this study is included in chapter VII. Table 3-3 presents the system characteristics for both cogeneration integration approaches, while part load performance characteristics of the cogeneration systems used are included in Appendix D.

3.3.3.7 Community annual primary energy consumption – with cogeneration

Hourly energy consumption data (including cogeneration electrical and thermal output, grid electricity purchases, and auxiliary heater thermal output) were extracted form HOMER and used to calculate the total community primary energy consumption for each of the two cogeneration approaches. The methodology, calculation procedures, and assumptions used here were the same as those described in section 3.3.3.2 for calculating the total community primary energy consumption without the cogeneration system with the exception that the thermal energy use in this case included both the heat input to the cogeneration system and the auxiliary heater.

Table 3-3 Base-Line Cogeneration System Characteristics for Centralized and Decentralized Cogeneration Approaches

System characteristics	Centralized system	Decentralized system
System type	Reciprocating Internal Combustion (IC) Engine	Reciprocating Internal Combustion (IC) Engine
System size (power rating)	250 kW	0.6 kW
Electrical efficiency (HHV)	31.1%	26.8%
Thermal efficiency	46.2%	61%
Overall system efficiency	77.3%	87.8%
Heat to Power Ratio	1.48	2.27
Operation strategy	Electric load-matching	Electric base-load
System configuration	System serving base-line electrical load, additional electric loads provided through grid connection. Additional thermal loads provided through an auxiliary boiler, system served through a central variable-speed pump.	Cogeneration system serving base-line electrical load, additional electric loads provided through grid connection. Additional thermal loads provided through an auxiliary heater.

3.3.3.8 Community annual CO_2 emissions – with cogeneration

Total community annual CO_2 emissions for each of the two cogeneration approaches were then calculated using the same methodology, calculation procedures, and assumptions used in section 3.3.3.3 for calculating the total community CO_2 emissions without cogeneration. The emissions included both on-site CO_2 emissions from the cogeneration system and the auxiliary heater as well as remote CO_2 emissions from the utility electricity.

3.3.3.9 Cogeneration system environmental performance assessment

The environmental performance of the cogeneration system, for both the centralized and the decentralized integration approaches, was evaluated using the two indicators described previously: 1) the reduction in the total annual community primary energy use, and 2) the reduction in the total annual community CO_2 emissions. For each indicator, both the magnitude and the percentage of the reduction were calculated. Results of this performance assessment for both integration approaches are presented in chapter V.

3.3.3.10 Cogeneration system economic performance assessment

Evaluating the economic performance of the cogeneration systems involved performing a life cycle cost analysis (LCCA) to calculate the internal rate of return (IRR) of the system. The IRR is a variation on the net present value (NPV) method of economic evaluation in which the earning rate of a project is determined by converting all the cash flows to present values which equal the initial investment (Caton, 2003). Therefore, determining the IRR for a project is an iterative process in which the rate of return is varied until the rate for which the present value of all project cash flows are exactly equal to its initial investments (i.e. NPV = 0) is identified. The selection of the IRR for this study over other economic indicators (e.g. discounted payback; NPV; or Uniform Annualized Costs) was primarily because IRR calculations allow for the comparison of several alternatives without specifying an arbitrary discount rate. To overcome the complexity of IRR calculations, the IRR function within the MS Excel software was used for this study as will be discussed later.

The economic evaluation within this study is conducted using constant 2004 dollars. The constant dollars approach is preferred to its alternative, the real dollars approach, because it avoids the need to project future rates of inflation or deflation (Fuller & Peterson, 1995). Consequently, by using this approach, prices of goods or services are not affected by the rate of general inflation, and if the price escalation of a certain commodity is different form the general inflation rate, only the real (differential) price escalations is considered. For the purposes of this study, only energy prices are assumed to have a real price escalation. Additionally, the economic evaluation was conducted over a 20 year study period. While study periods of up to 25 years are possible in long-term economic evaluations, the selection of 20 years was based on service life estimates reported by ASHRAE (2003) for major system components, which include estimates equal or close to 20 year for reciprocating engines, base-mounted pumps, furnaces, boilers, heat exchangers, and heating coils. Therefore, the selection of 20 years as a study period allows for the exclusion of replacement costs within the study.

Initial and annual cost assumptions for the economic evaluation included estimates of the initial and, when necessary, annual operation & maintenance (O&M) costs for cogeneration systems, district heating networks, and conventional heating systems. It also included estimates of annual energy costs, as determined by electricity and natural gas utility rates and fuel price escalation rates. Estimates of initial and O&M costs of cogeneration systems used in the centralized cogeneration approach were based on the NREL & GRI (2003) study discussed previously in section 3.3.3.6, while similar estimates for residential micro-cogeneration systems were based on the IEA study (Knight & Ugursal, 2005) discussed in the same section. In both studies, reported cost estimates represent total installed costs for typical system installations. In the case of commercially available system, costs were based on published manufacturers' equipment costs to the end-user and estimated installation costs for a typical installation with minimal site preparation (NREL & GRI, 2003); while costs of market entry systems (e.g. micro-cogeneration systems) were based on manufacturer market entry target prices and typical installation costs for similarly sized commercially available systems (Knight & Ugursal, 2005).

Estimates of the initial cost of district heating systems were based on a study by the Geo-heat Center, Oregon Institute of technology, of the costs of low-temperature geothermal district heating networks (Rafferty, 1996 & 1998). The study reported total installed cost estimates for district heating networks including costs of different pipe materials and sizes, insulation, fittings, valves, and construction. Estimates used within this study included a number of cost reductions measures suggested by Rafferty (1996) such as the use of pre-insulated ductile iron supply lines (using polyurethane insulation); un-insulated fiberglass return lines; and installation in unpaved areas, which avoids pavement cutting and removing and pipe hauling costs and is a reasonable assumption for the installation of district heating networks in new residential communities. As costs reported by Rafferty (1996) were in 1996 dollars, they were therefore converted into 2004 dollars using a Consumer Price Index inflation factor of 1.20. Additionally, initial costs of conventional heating systems were based on "*RS Means Mechanical Costs data*" (Means, 2004), while O&M costs for furnaces, boilers, and domestic water heaters were based on US DOE technical support documents for equipment efficiency regulations (U.S. DOE, 2000 & 2004). A summary of these costs is included in table 3-4.

Energy price estimates have special significance within this study as a number of previous studies (e.g. Baxter, 1997; Ellis, 2002; Caton, 2003) have identified energy prices and utility rates, including both their magnitude and rate structure, as having a significant impact on the economics of cogeneration systems. For example, Caton (2003) argued that the economics of cogeneration systems are strongly impacted by the structure of the electric utility rate, such as the existence of service charges, demand charges, back-up charges, and time of use (TOU) schedules. However, as these rate structures are unique to each individual utility, the use of any specific rate structure would considerably limit the generalizability of the study results. Therefore, similar to the case with utility electricity generation efficiency and CO_2 emissions rates, utility rates used in this study were based on EIA reported data of average 2004 Colorado retail electricity prices (EIA, 2005c), and natural gas prices (EIA, 2005d). These rates are shown in table 3-5 compared to average U.S. prices. These average 2004 fuel prices were then adjusted to account for real escalation rates through multiplying them by projected fuel price indices for U.S. census region 4, for different fuels and sectors, as reported in Shultz et al. (2004). These indices, when multiplied by annual energy costs computed at base-date prices (i.e. 2004), provide estimates of future-year costs in constant base-date dollars (Shultz et al., 2004).

With regard to income tax, centralized cogeneration systems were assumed to work as an electric cooperative and are therefore exempt from income tax; while building integrated system were assumed to have a 20% income tax rate. Property tax and insurance were assumed to be not significant and were therefore not included and no investment tax credit was assumed. Also, no replacement costs or salvage values were assumed for either the centralized or the decentralized systems. Finally, system capital costs for both systems were depreciated using a straight-line depreciation method over a 10 year period. Based on previous assumptions, the following procedures were performed to calculate the IRR for both the centralized and the decentralized approach unless otherwise noted:

Table 3-4 Estimates of Initial and Annual O&M System Costs Used in the Economic Evaluation of the Base-Line Cogeneration System

System component	**Centralized system**	**Decentralized system**
Cogeneration system installed cost ($/kW)	1160	3020
Cogeneration system O&M Cost ($/kWh)	0.013	0.014
District heating network:*		
1.0" diameter pipe ($/ft)	22.28	N/A
1.25" diameter pipe ($/ft)	26.55	N/A
1.5" diameter pipe ($/ft)	28.39	N/A
2.0" diameter pipe ($/ft)	31.20	N/A
3.0" diameter pipe ($/ft)	54.07	N/A
4.0" diameter pipe ($/ft)	61.10	N/A
Auxiliary heating system installed cost **	16.54 $/kBtu	820 $/unit
Auxiliary heating system O&M cost	39.17	39.17
Hot-Water heating coil*** ($)	N/A	695
Residential furnace installed cost**** ($)	N/A	1850
Residential furnace O&M cost ($)	N/A	39.17
Gas DWH installed costs ($)	N/A	616

* District heating pipe costs include unit cost of supply and return lines.
** Auxiliary heating systems for centralized approach include installed cost of boiler, pump, valves, expansion tank, and piping; and for the decentralized cogeneration approach include installed costs of an auxiliary natural gas heater.
*** Heating coil installed coil are based on a 2 ft x 2 ft hot water coil with 1 row of copper fins, 8 fins/in.
**** Residential furnace installed costs are for a 75 kBtu furnace size.
***** Gas domestic water heater costs are based on a 40 gallons size.

Table 3-5 Average 2004 Colorado and U.S. Electricity and Natural Gas Retail Prices

Sector	**Colorado**	**US average**
Electricity retail prices (cents/kWh)		
Residential sector	8.42	8.97
Commercial sector	6.89	8.16
Industrial sector	5.11	5.27
Natural gas prices ($/1000 scf)		
Residential sector	8.47	10.75
Commercial sector	7.84	9.41
Industrial sector	6.54	6.56

1) Initial system costs were calculated based on cogeneration and auxiliary system sizes. The change in initial costs for system components within the residential buildings, with and without the cogeneration system, was calculated for both approaches and is shown in table 3-6. Cost estimates for the centralized option showed no significant differences for the residential components and, therefore, were not included in the study. The decentralized system, however, showed a difference in initial costs and was therefore included within the study.

2) Annual O&M costs, with and without cogeneration, were calculated including system maintenance costs and energy (electricity and natural gas) costs. Energy costs were based on site electricity and natural gas use and were adjusted to account for real escalation using fuel price indices. The annual savings, or the annual cash flows, were then calculated. These annual cash flows were then adjusted to account for income tax and depreciation using an Excel workbook.

3) The IRR function in Excel was used to calculate the internal rate of return based on the initial costs and annual cash flows. As the excel function only attempts the IRR iterative process for a limited number of times and reports an error if a suitable value was not found within these attempts, an initial "*estimate*" of the IRR was sometimes required.

4) To validate the results, NPV calculations were performed, using the Excel workbook, in which the calculated annual cash flows were discounted using a discount rate equal to the calculated IRR. For a correctly calculated NPV, the results of this calculation must equal zero.

3.3.3.11 Environmental, economic, and combined performances

The purpose of this task was to synthesize the environmental and economic indicators of the cogeneration system performance into a combined indicator using a Multi-Attribute Decision Analysis (MADA) approach (see Norris & Marshall, 1995). This approach was adapted from the methodology used by NIST to evaluate the environmental and economic performances of building components in the BEES software (Lippiatt, 2002), which in turn follows the ASTM standard for conducting MADA evaluations of building-related investments. While BEES aims to calculate a combined environmental and economic score to compare, rank, and choose between a number of competing building products; the methodology developed within this study aims to calculate the change in the combined environmental and economic performance of the cogeneration system in a number of community design alternatives relative to that performance within the base-line community design. This goal was achieved through the following:

Table 3-6 Cost Estimates for System Components Within the Residential Buildings

Costs without cogeneration system		Costs with cogeneration system	
System component	**Cost* ($)**	**System component**	**Cost* ($)**
Centralized cogeneration integration approach:			
Residential furnace**	1850	Heating coil	695
Domestic water heater***	616	Heat exchanger	1000
		Auxiliary heater	715
		Valve	80
Total cost	*2466*		*2490*
Decentralized cogeneration approach			
Residential furnace**	1850	Heating coil	695
Domestic water heater***	616	Auxiliary heater	820
Total cost	*2466*		*1515*

* All costs are in 2004 dollars and are based on RS Means Mechanical Costs Data & US DOE technical support documents for residential furnaces and domestic water heaters.
** Residential furnace costs are based on a 75 kBtu furnace and include draft control and chimney.
*** Domestic water heater costs are based on a 40 gallon natural gas water heater.

1) For each design alternative, the three cogeneration system performance indicators, calculated previously, were identified. In the case of environmental performance, the indicators were the percentage of reduction in annual community primary energy use and the percentage of reduction in annual community CO_2 emissions resulting from the integration of the cogeneration system; while in the case of economic performance, the indicator was the internal rate of return of the cogeneration system.

2) As these indicators are expressed in noncommensurate units; a process of "*normalizing*" was used to place them on a similar relative scale. Norris & Marshall (1995) contend that normalizing quantitative data, within MADA, has several advantages including straightforwardness, unambiguity, and objectivity. The normalizing process typically involves dividing the values of each indicator, in the various design alternatives, by a normalizing value for this indicator, thus resulting in placing all indicators on the same relative scale. For the purposes of this study, the normalizing value for each indicator was selected as the performance of the cogeneration system within the base-line community design with regard to this indicator.

This process, therefore, placed all three indicators on the same relative scale in which the base-line community design scores 100 points, while the scores of other design alternatives represent the percentage of increase or decline in this indicator relative to the base-line case. This means that if, for example, one design alternative achieves an environmental performance score of 150, then this means that it outperforms the base-line case environmentally by 50%.

3) An environmental performance for the cogeneration system was determined by calculating a weighted average of the normalized values for the two environmental indicators. The relative weight of each of the two indicators, and their corresponding environmental impacts, within this calculation was determined according to the relative importance weights assigned by BEES to different environmental impact categories based on a study by the EPA's Science Advisory Board (SBA) (Lippiatt, 2002). In the SBA study, fossil fuel depletion is assigned a third of the relative importance weight of the global warming potential. Subsequently, the environmental performance was calculated by assigning a weight of 75% to the percentage of reduction in CO_2 emissions, and 25% to the percentage of reduction in primary energy use.

4) An economic performance for the cogeneration system was determined by normalizing the economic indicator (the IRR) using the same normalization method discussed previously in step (2).

5) A combined overall performance was determined by calculating a weighted average of the environmental and economic performances. As recommended in BEES, the two performances were assigned equal weights (50% each). However, sensitivity analyses of the impact of changing these weights were conducted when possible.

6) Similar to the overall performances calculated by BEES, the overall performances calculated within this study do not represent absolute performances. Rather, they represent proportional differences in performance among competing alternatives relative to a base-line performance. They are however suitable for the purpose of this study, which is comparing the relative impact of each of the design variations investigated within this study, relative to a base-line community design, on the performance of the cogeneration system.

3.3.4 Impact of Design Parameters on Cogeneration System Performance

3.3.4.1 Introduction

In this task, the impact of varying each of the selected design parameters, identified previously in section 3.3.1, on the performance of the cogeneration system is determined. Achieving this involved the following: first, determining the different assessment values for each design parameter, which were used to assess its impact on the cogeneration system performance; second, modifying the base-line community model according to these design variations; third, assessing the cogeneration system performance indicators within each of these modified designs; fourth, determining the environmental, economic and combined performances of the cogeneration system for each group of design variation, representing changes in one of the design parameters, compared to the system performance within the base-line design; and finally, comparing the relative impact of all the design parameters on the cogeneration system performance. The following sections present a detailed discussion of each of these steps.

3.3.4.2 Community design & model variations

Assessing the impact of the community design parameters on the cogeneration system performance represented one of the main objectives of this study. This assessment, in addition to representing the means by which the optimum community design characteristics will be identified, can also serve as a foundation for developing detailed design guidelines to inform designers of sustainable residential communities aiming to utilize cogeneration technologies. As the cogeneration system performance is impacted by numerous variables, e.g. community planning and architectural characteristics, system characteristics, climate, community energy use patterns, energy costs, etc, the identification of the impact of each of the design parameters required conducting a sensitivity analysis in which values of this parameter were varied while all other variables impacting the performance of the system are controlled. In other words, within this sensitivity analysis, the design parameters represented the independent variables, while the system performance indicators represented the dependent variables.

To achieve this, the analysis of the case studies, as well as other studies of the design of sustainable residential communities, were used as a basis for identifying alternatives for each design parameter that represent possible variations in the design characteristics of these communities as compared to conventional ones. Despite the fact that most of the design parameters investigated within the study represent categorical (or non-continuous) variables, effort was made to select alternative values for each parameter so that they represent, as much as possible, an interval scale, i.e. a scale in which both the order and difference between the alternatives of the variable are meaningful; or an ordinal scale, i.e. a scale in which only the order of the alternatives is meaningful. However, this could not be achieved for some design parameters for which only a nominal scale was possible. A summary of the alternatives selected for each parameter is included in table 3-7 while a discussion of the rational for selecting these alternatives is included in chapter IV.

Following this, for each of the alternatives listed in table 3-7, a variation of the base-line residential community model was developed in which only the design characteristic corresponding to this alternative was changed. In total, 46 design variations of the base-line model were developed including 12 design variations related to planning parameters; 15 design variations related to architectural parameters; and 19 design variations related to cogeneration system parameters. A summary of the community design characteristics for each of these design variations is included in Appendix C, Tables C-1 & C-3. Furthermore, model variations related to the "*mix of uses*" and *"housing typologies"* design parameter required the development of additional residential and commercial buildings prototypes as will be discussed in the following section.

3.3.4.3 Development of residential and commercial prototypes

The development of the community model variations required for assessing the impact of the "*housing typologies*" and "*mix of uses*" design parameters involved the development of several additional residential and commercial building prototypes. Table 3-8 shows a summary of the types and sizes of the residential buildings prototypes developed to evaluate the "*housing typologies*" design parameter, while table 3-9 shows a similar summary for the commercial buildings prototypes developed to evaluate the "*mix of uses*" design parameters. In total, 6 residential prototypes and 21 commercial prototypes were developed.

The development of the residential buildings prototypes followed a similar methodology to that used in developing the SFH prototype (see section 3.3.2.1). Based on this, sizes of the various residential prototypes were determined according to average sizes of new U.S. houses, for different housing typologies, as reported by the U.S. Census Bureau (US Census Bureau, 2005), while envelope characteristics for all prototypes were based on IECC 2003 requirements (ICC. 2003) as determined by the prescriptive method for their respective housing typology.

Building system types for all prototypes included electric air-conditioning and natural gas furnace heating and domestic hot water (DHW) systems. Similar to the SFH prototype, the selection of these system types was based on EIA 2001 RECS surveys (EIA, 2004b) and U.S. census data for new housing (US census Bureau, 2005), which both showed these system types to be the most common, while the efficiencies of these systems were determined based on IECC 2003 requirements and federal regulations.

Internal loads for all residential prototypes were determined based on IECC 2003 requirements, when available. Other internal loads not required by IECC, as well as average daily energy use profiles for various energy end-uses, were based on the Building America Program performance analysis procedure and research benchmark definition (Hendron et al., 2004; Hendron, 2005) previously used for the SFH model. While these performance analysis procedures do not specifically address differences between housing typologies, the annual energy use estimates specified in them were mostly given as a function of the house size. Load profiles specified in the performance analysis procedures, and previously used in the simulation of the energy use of SFH prototype, were also used for all the residential prototypes. Model inputs for all the residential building prototypes are included in Appendix B.

On the other hand, the development of the commercial prototypes was based on several sources of information. The selection of commercial building types and sizes was based on a categorization offered by Steuteville & Langdon (2003) of commercial centers integrated in residential communities. This categorization also corresponds well with a classification of the types of shopping centers developed by the Urban Land Institute (Beyard, O'Mara et al., 1999). Specific types & sizes of commercial buildings were based on a inventory of building typologies in traditional neighborhoods included in Steuteville & Langdon (2003) as well as on building typologies recommended by Andre Duany's Smart Code (Duany & Plater-Zyberk, 2005) for transect tiers 3, 4, and 5. A more detailed discussion of the rational for selecting the different commercial building typologies is included in section 4.3.1.4.

Table 3-7 Measurement Scales for Selected Design Parameters

Scale	Design parameter	Alternatives	Scale type
Planning parameters	Density of built form	1) 1 du/ac; 2) 4 b\du/ac (BL*); 3) 10 du/ac; 4) 15 du/ac; 5) Density gradient.	Ordinal (appx. interval)
	Mix of uses	1) Single use (BL*); 2) Low use mix; 3) Medium use mix; 4) High use mix; 5) Optimized use mix.	Ordinal
	Street configuration	1) Interconnected network/grid (BL*); 2) Fragmented network; 3) Modified, landscape-oriented network; 4) Loops & cul-de-sacs; 5) Dendritic network.	Nominal
Architectural parameters	Housing typologies	1) Detached single family houses (BL*); 2) Attached single family houses; 3) Town-homes; 4) Live-work units; 5) Multi-family houses.	Nominal
	Utilization of renewable energy resources	1) Orientation-neutral (BL*); 2) Low renewable energy utilization; 3) Medium renewable energy utilization; 4) High renewable energy utilization; 5) High utilization /reduced internal loads.	Ordinal
	Envelope & building system efficiencies	1) Energy code compliant (BL*); 2) 5% more efficient; 3) 10% more efficient; 4) 15% more efficient; 5) 20% more efficient.	Interval
Cogeneration system parameters	System type	*Centralized:* 1) Reciprocating engine (BL*); 2) Microturbine; 3) SOFC Fuel cell; 4) PEM fuel cell. *Decentralized:* 1) Reciprocating engine (BL*); 2) Fuel cell; 3) Stirling engine.	Nominal
	System size	*Centralized:* 50 kW to 400 kW; BL = 250 kW *Decentralized:* 0.5 kW to 4.5 kW; BL = 0.75 kW	Interval
	System operation strategy	1) Electric base-load (BL*); 2) Electric load matching; 3) net-metering;	Nominal

* BL = base-line community characteristic

Table 3-8 Types & Sizes of Residential Building Prototypes

Prototype	No. of dwelling units/model	Size per unit	No. of floors
Small single family house (SFH-S)	1	1,700 ft^2 (1,370 CFA* + 330 garage).	1
Large single family house (SFH-L)	1	3,050 (2,500 CFA* + 550 garage).	1
Attached single family houses (SFHA)	2	2,130 (1,800 CFA* + 330 garage)	1
Town homes (TH)	5	1500	1
Live-work units (LW)	5	2,000 (1,000 office + 1,000 residence).	2
Multi-family houses (MFH)	12	1,100	3 (4 units / floor)

* CFA = conditioned floor area.

Table 3-9 Types & Sizes of Commercial Building Prototypes

Prototype	Size (ft^2)	No. of floors	Working hours
Retail, small	5,000	1	8 am – 10 pm.
Retail, medium	20,000	1	8 am – 10 pm.
Retail, large	40,000	2	8 am – 10 pm.
Office building, small	10,000	1	7 am – 6 pm.
Office building, medium	20,000	1	7 am – 6 pm.
Community center, small	10,000	1	9 am – 11 pm
Community center, medium	20,000	1	9 am – 11 pm
Community center, large	40,000	2	9 am – 11 pm
Child-care center, small	6,000	1	7 am – 6 pm
Child-care center.], medium	12,000	2	7 am – 6 pm
Sit-down restaurant	5,000	1	6 am – 12 pm
Fast-food restaurant	2,500	1	6 am – 12 pm
Food store	5,000	1	6 am – 12 pm
Grocery store – 18 hours	20,000	1	6 am – 12 pm
Grocery store – 24 hours	20,000	1	24 hours

Table 3-9 Continued

Prototype	Size (ft^2)	No. of floors	Working hours
Bakery, small	2,500	1	6 am – 12 pm
Bakery, large	5,000	1	6 am – 12 pm
Bakery, night schedule	5,000	1	24 hours
Laundry/dry cleaning	5,000	1	6 am – 6 pm
Primary school	35,000	1	7 am – 3 pm
Nursery home	20,000	2	24 hours

Model inputs for the different commercial prototypes were based first on the requirements of the IECC 2003 (ICC, 2003) and then, for issues not covered by the IECC, on two studies by LBNL, which aimed to develop commercial prototypical buildings and commercial end-use load profiles. The study by Huang et al. (1991) was part of an effort to develop a market assessment tool for analyzing the potential for cogeneration in commercial buildings in twenty U.S. city markets. The study aimed to characterize the building stock in these cities by 1) estimating the number and sizes of buildings by class type, location, vintage, and equipment, 2) developing prototypical buildings for each category, and 3) performing DOE-2 computer simulations for these prototypical buildings. A total of 12 commercial prototypes were developed including retail, 18 hour supermarket, 24 hour supermarket, fast-food restaurant, sit-down restaurant, office building, and small and large hotel. On the other hand, the study by Akbari et al. (1993) aimed to develop a set of commercial sector end-use energy use intensity (EUI) data that has been fully reconciled with measured data. The study developed electricity endues EUI's and load shapes for 11 commercial building types including small and large office building, small and large retail, fast food restaurant, sit-down restaurant, and food store. While both studies included inputs for envelope and system characteristics, internal loads, and schedules for the developed prototypes, the study by Huang et al. (1991) included the development of prototypes in several city markets in different climate regions. Therefore, it was considered as a primary source for the model inputs developed within this study. Other studies were also helpful with regard to specific building types such as Haberl et al. (2001) for office buildings, and Cox (19933) and Cox et al. (1993) for grocery stores.

All commercial prototypes had simplified geometries with similar average aspect ratios (1:1 or 1:2 according to the building type) in order to achieve results that represent average energy use for each building type. Building envelope characteristics for all prototypes were determined based on the requirements of IECC 2003 (ICC, 2003) for climate zone 15 (the climate zone for Helena, MT in the IECC climate classification) and assuming a glazing area equal to 35% of the total area or the above grade walls. Based on this, external walls were assumed to have metal frames construction with R-13 cavity insulation and R-3 continuous insulation; roofs were assumed to have metal joist/truss construction with R-24 continuous insulation; while floors were assumed to be a slab-on-grade with 4 ft of R-8 perimeter insulation. Windows were modeled using the windows library method of DOE-2.2, using suitable glass-type-codes to achieve the required window U-factor. All windows and doors were assumed to have horizontal shading devices with a projection factor (PF) of 0.5. The glazing area was distributed equally on all 4 building elevations. While this equal distribution may not be typical to all building typologies (e.g. grocery stores, where windows are mostly concentrated in one or two elevations), this method was shown by Huang et al. (1991) to reproduces the average condition of a multitude of individual buildings of various orientations even for highly directional building types. With regard to building systems, all prototypes were assumed to have electric air-cooled air-conditioning, natural gas furnaces and hot water systems. System efficiencies were determined based on IECC 2003 requirements (ICC, 2003) with regard to air-conditioning systems and furnaces, and on federal regulations with regard to natural gas hot water systems. With regard to internal loads, internal lighting intensities were determined based on IECC requirements (ICC, 2003, p. 76) for different building or area types. Other internal loads, e.g. occupancy, equipment, hot water loads, and process loads; and schedules were based on the studies by Huang et al. (1991), and Akbari et al. (1993) as discussed previously. Detailed model inputs for all the commercial prototypes developed within this study are included in Appendix B.

3.3.4.4. Validation of individual prototypes

The annual electrical and thermal energy consumption of each of the developed residential and commercial prototypes was simulated using the eQUEST software. Similar to the SFH prototype, this annual energy use was validated by comparing it to average annual energy use values reported in EIA surveys. Therefore, All residential prototype were compared to energy use values reported in the EIA's 2001 Residential Energy Consumption Survey (RECS)

(EIA, 2004b); while all commercial prototypes were compared to annual energy values reported in the EIA's 1999 Commercial Buildings Energy Consumption Survey (CBECS) (EIA, 2002).

In the case of the residential prototypes, the simulation outcome for each building typology was compared to 2001 RECS average U.S. energy use values for new construction (1990 – 1999) after adjusting these values to account for housing type (single-family attached, 2-4 apartments, or more than 5 apartments); house size; climate zone (> 7000 HDD), heating fuel (natural gas), and range of heated floor space. With regard to the commercial prototypes, the 1999 CBECS average U.S. energy use values for new construction (1990 – 1999) were also adjusted to account for building activity, range of floor space, climate zone (< 2000 CDD & > 7000 HDD), primary space heating fuel (natural gas), and cooling energy source (electricity). The selection of suitable building activities for each commercial prototype was based on the description of building types included in the CBECS data (EIA, 2002). The resulting energy consumption values were then compared to annual energy consumption data resulting from the eQUEST simulation and adjustments were made to the internal loads of some of the models to achieve a better match between the simulation results and the EIA survey values taking into consideration that EIA data, especially in the case of CBECS data, represent averages of a variety of building types and sizes, and depend on many parameters such as response rates from different regions, and accuracy of reported energy use values. In the case of commercial prototypes, the results of the simulation were also compared to the results reported by Huang et al. (1991) for similar prototypes, although the comparison in this case was focused more on the fuel to electricity ratio of the prototype's annual energy consumption. A summary of the results of the validation process for both the residential and the commercial prototypes is included in appendix B.

3.3.4.5 Cogeneration system performance indicators

The three environmental and economic performance indicators of the cogeneration system, for each of the 46 design variations described in table 3-7, were then assessed for both the centralized and decentralized integration approaches. The assessment process followed the same methodology used for the base-line community (see sections 3.3.3.1 through 3.3.3.10 and figure 3-3). This procedure included using the results of the eQUEST simulation to calculate the annual community primary energy use without the cogeneration system, and subsequently the annual community CO_2 emissions without the cogeneration system. The electrical and thermal loads of the cogeneration system were then calculated, including, in the case of the centralized approach, the design of a district heating network and the calculation and the thermal energy losses within this network. The annual energy use of the community with the cogeneration system was then simulated using the HOMER software and the results of the simulation used to calculate the annual community primary energy use and CO_2 emissions with the cogeneration system. The reductions in annual primary energy use and annual CO_2 emissions were then calculated. The cogeneration system size and efficiency used in the base-line community were also used for all planning & architecture design variation. Next, an economic assessment of the cogeneration system was conducted to calculate its internal rate of return. Assumptions used for assessing the cogeneration system performance indicators within this task were identical to those used to assess those performance indicators within the base-line community.

3.3.4.5 Impact of design parameters on system performance

The resulting environmental and economic performance indicators for each group of design variations, representing one of the design parameters being investigated, were then used to assess the environmental, economic, and combined performances of the cogeneration system within these design variation relative to its performance within the base line community. The procedures used to achieve this were similar to those used for the base-line community and described in section 3.3.3.11. The results of this process showed the relative increase or decrease in system performance due to the impact of each design parameter. Following this, the impacts of all design parameters were compared to identify the design parameters having the most impact on the performance of the cogeneration system.

3.3.5 Optimization of Community Design

3.3.5.1 Optimum community design characteristics

The purpose of this task was to identify the optimum combination of planning, architectural, and cogeneration system design characteristics that would produce the best cogeneration system performance for each of the two integration approaches being investigated. This identification was based on the results of the sensitivity analysis of the impact of each design parameter on the cogeneration system performance conducted in the previous task. However, as the previous task aimed to explore the ability of each of the design parameters being investigated to impact the cogeneration system performance, certain values for some parameters were evaluated that may not be suitable for some real design situation. In the optimization process, these values were excluded even if they result in an improvement in the system performance. The identification of the optimum design characteristics also took into consideration the potential conflicts between the certain design parameters (e.g. density vs. utilization of renewable energy resources).

To identify the optimum design characteristics, the results of the previous task were used to divide the investigated design parameters into three categories according to their impact on the cogeneration system performance: first, parameters shown to have the most significant impact on the cogeneration system performance; second, parameters shown to have no significant impact or a negative impact on the system performance; and third, parameters shown to have a varied impact on the environmental and economic performances of the system (i.e. increase in environmental performance accompanied by a decrease in economic performance or vice versa). For the first category, the values achieving the best system performance were identified and included as a main characteristic of the optimized community design; for the second category, the value used in the base-line design were included directly into the optimized community design; while for the third category, several possible values for each parameter were tested within the optimized design and the value achieving the best combined cogeneration system performance was identified. The assessment of the combined system performance followed the same procedures described for the base-line case, and for its design variations (see section 3.3.3 and figure 3.3). Following the identification of the optimum community design characteristics, the environmental, economic, and combined cogeneration system performances within the optimum design were calculated relative to the base-line case. This process was conducted separately for each of the two integration approaches, centralized and decentralized, depending on the relative impact of the design parameters in each approach.

3.3.5.2 Minimum acceptable design characteristics

As the design of residential communities is impacted by a variety of factors, achieving the optimum design characteristics from the point of view of cogeneration system performance will not be possible in all scenarios. This limitation becomes significantly more important if the design characteristics that can not be achieved are related to the first category of design parameters identified in the previous section, i.e. those having the most impact on the cogeneration system performance. An example of this would be the design of a residential community in a location where high densities are not possible (e.g. communities on the urban fringe). For such scenarios, the study aimed to identify the combination of design characteristics that would achieve a minimum acceptable performance for the cogeneration system, and therefore would still allow these systems to be utilized within those communities. As economic performance typically plays a more important role in project feasibility decisions under these scenarios, and as previous studies of cogeneration system performance, see section 2.4.3.3, showed that residential cogeneration system typically have a better environmental performance than economic performance, the minimum acceptable performance for the cogeneration system in this scenario was determined based on its economic performance and defined as the combination of community design characteristics that achieves an IRR of at least 10%, which represents the minimum economic performance used to determine the feasibility of cogeneration technologies in previous studies (e.g. NREL & GRI, 2003).

The procedures used for identifying the desired design characteristics in this scenario were similar to those used previously in section 3.3.5.1 and were conducted as follows: first, the investigated design parameters were divided to the same categories as the previous section; second, for design parameters in the second category, i.e. those with small or negative impact on the system performance, the values of the base-line design were identified and directly used in the optimized design; third, for the first category parameters, i.e. those with the most significant impact on the system performance, the values considered difficult to achieve under this scenario were excluded, while the remaining values were tested, along with those from the third category parameters, to identify the optimum combination of design characteristics that would achieve the minimum acceptable economic performance. The assessment of this economic performance used the same procedures used previously for the base-line community. Following the identification of the desired design characteristics, the environmental, economic, and combined cogeneration system performances within this design were calculated relative to the base-line case. This process was conducted separately for each of the two integration approaches, centralized and decentralized, depending on the relative impact of the design parameters in each approach.

3.4 SUMMARY OF METHODOLOGY

This chapter presented a detailed description of the research design and methodology used within this study to assess the impact of a number of selected community design parameters on the environmental and economic performances of residential cogeneration systems as a means of optimizing the design of residential community to improve the performance of the cogeneration system. This description included a summary of the tasks performed in the research as well as the information sources, assumptions, specific method, and tools used within each task. The research design followed a mixed research design model involving two phases, a qualitative phase, utilizing the methods of document and case study analysis, followed by a dominant quantitative phase, utilizing building energy simulation. The study used three indicators to assess the performance of the cogeneration systems including two environmental indicators: the reduction in annual community primary energy use due to the cogeneration system; and the corresponding reduction in annual community CO_2 emissions; and one economic indicator, the internal rate of return of the cogeneration system.

The performance assessment procedures performed within this study involved the identification and selection of the following key community design parameters: density, mix of uses, and street configuration, on the planning scale; housing typology, envelope and building systems' efficiencies, and utilization of renewable energy, on the architecture scale; and cogeneration system type, size, and operation strategy, on the cogeneration system scale. These design parameters were selected based on an analysis of three case studies of sustainable residential communities in the U.S. and Europe and according to several selection criteria including: having an impact on the design of residential communities; having an impact on the performance of the cogeneration systems; having wider implications on the overall sustainability of residential communities; and representing major design differences between sustainable residential communities and their conventional counterparts.

Assessing the impact of the selected design parameters on the performance of the cogeneration system involved the development of a base-line residential community model representing the average design characteristics of U.S. residential communities, and assessing the performance of a residential cogeneration system integrated within this base-line community in each of the two integration approaches being investigated. This assessment involved simulating the annual energy use of the base-line community without cogeneration using the eQUEST software, and calculating the annual primary energy use and CO_2 emissions of the community without cogeneration. The electrical and thermal loads of the cogeneration system were then calculated and used to simulate the annual energy consumption of the community with cogeneration using the HOMER software. The results of this simulation were then used to calculate the annual primary energy use and CO_2 emissions of the community with cogeneration.

The reduction in annual energy use and reduction in CO_2 emissions were then calculated followed by an economic evaluation in which the internal rate of return was also calculated.

A sensitivity analysis was then performed to determine the impact of each design parameter on the performance of the cogeneration system. This involved developing variations of the base-line residential community model representing the selected values of each design parameter. This was followed by calculating the environmental and economic performance indicators for the cogeneration system within each of these model design variations following the same assessment procedures used in the case of the base-line community. MADA methodology was then used to calculate the environmental, economic, and combined performances of the cogeneration system in each of these design variations relative to its performance within the base-line community, which was then used to assess the relative impact of each of the design parameters on the cogeneration system performance.

Following this, the optimum design characteristics producing the best combined environmental and economic cogeneration system performance were identified and the improvement in the performance of the system within the optimum community design compared to its performance within the base-line design was calculated. A second combination of design characteristics was then also identified which result in a minimum acceptable economic performance for the system in situations where the most significant community design characteristics, from the point of view of system performance, can not be achieved because of other design considerations (e.g. community location).

CHAPTER IV
COMMUNITY DESIGN PARAMETERS

4.1 INTRODUCTION

The purpose of this chapter is to present the community design parameters investigated within this study on the planning, architectural, and cogeneration system scales. First, the importance of integrating environmental performance considerations in the design process in general and in the early stages of this process in particular is discussed. The design parameter selection process is then presented and the selected design parameters are introduced. This is followed by a more detailed discussion of each of the selected parameters, which includes its significance in the design of residential communities, its impacts on the sustainability of those communities, and its potential impact on the performance of the cogeneration systems utilized within the community. Finally, the three selected case studies are analyzed from the point of view of each design parameters and this analysis is used as a basis for identifying the design alternatives of each of the parameters, which will subsequently be used in the evaluation of the impact of these parameters on the cogeneration system performance in the following chapter.

4.2 COMMUNITY DESIGN AND ENVIRONMENTAL PERFORMANCE

The design of residential communities involves the integration of a large number of interdependent and sometimes conflicting design considerations on a number of scales. These include, but are not limited to, functional, social, cultural, aesthetic, structural, environmental and economical considerations. The importance of integrating environmental considerations, in particular, in the design process has increased with the growing interest in achieving a more sustainable and environmentally conscious built environment. Such integration is achieved through various methods which differ according to the stage of the design process they are intended for. All methods, however, aim to inform design decisions by an assessment of the expected environmental performance of the community, or its components, based on measurable criteria (e.g. energy consumption, harmful emissions, or other environmental impacts). Such an assessment is typically based on a theoretical model of the community being designed.

Integrating environmental considerations in the design process faces certain obstacles that frequently cause them to be overlooked. Mazouz & Zerouala (2001) identify some of these obstacles as the influence of "iconic" models, conceptual modes and pictorial movements that tend to transcend other design variables. Reliance on technical solutions to solve any building thermal or environmental problems also adds to this tendency to overlook environmental considerations in design as do time constraints of the design process especially in its early stages.

Integrating environmental considerations in the early design stages is particularly important because of the high impact that design decisions taken in these stages have over the environmental performance of the community. Decisions such as community density and mix of uses, on the planning scale, or building aspect ratio, volume, orientation, and solar access, on the building scales, can have a profound impact on the energy consumption and subsequent harmful emissions of the community buildings. The ASHRAE Green Guide (Grumman, 2003 p. 27) contends that *"it is much easier to have a major impact on the potential energy savings in a building … at the very early stages of the design process"* and that *"the available impacts diminish [in later] design and construction phases*". Integrating such considerations in these early stages typically relies on expert rules of thumbs and design guidelines that indicate to designers the optimum alternatives and/or acceptable ranges for relevant design parameters under certain conditions. Basing such rules of thumb on detailed studies utilizing the increased abilities of modern building simulation tools, which allow for a more accurate assessment of the impact of design variation and take into consideration the relationships between different design variables, can increase the validity of design solutions that utilize these rules and reduce the cases in which detailed environmental assessments, in later design stages, indicate the need for major design changes, which are typically difficult to achieve at that time.

Consequently, this study, as discussed earlier, focuses on design parameters investigated in the early stages of the design process. However, even with this limitation of the scope, a selection process was required to determine the key and influential design parameters which this study can effectively investigate. The following sections describes this selection process and then present a discussion of each of the selected parameters which includes its significance within the community design process, its potential impact on the performance of the residential cogeneration system, its impact on the sustainability of the residential community, and an analysis of the design characteristics of selected case studies of sustainable communities with regard to this parameter. By discussing the wider sustainability implications of these design parameters, this chapter attempt to relate the issues being investigated in this study, the performance of the cogeneration system, to the wider context of increasing the sustainability of residential communities and the built environment as a whole.

4.3 SELECTION OF DESIGN PARAMETERS

While the design of residential communities involves a large number of parameters, not all of these parameters influence the environmental performance of the communities and/or the cogeneration systems in them and are therefore suitable for this study. Additionally, the number of parameters selected for the study needed to be small enough to be effectively investigated within the time available, however, these selected parameters needed to be influential enough in the design of the community so that the investigation of their impact can be informative to designers. The importance of this requirement is increased by the fact that the community design optimization, conducted later in this study, will be based solely on variations in these selected parameters, while keeping all other community design characteristics constant.

As discussed in the previous chapter, a set of criteria were used to select a group of planning, architectural, and cogeneration system design parameters to be used in the study. These parameters include: on the planning scale, 1) density of urban form; 2) mix of uses; and 3) street configurations; on the architectural scale: 1) housing typology; 2) envelope and building systems' efficiencies; and 3) utilization of renewable energy resources; and on the cogeneration system scale: 1) cogeneration system type; 2) size; and 3) operation strategy. A discussion of each of these parameters is presented next.

4.4 PLANNING PARAMETERS

With regard to design parameters on the planning scale, a literature review was conducted to identify the key parameters that both sufficiently describe a residential community and, in the same time, have a major impact on its sustainability. The following parameters were identified: 1) density of built form; 2) mix of uses; and 3) street configurations. Teed & Condon (2002) in a study of neighborhood pattern typologies argue that these parameters both describe the neighborhood's development patterns and in the same time influence sustainability indicators such as: travel behavior, home affordability and value, formation of social ties, and permeability to rainwater. These three design parameters were also identified as having a potential impact on the performance of centralized residential cogeneration systems (see Owens, 1986; and Houghton, 2000) and also represent major differences between the design of conventional residential communities and more recent directions such as neo-traditional developments (see Steuteville & Langdon, 2003) and smart growth strategies (see O'Neill, 1999 and Corrigan et al., 2004). A more detailed discussion of each parameter is presented next.

4.4.1 Density of Built Form

4.4.1.1 Current suburban densities

Current U.S. suburban residential areas are characterized by their low-density. Burchell et al. (2002) reports an average density of 4.19 du/ac for residential areas with single-family homes. Tendencies for lower residential densities are linked to the perception that low-density suburban communities have higher quality environments away from the problems of crime and decay in cities (Neuman, 2005). Researchers also link these tendencies to increased concern for personal security and privacy (Southworth and Owns, 1993), and diminishing energy constraints (Owens, 1992).

4.4.1.2 Urban growth: compactness vs. sprawl

Urban sprawl, of which low-density is a major characteristic, has been criticized by many researchers for its negative impacts such as loss of land resources, increased energy consumption, increased travel, negative impacts on downtowns, and negative social consequences (Ewing, 1997; Burchell et al., 2002; Neuman, 2005). Additionally, researchers calling for various forms of increased densities (e.g. Elkin & McLaren, 1991; Jenks et al., 1996; Barton, 2000) cite benefits such as reducing energy consumption in transport, space heating and cooling, improving economic support for public transportations, and saving of open space. Krizik (2003) also argues that higher density development reduces the number and percentage of trips taken by automobiles. The Urban Land Institute (Haughey, 2005) also argues that higher-density developments requires less extensive infrastructure, generate less traffic, have similar if not higher property values, have similar crime rates, and result in lower environmental impacts compared to their low-density counterparts. New directions in residential development in the U.S., e.g. new urbanism and smart growth, generally call for higher residential densities and compact designs. Examples of this include Calthorpe's (1993) guiding principles for urban TODs, which recommend a density gradient, from the neighborhood edge to its center, of 10 to 25 du/ac and a minimum gross density of 10 du/ac.

4.4.1.3 Density and cogeneration system performance

Residential density has long been considered a major factor impacting the efficiency and the economic feasibility of centralized residential cogeneration systems, with areas of high density offering the most potential for such systems (Owens, 1986; ASHRAE 2000). Owens (1986) while arguing that there is no simple answer to the question of minimum density requirements, identifies a minim density range (or a break-even point) for residential developments in the UK of 25 to 75 du/ha (10 to 30 du/ac) according to different fuel price and discount rate assumptions. The impact of higher densities on decentralized cogeneration systems has not been addressed in the literature. However, some impact can be expected from the changes in residential loads resulting from these higher densities such as the increase in heating loads resulting from the lower solar access potential of buildings in these high density communities. This issue will be addressed in this study.

4.4.1.4 Density, analysis of case studies

An analysis of the case studies (shown in Table 4-1) indicates that all of them aim for or achieve densities higher than the 4.19 du/ac average density reported by Burchell et al. (2002). These densities are higher in the case of Highlands Garden Village, corresponding with its location as an urban revitalization project, than in the case of Civano, also corresponding with its location on the suburban fringe. The densities of the Kronsberg community are significantly higher as would be expected in European residential communities. Another notable feature in both Civano and Kronsberg is the decreasing of densities from the center of the community towards its edges. While available information about HGV do not clarify if the same principle is applied, this is likely to be the case since its master plan was prepared by Calthorpe Associates.

4.4.1.5 Selected assessment alternatives

The selection of density alternatives to be assessed in this study was based on both the analysis of the case studies, summarized in table 4-1, as well as on a review of suggested density guidelines for smart growth and new urban communities. As discussed previously, the density of the baseline community was set as 4 du/ac based on the average density reported by Burchell et al. (2002). Additional density alternatives were then selected to cover the range of possible densities of U.S. residential communities as well to represent, as much as possible, an interval measurement scale. These alternatives were subsequently determined as follows:

1) A density of 1 du/ac was selected to represent low-density suburban residential areas.

Table 4-1 Gross Densities of Selected Case Studies

Community Name	Area (acres)	Number of Dwellings	Gross Density (du/ac)	Source
Conventional residential communities	-	-	4.19	Burchell et al. (2002, p. 184)
Civano Neighborhood 1 Tucson, AZ.	170.8	658 - 1020	3.85 – 5.97	CDA (1998)
- Neighborhood center	39.4 (5 commercial)	203 - 345	5.90 – 10.0	
- Neighborhood general	59.0	217 - 301	3.67 – 5.10	
- Neighborhood edge	72.4	238 - 370	3.28 – 5.11	
Highlands Garden Village, Denver, CO.	27.0	291	10.8	Calthorpe & Fulton (2001)
Kronsberg, Hannover, Germany			Decreasing towards country side	City of Hannover (2004, p. 10-11)
- Expo settlement (current)	173 (70 ha) (19% public space)	3000	21.4	
Total		6000		

2) Higher density residential communities were then represented by density alternatives of 10 du/ac and 15 du/ac. The 10 du/ac density corresponds with HGV's average density and the maximum density of Civano's neighborhood center. It also corresponds with Calthorpe's (1993) recommended minimum average density for TODs and falls within the 6 to 20 du/ac range of densities suggested for general urban areas in Duany's transect (Steuteville & Langdon, 2003).

3) The 15 du/ac density represents the high end of the residential densities range and corresponds with the minimum residential density suggested for urban center zones in Duany's transect (Steuteville & Langdon, 2003) as well as with the average residential density suggested by Calthorpe (1993) for urban TOD.

4) Finally, a community with a density gradient ranging from 15 du/ac, at the center, to 4 du/ac, at the edge, was selected to investigate the potential of density gradients to achieve improvements is system performance while allowing for some lower-density areas within the community. This community included 72 units at a density of 15 du/ac; 120 units at a density of 10 du/ac; and 108 units at a density of 4 du/ac, therefore having an average density of 6.8 du/ac.

4.4.2 Mixing of Uses

4.4.2.1 Single-use vs. mixed-use residential communities

Historically, neighborhoods have been a place where people can both live and work and that offered them many of the services they need. However, early 20th century planning practices, which started in the U.S. in the 1920's & 1930's and increased after the second world war, aimed to segregate land-uses and create single-purpose districts (Grant, 2002). More recent planning approaches have been calling for a return to the mixing of land-uses on a fine grain (e.g. Calthorpe, 1993; Katz, 1994; Duany and Plater-Zyberk, 2000). The Urban Land Institute (Corrigan, 2004) encourages the development of mixed use neighborhood centers within walking distance of each other; and recommends that these centers have a strong residential base and include retail, office, entertainment, public services, and civic institutions. Grant (2002) also identifies two current strategies for mixing uses: the first is the planned community with its clusters of compatible uses oriented to encourage pedestrian and transit use; and the second is multi-use projects within inner urban core areas. However, both Tabb (1984) & Rickaby (1985) argue that the mix of uses within a residential community must be a sustainable and useful one.

Proponents of mixed use argue that it will result in the following benefits: 1) creating an all-day active urban environment that makes optimum use of infra structure; 2) reduction in car ownership and vehicle trips; 3) increasing pedestrian and transit use; and 4) alleviating environmental consequences of automobile use (Grant, 2002). Teed & Condon (2002) argue that a fine-grained diverse land use mix puts residents close to their daily needs and, combined with higher densities and interconnected street configurations, can decrease trip duration, frequency and distance, and increase the walk/transit mode share. The impact of mixed uses on travel behavior, however, is doubted by some researchers. Boarnet and Sarmiento (1998), for example, conclude that evidence on the link between land use and travel behavior is inconclusive. Frank (2000), however, argues that research work extending the relationship between land use and travel choice to air quality conclude that any resulting increase in vehicle trip generation, due to mixed uses, is overwhelmed by reductions in travel distances due to shorter trips.

4.4.2.2 Mixing of land uses and cogeneration systems

The mixing of residential and non-residential land uses offers a significant potential for improving the performance of centralized residential cogeneration systems. The addition of non-residential building types, e.g. retail, office, food services, and food sale, which consume most of their energy in the day-time, could result in considerable improvements in the over all daily load profile of the community as a whole, thus making it more suitable for centralized cogeneration systems, which perform much better with lower variations in load profiles (Caton, 2003). Adding non-residential uses that consume energy in the late night and early morning hours, e.g. 24 hour grocery stores, can result in even further improvements in the load profile and therefore the cogeneration system performance. On the other hand, mixing of land uses has no added impact on the performance of decentralized residential micro-cogeneration systems.

4.4.2.3 Mixing of uses, an analysis of case studies

All three case studies analyzed were characterized by high levels of mixing of uses as well as by the higher concentration of non-residential land uses (mostly commercial, business, and civic uses) in their central areas and/or main streets. Plans for HGV include the revitalization of a main commercial street by adding retail shops and restaurants. Other project areas also include restaurants, cafés, retail and office space (Haughey, 2005). Also, plans for Neighborhood 1 of Civano community (CDA, 1998) include a mixed-use neighborhood center. Permitted uses for the neighborhood include retail, commercial services, civic, small industrial, and recreational uses. More non-residential uses are permitted in the center and general districts than the edge district of Civano. Non residential uses in Kronsberg include a shopping center, a community center, office space, retail, restaurants, a health center and a church. The majority of these uses are concentrated in the central area of the community; however, some are also distributed in other parts but are still within walking distance from most of the community's residential units.

4.4.2.4 Selected assessment alternatives

The selection of assessment alternatives for the mix of uses parameters was based on a classification of the hierarchy of commercial centers within residential communities offered by Steuteville & Langdon (2003), which in turn was based on a ULI classification of shopping center types and sizes (Beyard, O'Mara et al., 1999). The selection of civic building types was adapted from suggested building types in Steuteville & Langdon (2003) and in Duany & Plater-Zyberk (2005). Only building types judged to be suitable for integration into residential communities of the size investigated in this study were included. This meant that certain building types were excluded from the study even though they may offer good potential for cogeneration. Examples of these include hospitals, large hotels and motels, secondary schools, and colleges.

The size of the community in this parameter was maintained at 300 dwelling units by reducing the number of residential units by one for each 1000 ft^2 of commercial & civic activity (Duany & Plater-Zyberk, 2005). The maximum percentage of reduction in residential units was kept below 50% so that the residential characterization of the community can be maintained. Based on this, a description of the selected alternatives is included below, while the details of the building types and sizes within each alternative are shown in table 4-2. These alternatives are:

1) A low use mix alternative, corresponding with low density suburban areas.

2) A medium use mix alternative corresponding with Steutville & Langdon's main street grouping and ULI's convenience shopping center. This alternative is anchored by a convenience store/food store and its average area ranges from 20,000 to 30,000 ft^2.

4) A high use mix alternative corresponding with Steutville & Langdon's town center grouping and ULI's neighborhood shopping center. This alternative is anchored by a grocery store or supermarket and ranges in area between 30,000 to 100,000 ft^2.

5) An optimized mix alternative, which is a variation of the high mix one in which changes are made to building types and operation schedules to improve the performance of the cogeneration system (increasing energy use in daytime and late night/early morning periods).

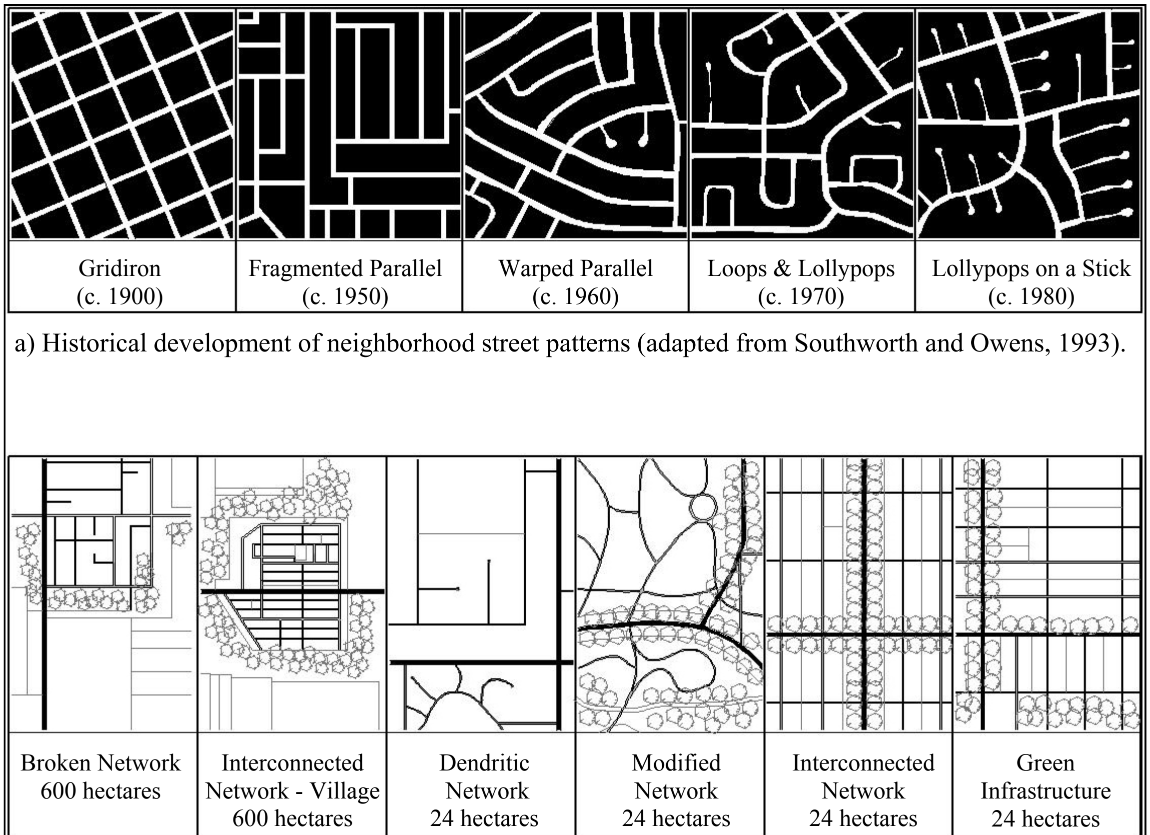
4.4.3 Street Configurations

4.4.3.1 Typology of neighborhood street configurations

The street configuration of a residential community is a reflection of its organizing principles and spatial typologies. Southworth and Owens (1993), in a study of street configuration for several historical periods of U.S. suburban development, argue that several aspects of street configurations contribute to the quality and character of a neighborhood including: length of streets, number of intersections, route options available, number of cul-de-sacs and loops, amount of land devoted to streets, which relates directly to infrastructure costs, and degree of connectedness. In their study, Southworth and Owens identify five typologies that describe the historical changes in US neighborhood street configurations as shown in figure 4-1 (a). Their analysis shows that street configurations have historically transitioned from being open and interconnected to being more closed and discontinuous. The researchers relate that to an increased concern for personal security and privacy; a perception that curved street are more natural; and the advantages of reduced infrastructure costs associated with new configurations.

Table 4-2 Commercial and Civic Building Types & Sizes for Mix of Uses Parameter

Mix of use alternative	Building type	Area/building (ft2)	Number	Equivalent dwelling units
Low use mix	Single family houses	2130	279	279
	Small community center	10,000	1	10
	Child care center	6,000	1	6
	Corner store	5,000	1	5
	Total			*300*
Medium use mix	Single family houses	2130	236	236
	Community center	20,000	1	20
	Child care center	6,000	1	6
	Food store	5,000	1	5
	Retail	20,000	1	20
	Office	10,000	1	10
	Bakery	2,500	1	3
	Total			*300*
High use mix	Single family houses	2130	180	180
	Community center	20,000	1	20
	Child care center	12,000	1	12
	Grocery (18 hrs schedule)	20,000	1	20
	Retail	40,000	1	40
	Office	20,000	1	20
	Bakery	5,000	1	5
	Fast-food Restaurant	2,500	1	3
	Total			*300*
Optimized use mix	Single family houses	2130	164	164
	Community center	20,000	1	20
	Child care center	12,000	1	12
	Grocery (24 hrs schedule)	20,000	1	20
	Retail	40,000	1	40
	Office	20,000	1	20
	Dry cleaning/laundry	10,000	1	10
	Bakery (24 hrs schedule)	5,000	1	5
	Sit-down Restaurant	5,000	1	5
	Fast-food Restaurant	2,500	2	5
	Total			*300*



a) Historical development of neighborhood street patterns (adapted from Southworth and Owens, 1993).

b) Neighborhood street pattern typology (adapted from Teed & Condon, 2002)

Figure 4-1 Typologies of Residential Neighborhood Street Configurations

For current communities, Teed & Condon (2002), in a study of neighborhood pattern typologies, identify six street configurations of residential neighborhoods (Figure 4-1 (b)). While the first two of these configurations represent low-density rural development patterns, the other four represent suburban patterns of residential development, which vary according to their organizing principles and level of interconnectedness. These suburban patterns correlate strongly the historical typologies identified by Southworth and Owens.

4.4.3.2 Street configurations and sustainability

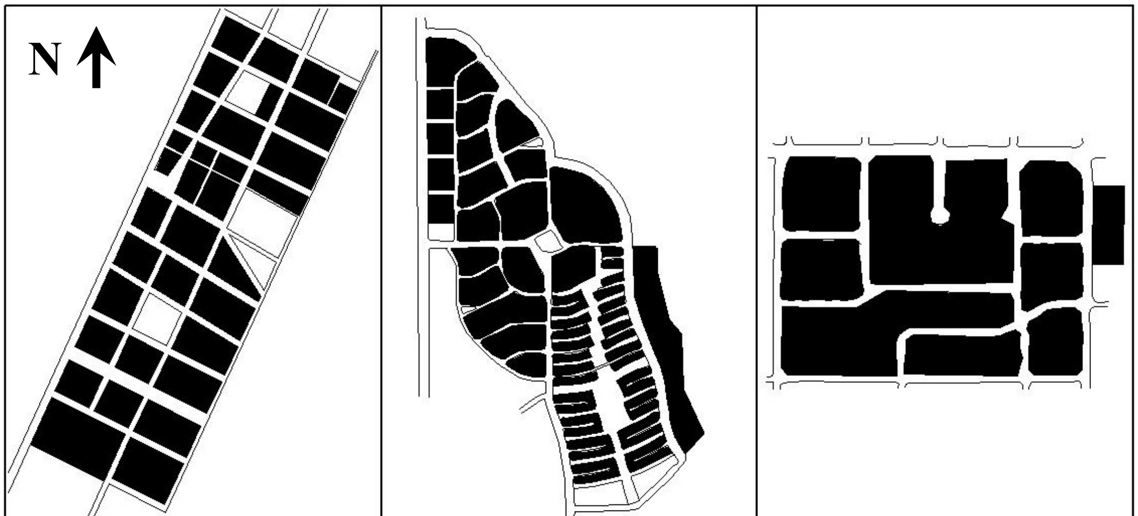
Street configurations influence several sustainability indicators, the most notable of which are walkability, vehicle travel distances, and infrastructure cost. In Teed & Condon's study (2002), the interconnected and interconnected-green infrastructure configurations were shown to have the highest walkbaility and lowest vehicle travel distances, thus reflecting reduced automobile dependence and higher social interaction. They, however, relate this influence to a combination of the three parameters studied, which also include density and land-use mix. Southworth (1997) also identifies interconnectedness of streets and concern with walkability and access as major differences between conventional residential communities and neo-traditional developments. He, however, agues that neo-traditional developments have more linear feet of street, blocks, intersections, and access points than conventional ones, making them more costly to build and maintain; and questions if walkable suburbs are possible under current market conditions and if they can actually lead to large-scale reductions in automobile dependence.

4.4.3.3 Street configurations and cogeneration system performance

Street configurations can substantially impact the performance of centralized systems through their influence on the length, hierarchy, and number of connections in a district energy network. These factors impact the initial cost of the system, a major component of which is piping cost (Phetteplace, 1995b). They also impact the magnitude of energy losses in the network, which is directly proportional to the surface area of the piping, and therefore the efficiency of the system. While street configuration does not have a direct impact on the performance of decentralized cogeneration systems, they can indirectly impact it through mutual shading of building especially at higher densities.

4.4.3.4 Street configurations, analysis of case studies

By analyzing the street configurations of the three selected case studies (Figure 4-2), it is obvious that all of them represent various modifications of the “interconnected” configurations identified previously. These modifications are most likely related to other design considerations (e.g. conceptual, topographical, site-related…. etc). All case studies, therefore, show an attempt to achieve a high degree of vehicular and pedestrian connectivity, which indicates the influence such interconnected street configurations can have on the sustainability of the community as discussed in the previous section.



Kronsberg Community Hannover, Germany (based on City of Hannover, 2004)	Civano Neighborhood 1 PAD Tucson, AZ (based on CDA, 1998)	Highlands Garden Village Denver – CO (based on Haughey 2005)

Figure 4-2 Street Configurations of Selected Case Studies

4.4.3.5 Selected assessment alternatives

The street configurations selected for assessment in this study were based on the two studies discussed previously in section 4.4.3.1 and shown in figure 4-1. These alternatives represent a range of interconnectedness of street configuration and include: 1) interconnected network/grid; 2) fragmented network; 3) landscape-oriented network; 4) Loops & cul-de-sacs; and 5) dendritic network. Layouts of these street configurations are included in Appendix C.

4.5 ARCHITECTURAL PARAMETERS

The design of residential buildings is influenced by a large number of parameters, which are considered in different design stages. With regard to parameters having a strong influence on the energy efficiency of these buildings, NAHB guidelines for developing green building programs (NAHB, 1999) categorized influential design parameters into: the site (including solar access, shading, and orientation); the building envelop (including passive solar design, insulation, and air-leakage); HVAC and plumbing equipment (including space heating/cooling and hot water systems); and appliances and lighting. Similarly, the Rocky Mountain Institute (RMI, 1995), in its design guidelines for sustainable buildings, also categorizes these parameters into: building configuration (including layout, size, and solar orientation), building shell (including windows and opaque envelop elements), and inside energy use (including space heating and cooling, water heating, lighting, and appliances).

Based on the previous, and taking into consideration that final decisions regarding many of these individual design parameters, e.g. insulation R-values, glazing U-value, HVAC system efficiencies, are typically taken in later design stages, the study aimed to focus on general design parameters, each including a number of issues and each aiming to achieve a certain design objective typically considered in early building design stages and which correspond to the parameters and categories identified previously. Therefore the following building scale design parameters were selected: 1) housing typology; 2) envelop and building systems' efficiencies (including window U-value, insulation levels, and efficiencies of heating/cooling and domestic water heating systems); and 3) utilization of renewable energy resources (including issues of solar orientation, solar access, thermal mass, and percentage and distribution of glazing). The second design parameter, envelop and building systems' efficiencies, aims to investigate the impact of improvements on energy code requirements, which are typically either required or awarded points by green building programs and sustainable communities performance standards; while the third parameter, utilization of renewable energy resources, aims to investigate the potential of architectural design to improve the energy efficiency of residential buildings within the requirements of building codes (which are considered as a base-line for this study. A more detailed discussion of each of these design parameters is presented next.

4.5.1 Housing Typologies

4.5.1.1 Sustainable communities and mix of housing typologies

Single family houses (SFH) are currently the dominant U.S. housing type especially in suburban areas. According to the U.S. census Bureau (2004), detached SFH account for 62% of all housing units in the U.S., and about 82% of new housing units in 2003 (U.S. Census Bureau, 2005). However, as discussed previously, this dominance of SFH is linked by many researchers to urban sprawl and the many negative costs associated with it. New directions in residential development (e.g. CNU, 2000; Teed & Condon, 2002; Corrigan et al., 2004; Duany & Plater-Zyberk, 2005; Haughey, 2005) are, therefore, calling for providing a wider range of housing typologies in residential developments. Proponents of the mixing of housing typologies argue that meeting the varied lifestyles of people, especially with the shift in demographics towards smaller families and singles, requires providing a range of rental and ownership single-family houses, town homes, and multifamily apartments. They also argue that providing diverse housing typologies increases the ability of people to live near their jobs thus improving the economic vitality of residential communities, and makes sure that a wide range of family types can find their preferred housing needs in the community thus achieving a desired social mix.

From the point of view of energy consumption and environmental impact, housing types such as town homes and multifamily houses are typically smaller in size than SFHs and therefore consume less energy. Additionally, as residents live closer to their working place, their work commuting distances are reduced, thus reducing both transportation energy consumption and traffic congestions (Haughey, 2003). Examples of new urbanist and smart growth communities (NAHB, 2002a & b; Steuteville & Langdon, 2003) show that the majority of them aim to provide a wider range of housing typologies as will be further illustrated in the analysis of case studies presented in section 4.5.1.3.

4.5.1.2 Housing typologies and cogeneration systems

As previously shown in the literature review, the majority of studies dealing with residential cogeneration system performance focused on single-family houses. However, changing or mixing of housing typologies can potentially have a significant impact on the performance of residential cogeneration systems. In the case of centralized systems, this impact will result from changes in the energy consumption characteristics of the community from those of a base-line community consisting only of single-family houses. In this regard, housing typologies such as live/work units offer a potential for achieving improvements in cogeneration system performance as they consume energy the morning, working day, and evening periods, thus resulting in increased utilization of the cogeneration system. This change in energy consumption characteristics will also have a potential impact on the performance of decentralized, building-integrated, residential cogeneration systems. Some housing typologies can also offer other potential advantages for decentralized systems if one system was used to meet the loads of a group of dwelling units, e.g. a group of town homes or an apartment building, as this would take advantage of the higher efficiencies and lower unit cost of the medium size cogeneration systems that will be needed in this case.

4.5.1.3 Housing typologies, an analysis of case studies

All three case studies are characterized by their mixing of housing typologies. Haughey (2005) reports that HGV will include a full range of housing typologies including: single family, town homes, live/work units, apartments, senior housing, and co-housing. On the other hand, design guidelines for PAD 1 of Civano community (CDA, 1998), while calling for a mix of housing typologies, limit the number of apartments to a maximum of 20% of dwelling units and require most of them to be concentrated in the neighborhood center district. In contrast to Civano, Kronsberg includes about 2,700 apartments compared to only 200 privately owned single-family terraces houses. The concept of housing mix in Kronsberg is, however, achieved through providing a wide range of apartment sizes, from 1 bedroom to 5 and more bedrooms, which reflect the social composition of society (City of Hannover, 2004).

Based on this, it is clear that mixing of housing typologies is a main characteristic of sustainable residential communities in general. However, the extent and range of this mix is affected by the type and location of the residential development. While both U.S. case studies aim to achieve a level of mixing of housing typologies, this mix is higher in the case of Highlands Gardens, an urban infill development project, than in the case of Civano, an urban fringe development project, which typically include a higher percentage of single-family houses.

4.5.1.4 Selected assessment alternatives

This study aims to evaluate the range of housing typologies generally found in residential communities of the size being investigated. While definitions of housing typologies vary, the selection of typologies for this study was primarily based on differences in design characteristics (e.g. size, configuration, number of floors) between typologies. These characteristics were adapted from those of new housing reported by the U.S. census bureau (2005) taking into consideration the fact that, for new housing, the census bureau only reports the characteristics of one-family housing, and multi-family housing.

Based on this, the following housing typologies were selected for assessment: 1) single family detached; 2) single family attached; 3) town homes; 3) live-work units; and 5) low-rise multi-family apartments. The study also aimed to assess the impact of the size of single-family houses on the cogeneration system performance. While the base line model represented the median size of new U.S. one-family houses, two other sizes were evaluated, representing a small and a large single-family house. The design characteristics of each of these typologies are shown in table 4-3. Housing typologies not investigated in this study include: high-rise apartment buildings, co-housing, mobile homes, and ancillary units (small rentable units in the backyard of single-family houses). While some or all of these typologies can offer potential for cogeneration, they were not evaluated within this study primarily because they are not typically found in residential communities of the size being investigated.

The evaluation of the decentralized approach, for housing typologies other than single-family detached, was based on having one cogeneration system serving all units within one structure. While the number of units per structure can impact the size, efficiency, and cost of the cogeneration system, currently available performance data do not allow for the evaluation of this impact. A more detailed study of this issue is needed, to determine the optimum number of units per structure, as more performance data of micro-cogeneration systems become available. For the purposes of this study, the numbers of units per structure include: two units, for the single-family-attached typology; five unit, for the town homes and live/work units typology; and 12 units, for the multi-family housing typology.

Table 4-3 Design Characteristics of Selected Housing Typologies

Housing typology	Units/structure	Unit size (ft^2)	No. floors
Single family house – detached (base-line)	1	2130	1
Single family house – small	1	1700	1
Single family house - large	1	3050	1
Single family house - attached	2	2130	1
Town homes	5	1500	1
Live work units	5	2000	2
Multi-family house	12	1100	3

4.5.2 Envelope and Building Systems' Efficiencies

4.5.2.1 Sustainable communities and envelope and building systems' efficiencies

The efficiencies of the building envelopes and the heating, cooling, and DHW systems have a significant impact on the energy consumption of residential buildings. Minimum efficiencies of heating, cooling, and DHW systems are determined by federal legislations and/or energy efficiency codes (e.g. the International Energy Efficiency Code, IECC),, while minimum envelope efficiencies (e.g. minimum wall and roof R-values and maximum window U-values) are typically included in energy efficiency codes, which vary according to climate and are adopted locally. While increasing efficiencies from those minimum levels will result in a reduction in the energy consumption, and therefore the environmental impact, of buildings, the use of higher efficiency systems and envelope components is typically impacted by a number of considerations including initial cost, pay-back periods, availability, and practicality. On the other hand, leading national energy efficiency programs (e.g. the EPA's Energy Start Program) require the use of higher efficiency building systems and envelope elements. Additionally, the majority of local green building programs require an increase in the energy efficiency of residential buildings from a base-line level (typically the local energy code), which is achieved in one of two methods illustrated in the NAHB Model green house program guidelines (NAHB, 2004): the first is a prescriptive method, in which points are awarded for increases in the efficiency of each system or building element; while the second is a performance path, in which a certain percentage of reduction needs to be achieved through a combination of efficiency increases. This study will adopt the second approach in its investigation of the impact of increased envelope and building systems' efficiencies.

4.5.2.2 Impact on cogeneration system performance

In general, the reduction in annual residential energy use and the improvement in load profiles which result from the use of higher efficiency envelope and heating, cooling and DHW systems can potentially impact the energy and emissions performance of the residential cogeneration system both in the case of the centralized and the decentralized approaches. The impact of using these higher-efficiency envelope and HVAC systems on the economic performance of the cogeneration system, however, is affected by whether the increase in initial costs due to the use of these higher efficiency systems and envelope components will be taken into consideration in the economic analysis. This study assumes that such improvements are already necessary to meet the energy consumption requirements of green building programs or sustainable community performance standards, which is the case in many of them as indicated by the literature review and the case study analysis. Such increases in cost, therefore, will be excluded from the economic assessment conducted in this study.

4.5.2.3 Envelope and building systems' efficiencies, an analysis of case studies

Design guidelines for all three case studies aim to achieve improvements in building and community energy consumption from typical residential levels. Residential buildings in HGV will meet the requirements of the "Built Green Colorado" green building program (NAHB, 2002a). This program requires a minimum energy performance of 10% less than IECC 2003 levels or an 82 HERS score, and awards 3 points for achieving an 84 HERS score and 9 points for meeting the EPA Energy Star program levels (86 HERS score). In the case of Civano, a set of standards were developed for the community called the CIVANO IMPACT system for sustainable development (City of Tucson, 2003). These standards aim to reduce residential energy consumption by 65% and commercial energy consumption by 55% from the 1990 levels of metropolitan Tucson. These standards include the use of high-efficiency envelop and HVAC systems that aim to reduce heating and cooling energy consumption to 20 kBtu/ft/yr. ANE (2003) reports the total energy use in Civano homes in 2002 to be 64 kBtu/sf/year, or 70% of that of Tucson 1998/99 homes, while the heating/cooling energy consumption was 20 kBtu/ft/yr, thus meeting the IMPACT standards target. On the other hand, in Kronsberg, energy consumption targets were set based on reducing CO_2 emissions by 60% compared to 1995 average German levels, 17% of this reduction was based on a set of low-energy homes (LEH) standards, which aimed to achieve a heating index of 50-55 kWh/m^2/yr (app. 17.5–19.2 kBtu/ft/yr) compared to the German standards level of 96 kWh/m^2/yr (app. 33.6 kBtu/ft/yr). A further 23% was based on the use of cogeneration and district heating, while 13% were based on savings in electricity use and 7% were based on quality assurance procedures. A 2001 audit of energy use in Kronsberg homes shows an average home heating index of 56 kWh/m^2/yr, very close to their established target range (City of Hannover, 2004).

From the previous analysis, it is clear that sustainable residential communities typically aim for, and achieve, considerable reductions in energy consumption and emissions levels either through complying with the requirements of green building programs or through developing project-specific standards. Such reductions are also shown to be based, at least partially, on increased envelope and HVAC system efficiencies. This supports the decision to exclude the added costs of these efficient systems from the economic assessment part of the study.

4.5.2.4 Selected assessment alternatives

For this parameter, design alternatives were selected on the basis of achieving reductions in the annual house energy use of 5% each (corresponding with 1 point on the HERS scale). A combination of increased envelope and building systems' efficiencies were identified for each alternative that would achieve the required reduction. For envelope efficiencies, only glazing U-values were increased, while for building systems, efficiencies of furnaces, air-conditioning, and domestic hot water systems were incrementally increased. For the most efficient alternative (a 20% reduction in annual energy use), internal loads of the house were also reduced by 15% corresponding with the use of energy efficient lighting and appliances. Envelope and building systems' efficiencies as well as internal loads for each alternative are included in table 4-4.

4.5.3 Utilization of Renewable Energy Resources

4.5.3.1 Sustainable communities and utilization of renewable energy resources

As discussed in Chapter II, the utilization of renewable energy resources, either through passive design strategies or the integration of active renewable energy systems, has always played a major role in reducing the energy consumption of residential buildings. In cold climates for example, designers using passive solar design strategies such as solar access, proper building orientation and form, ratio and distribution of glazing (among many others) can produce buildings with considerably less building heating loads, the main component of residential energy consumption in this climate. Active solar and solar-assisted systems such as solar DHW, solar thermal and photovoltaic systems can achieve further reductions in energy consumptions and/or produce electrical energy that can meet energy demands such as lighting and appliances. The combined use of both passive strategies to reduce energy demand and active renewable energy systems to meet this low demand can and does result in low-energy buildings and, in some cases, in stand-alone or zero-energy ones with minimal environmental impact.

Table 4-4 Envelope and Building Systems' Efficiency Alternatives

	Base-line	**5% reduction**	**10% reduction**	**15% reduction**	**20% reduction**
Envelope component:					
Glazing type	Double glazing/low-e/air	Double glazing/low-e /argon	Double glazing/low-e /argon	Tripe-glazing/low-e /argon	Tripe-glazing/low-e /argon
Window U-value	0.33 GTC 2634	0.32 GTC 2615	0.32 GTC 2612	0.22 GTC 3603	0.22 GTC 3603
Building systems					
Furnace(AFUE)	78%	84%	92%	96%	96%
Air-conditioning (SEER)	10	12	14	16	16
DWH (EF)	0.594	0.594	0.68	0.68	0.68
Internal Load densities (W/ft^2.day)					
Artificial lighting	2.885	2.885	2.885	2.885	2.308
Refrigeration loads	1.019	1.019	1.019	1.019	0.816
Cocking loads	1.234	1.234	1.234	1.234	0.926
Washer/dryer)	1.432	1.432	1.432	1.432	1.074
Plug appliances	4.575	4.575	4.575	4.575	3.66

The influence of early design stages on the energy performance and environmental impact of buildings is most clearly illustrated in the case of design decisions relating to the utilization of renewable energy resources, such as those related to building form, aspect ratio, orientation, volume, and solar access. Shaviv et al. (1996) argues that the design of passive and low-energy buildings, where the building itself is the solar system, requires knowledge of solar design rules at the very early design stage, when the solar characteristics of the building are determined. Changing these characteristics in later design stages, if they are not suitably determined, is difficult if not impossible. This increases the importance of providing knowledge-based design guidelines that take advantage of the increased capabilities of modern building energy simulation tools to inform designers in these early stages of the design process.

4.5.3.2 Impact on cogeneration system performance

The utilization of renewable energy resources, especially in the cold climate investigated in this study, can potentially have a mixed impact on the performance of residential cogeneration systems especially in the case of the centralized approach. On the one hand, the effective utilization of renewable energy resources can potentially reduce both the annual and peak heating loads of the residential building, which, in cold climates, constitute the largest components of its overall energy consumption. On the other hand, the solar access requirements associated with the effective utilization of these resources result in the need for relatively low-density residential development, which in turn can have a negative impact on the performance of centralized cogeneration systems because of the need for larger distribution networks, resulting in larger energy losses and a higher system initial cost. This negative impact, however, is limited to the centralized approach and will not affect the decentralized, building integrated one.

4.5.3.3 Analysis of case studies

Analysis of the three selected case studies showed varied levels of utilization of renewable energy resources. In the case of Civano community, Civano's design guidelines encourage the acknowledgement of the natural patterns of the sun, wind, and seasons through proper orientation, shading, and minimization of heat absorption (CDA, 1998). Planning objectives for Civano specifically refer to the utilization of solar resources as one of the means of achieving Civano's energy conservation targets. Such utilization includes both passive cooling strategies as well as the use of active solar systems such as solar DHW and photovoltaic systems. The Building America program is involved in a demonstration project of solar assisted DHW systems in 18 Civano residences (Rittelmann, 2004) which showed many of them achieving a solar fraction of more than 0.50, thus surpassing the goals of the Civano energy code.

In contrast, while the design guidelines of Highlands Garden Village state reducing energy consumption as one of their objectives, they do not specifically refer to the utilization of solar energy to reduce heating loads although the local cold climate provides the potential for that. This is possibly due to the urban location of the project and its high density which reduces the solar access of individual buildings and therefore limits their potential utilization of solar energy. However, the "Built Green Colorado" program, which the community aims to follow, award points for the use of active solar heating, photovoltaic and solar DHW systems.

In the case of Kronsberg, in addition to the project's low-energy housing (LEH) standards which aim to achieve reductions in energy use and emissions through multiple strategies including a level of utilization of solar energy (see section 4.4.3.3), Kronsberg includes a number of demonstration projects which feature the utilization of renewable energy among their main objectives (City of Hannover, 2000). The most prominent of those are: 32 passive solar houses; a housing development with a covered courtyard serving as a micro-climate zone; and "Solar City" which utilizes solar thermal technologies for space heating. Photovoltaic systems are also utilized in the primary school and community center buildings.

4.5.3.4 Selected assessment alternatives

The design alternatives identified for this parameter represent increasing levels of utilization of renewable energy resources with the aim of reducing annual energy use by levels equal to those investigated in the increased envelope and building system efficiency design parameter (i.e. incremental reduction of 5% of the annual house energy use). These alternatives investigate the impact of combinations of building form, orientation, percentage and distribution of glazing, external shading, thermal mass, and insulated shutters. Similar to the case with the envelope and building systems efficiency parameter, achieving the 20% reduction in annual energy use, required a reduction in internal loads by 20% corresponding to the use of energy efficient appliances. Envelope and building systems' efficiencies for these alternatives were determined based on the requirements of the IECC 2003 (ICC, 2003) for each glazing percentage. The design characteristics of each of the alternatives investigated in this parameter are described in table 4-5.

Table 4-5 Renewable Energy Utilization Alternatives

	Base-line	**Low utilization**	**Medium utilization**	**High utilization**	**Reduced loads**
Design characteristics:					
Building form	Square	Rectangle, 1:2 ratio	Rectangle, 1:2 ratio	Rectangle, 1:2 ratio	Rectangle, 1:2 ratio
Location of garage	South of building	North of building	North of building	North of building	North of building
Orientation	neutral	East/West Axis	East/West Axis	East/West Axis	East/West Axis
Percentage of glazing	18%	18%	25%	25%	25%
Distribution of glazing (S/E/W/N)	Equally on all elevations	75%/10%/10%/5%	80%/7.5%/7.5%/5%	80%/7.5%/7.5%/5%	80%/7.5%/7.5%/5%
External shading	No	1 ft overhang - south elevation	1 ft overhang - south elevation	1 ft overhang - south elevation	1 ft overhang - south elevation
Thermal Mass	No	Exposed concrete floor	Exposed concrete floor	Exposed concrete floor	Exposed concrete floor
Insulated shutters	No	No	No	Yes	Yes
Internal Load densities (W/ft^2.day)					
Artificial lighting	2.885	2.885	2.885	2.885	2.3081
Refrigeration loads	1.019	1.019	1.019	1.019	0.8155
Cocking loads	1.234	1.234	1.234	1.234	0.9256
Washer/dryer)	1.432	1.432	1.432	1.432	1.0742
Plug appliances	4.575	4.575	4.575	4.575	3.432

4.6 COGENERATION SYSTEM PARAMETERS

While this study focuses more on the impact of planning and architectural parameters on the performance of residential cogeneration systems, it is obvious that this performance is significantly impacted by the characteristics of the system itself. Consequently, it was important to include certain major cogeneration system design considerations in the study. However, in selecting the system design parameters to be investigated, the study primarily focused on issues typically addressed in the early design and feasibility assessment phase of cogenerations projects as identified from the literature (e.g. Baxter, 1997; Ellis, 2002; & Caton, 2003). Such initial feasibility assessments are typically based on the average load characteristics of the project, and address basic design issues such as selection of prime mover technology, determination of suitable operation strategy, and initial system sizing. Other system details, while certainly having an impact on its performance, were assumed to be constant across all simulation scenarios and, therefore, should not impact the results of the study. The following sections will discuss the selected cogeneration system design parameters, their significance and their potential impact on the system performance. With regard to case studies, the analysis will be limited to Kronsberg community as this is the only case study which utilizes a residential cogeneration system.

4.6.1 Prime-Mover Type and Efficiency

4.6.1.1 Prime mover type & system performance

The selection of a suitable prime mover for a cogeneration system is a basic yet critical aspect of its design. Caton (2003) links this selection to a number of technical issues such as the operation strategy of the facility, its required heat to power ratio, its overall power level, as well as characteristics of the prime mover itself such as available sizes, possible fuels, pollutants emissions levels, part load efficiencies, type and temperature of rejected thermal energy, and initial cost. Various prime mover technologies are available in a wide range of sizes, which have considerably different combinations of thermal and electrical efficiencies. The ratio of a prime mover's rate of supplied thermal energy to its power output (its heat to power or H/P ratio) is a major consideration in this selection process as it should match, as closely as possible, the required heat to power ratio of the project, or in the case of this study, the building/s which the cogeneration system aims to serve.

While sometimes utilizing the same technology, prime mover types that can be used in the centralized approach have considerably different efficiencies than those that can be used in the decentralized approach. Larger prime movers (e.g. medium-sized IC Engines and Microturbines) are more commercially established and typically have higher efficiencies and lower initial cost (per kW) than their smaller counterparts. On the other hand, smaller micro-cogeneration prime movers that can be integrated into individual building (e.g. small IC engines, Stirling engines, and small fuel cells) and typically have lower efficiencies, higher initial cost, and are less commercially established.

The Kronsberg case study includes two central cogeneration plants both utilizing gas turbine technology (City of Hannover, 2000). The smaller plant, serving 742 residential units, is closer to the size investigated in this study. This plant includes two cogeneration modules that utilize gas-turbine technology and produce 110 kW of electricity and 220 kW of thermal energy each (an H/P ratio of 2.0). Additional thermal energy is supplied by two gas-fired condensing boilers each producing 1,650 kW of thermal energy. The size of the system is linked to its electrical base-load operation strategy which will be discussed in the following section.

4.6.1.2 Selected assessment alternatives

The selection of system types to be evaluated in this study aimed to represent the major cogeneration technologies currently either commercially available or under development. The selected systems varied between the centralized and the decentralized approaches according to the available technologies for each size range. The selection of system types was based on several technology review reports (e.g. ONSITE (1999 & 2000), Caton (2003), & NREL-GRI (2003), for medium size system suitable for the centralized approach; and DOE (2003), Fischer (2003), & Knight & Ugursal (2005), for the micro-cogeneration systems suitable for the decentralized approach). Based on this review, the following system types were selected for evaluation: 1) reciprocating engines, 2) microturbines, 3) PEM fuel cells, and 4) SOFC fuel cell; for the centralized approach; and 1) reciprocating engines, 2) stirling engines; and 3) SOFC fuel cells, for the decentralized approach. While reciprocating engines and SOFC fuel cells were selected for both approaches, their characteristics, such as electrical and thermal efficiencies and cost, varied considerably between the two approaches. As discussed previously in section 3.3.3.6, efficiency and cost characteristics for each system type were based primarily on two studies: NREL-GRI (2003) for the centralized approach; and Knight and Ugursal (2005), for the decentralized one.

As identification of optimum prime mover type is impacted by the size of the system (Speiwak & Weis, 1994; Caton, 2003), a range of system sizes was evaluated for each integration approach. In the case of the centralized approach, evaluated systems ranged from 100 kW to 500 kW, while for the decentralized approach, they ranged from 0.6 kW to 4.25 kW. While the range of sizes, for the centralized approach, does not cover the full range of possible sizes (as maximum community electrical loads exceed 1200 kW), system sizes larger than 500 kW resulted in very poor economic performance for all system types being evaluated.

4.6.2 Cogeneration System Size & Operation Strategy

4.6.2.1 System size, operation strategy and system performance

Selecting the appropriate cogeneration system size, or more specifically the power rating of its prime mover, is closely linked with the selection of the optimum operation strategy for the system. The size of the system has a major impact on both the environmental and economic performances of the cogeneration system. The use of larger system sizes can result in higher reductions in overall energy use and CO_2 emissions as the larger size results in more utilization of the higher combined efficiencies of the cogeneration systems compared to conventional ones. However, further increases of the system size can eventually lead to reductions in overall system efficiencies as the cogeneration systems are forced to work more under part-load conditions, in which they are typically much less efficient. This negative impact is further increased in projects with highly variable daily and seasonal load profiles, as is the case with residential buildings. Additionally, from the point of view of economic feasibility, the use of larger system sizes increases the initial cost of the cogeneration system.

The operation strategy of the cogeneration system, on the other hand, can also impact the system's reliability requirements, utility interface, and economic performance. The selection of a suitable operation strategy for a cogeneration system is typically dependant on the electrical and thermal loads of the project. Ellis (2002) identifies four possible strategies: 1) electrical load tracking; 2) thermal load tracking; 3) electrical base loading; and 4) thermal base loading. Out of these four strategies, Ellis recommends base loading strategies because they allow the system to work at peak efficiencies. Caton (2003) also recommends base-load systems except for certain special circumstances. Additionally, Braun et al. (2004) suggest a net metering operation strategy for residential cogeneration systems, in which excess electrical energy is sold back to the grid. Such a strategy can increase the utilization of the cogeneration system; however, they require a utility interface that allows for that, and a sell-back program that provides suitable rates. The preference for base-load strategies is supported by the Kronsberg case study, in which both cogeneration plants were sized based on such a strategy, with the remaining electrical energy provided through the grid, and the additional thermal energy provided through gas boiler.

The selected operation strategy of a cogeneration system determines the size of its prime mover, with electrical base-load systems requiring the smallest prime movers. With regard to grid connection, only systems sized to meet the maximum electrical loads or those utilizing electrical storage (e.g. batteries) can be completely disconnected from the grid. However, for such system to be economically effective, the electrical load variations should be small enough so that the overall system efficiency is not impacted by the typically lower part-load efficiencies of cogeneration systems. Even then, a connection to the grid is often needed to provide the required load in cases of emergencies and in system maintenance periods. As issues of cogeneration system size and operation strategy are clearly linked, initial feasibility studies of cogeneration system performance (e.g. Baxter, 1997; Caton, 2003) generally conduct a combined investigation of both issues in which several system sizes are investigated for each operation strategy to identify the optimum combination of operation strategy and system size. This approach is also followed within this study.

4.6.2.2 Selected assessment alternatives

Cogeneration operation strategies evaluated in this study include: 1) electric base-loading; 2) thermal base-loading; 3) electric load-matching; and 4) net metering. For each strategy and integration approach, suitable system sizes were identified based on the load profile analysis of the base-line community. Based on this analysis, for the centralized approach, system sizes of 50 kW and 120 kW were required for the thermal base-load and electrical base-load strategies, respectively; while for the decentralized approach, a system size of 0.6 was required for the electric base-loading strategy. Thermal base-loading was not tested for the decentralized approach as the required system size was extremely small (less than 200 W). On the other hand, for both the electric load-matching and the net metering operation strategies, a range of sizes was tested to identify the optimum system size for each strategy. These sizes ranged from 100 kW to 500 kW, for the centralized approach, and from 0.6 kW to 4.25 kW, for the decentralized one. Thermal load-matching operation strategy was not tested for either approach as the literature review (Speiwak & Weiss, 1994; and Caton, 2003) indicated it was not widely used. Economic calculations for the net metering operation strategy were based on an assumption of equal buying and selling electricity rates. While this assumption is valid for certain locations and utilities, many other utilities, while offering the net metering option, price it on an "*avoided cost*" basis which results in lower electricity buy-back rates.

4.7 SUMMARY

This chapter presented the design parameters selected for investigation in this study on the planning, architectural, and cogeneration system scales. The chapter aimed to establish the significance of each parameter within the design of residential communities as well as its potential impacts on the sustainability of those communities and on the performance of the cogeneration systems that will be integrated in them. With regard to planning parameters, the current low densities of U.S. residential communities, and their subsequent negative impacts, were discussed as were the potential positive impacts of increased densities on the sustainability of those communities as well as on the performance of the cogeneration systems. With regard to mixing of uses within residential communities, the conflict between the current single-use nature of many residential communities and the potential positive impacts that mixing of uses can have on the sustainability of residential communities and on the performance of cogeneration systems was presented and discussed. Finally, two studies of the categorization of neighborhood street configurations were presented and the impact of different configurations on sustainability issues such as walkability, reduced vehicular travel, and social interaction was discussed as was the potential impact of these street configurations on the performance of cogeneration systems.

For architectural parameters, the current dominance of single-family housing in the US was discussed and several studies explaining the benefits of mixing of housing typologies on the energy consumption, social sustainability, and economic vitality of the communities were presented. The possible impact of different housing typologies on the performance of cogeneration systems was also discussed. Following that, the principles of utilizing renewable energy resources in the design of residential buildings were presented, as a means of reducing the energy consumption of those buildings, and the implication of applying those principles on the performance of cogeneration systems were discusses. Finally, the chapter addressed the issue of reducing the energy consumption of residential buildings by increasing the efficiencies of building envelopes and systems. The guidelines of many sustainable communities, which require having these higher efficiencies, were then discussed as was the potential impact that these increased efficiencies can have on the performance of residential cogeneration systems.

With regard to cogeneration system parameters, the issues usually considered in initial cogeneration systems' feasibility studies were discussed including prime mover type, system size, and system operation strategy. With regard to prime mover type, the advantages and disadvantages of larger, well established technologies vs. smaller emergent ones were presented; while, for system size and operation strategy, the relation between those two parameters was discussed as was the advantages and disadvantage of using larger cogeneration system sizes.

Finally, for each of the design parameters discussed in this chapter, the discussion was concluded by an analysis of the selected case studies of sustainable residential communities from the point of view of the parameter in question. This analysis was then used as a basis for identifying the alternatives for this parameter which will be used in the following chapter to assess its impact on the performance of the residential cogeneration systems. As previously discussed in chapter III, each of these alternatives will be used to develop a variation of the base-line community design, in which the performance of the cogeneration system will be assessed.

CHAPTER V
DESIGN PARAMETERS AND SYSTEM PERFORMANCE

5.1 INTRODUCTION

This chapter describes the impact of each of the design parameters selected for this study on the environmental and economic performances of residential cogeneration systems for both the centralized and decentralized integration approaches. To achieve this, first, the results of the performance assessment of the cogeneration system within the base-line community are presented and analyzed for both approaches. This includes an analysis of the electrical and thermal energy use profiles of the community compared to the electrical and thermal output of the cogeneration system. The resulting performances of the two approaches are then compared. Following this, for the centralized approach, the impact of each of the design parameters is illustrated through presenting and analyzing the results of the cogeneration system performance assessment procedures, described in chapter III, which were conducted for each of the community design variations representing the alternatives of each parameter. The impact of the parameters is then compared, relative to the base-line performance, and the results analyzed to identify the parameters having the most impact on the cogeneration system performance. The same process is then conducted for the decentralized approach and the parameters having the most impact on the system performance for that approach are also identified. Finally, the results for both approaches are summarized. The results reported in this chapter, for each design parameter, include the change in the three cogeneration system performance indicators used in this study (i.e. reduction in annual primary energy use, reduction in annual CO_2 emissions, and internal rate of return), as well as the resulting combined, environmental and economic, performance scores of each design variation relative to the base-line case.

5.2 BASE-LINE COGENERATION SYSTEM PERFORMANCE

5.2.1 Community Energy Use Profiles

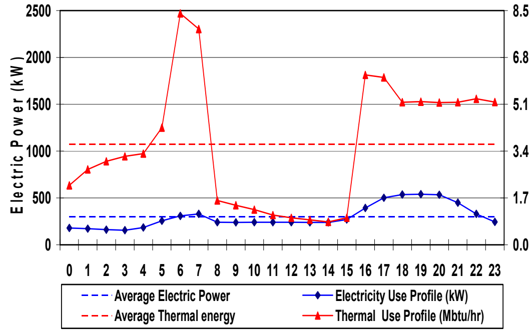
The results of the simulation of the base-line community electrical and thermal energy use were used to develop average daily seasonal weekday and weekend electrical and thermal energy use profiles, which are shown in figure 5-1. These profiles were then used to analyze the energy use characteristics of the community and subsequently to size the residential cogeneration system for both approaches. From the figure, the following can be concluded:

1) With regard to electricity use, all seasons, except summer, show a similar daily profile averaging around 300 kW with afternoon peaks approaching 550 kW. The summer profile, on the other hand, shows a considerable increase in afternoon and evening electricity use consistent with the use of air conditioning, with an average maximum use exceeding 1 MW.

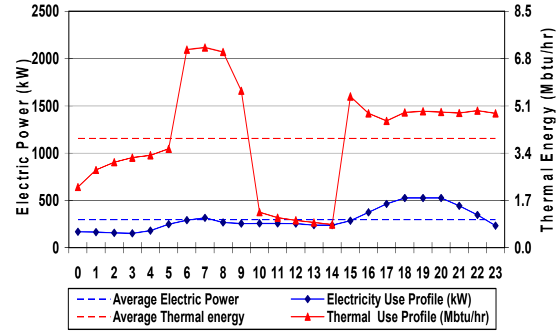
2) With regard to thermal energy use, the summer profile is shown to be relatively constant for most of the day. However, as the climate gets colder, the thermal energy use starts to increase in both morning and afternoon / evening periods consistent with the increase in space heating, hot water use, and cooking activities. The magnitude of the increase is much larger in winter as would be expected. In all cases, morning periods had higher levels of energy use.

3) Based on this, a centralized cogeneration system approximately 250 kW in size, or an equivalent decentralized system, would meet the electrical needs of the community for most of the day in all seasons except for afternoon and evening periods where utility grid backup would be needed. Such a system would work at or close to full load for most of the day, thus resulting in a good overall efficiency. A smaller, base loaded, system (about 150 kW for the centralized approach) would have higher overall efficiencies but would result in smaller environmental benefits and annual energy costs reductions This issue will be investigated further in sections 5.3.3 & 5.4.3 for the centralized and decentralized approaches respectively. The summer increase in electricity use and decrease in thermal energy use show the potential for using thermally activated cooling technologies, which would utilize the excess thermal output of the cogeneration system, thus reducing summer electricity use. While this issue is not investigated in this study, it represents a potential for future research as discussed in chapter VII.

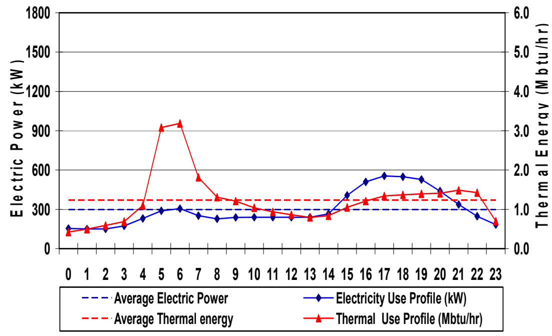
4) The large seasonal variation in the community's H/P ratio (from a 0.55 in summer to more than 4.2 in winter) shows that while a cogeneration system with a high H/P would be more effective in winter, it will produce a lot of unused thermal energy in summer. On the other hand, a lower cogeneration H/P ratio would perform better in summer but require a larger auxiliary heater to meet winter needs. This, along with the large fall and winter daily variations in thermal energy use, show a potential for the use of thermal storage. While the limitations of the simulation tools used in this study prevented the investigation of thermal storage, this option also represents a potential for future research.



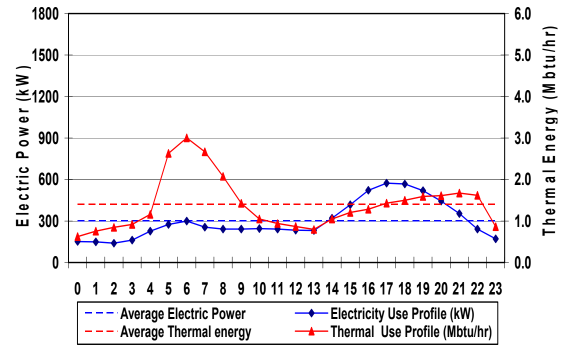
a) Average daily winter weekday energy use profile



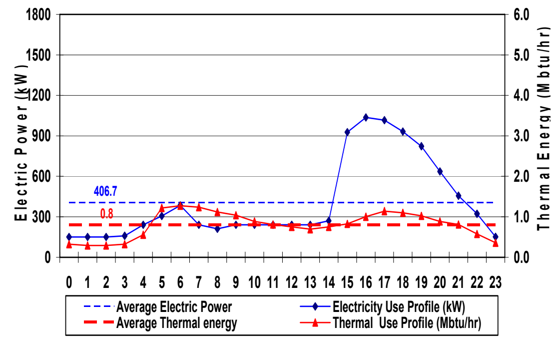
b) Average daily winter weekend energy use profile



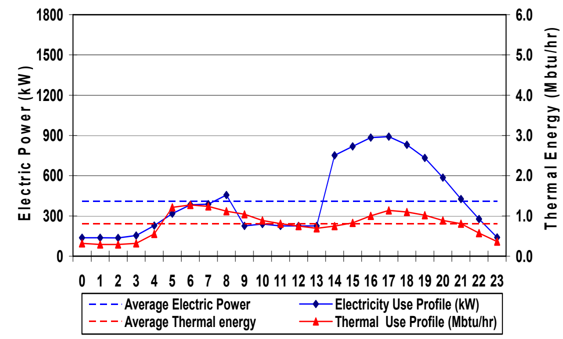
c) Average daily spring weekday energy use profile



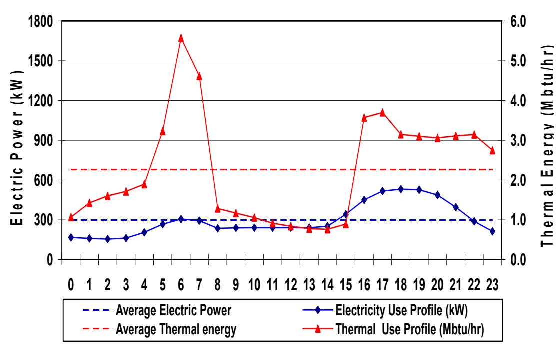
d) Average daily spring weekend energy use profile



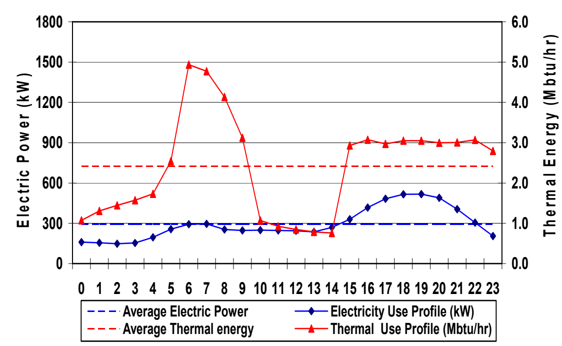
e) Average daily summer weekday energy use profile



f) Average daily summer weekend energy use profile



g) Average daily fall weekday energy use profile



h) Average daily fall weekend energy use profile

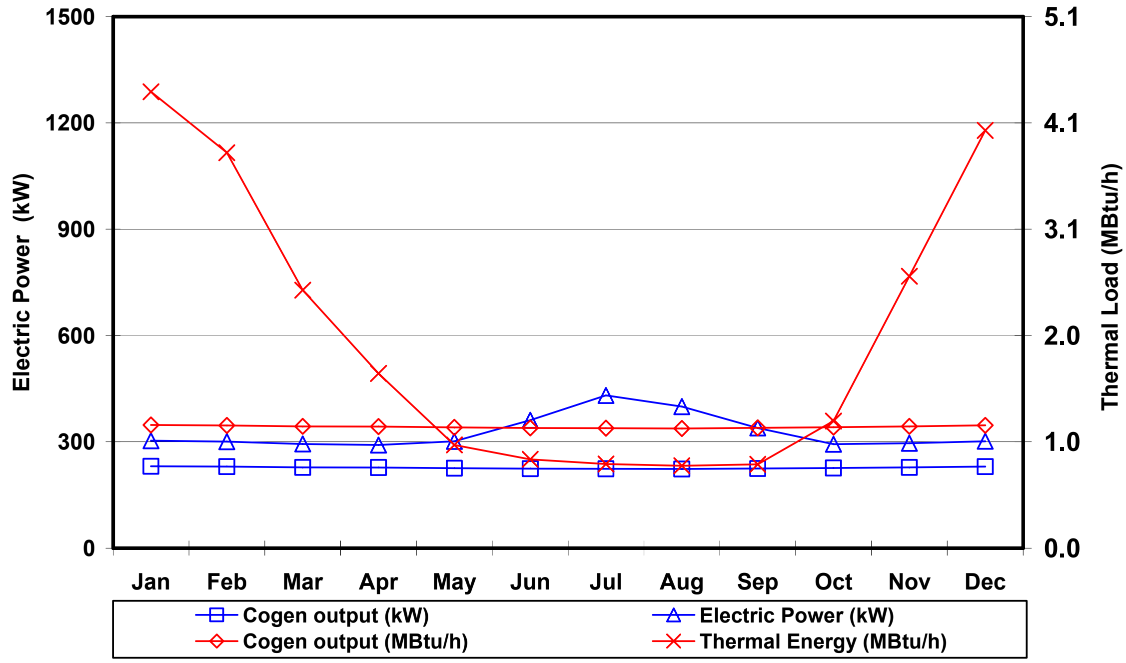
Figure 5-1 Average Daily Seasonal Weekday and Weekend Community Energy Use Profiles – Base-Line Community

5.2.2 Cogeneration System Performance Assessment Results

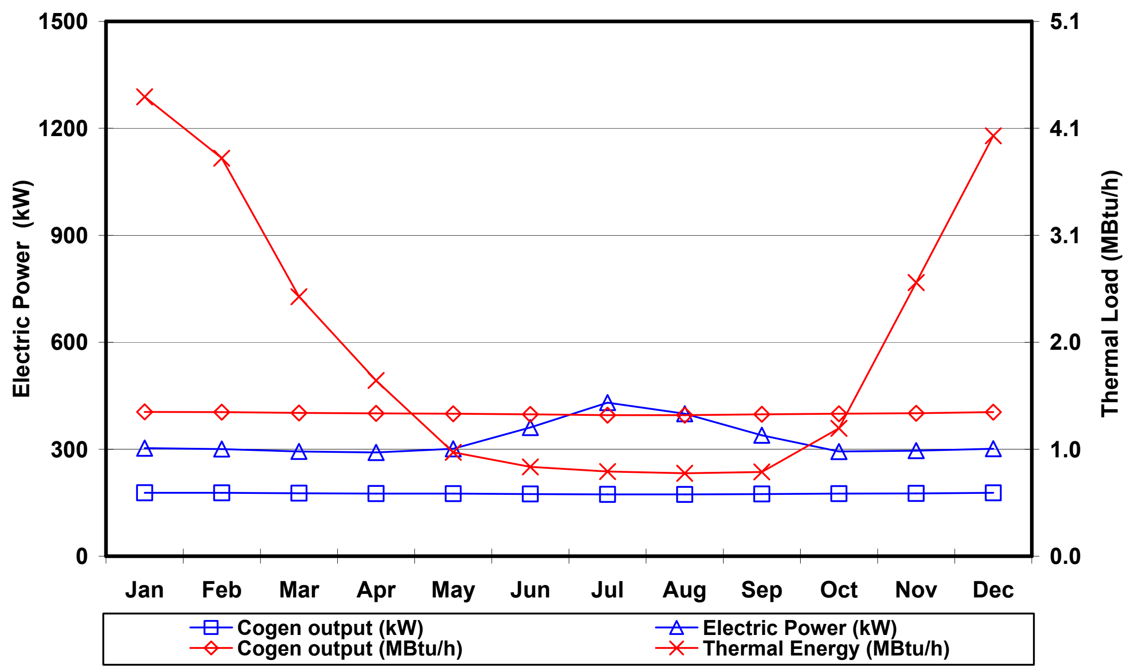
As discussed in chapter III, a residential cogeneration system was integrated into the base-line community following both a centralized and a decentralized integration approach. Figure 5-2 shows a comparison between the average hourly electrical and thermal needs of the community compared to the average hourly output of the cogeneration system for each month of the year for each integration approach. Subsequently, the results of the assessment of the cogeneration systems' environmental and economic performances are shown in figure 5-3 through 5-6 for both approaches. Figure 5-3 shows the annual primary energy consumption for the base-line community without cogeneration and with cogeneration as well as the percentage of reduction for both integration approaches. Similarly, figure 5-4 shows the annual CO_2 emissions without cogeneration and with cogeneration for both integration approaches as well as the resulting percentage of reduction, while figure 5-5 shows the IRR for both integration approaches. Finally, figure 5-6 shows the resulting combined environmental and economic performance scores for both approaches. The calculation of the three performance indicators and the combined performance followed the methodology detailed in sections 3.3.3.1 through 3.3.3.9, for the two environmental performance indicators; section 3.3.3.10, for the economic performance indicator; and section 3.3.3.11, for the combined performance. Cost assumptions for the IRR calculations are previously included in tables 3-4 through 3-6.

5.2.3 Centralized Approach vs. Decentralized Approach

Figure 5-2 shows that, for both approaches, the average hourly output of the cogeneration system is approximately constant throughout the year consistent with a system size close to the electrical base-load. The higher electrical efficiency of the cogeneration system in the centralized approach results in meeting a larger portion of the community's electric needs than in the decentralized approach,. On the other hand, the higher H/P of the system in the decentralized approach results in meeting more of the community's winter thermal needs than in the centralized approach and therefore it requires a smaller auxiliary heater. However, while both approaches result in excess thermal energy in summer months, the higher H/P of the decentralized approach also results in more excess thermal energy in this period. As discussed earlier, this excess thermal energy can be utilized to run thermally activated cooling technologies (e.g. absorption chillers). The resulting performance of the cogeneration system for both approaches is discussed next.



a) Centralized approach.



b) Decentralized approach.

Figure 5-2 Average Hourly Electrical and Thermal Needs Compared to Average Hourly Output of the Cogeneration System for Each Month of the Year – Base-Line Community

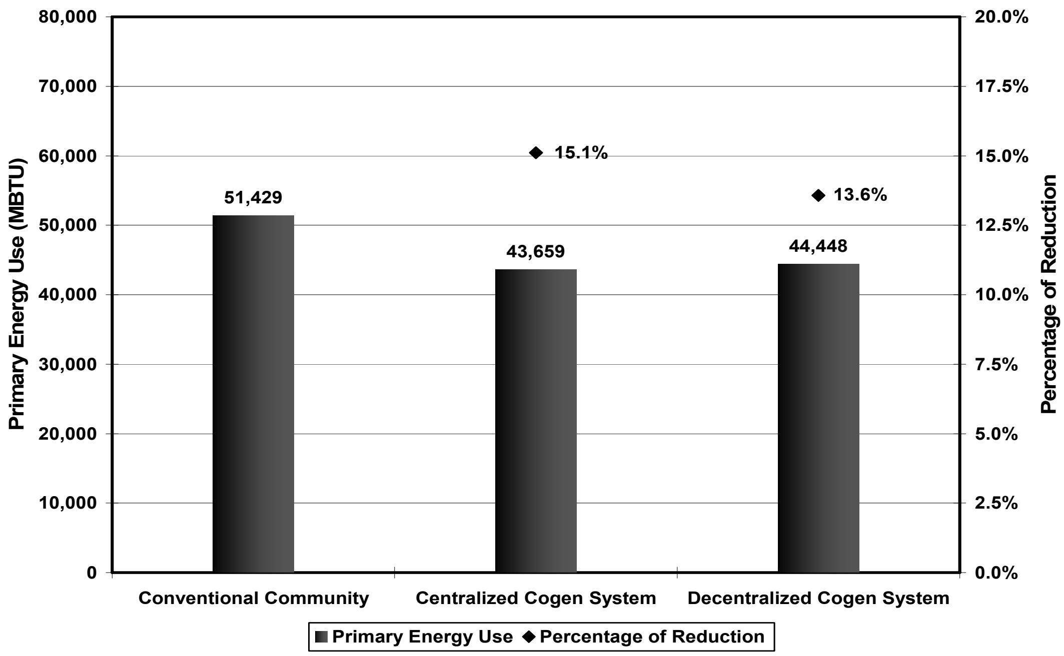


Figure 5-3 Base-Line Community Annual Primary Energy Use With and Without Cogeneration for Both Centralized and Decentralized Approaches

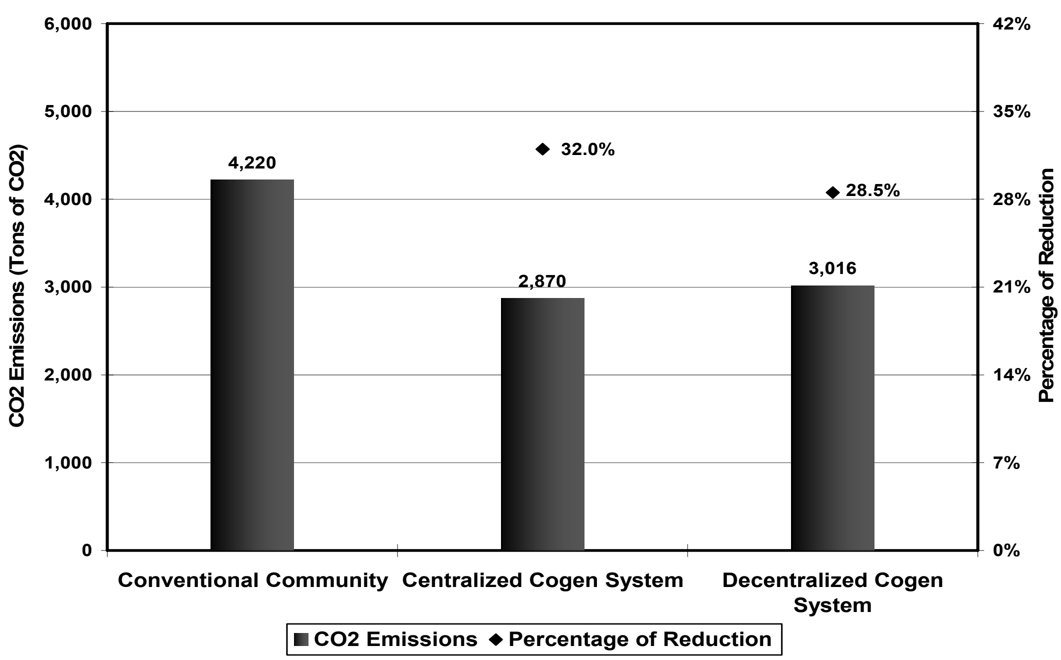


Figure 5-4 Base-Line Community Annual CO_2 Emissions With and Without Cogeneration for Both Centralized and Decentralized Approaches

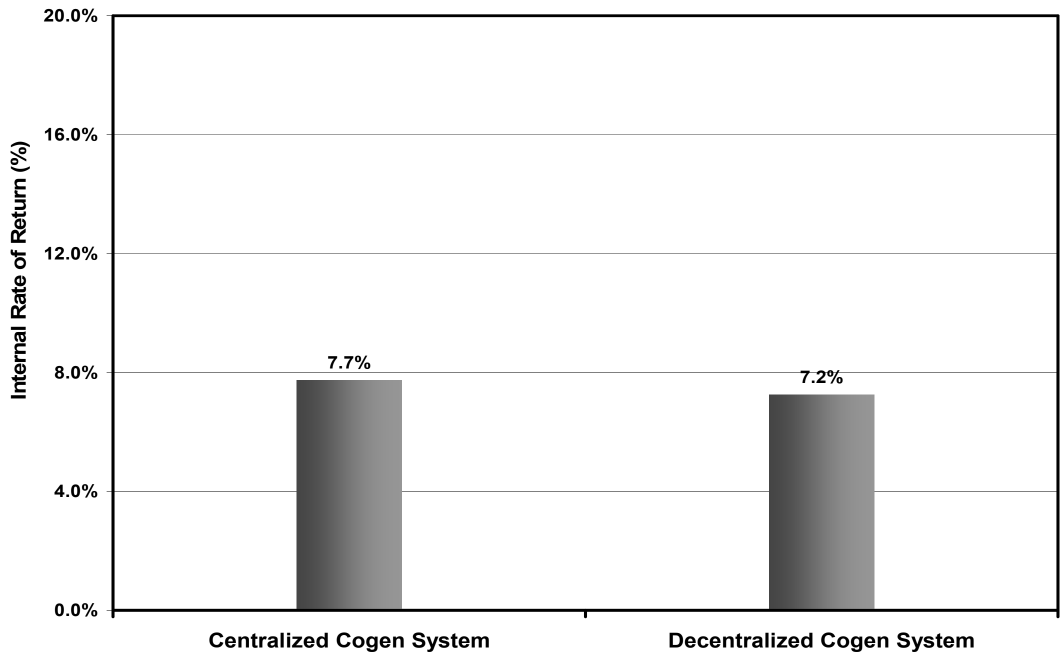


Figure 5-5 Base-Line Internal Rate of Return for Both Centralized and Decentralized Approaches

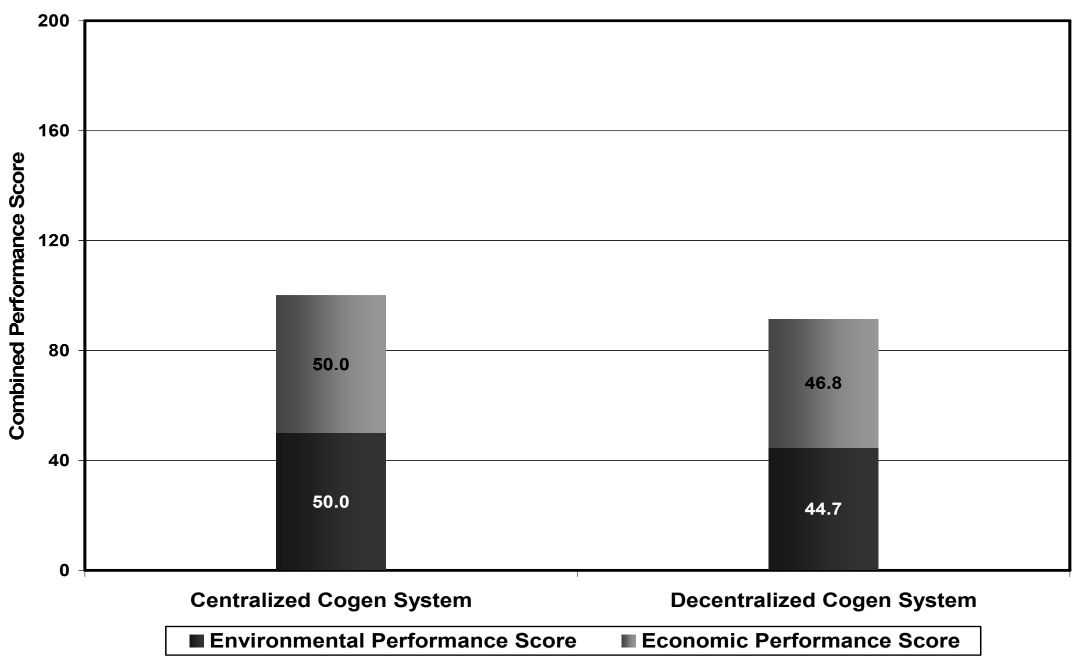


Figure 5-6 Combined, Environmental and Economic, Performance of Cogeneration System in Base-Line Community for Centralized and Decentralized Approaches

From figures 5-3 & 5-4, it can be seen that the centralized approach achieves higher reductions in both primary energy use and CO_2 emissions than the decentralized one; however the difference between the two is small. These results show that the impact of the lower electric efficiencies of the micro-cogeneration systems in the decentralized approach, compared to the larger and more efficient centralized systems, is compensated for to some extent by their higher overall efficiencies combined with the impact of the thermal losses within the district heating network in the centralized approach. Figure 5-6 shows that combining these two performance indicators results in a drop of approximately 10% in environmental performance for the decentralized approach compared to the centralized one. However, the performance of the micro-cogeneration systems in the decentralized approach was very sensitive to the size of the system with very small changes in system size resulting in significant variations in its performance. This issue will be discussed in more details in sections 5.4.3.1 & 5.4.3.2.

With regard to economic performance, figures 5-5 & 5-6 show that the centralized approach also outperforms the decentralized one by approximately 10%. A major factor behind this is the higher reductions in annual energy costs achieved in the centralized approach, which are caused by the assumption that in this approach, annual cost calculations with cogeneration use average industrial fuel prices, which are about 23% lower than the average residential fuel prices used to calculate annual costs without cogeneration. This clear economic advantage, combined with the assumption that centralized systems will perform as an electric cooperative and will therefore be exempt from income tax, offsets the negative economic impact of the higher total initial costs of the centralized system. These higher costs are caused primarily by the costs of the district energy network, which represents 57% of the total initial system costs. The IRR of the decentralized approach was sensitive to the size of the micro-cogeneration system, with very small increases in system size resulting in major IRR decreases as will be discussed later in section 5.4.3. Initial costs of micro-cogeneration systems were adapted from data reported by Knight and Ugursal (2005). However, it has to be taken into consideration that most of the systems described by Knight & Ugursal are either in their early commercialization stages or are still in the R&D stage, and therefore, changes in their costs can be reasonably expected.

Based on this, and as seen in figure 5-6, under the assumptions of this study, the centralized cogeneration approach outperforms the decentralized one in both environmental and economic performances by about 10%. However, it has to be noted that fuel prices assumptions used is this study are average state prices, and that a change in these fuel prices (either with regard to the price of electricity compared to natural gas, or with regard to residential prices vs. industrial ones) can have a major impact on the economic performance of both approaches and therefore on their combined performance. Also, expected improvements in the initial and maintenance costs for micro-cogeneration systems (discussed in NREL-GRI, (2003)) can also improve the economic performance of these systems compared to centralized ones. Finally, the sensitivity of the performance of the micro-cogeneration systems to their size and initial costs can also impact these results as will be discussed in later sections.

5.3 IMPACT OF DESIGN PARAMETERS – CENTRALIZED APPROACH

The following sections present and analyze the results of the impact of each design parameter on the performance of the cogeneration system for the centralized approach, while appendix F includes the average energy use profiles developed for each of the design variations.

5.3.1 Impact of Planning Parameters

5.3.1.1 Density of urban form

The results of the performance assessment for the residential density alternatives are shown in figures 5-7 through 5-10. Figure 5-7 shows, for each of the different density alternatives, the annual community primary energy use with cogeneration, the magnitude and percentage of the reduction in primary energy use due to the use of cogeneration relative to the community energy use without cogeneration. Figure 5-8 shows the same information with regard to annual CO_2 emissions, while figure 5-9 shows the internal rate of return of the cogeneration system in the different density alternatives and figure 5-10 shows the combined performance for each density alternative relative to the base line community.

Figures 5-7 & 5-8 show that increasing the density of the residential community only results in small improvements in the percentages of reduction in primary energy use and CO_2 emissions. These improvements can be attributed to the larger heating loads of the high-density alternatives, resulting in higher system utilization, as well as to the decrease in the thermal losses within the district heating network. With regard to the density gradient alternative, its performance indicators fall between those for the base-line alternative and the 10 du/ac one. This corresponds well with the average density of that community (6.8 du/ac) which also falls between the densities of the other two alternatives.

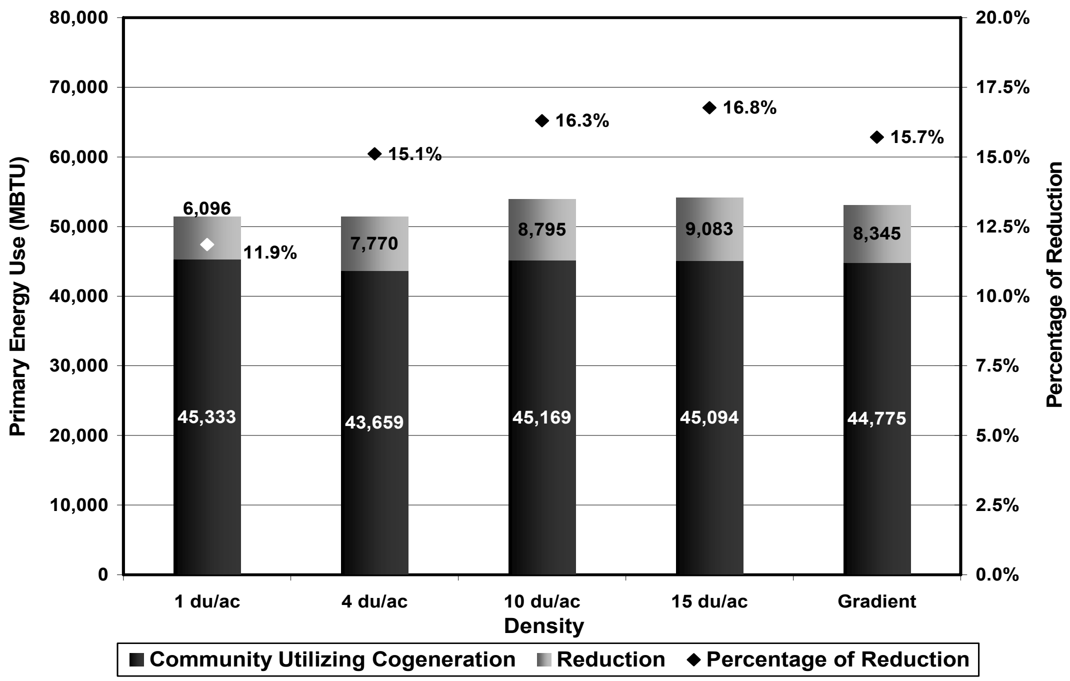


Figure 5-7 Impact of Density on Primary Energy Use – Centralized Approach

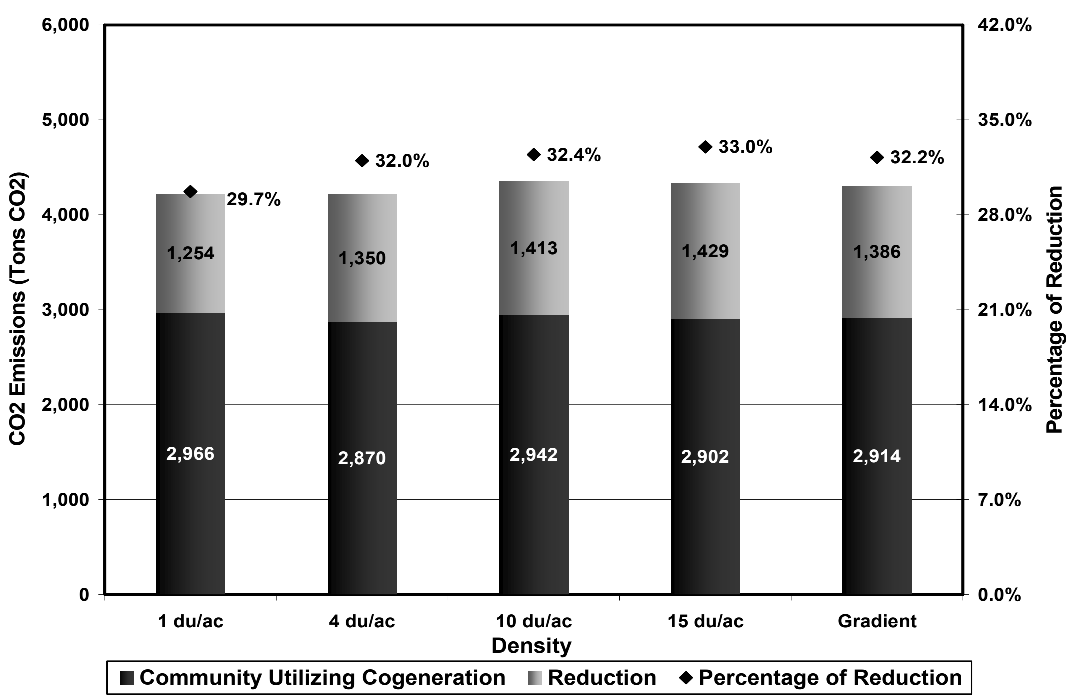


Figure 5-8 Impact of Density on CO_2 Emissions – Centralized Approach

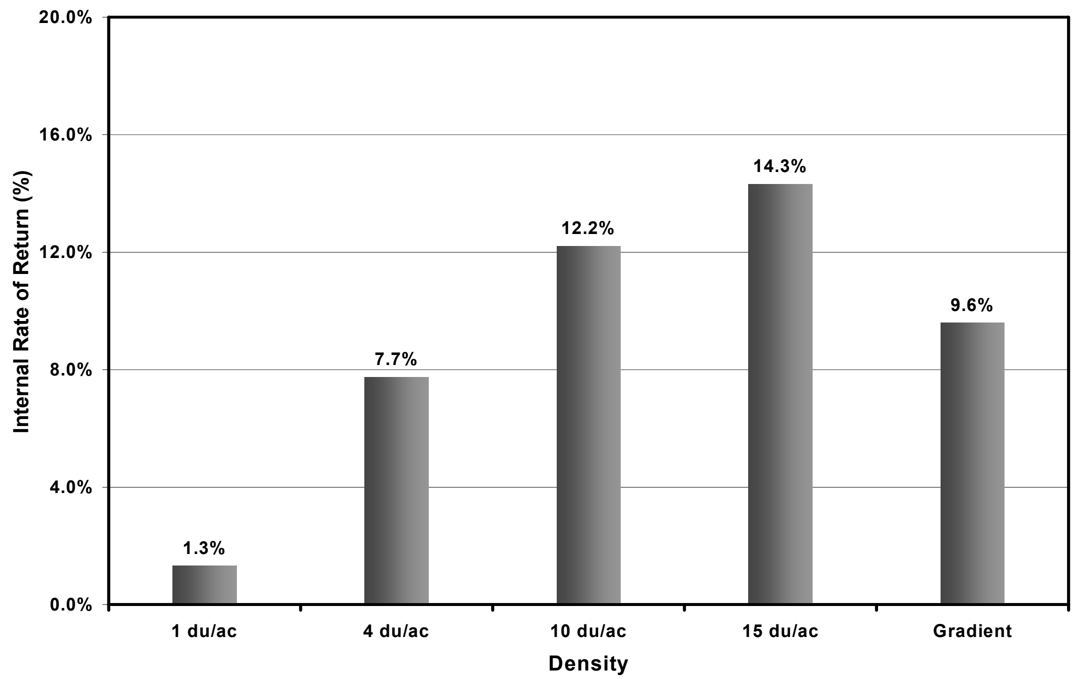


Figure 5-9 Impact of Density on Internal Rate of Return - Centralized Approach

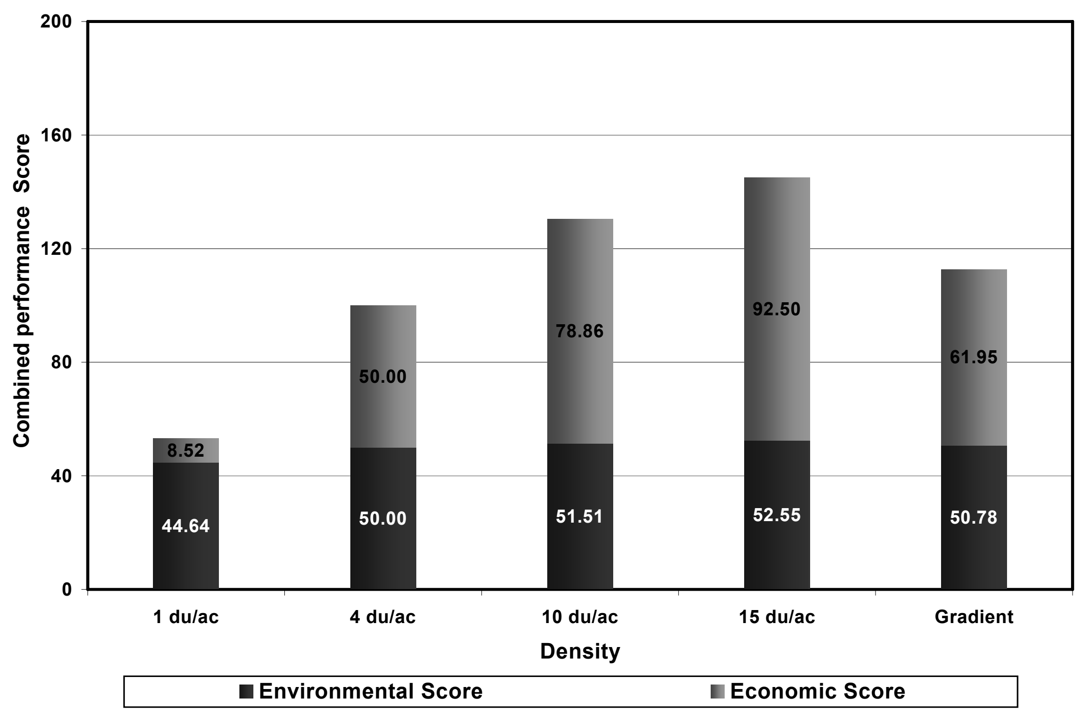


Figure 5-10 Impact of Density on Combined Performance – Centralized Approach

On the other hand, the impact of increasing density is much more pronounced in the case of the economic performance, as shown in figure 5-9, with higher densities having a large positive impact on the IRR of the cogeneration systems, and lower density having a similar negative impact. This can be directly linked to changes in the initial cost of the district heating network. The results also suggest that the relationship between increased densities and increased IRR is not a linear one, with the increase in IRR from the 4 du/ac alternative to the 10 du/ac alternative being considerably larger than from the 10 du/ac alternative to the 15 du/ac one. The density gradient alternative also performs roughly equal to its average density. More importantly, figure 5-9 allows for the approximate identification of the density range that would achieve a certain IRR. For example, an IRR of 10% (identified as a minimum acceptable economic performance) would be achieved by a community with a density between 7 du/ac and 8 du/ac.

With regard to combined performance, figure 5-10 shows that the 10 du/ac alternatives performs approximately 31% better than the base-line alterative, while the 15 du/ac one performs about 46% better, also indicating a non linear relationship. The density gradient alternative shows an improvement of approximately 13%. This improvement in performance, in all cases, is mostly due to the economic performance, which indicates that increasing the relative weight of economic performance within the combined performance calculations would result in more relative improvements in combined performance for the higher density alternatives.

5.3.1.2 Mix of uses

The results of the cogeneration system performance assessment for the selected mix of uses alternatives, discussed previously in section 4.4.2.4 and detailed in table 4-2, are shown in figures 5-11 through 5-14. Figure 5-11 shows the annual community primary energy use with cogeneration, the magnitude of the reduction in primary energy use due to the use of cogeneration, and the percentage of this reduction for each of the mix of uses alternatives. Figure 5-12 shows the same information with regard to annual CO_2 emissions, while figure 5-13 shows the resulting internal rate of return of the cogeneration system for all mix of uses alternatives and figure 5-14 shows the resulting combined performance for all the mix of use alternatives relative to the base-line case.

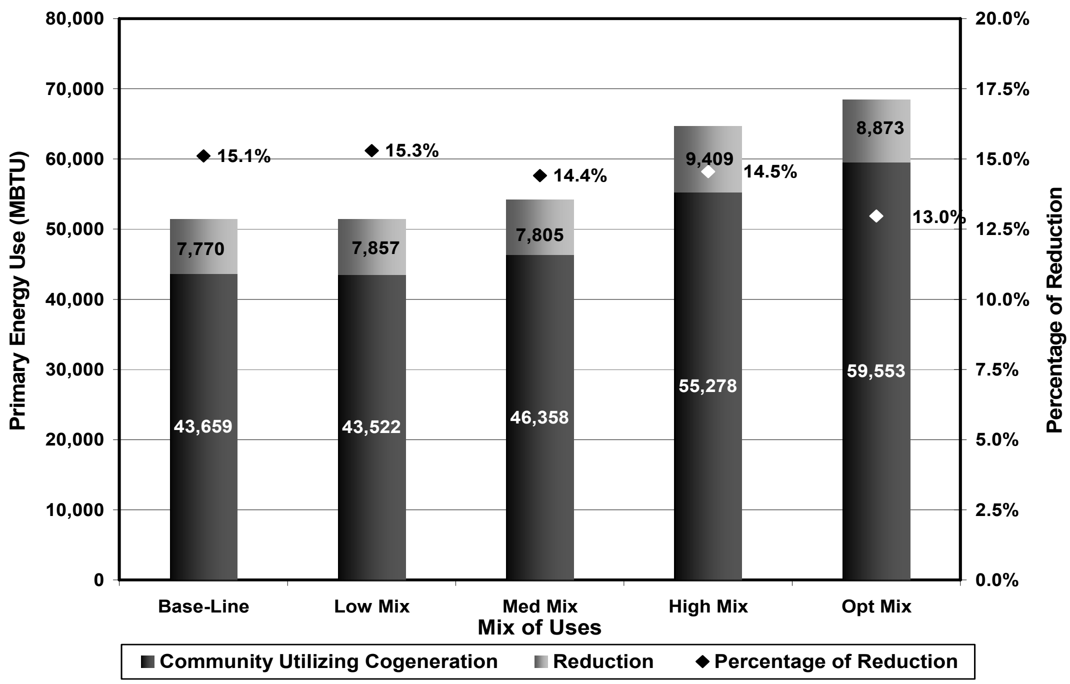


Figure 5-11 Impact of Mix of Uses on Primary Energy Use – Centralized Approach

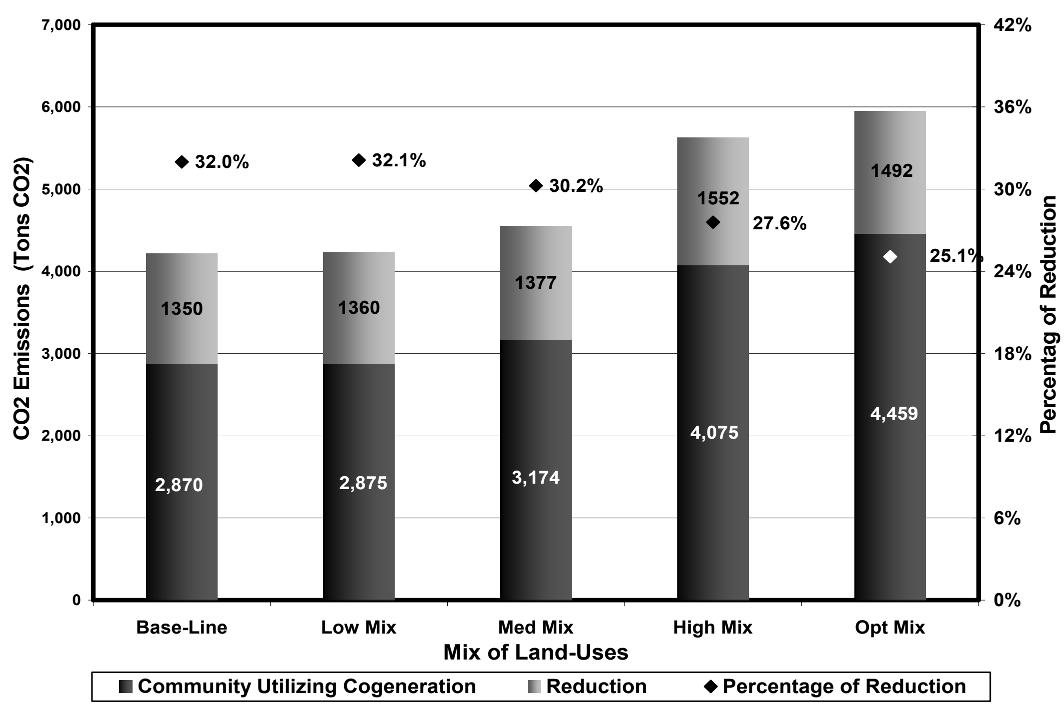


Figure 5-12 Impact of Mix of Uses on CO_2 Emissions – Centralized Approach

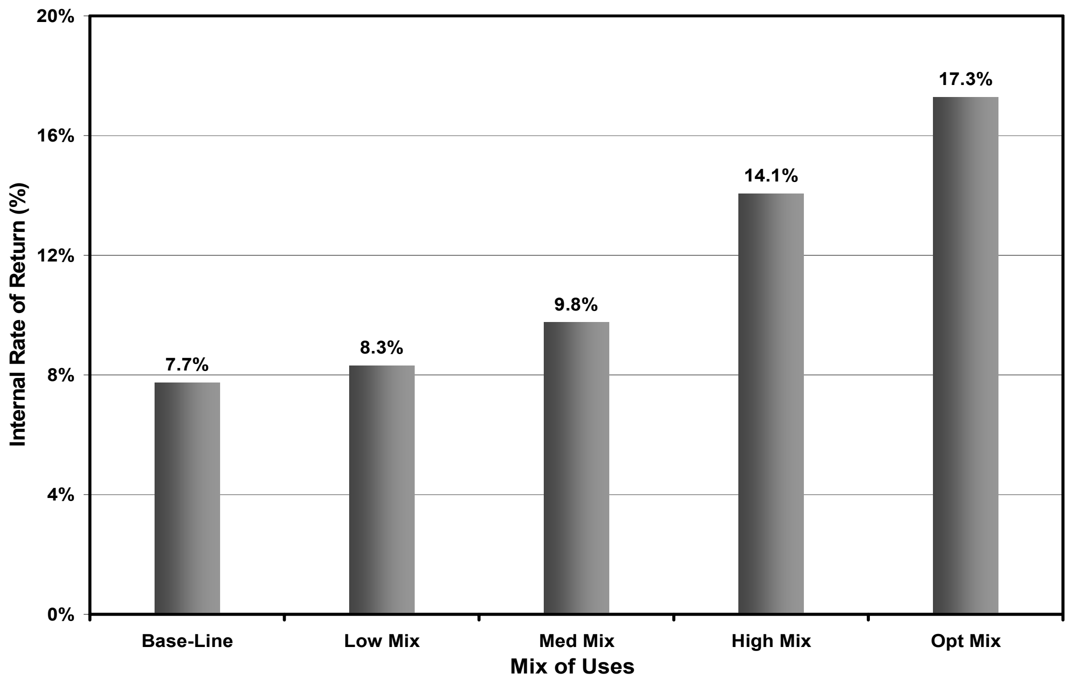


Figure 5-13 Impact of Mix of Uses on Internal Rate of Return – Centralized Approach

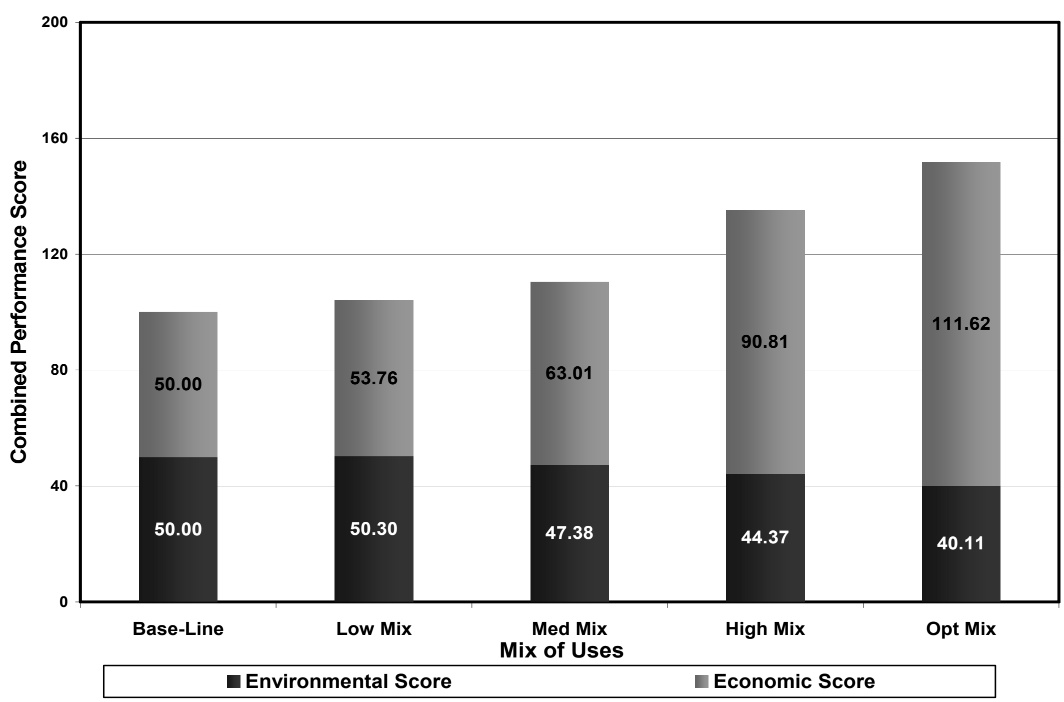


Figure 5-14 Impact of Mix of Uses on Combined Performance – Centralized Approach

Figures 5-11 & 5-12 show that while increasing the mix of uses within the community results in higher magnitudes of reduction in both primary energy use and CO_2 emissions, for the same system size, the percentage of the reduction relative to the case without cogeneration is reduced. This is primarily because the mix of uses alternative use more electricity than the base-line case (an increase of up to 40% for the optimized mix alternative). As the cogeneration system size is fixed for all alternatives, less percentage of utility electricity is replaced by electricity from the cogeneration system, thus resulting in the lower percentages of reduction in primary energy use and CO_2 emissions. However, figure 5-13 also shows that increasing the mix of uses results in considerable increases in the IRR especially for the high mix and optimized mix alternatives. This inverse relationship between the environmental and economic performance indicators will be also discussed in later sections.

The resulting combined performance shown in figure 5-14 indicates that the improvement in economic performance due to increasing the mix of uses is considerably larger than the corresponding reduction in environmental performance. For example, the high use mix alternative (see table 4-2) shows an improvement in economic performance of approximately 80% compared to a decrease in environmental performance of less than 10%. This indicates that the cogeneration system is being better utilized in the mix of uses alternatives. The improvement in economic performance is related to improvements in the patterns of use of energy, as well as to small reductions in the heating network pipe lengths in the mix of uses alternatives. Based on the trade-off relationship identified between environmental and economic performances, this result indicate that the use of larger cogeneration system sizes will result in better environmental performance, while in the same time achieving a reasonable economic performance.

In the optimized use mix alternative, a number of modifications were performed to improve the energy use profiles of the community. These include changing the working hours of the grocery and bakery to 24 hours instead of 18 to increase the night-time electricity and thermal energy use of the community, and adding a laundry/dry cleaner, a sit-down restaurant, and a second fast-food restaurant to increase the thermal energy demand in the day time. Based on this, as shown in figure 5-14, the optimized use mix alternative achieved an improvement in economic performance of more than 225% compared to the base-line case and about 25% compared to the high uses mix one and the corresponding reduction in environmental performance was considerably less (about 20% relative to he base-line case and 5% relative to the high use mix alternative). Two other commercial building types were evaluated within this alternative including a primary school, and an assisted living facility (nursing home). Both of these building types did not result in improving either the environmental or the economic performance of the alternative.

5.3.1.3. Street configuration

The results of the performance assessment for the selected street configuration alternatives (see section 4.4.1.5 & appendix C) are shown in figures 5-15 through 5-18. Figure 5-15 shows the annual community primary energy use with cogeneration, the magnitude of the reduction in primary energy use due to the use of cogeneration, and the percentage of this reduction for each of the street configuration alternatives. Figure 5-16 shows the same information with regard to annual CO_2 emissions, figure 5-17 shows the IRR of the cogeneration systems for all alternatives, while figure 5-18 shows the resulting combined performance.

Figure 5-15 shows that street configuration has a minimal impact on reductions of primary energy use, while figure 5-16 shows the same result for reductions in CO_2 emissions. In both cases, the base-line case (interconnected network) achieved the best performance. This decrease in energy and CO_2 reductions for all alternatives, relative to the base-line case, is linked to the corresponding increase in the percentage of thermal losses in the district heating network, which ranges from 16.6% to 18.1% for the street configuration alternatives compared to 14.7% for the base-line case. This increase is due to the increases in network piping lengths for all alternatives. While changes in street configuration also impacts mutual shading between buildings, and therefore their energy consumption; this factor was not included in this assessment as it had minimal impact on the annual energy consumption of the houses for the base-line density of 4 du/ac. However, it is reasonable to expect this factor to have more of an impact at higher densities.

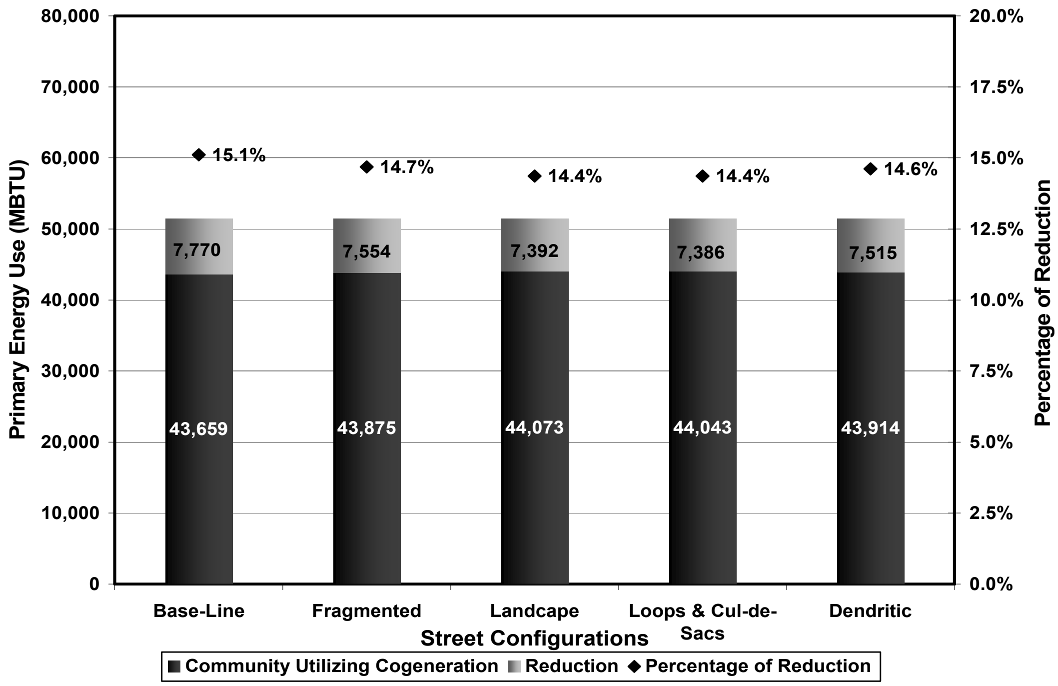


Figure 5-15 Impact of Street Configuration on Primary Energy Use – Centralized Approach

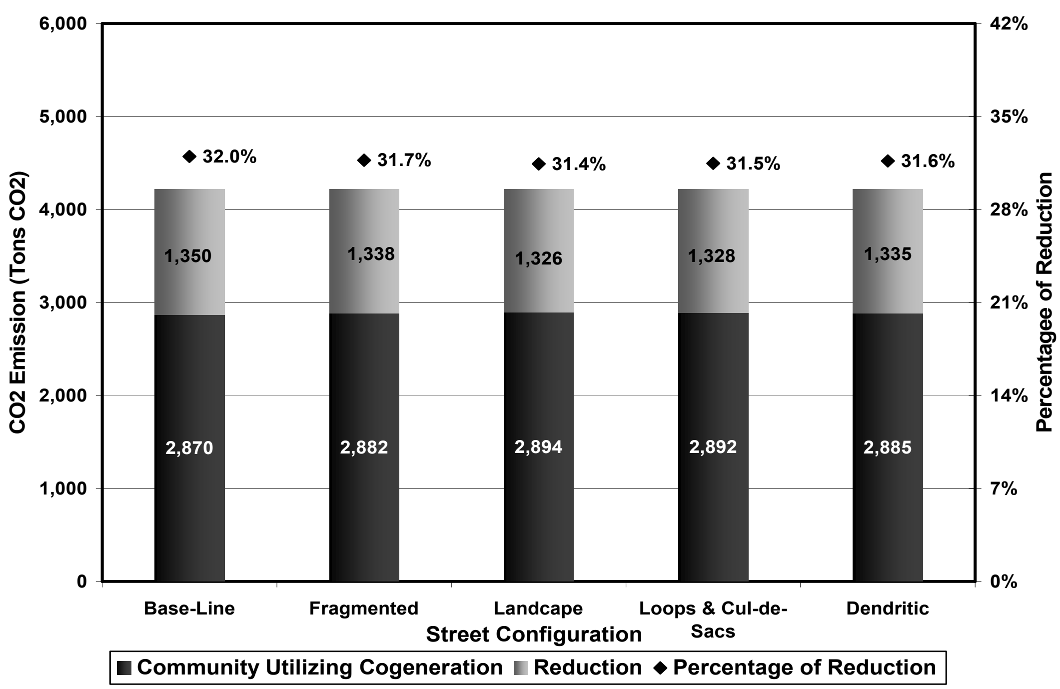


Figure 5-16 Impact of Street Configuration on CO_2 Emissions – Centralized Approach

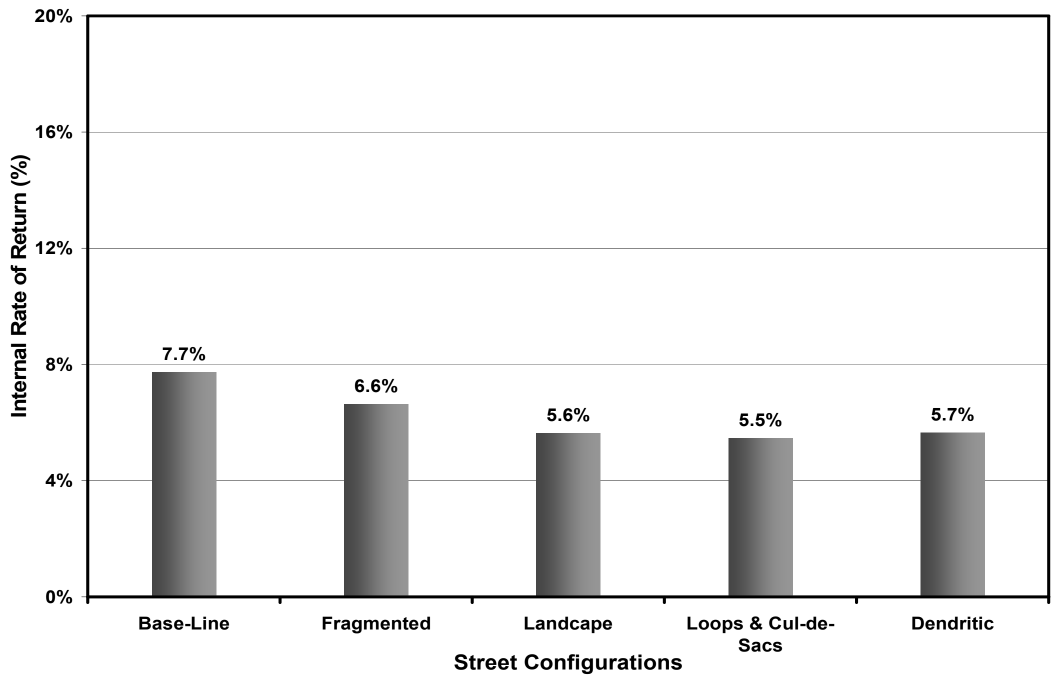


Figure 5-17 Impact of Street Configuration on Internal Rate of Return – Centralized Approach

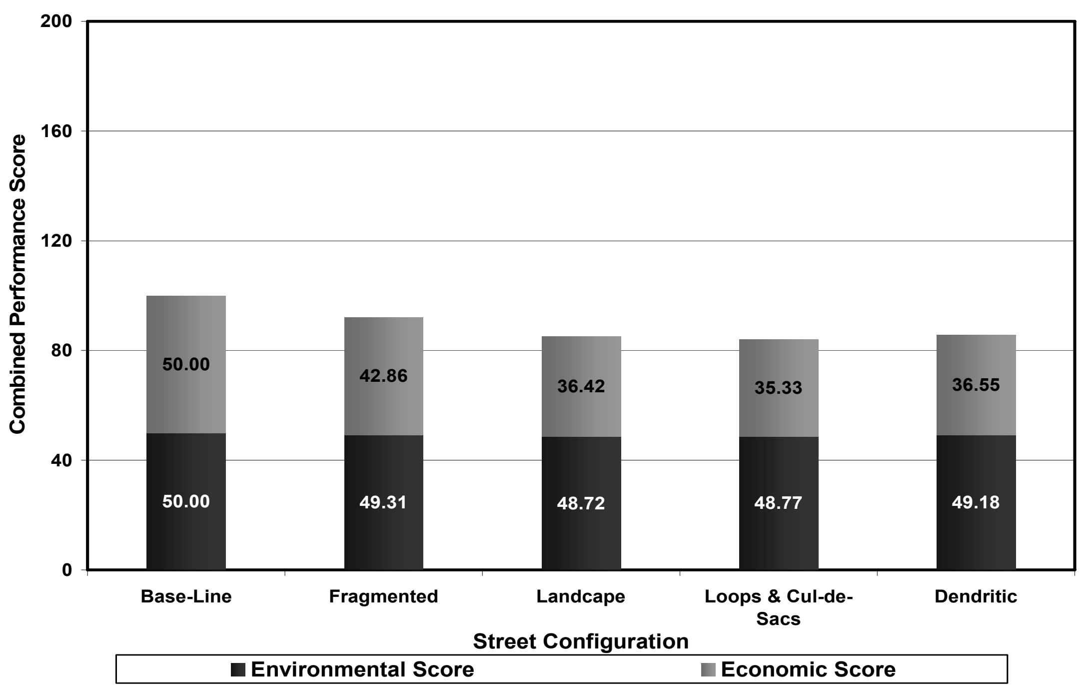


Figure 5-18 Impact of Street Configuration on Combined Performance – Centralized Approach

A decrease in IRR for all alternatives can also be seen in figure 5-17, and similarly, this negative impact is due to the increased initial cost of the system due to the increased network lengths. However, figure 5-18, shows that the increased network lengths results in a much larger negative economic impact, between 15% to 30% reduction in economic performance, than it does for environmental impact, a minimal 1.25% to 2.5% drop in performance. The results of the assessment indicate that the interconnected network configuration is, by far, the best street configuration from the point of view of cogeneration system performance. This is because its high interconnectedness allows for an efficient district heating network design with clear hierarchy, shorter piping lengths, and fewer connections. Out of the four alternatives to the base-line case investigated here, the fragmented configuration shows a clear advantage over the other three alternatives, which achieve rather similar environmental and economic performances.

5.3.2 Architectural Parameters

5.3.2.1 Housing typologies

The results of the cogeneration system performance assessment for the selected housing typology alternatives are shown in figures 5-19 through 5-22. Figure 5-19 shows the annual community primary energy use with cogeneration, the magnitude of the reduction in primary energy use due to the use of cogeneration, and the percentage of this reduction for each of the alternatives. Figure 5-20 shows the same information with regard to annual CO_2 emissions, figure 5-21 shows the internal rate of return of the cogeneration systems for all alternatives, while figure 5-22 shows the resulting combined performance.

Figures 5-19 & 5-20 show that housing typologies, other than SFHs, generally result in increases in both environmental indicators. While this increase is relatively small in the case of attached single-family houses and town homes, much larger increases can be seen with multi-family housing. Live-work units, however, result in significant reductions in both environmental indicators. With regard to the size of the single family house, the figures show that both environmental indicators tend to increase with decreases in SFH size. IRR results in figure 5-21 show a more diverse picture. While town homes result in a small decrease in IRR, multi-family houses and single family attached houses result in small increases in it while considerably larger increases result from live-work units. SFH size has an opposite impact on IRR compared to environmental indicators with the IRR increasing for larger SFH's. This can be attributed to increases in heating loads which allow for a better utilization of the cogeneration system.

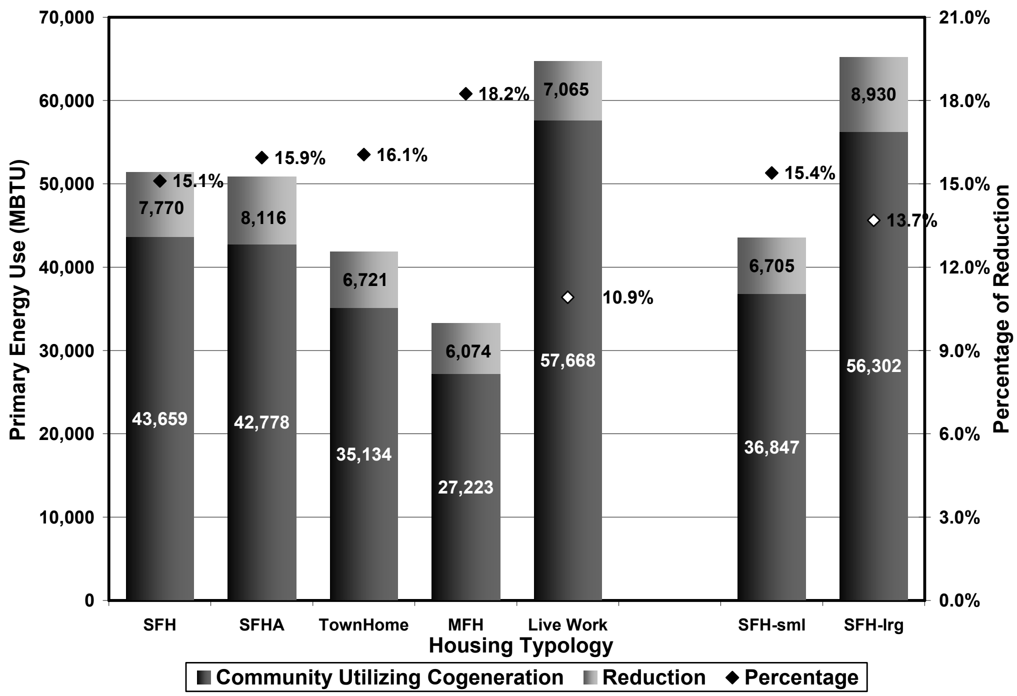


Figure 5-19 Impact of Housing Typology on Primary Energy Use – Centralized Approach

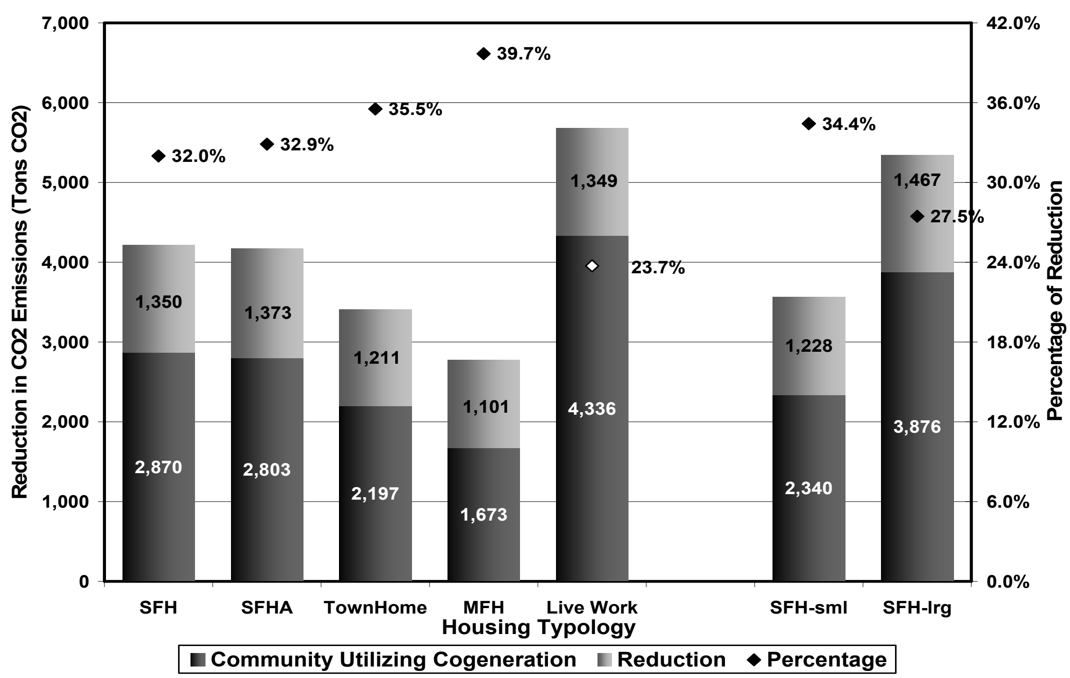


Figure 5-20 Impact of Housing Typology on CO_2 Emissions – Centralized Approach

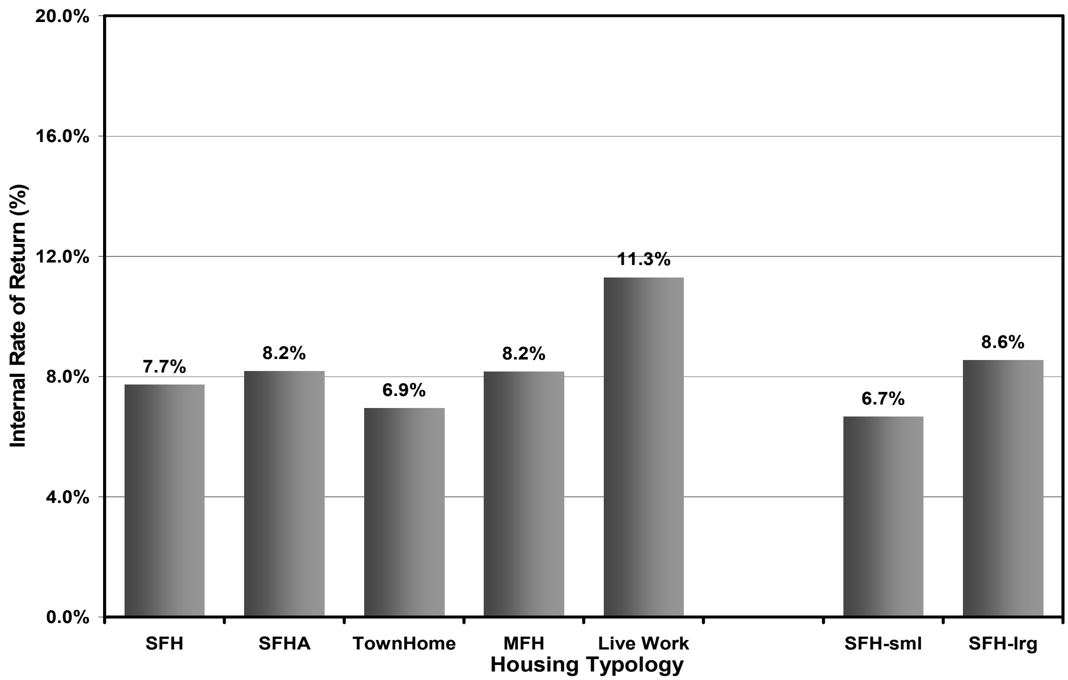


Figure 5-21 Impact of Housing Typology on Internal Rate of Return – Centralized Approach

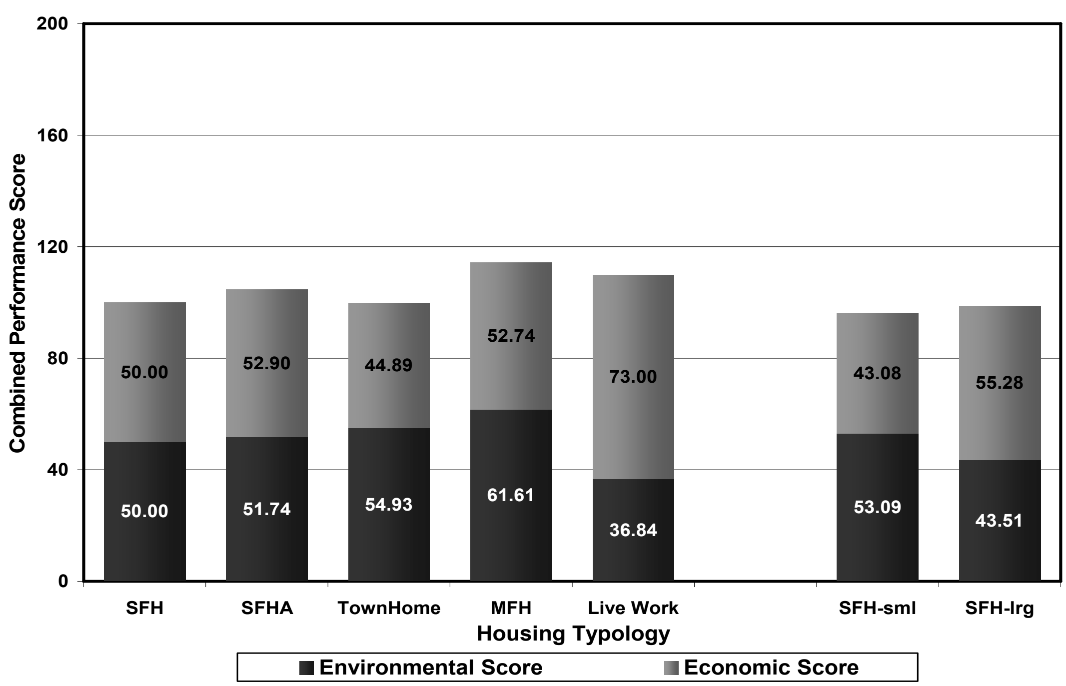


Figure 5-22 Impact of Housing Typology on Combined Performance – Centralized Approach

The combined performance results in figure 5-22 show that the largest performance improvements are caused by the multi-family housing alternative followed by the live-work unit alternative, while town-homes achieve approximately the same performance as the base-line case. However, considering that multi-family houses, live-work units, and town homes typically have larger densities than the baseline density (4 du/ac) used in this assessment, it can be c that all of these alternatives can achieve much better combined performances especially in the case of multi-family housing. Residential communities with multi-family housing, therefore, represent a clear potential for the use of centralized cogeneration systems. With regard to SFH size, the improvements in environmental performance with smaller SFHs appear to offset the decrease in economic performance under the assumptions of this study. However, an increase in the weighting of environmental factor would make smaller SFHs more favorable and vice versa.

5.3.2.2 Envelope and building systems' efficiencies

The results of the cogeneration system performance assessment for the envelope and building systems' efficiencies alternatives are shown in figures 5-23 through 5-26. Figure 5-23 shows the annual community primary energy use with cogeneration, the magnitude of the reduction in primary energy use due to the use of cogeneration, and the percentage of this reduction for each alternatives. Figure 5-24 shows the same information with regard to annual CO_2 emissions, figure 5-25 shows the internal rate of return of the cogeneration systems for all alternatives, while figure 5-26 shows the resulting combined performances.

Figures 5-23 and 5-24 show that reductions in annual energy use, caused by increases in envelope and systems' efficiencies, only result in small increases in the environmental performance indicators with the 4^{th} alternative, a 20% reduction in building energy use, achieving the most increases in both indicators. This is mainly because, in cold climates, reductions in energy use mostly occur in heating loads, which decreases the H/P of the loads and creates an increasing mismatch between it and the H/P of the cogeneration system thus reducing the positive impact of improving daily load profiles. The use of a cogeneration system with a more suitable H/P to the these energy efficient design alternatives can reduce this impact. Reductions in loads also adversely affect the economic performance of the cogeneration system in all alternatives by reducing the possible annual savings. This is shown by the results of the IRR calculations in figure 5-25 in which increases in envelope and building system efficiencies result in an incremental decrease in IRR, with the 4^{th} alternative again being affected the most.

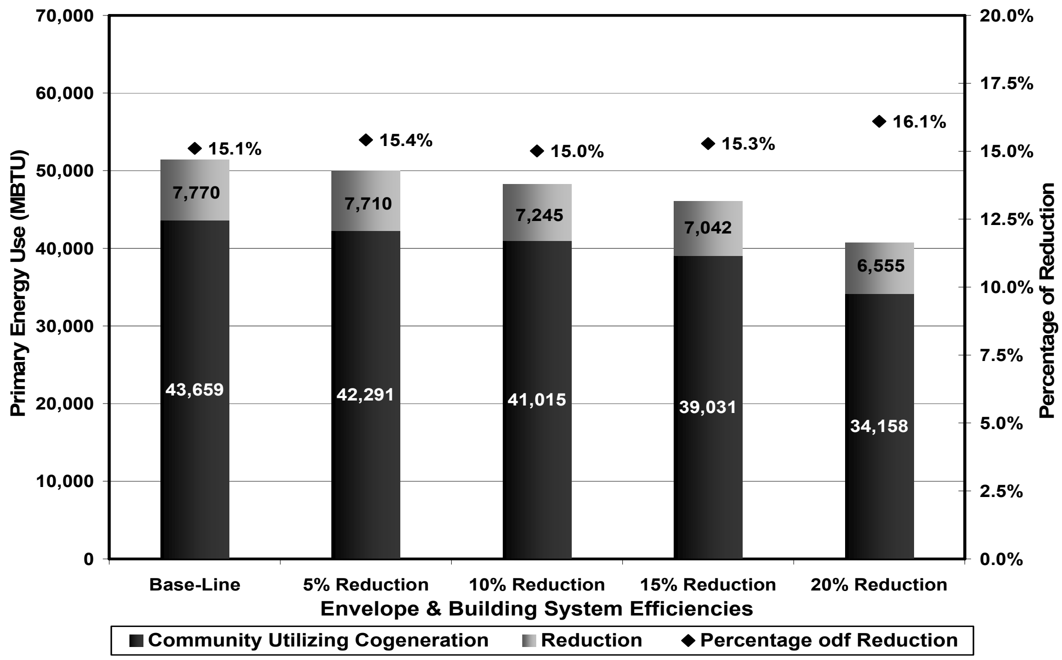


Figure 5-23 Impact of Envelope & Building Systems' Efficiencies on Primary Energy Use – Centralized Approach

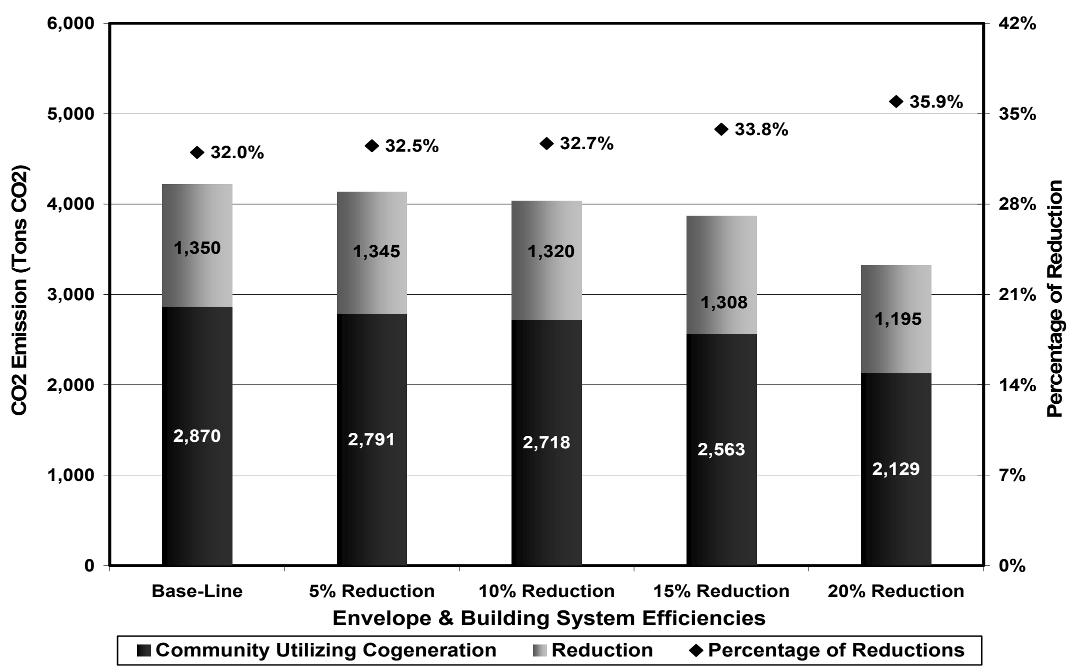


Figure 5-24 Impact of Envelope & Building Systems' Efficiencies on CO_2 Emissions – Centralized Approach

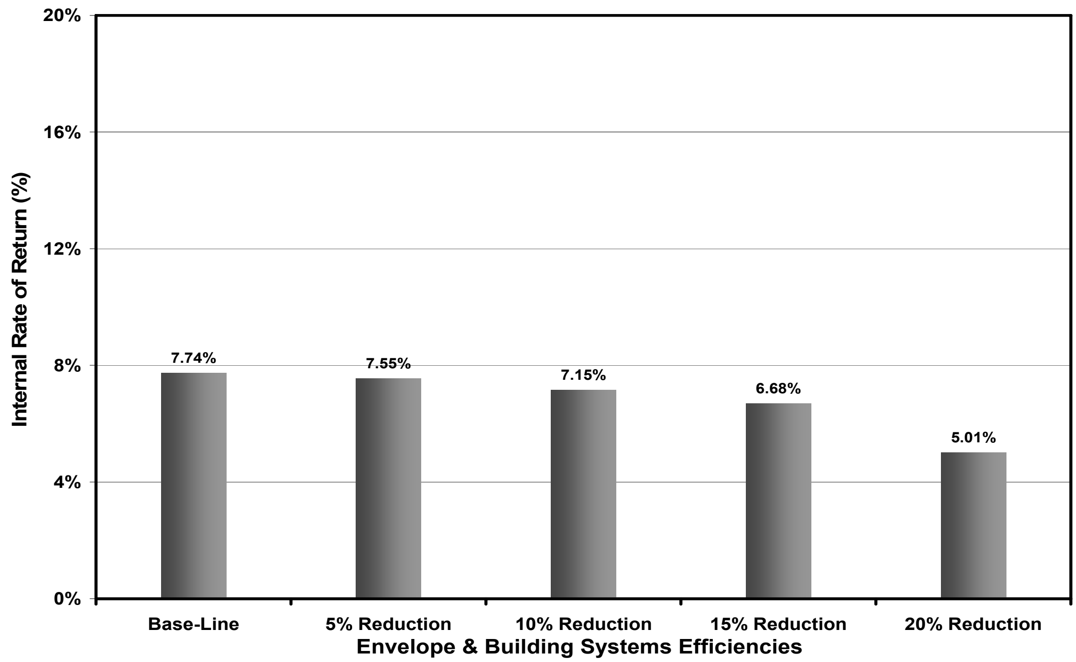


Figure 5-25 Impact of Envelope & Building Systems' Efficiencies on Internal Rate of Return – Centralized Approach

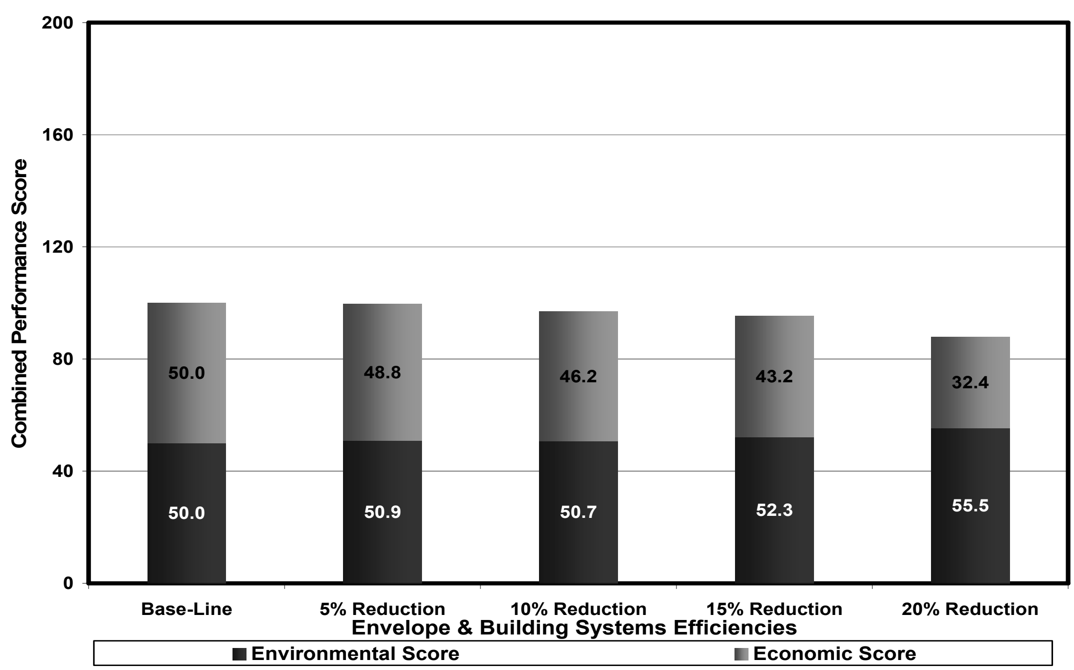


Figure 5-26 Impact of Envelope & Building Systems' Efficiencies on Combined Performance – Centralized Approach

Figure 5-26 shows that, under the assumptions of this study, the drop in economic performance for the envelope & building systems efficiencies alternatives exceeds the corresponding improvements in environmental performance, thus resulting in an overall decrease in combined performance. This result, however, is affected by the weighting assigned to environmental and economic performances. Therefore, increasing the relative weight of the environmental performance would improve the combined performance of the design alternatives investigated here and vice versa. It also has to be noted that combining this design parameter with another parameter with a positive economic impact, e.g. density, can allow for the utilization of the improvements in environmental performance resulting from it while at he same time achieving a reasonable economic performance..

5.3.2.3 Utilization of renewable energy resources

The results of the cogeneration system performance assessment for the utilization of renewable energy resources alternatives are shown in figures 5-27 through 5-30. Figure 5-27 shows the annual community primary energy use with cogeneration, the magnitude of the reduction in primary energy use due to the use of cogeneration, and the percentage of this reduction for each alternatives. Figure 5-28 shows the same information with regard to annual CO_2 emissions, figure 5-29 shows the internal rate of return of the cogeneration systems for all alternatives, while figure 5-30 shows the resulting combined performances.

Figure 5-27 to 5-29 show that reducing the community's energy use by increasing the utilization of renewable energy impacts the performance of the centralized cogeneration system in a very similar manner to the impact of increasing building envelopes and systems' efficiencies. In both cases, the results are small increases in the two environmental performance indicators as well as slightly larger decreases in the economic indicator. However, the magnitude of the changes in the case of the renewable energy utilization alternatives are even less than their counterparts in the envelope and systems alternatives. These small changes in performance are also caused by the increasing mismatch between the H/P of the community loads and the H/P of the cogeneration system for the more energy efficient design alternatives, as well as the reduced potential for annual savings, for the same cogeneration system size, in those alternatives. The reduction in the magnitude of the changes is because the utilization of renewable energy impacts heating loads even more than increasing the efficiencies of building systems, which, while having a larger impact on heating loads in cold climates, also reduces cooling loads.

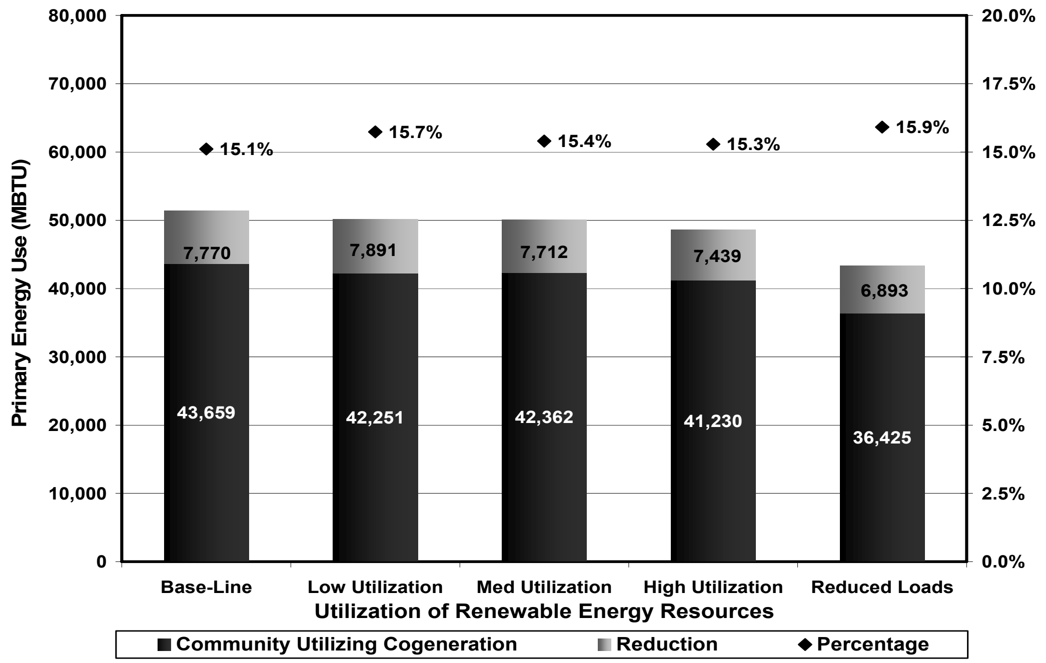


Figure 5-27 Impact of Renewable Energy Utilization on Primary Energy Use – Centralized Approach

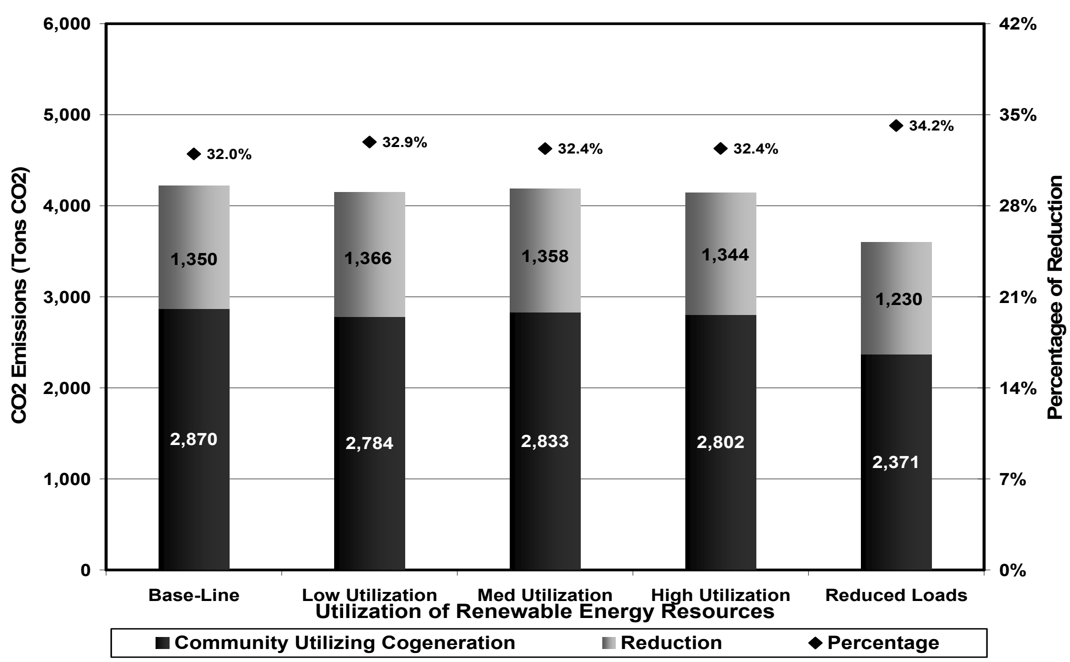


Figure 5-28 Impact of Renewable Energy Utilization on CO_2 Emissions – Centralized Approach

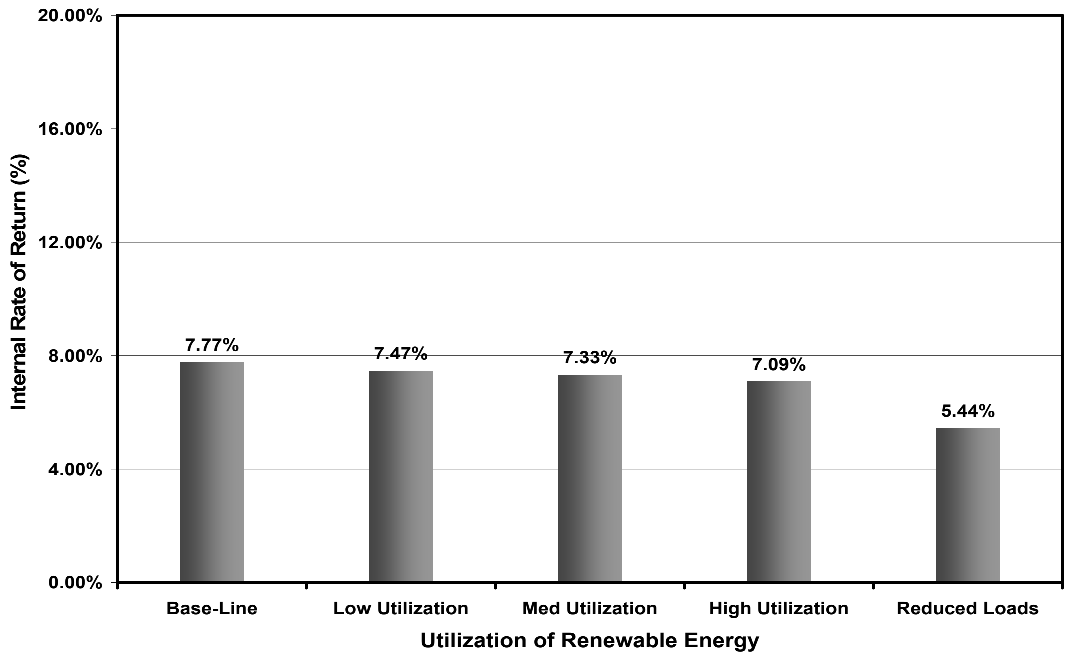


Figure 5-29 Impact of Renewable Energy Utilization on Internal Rate of Return – Centralized Approach

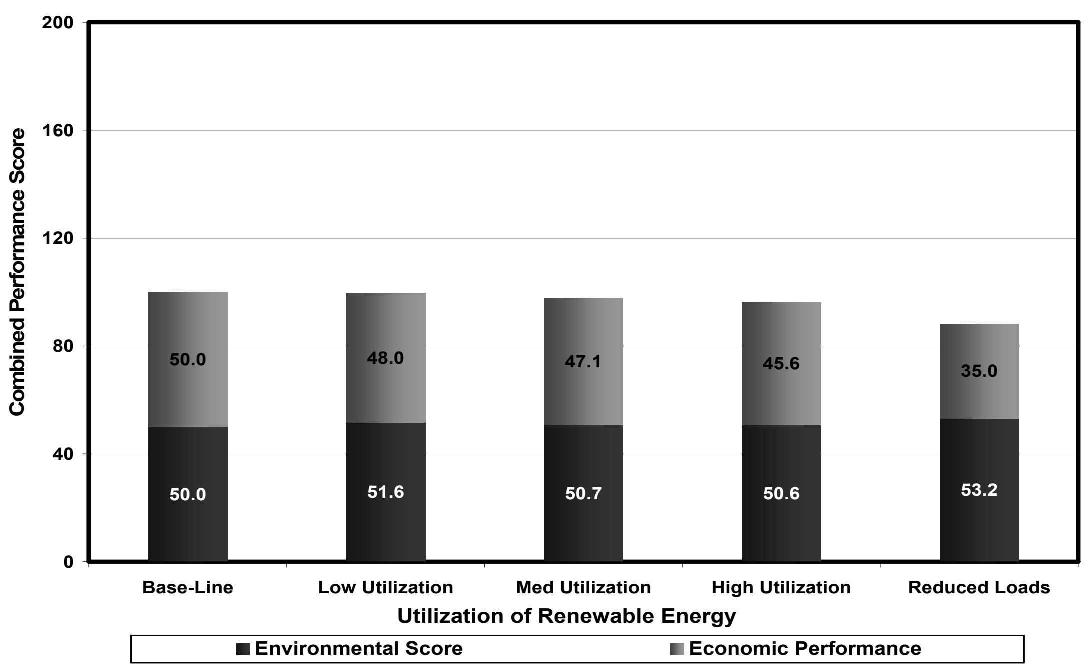


Figure 5-30 Impact of Renewable Energy Utilization on Combined Performance – Centralized Approach

Figure 5-30 shows that the combined performances for the design alternatives of this parameter do not show any noticeable change from the performance of the base-line case. Additionally, while the economic performance of the building envelope and systems efficiency alternative can be improved by increases in density, such density increases would reduce the potential for the utilization of renewable energy. However, a cogeneration system with an H/P that is more suitable to those alternatives (such as fuel cells for example) could result in more significant improvements in performance. Nevertheless, the economics of fuel cells at the moment do not make them a viable alternative as will be discussed in the following section.

5.3.3 Cogeneration System Parameters

5.3.3.1 Prime mover type and efficiency

The results of the performance assessment with regard to the impact of cogeneration system type on its performance for the centralized approach are included in figures 5-31 to 5-34. Figure 5-31 shows the impact of various sizes for each of the system types investigated on the percentage of reduction in annual community primary energy use due to the cogeneration system, figure 5-32 shows the same information with regard to the reduction in annual community CO_2 emissions, figure 5-33 shows the resulting IRR for these different system types and sizes, while figure 5-34 shows the results of the combined performance score calculations for the same system types and sizes.

Figure 5-31 & 5-32 show that, for system sizes up to 200 kW, the three system types investigated in this study, reciprocating engines, PEM fuel cells, and SOFC fuel cells, achieve comparable reductions in energy use and emissions. As the system size increases, both fuel cell types, and particularly the SOFC, achieve considerably higher reductions. This is primarily due to the good part load efficiency characteristics of fuel cells compared to IC engines (see Appendix D), and in the case of SOFC, also to its higher electric efficiency. For all system sizes, however, microturbines achieve the least reductions. In contrast, results of the IRR calculations, shown in figure 5-33, indicate that IC engines clearly outperform the other system types for all sizes. This is a result of the current higher initial and maintenance costs of fuel cells compared to IC engines. Figure 5-33 also shows that all the evaluated system types, except perhaps the IC engines, achieve very small or negative IRR's, thus making them economically unfeasible.

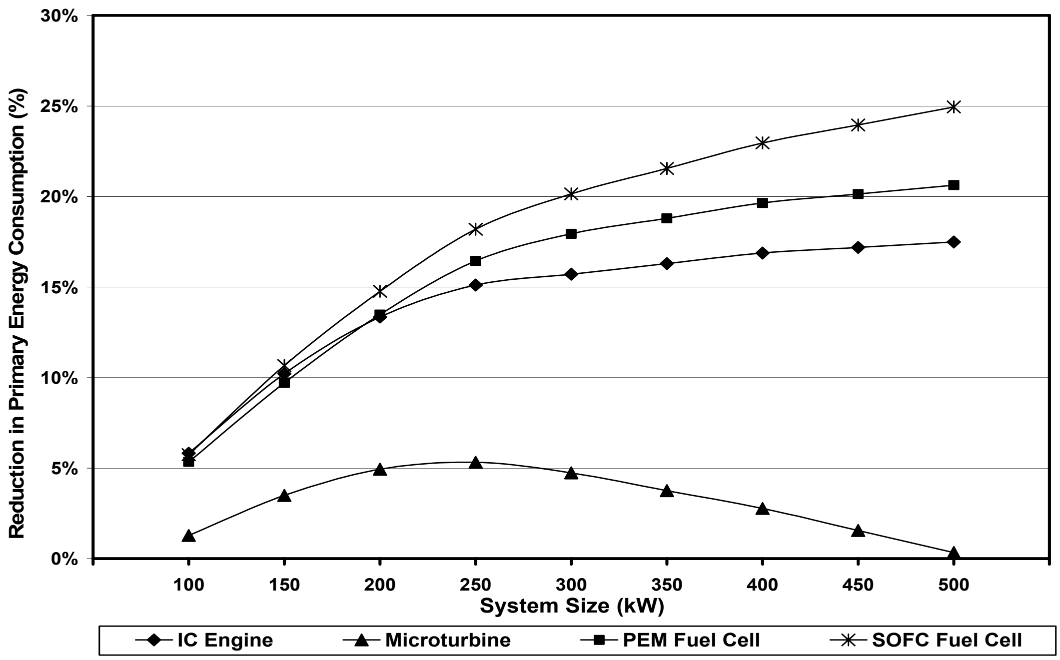


Figure 5-31 Impact of Cogeneration System Type on Primary Energy Use – Centralized Approach

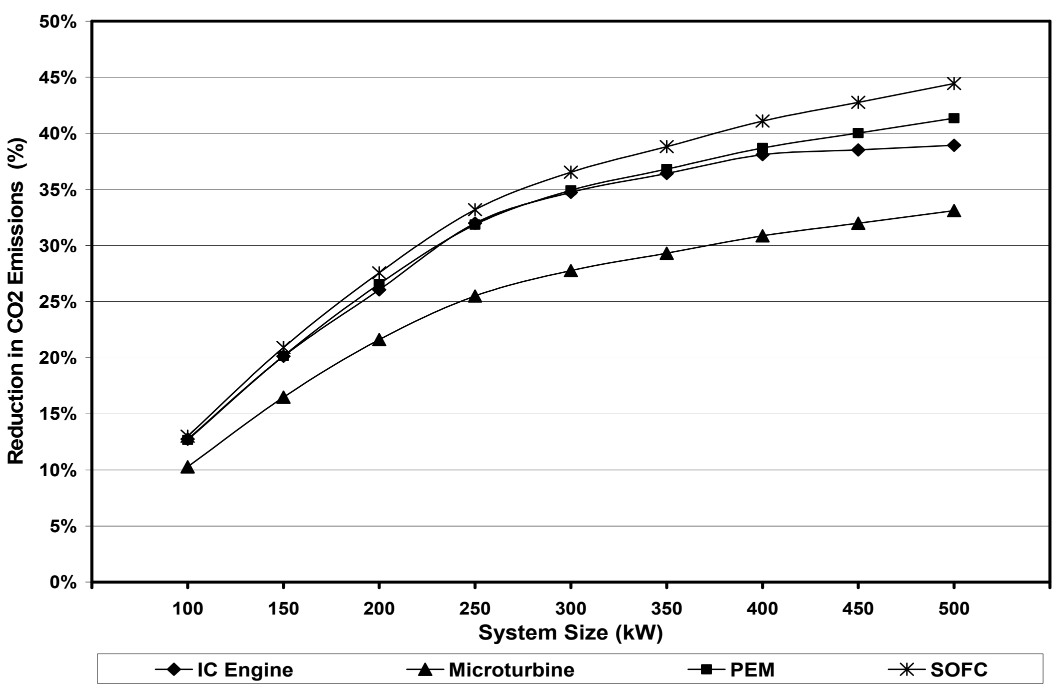


Figure 5-32 Impact of Cogeneration System Type on CO_2 Emissions – Centralized Approach

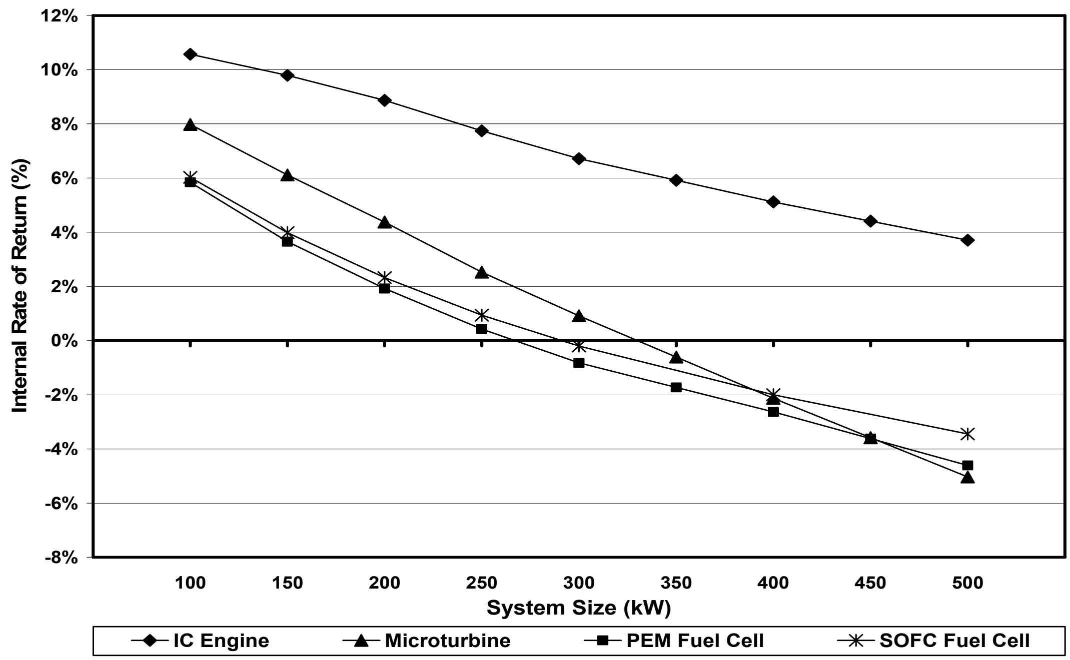


Figure 5-33 Impact of Cogeneration System Type on Internal Rate of Return – Centralized Approach

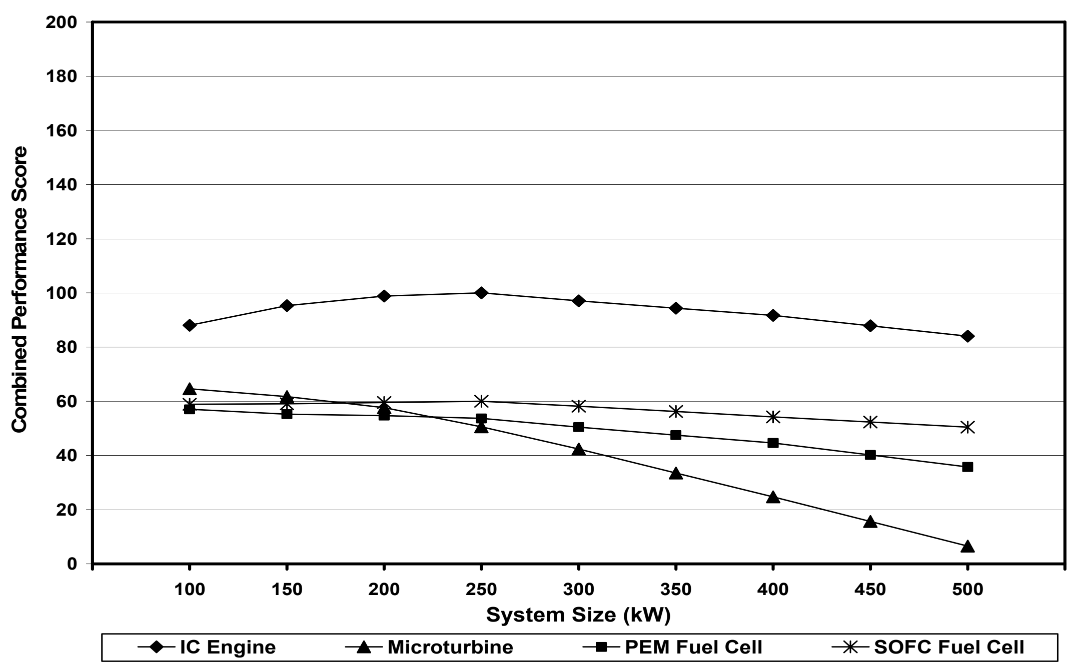


Figure 5-34 Impact of Cogeneration System Type on Combined Performance – Centralized Approach

Figure 5-34 shows that the strong economic performance of IC engines clearly makes up for its weaker environmental performance making them the best option under the current technical and economic circumstances. From the other three system types, SOFC fuel cells and microturbines show a small advantage over PEM fuel cells. However, if the large expected future reductions in fuel cell initial and maintenance costs (NREL-GRI, 2003) are achieved, the gab in economic performance between fuel cells and reciprocating engines can be overcome, and the higher electrical efficiencies (both total and part-load) of the fuel cells will make it a clear favorite under these conditions. It can also be seen that increases in system size, for all system types except microturbines, typically result in improvements in the environments performance of the system, while in the same time negatively impacting its economic performance. However, it can also be seen that, under the assumptions of the combined performance calculations (i.e. equal weighting of environmental and economic performances), the optimum system size is 250 kW. Assigning a higher weighting for the environmental performance increases this optimum size and reduces the gab in performance between the IC engine and other types specifically SOFC fuel cells. Conversely, assigning a higher weight to economic performance reduces the optimum system size and increases this gab in performance.

5.3.3.2 Cogeneration system size and operation strategy

The results of the performance assessment with regard to the impact of cogeneration system size and operation strategy on its performance for the centralized integration approach are included in figures 5-35 to 5-38. Figure 5-35 shows the impact of changing the operation strategy on the percentage of reduction in annual community primary energy use due to the use of cogeneration, figure 5-36 shows the same information with regard to the reduction in annual community CO_2 emissions, figure 5-37 shows the resulting IRR for these different operation strategy and sizes, while figure 5-38 shows the results of the combined performance score calculations for all operation strategies.

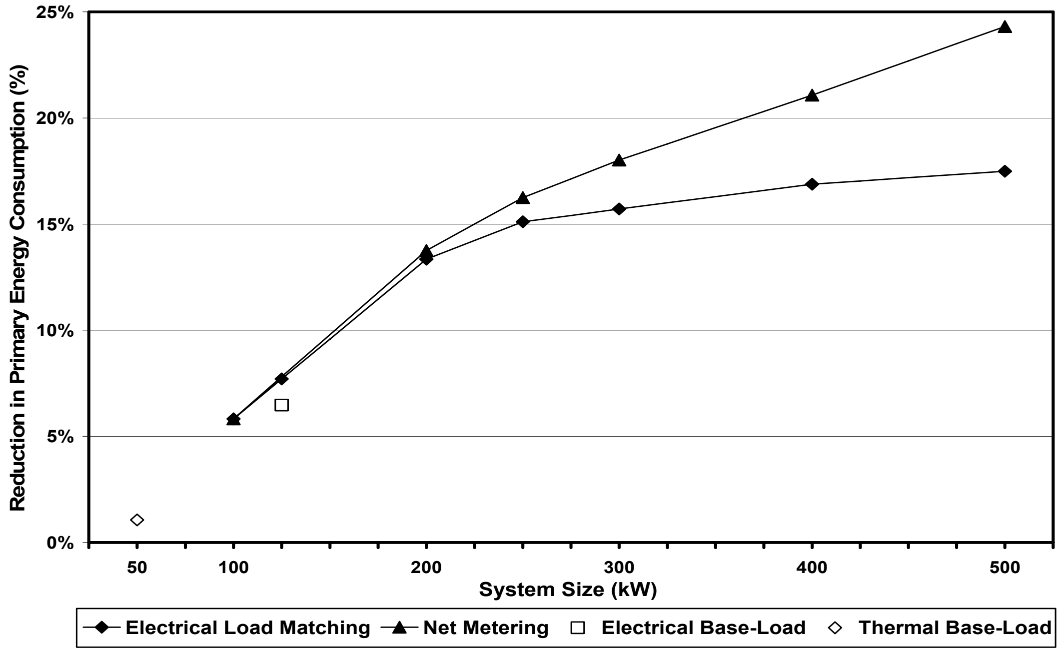


Figure 5-35 Impact of Cogeneration System Operation Strategy on Primary Energy Use – Centralized Approach

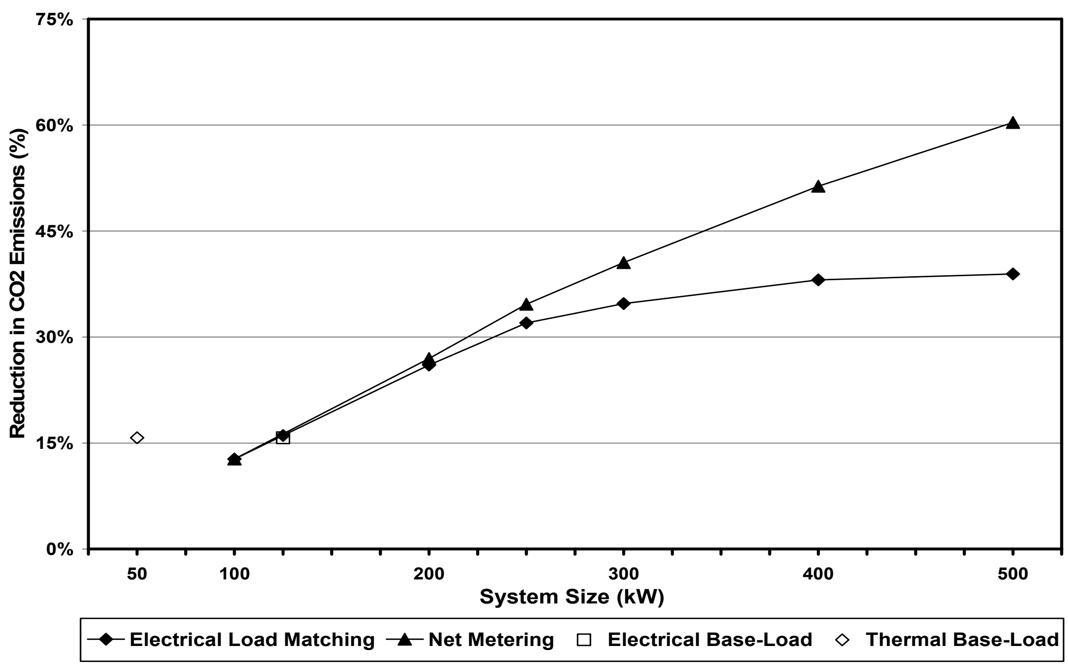


Figure 5-36 Impact of Cogeneration System Operation Strategy of CO_2 Emissions – Centralized Approach

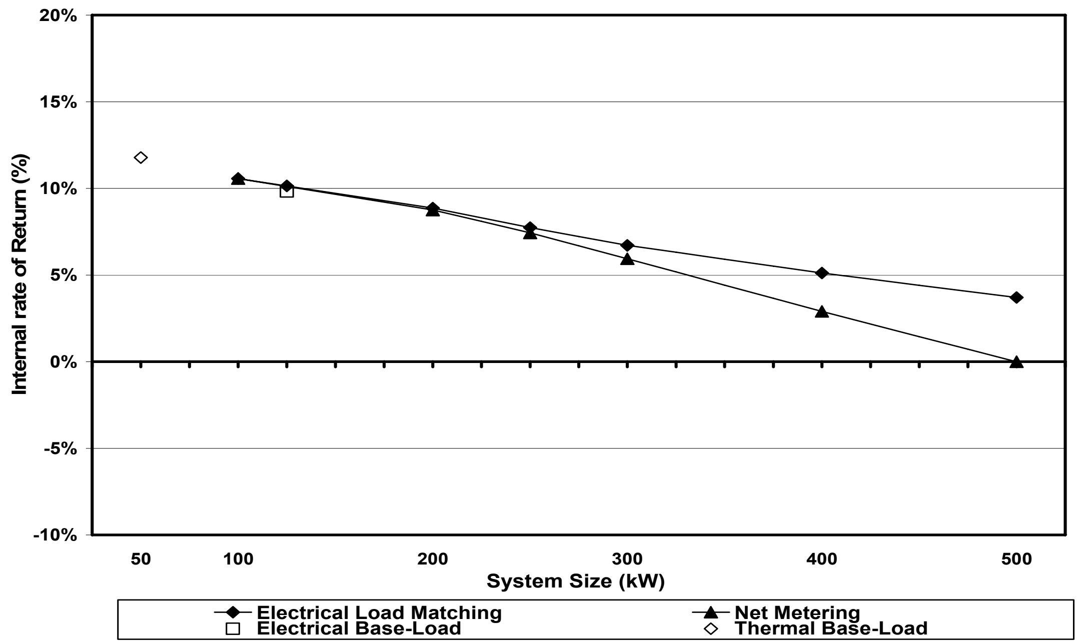


Figure 5-37 Impact of Cogeneration System Operation Strategy on Internal Rate of Return – Centralized Approach

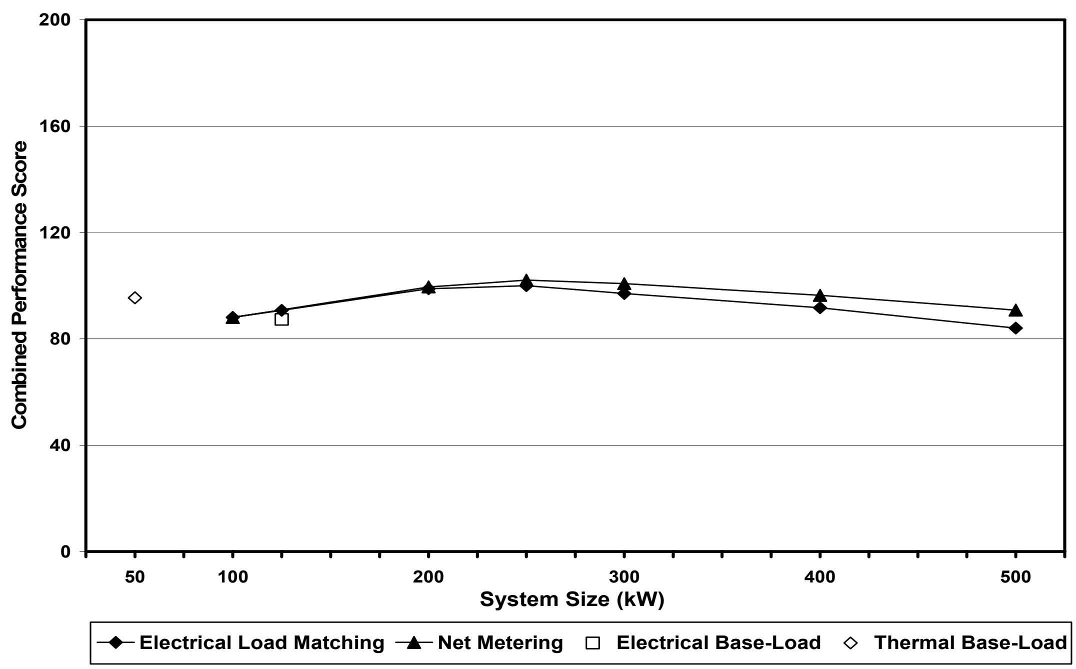


Figure 5-38 Impact of Cogeneration System Operation Strategy on Combined Performance – Centralized Approach

Figures 5-35 & 5-36 show that, for small system sizes, both electric load-matching and net metering achieve comparable performances because the amount of excess electricity that could be sold back to the utility, for these system sizes, is very small. As the system size increases, net metering shows an increasing advantage with regard to reductions in both primary energy use and emissions. Both electric and thermal base-loading do not result in any significant reductions in either energy or emissions. With regard to IRR, as shown in figure 5-37, a difference in performance only appears for larger system sizes with electric load-matching showing a small advantage over net metering. This is because the larger fuel consumption in the net metering strategy increases its annual costs, thus negatively affecting its IRR. It has to be noted though that IRR calculations here are based on an assumption of equal electricity buying and sell-back rates, and that, if electricity selling rates are lower, the difference in IRR between the electric load-matching and net metering options will increase considerably.

Figure 5-38 shows that, under the assumptions of this study, both electric load-matching and net metering achieve similar combined performances with net metering having a small advantage especially for larger system sizes. The optimum system size for both strategies is approximately 250 kW. As discussed previously, a change in the utility net metering rate will negatively impact its performance and give the advantage to electric load-matching.

5.3.4 Summary of Design Parameters' Impacts – Centralized Approach

The results of the individual assessments of the impacts of the planning and architectural parameters on the performance of centralized cogeneration systems were compared and the results shown in figure 5-39. The outcome of this comparison will form the basis of the design optimization process described in chapter VI. These outcomes include the following:

1) The "*optimized mix of uses*" design alternative achieves the largest improvements in combined performance, approximately 53%, relative to the base-line case under the assumptions of this study. While most of the improvement is in economic performance, a trade-off is possible in which a larger system size is used thus achieving an improved environmental performance while still achieving an acceptable economic one.

2) The "*mix of uses*" and "*density of urban form*" parameters clearly have the most impact on the performance of the cogeneration system with the high density and optimized mix of uses alternatives achieving the best performances. These alternatives will form the basis of the optimized community design presented in the following chapter.

3) Several housing typology alternatives, especially multi-family housing and live work units, show clear potential for significant performance improvements when combined with the high densities typical for those housing typologies.

4) With regard to street configuration, the "*interconnected network*" alternative is a clear favorite, with all other alternatives resulting in reductions in both performances.

5) The "*envelope and building systems' efficiencies*" and the '*utilization of renewable energy resources*" parameters result in similar impacts on the combined performance of the cogeneration system. However, improvements in environmental performance resulting form increasing the efficiencies of building systems can be utilized within a community design characterized by high density or high mix of uses so that their positive impact on economic performance counteracts the negative economic impacts of increased system efficiencies.

6) For residential communities with a high utilization of renewable energy, cogeneration systems with more suitable performance characteristics (especially heat to power ratio) than reciprocating engines are required. While fuel cells offer a good potential in this regard, their current high initial and maintenance costs make them economically unfeasible. Expected future decreases in fuel cell costs can make them a viable alternative for such communities.

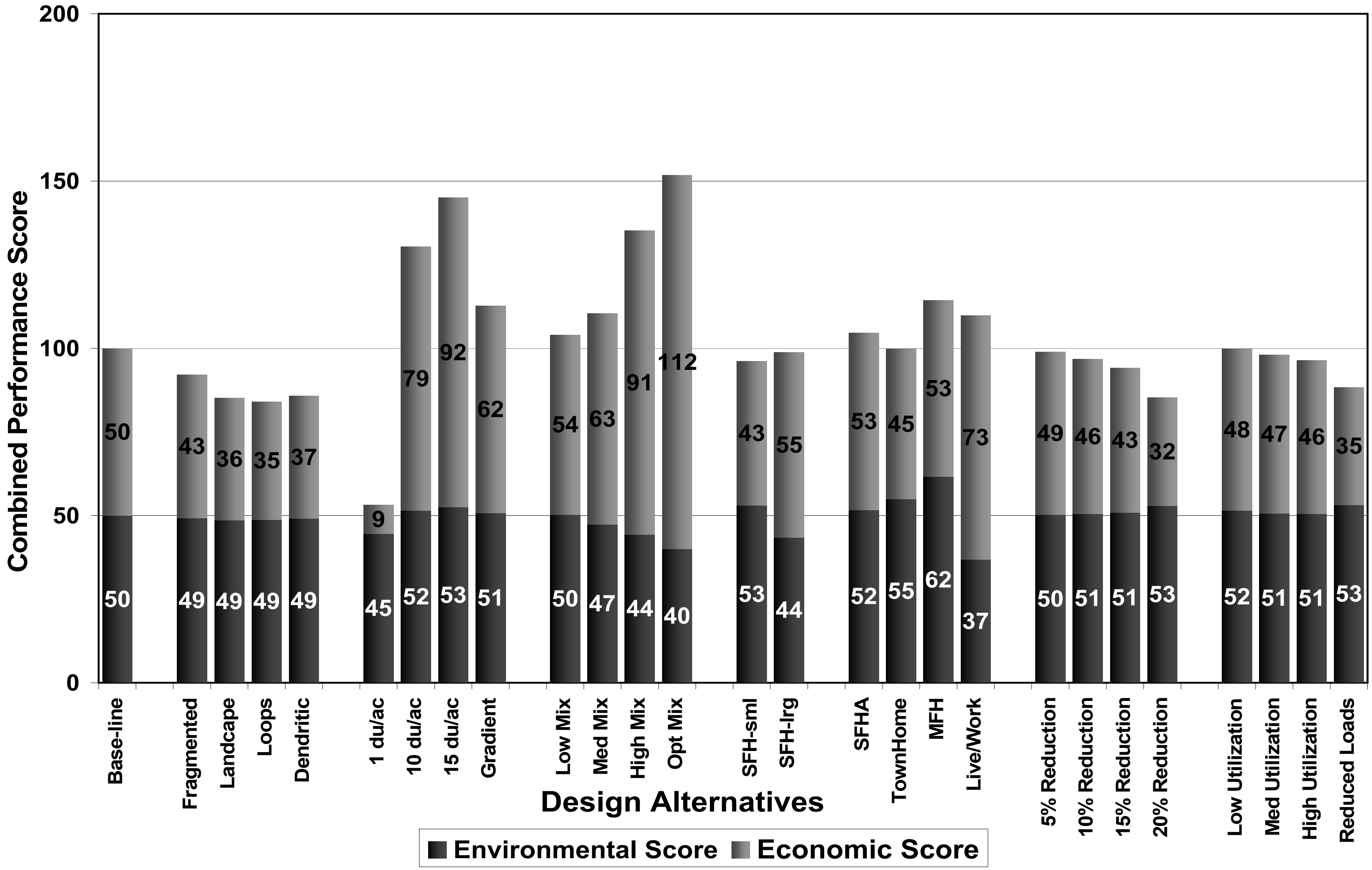


Figure 5-39 Summary of Impacts of Design Parameters on Combined Performance of Cogeneration System – Centralized Approach

5.4 IMPACT OF DESIGN PARAMETERS – DECENTRALIZED APPROACH

The following sections present the results of the impact assessment for the selected community design parameter on the performance of the cogeneration systems for the decentralized approach. With regard to the two environmental performance indicators, reduction in primary energy use and reduction in CO_2 emissions, the result show the reductions in the overall community energy use and emissions, while for the economic performance indicator, the results show the average IRR of all micro-cogeneration systems integrated into the individual residential buildings in the community.

5.4.1 Planning Parameters

With regard to the impact of planning parameter on the decentralized cogeneration approach, only the impact of density was evaluated. As mutual shading between buildings had minimal impact on the energy consumption of the SFH base-line prototype, for the base-line density, the street configuration parameter was excluded from evaluation for the decentralized approach. Similarly, the mixing of uses does not impact the performance of micro-cogeneration systems integrated into individual residential buildings in the decentralized approach.

5.4.1.1 Density of urban form

The impact of density on the performance of decentralized micro-cogeneration systems is shown in figures 5-40 to 5-43. Figure 5-40 shows the impact of increasing densities on the percentage of reduction in annual community primary energy use due to the use of cogeneration, figure 5-41 shows the same information with regard to reductions in annual CO_2 emissions, figure 5-42 shows the average IRR for all micro-cogeneration system in the community for different densities, while figure 5-43 shows the results of the combined performance calculations for all investigated densities.

Increasing densities reduces the solar access of buildings which in turn leads to increases in heating loads. Figures 5-40 & 5-41 show that density increases result in small increases in both environmental indicators. These improvements are due to the increased utilization of the cogeneration system because of the availability of heating loads. Figure 5-42, however, shows that this increase in utilization results in larger improvements in the IRR of the cogeneration systems. For all indicators, the density gradient option, similar to the centralized approach, results in performance indicators comparable to its average density.

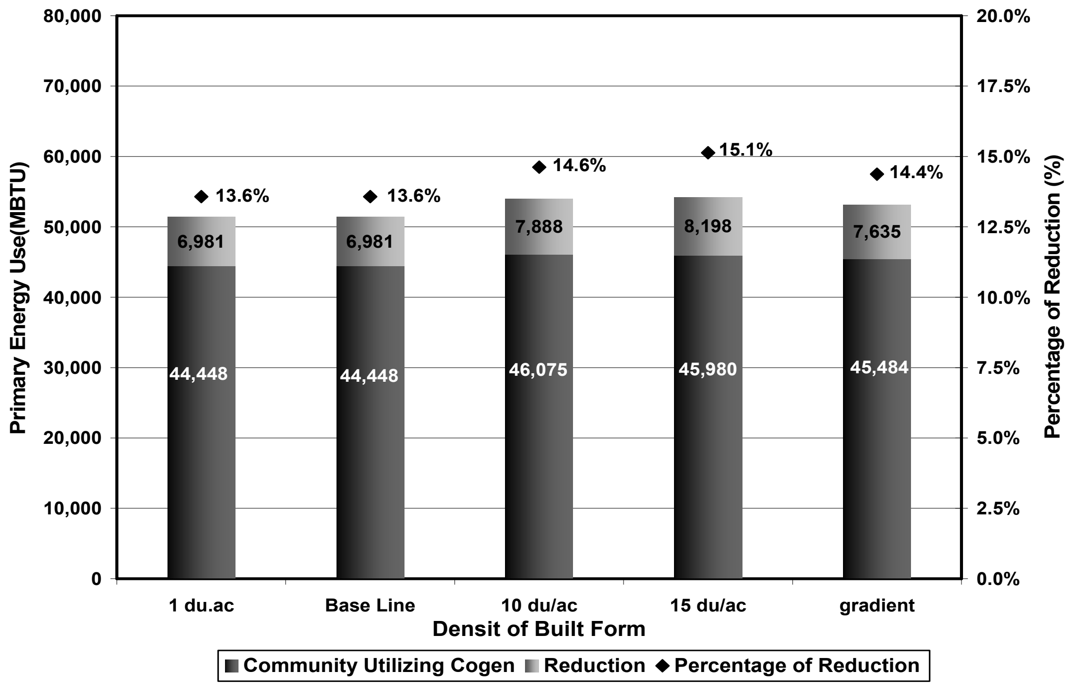


Figure 5-40 Impact of Density on Primary Energy Use – Decentralized Approach

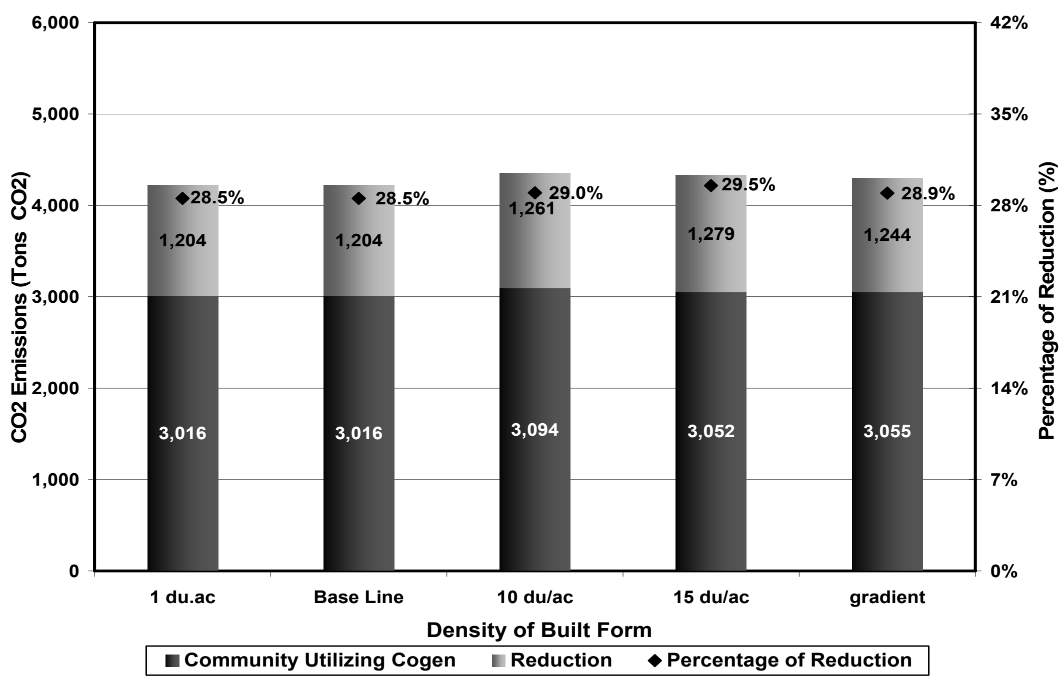


Figure 5-41 Impact of Density on CO_2 Emissions –Decentralized Approach

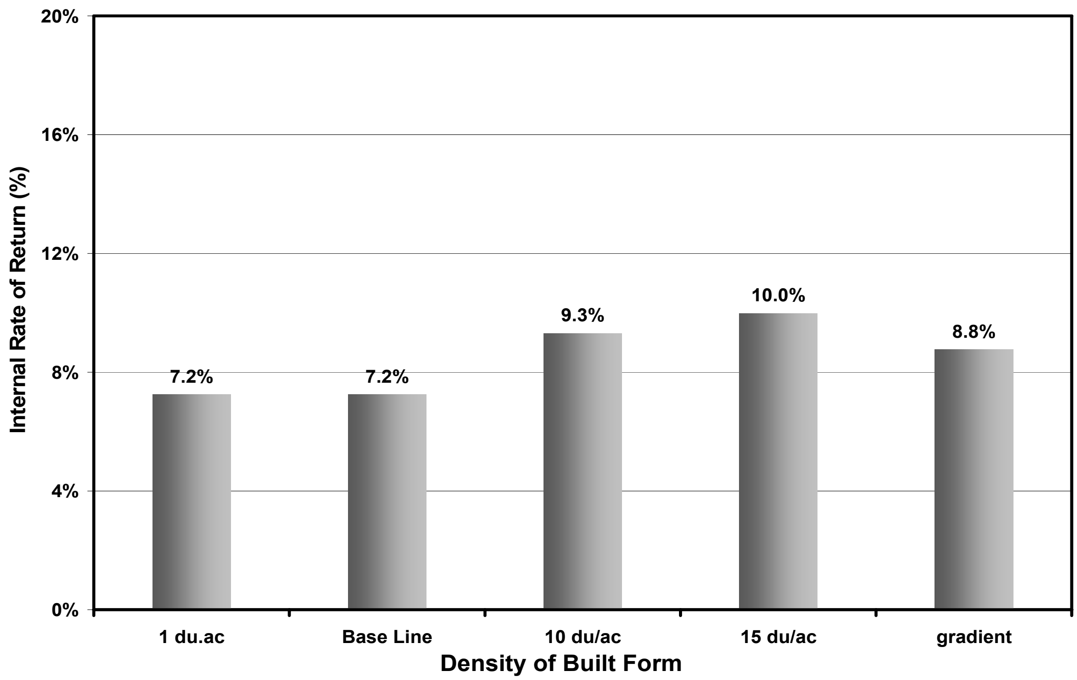


Figure 5-42 Impact of Density on Internal Rate of Return – Decentralized Approach

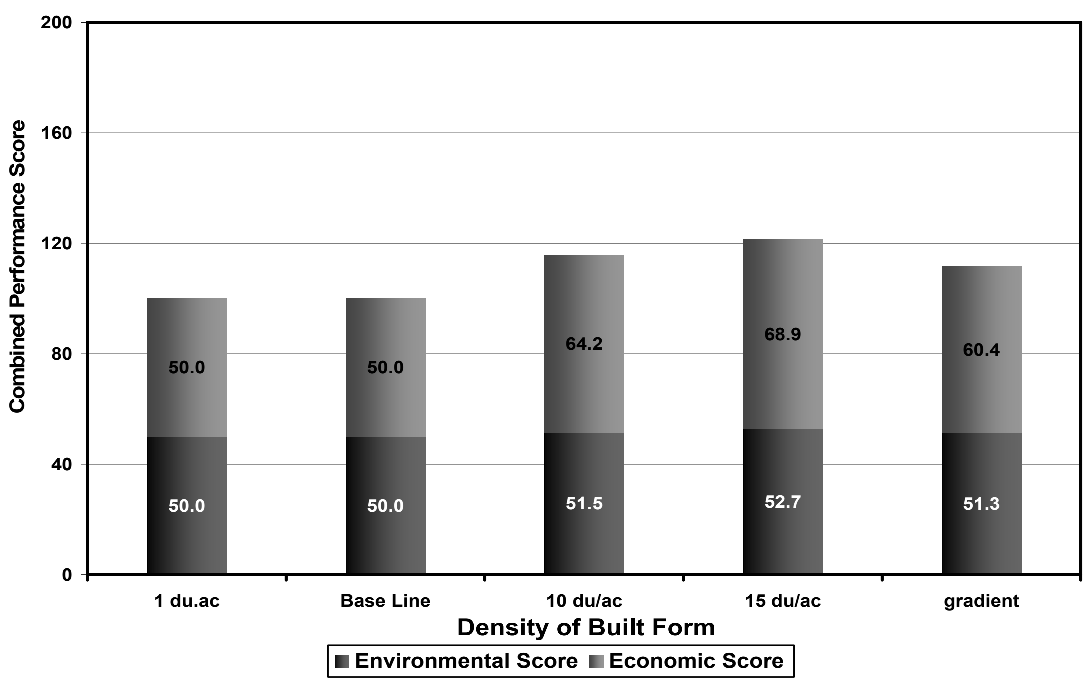


Figure 5-43 Impact of Density on Combined Performance – Decentralized Approach

The larger impact of density on economic performance is further indicated by figure 5-43, in which it can be seen that increases in densities can result in up to 25% improvements in the combined, environmental and economic, performance of the micro-cogeneration system and that the majority of this improvement is in economic performance. Subsequently, increasing the relative weight of economic performance within the combined performance calculations would give further advantage to the higher density alternatives, and vice versa.

5.4.2 Architectural Parameters

5.4.2.1 Housing typologies

Figures 5-44 to 5-47 show the impact of housing typology on the performance of decentralized cogeneration systems. Figure 5-44 shows the percentages of reduction in annual community primary energy use due to variations in housing typology, figure 5-45 shows the same information with regard to the reduction in annual community CO_2 emissions, figure 5-46 shows the average IRR for micro-cogeneration system in various housing typologies, while figure 5-47 shows the results of the combined performance calculations for all typologies.

From figures 5-44 & 5-45, it can be seen that typologies other than SFH's, except live/work units, result in larger reduction in both energy use & emissions, with multi-family houses having the best performance. Live/work units, on the other hand, result in a clear decrease in both environmental indicators. The figures also show that decreasing the size of the SFH increases the resulting reductions in both indicators and vice versa. With regard to IRR, figure 5-46 shows that only attached SFHs result in higher IRRs. Additionally, the impact of SFH size on the IRR is the reverse of its impact on environmental indicators with larger SFH sizes resulting in improvements in IRR due to the larger availability of heat and the subsequent higher potential for annual savings. The figure shows that, for the system sizes investigated here (0.6 kW/unit), only attached & detached SFHs, especially large ones, are economically feasible under the conditions of this study. However, the high sensitivity of the IRR to the size of the decentralized cogeneration system, which will be discussed later is section 5.4.3, indicate that, for multi-family housing and, to a lesser extent, town homes, using a smaller system size can result in considerably higher IRRs with small reductions in environmental performance. This is because the base-electrical load of these housing typologies is lower than the size investigated here. These smaller systems will be utilized in the design optimization described in chapter VI.

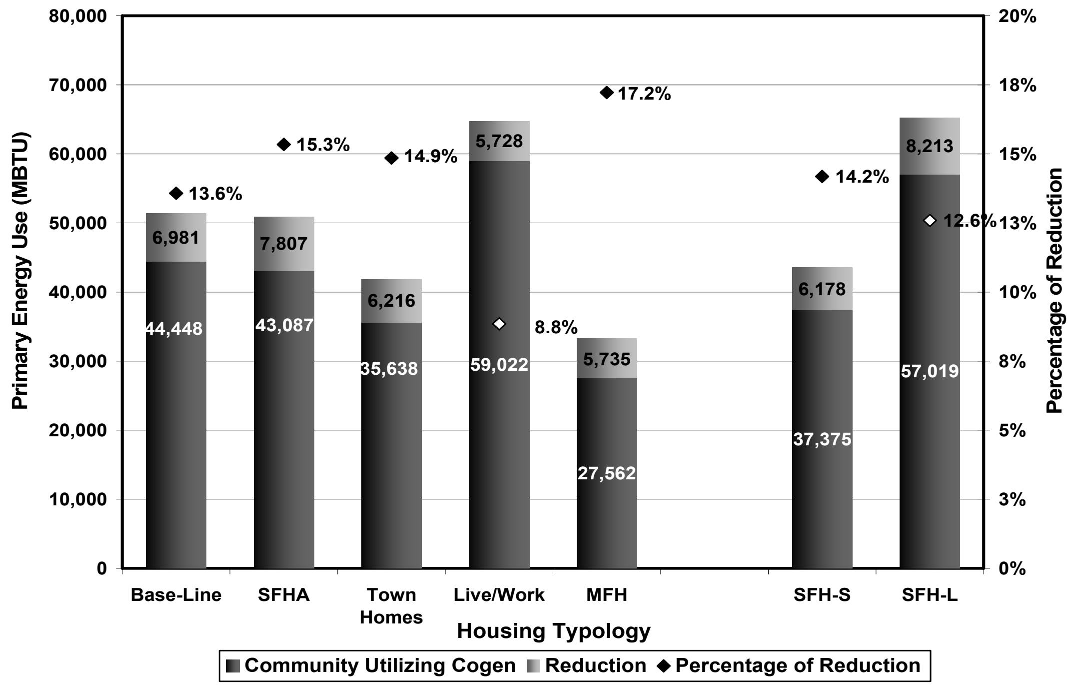


Figure 5-44 Impact of Housing Typology on Primary Energy Use – Decentralized Approach

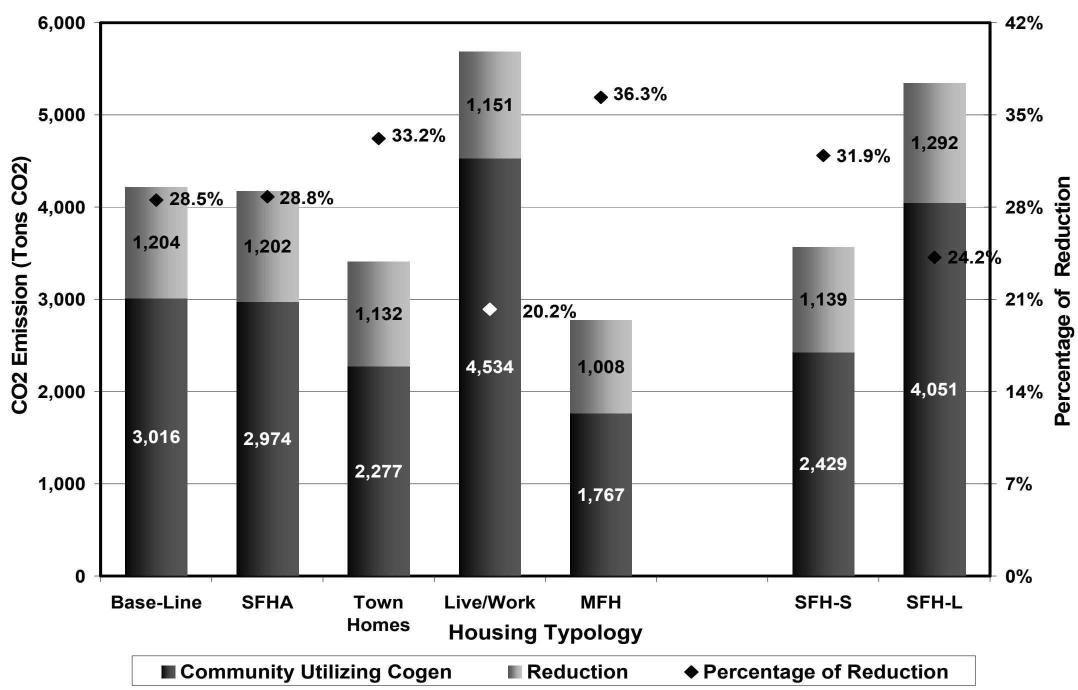


Figure 5-45 Impact of Housing Typology on CO_2 Emissions – Decentralized Approach

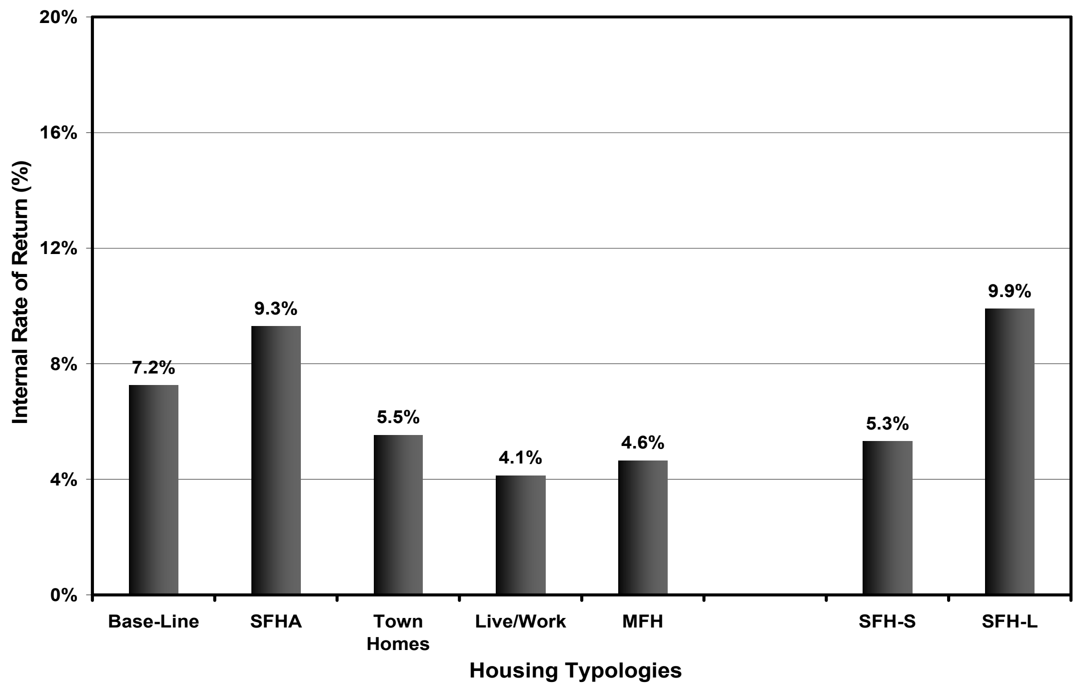


Figure 5-46 Impact of Housing Typology on Internal Rate of Return – Decentralized Approach

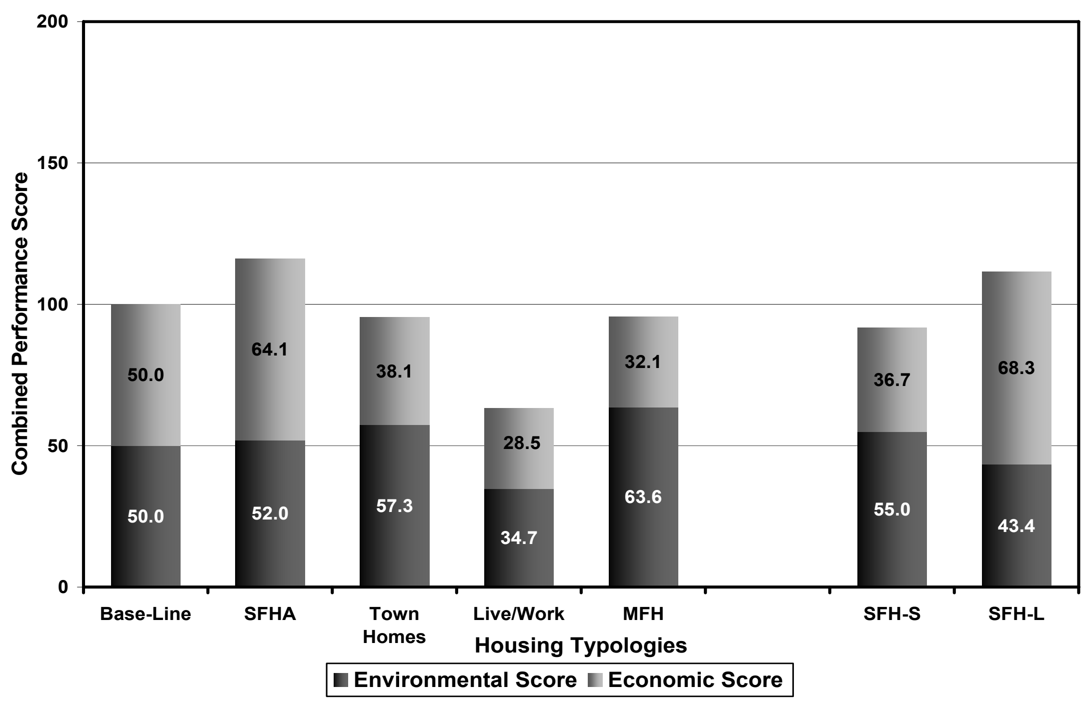


Figure 5-47 Impact of Housing Typology on Combined Performance – Decentralized Approach

The impact of housing typology on the combined cogeneration system performance can be seen in figure 5-47. The figure shows that only attached SFHs and large SFHs achieve a higher combined performance than the base-line SFH. On the other hand, decreases in economic performance for town homes, live/work units, and multi-family housing outweigh the corresponding improvements in environmental performance. Similar to the centralized approach, this could be explained by the fact that, in cold climates, reductions in energy use in typologies such as town homes and multi-family houses, compared to SFHs, happen mostly in heating loads thus changing the H/P of these typologies and increasing the mismatch between them and the H/P of the IC engines used in the evaluation. Based on this, it can be concluded that a different cogeneration system with a lower H/P, such as fuel cells, can result in better improvements in performance for these housing typologies compared to the base-line case. Additionally, as discussed previously, multi-family houses have the potential of achieving a better combined performance with smaller cogeneration system sizes.

5.4.2.2 Envelope and building systems' efficiencies

Figures 5-48 to 5-51 show the impact of the envelope and building systems' efficiencies on the performance of micro-cogeneration system in residential buildings. Figure 5-48 shows the percentages of reduction in annual community primary energy use for different alternatives of envelope and building systems' efficiencies, figure 5-49 shows the same information with regard to the reduction in annual community CO_2 emissions, figure 5-50 shows the IRR for each of the alternatives, while figure 5-51 shows the resulting combined performance for all alternatives.

Figure 5-48 through 5-51 show that increases in envelope and building systems' efficiencies result in minimal improvements in the environmental performance of the micro-cogeneration system, except for the most energy efficient alternative where larger improvements can be seen relative to the base-line case. On the other hand, these alternatives result in larger reductions in economic performance. Similar to the case with housing typologies, this is caused by the fact that energy efficiency measures in cold climate primarily impact heating loads, and therefore, increases the mismatch between the H/P of the buildings and that of the IC engine. The reduction in heating loads also reduces the potential for annual cost savings thus impacting the economics of the system.

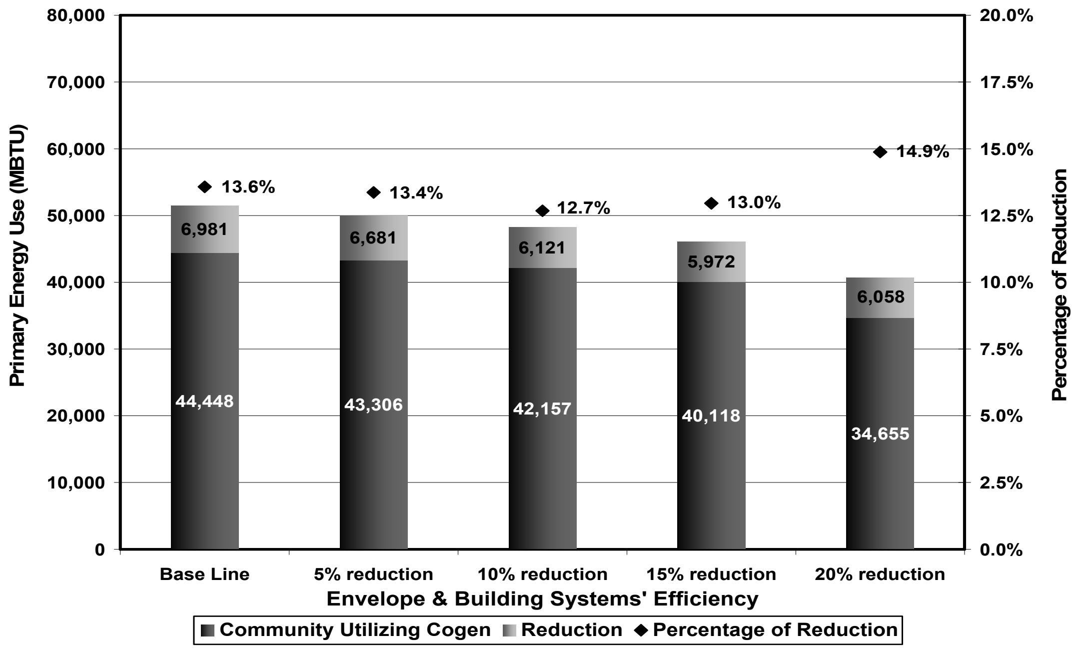


Figure 5-48 Impact of Envelope & Building Systems' Efficiencies on Primary Energy Use – Decentralized Approach

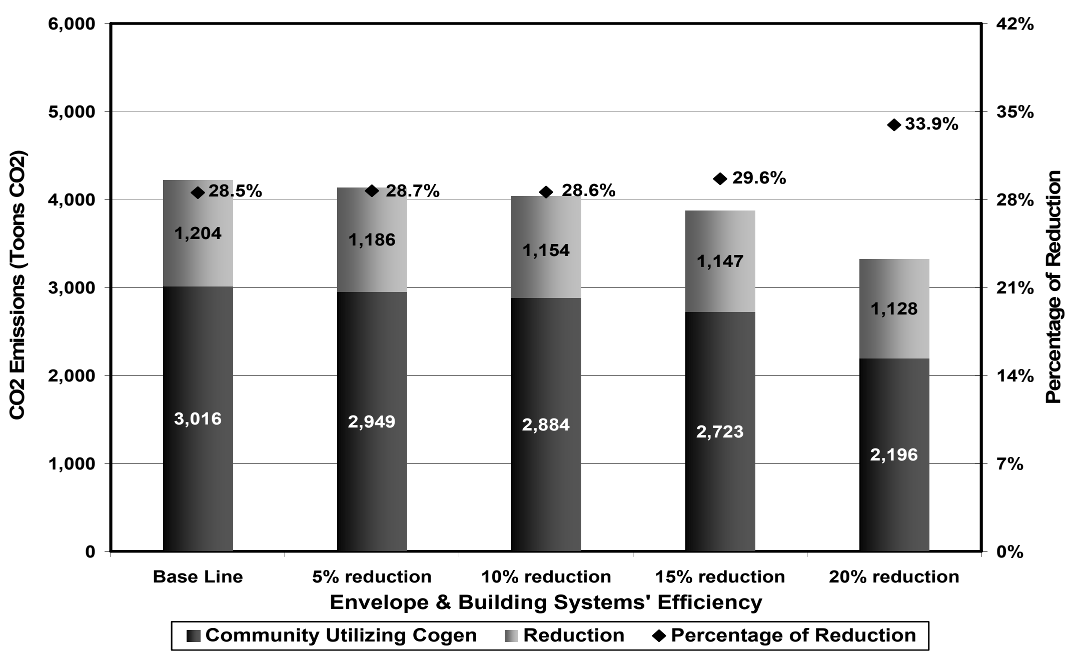


Figure 5-49 Impact of Envelope & Building Systems' Efficiencies on CO_2 Emissions – Decentralized Approach

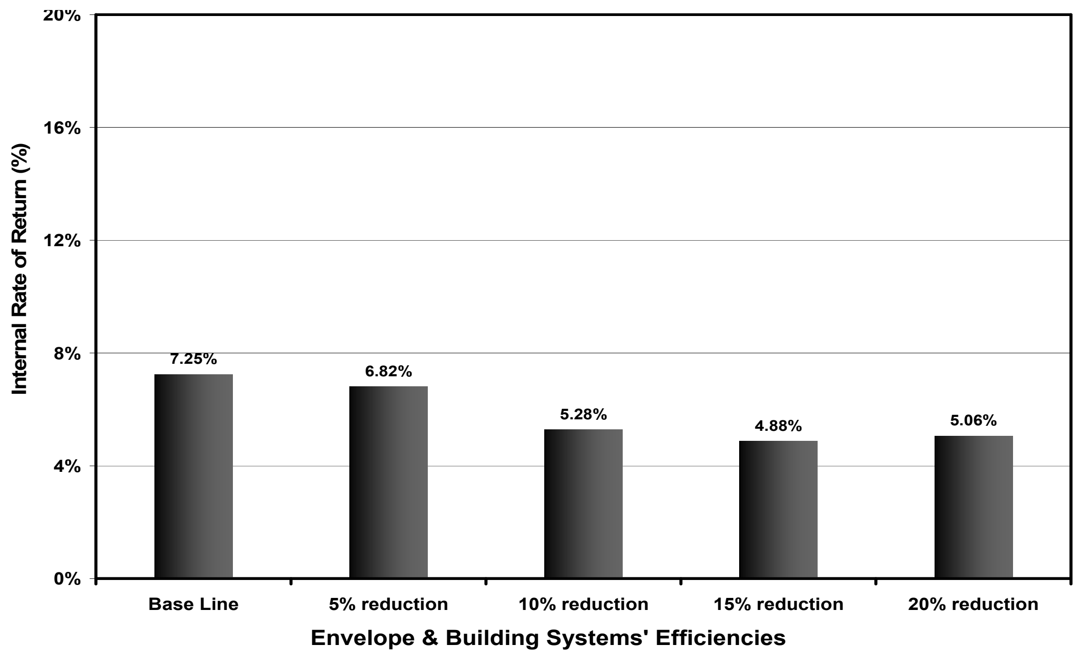


Figure 5-50 Impact of Envelope & Building Systems’ Efficiencies on Internal Rate of Return – Decentralized Approach

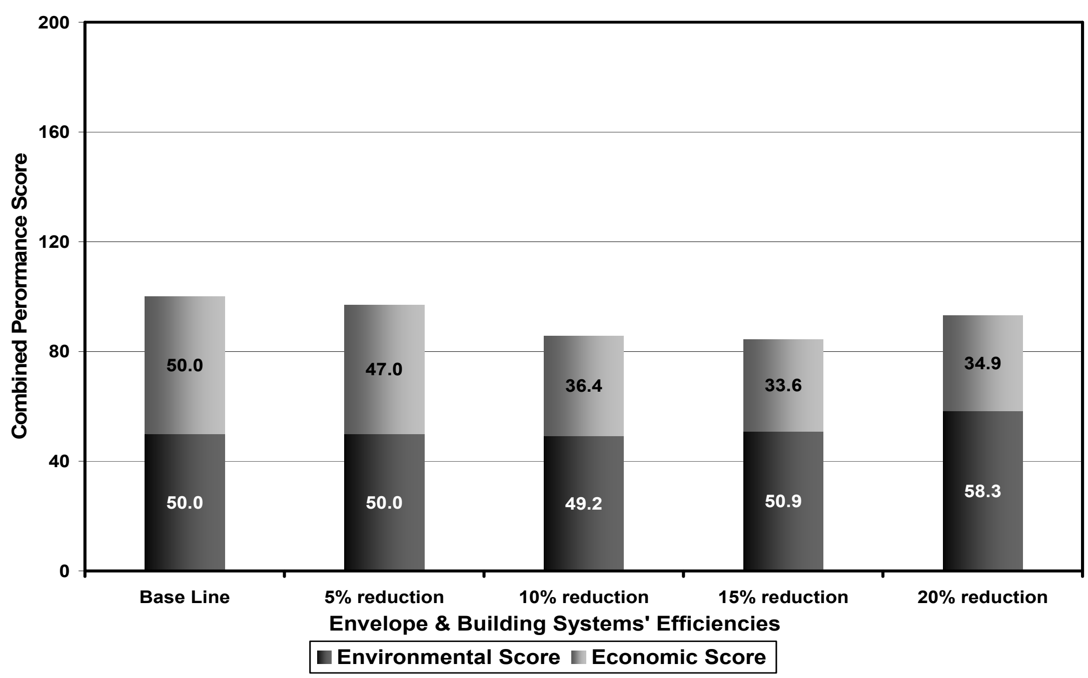


Figure 5-51 Impact of Envelope & Building Systems’ Efficiencies on Combined Performance – Decentralized Approach

5.4.2.2 Utilization of renewable energy resources

Figures 5-52 to 5-55 show the impact of the utilization of renewable energy resources on the performance of micro-cogeneration systems. Figure 5-52 shows the percentages of reduction in annual community primary energy use for different levels of renewable energy utilization, figure 5-53 shows the same information with regard to the reduction in annual community CO_2 emissions, figure 5-54 shows the IRR for each of the renewable energy utilization design alternatives, while figure 5-55 shows the resulting combined performance for all alternatives.

Figures 5-52 and 5-53 show that increasing the utilization of renewable energy resources do not result in any significant impact on the environmental performance indicators of the cogeneration system except for the "*reduced loads*" alternative, which results in minor improvements in these indicators. This is again caused by the H/P of this alternative matches better with the H/P of the IC engine micro-cogeneration system. On the other hand, figure 5-54 shows that increasing the utilization of renewable energy resources results in small reductions in IRR, with the "*reduced loads*" alternative having the most reductions. The combined performance results, shown in figure 5-55, also shows that increasing the utilization of renewable energy resources does not result in any noticeable impact on this performance again indicating the need for micro-cogeneration systems that better match the load characteristics of these more energy efficient design alternatives.

5.4.3 Cogeneration System Parameters

5.4.3.1 Prime mover type and efficiency

Figures 5-56 to 5-58 show the impact of the type of micro-cogeneration system on its performance in residential buildings. Figure 5-56 shows the percentages of reduction in annual community primary energy use for different system types, figure 5-57 shows the same information with regard to the reduction in annual community CO_2 emissions, and figure 5-58 shows the environmental performance score resulting from those two indicators. Table 5-1, on the other hand, shows the resulting IRR for various system types and sizes.

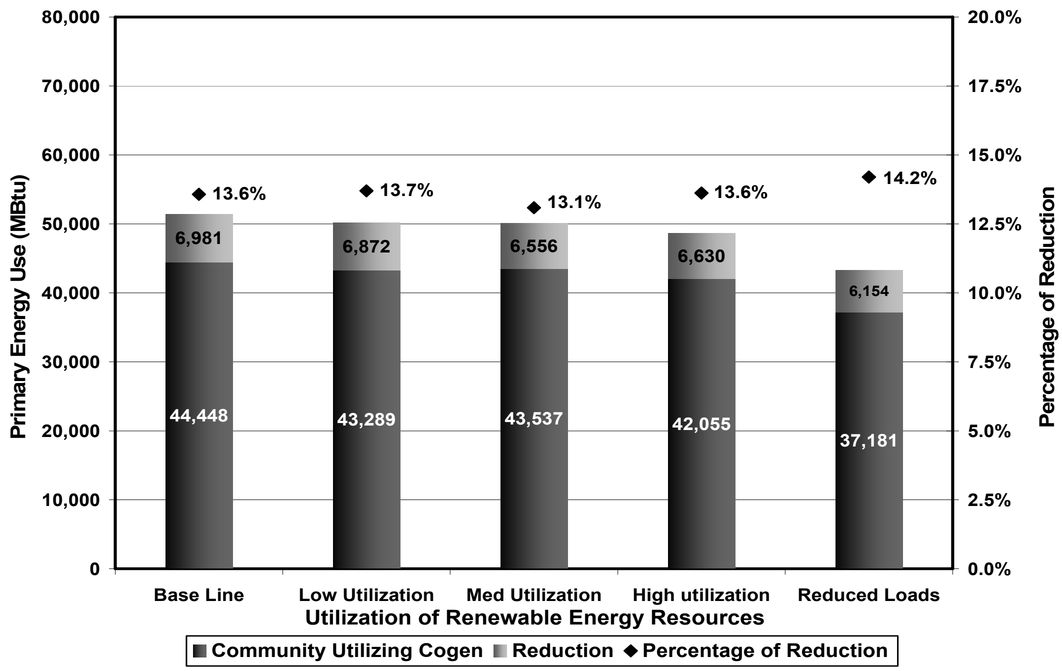


Figure 5-52 Impact of Utilization of Renewable Energy Resources on Primary Energy Use – Decentralized Approach

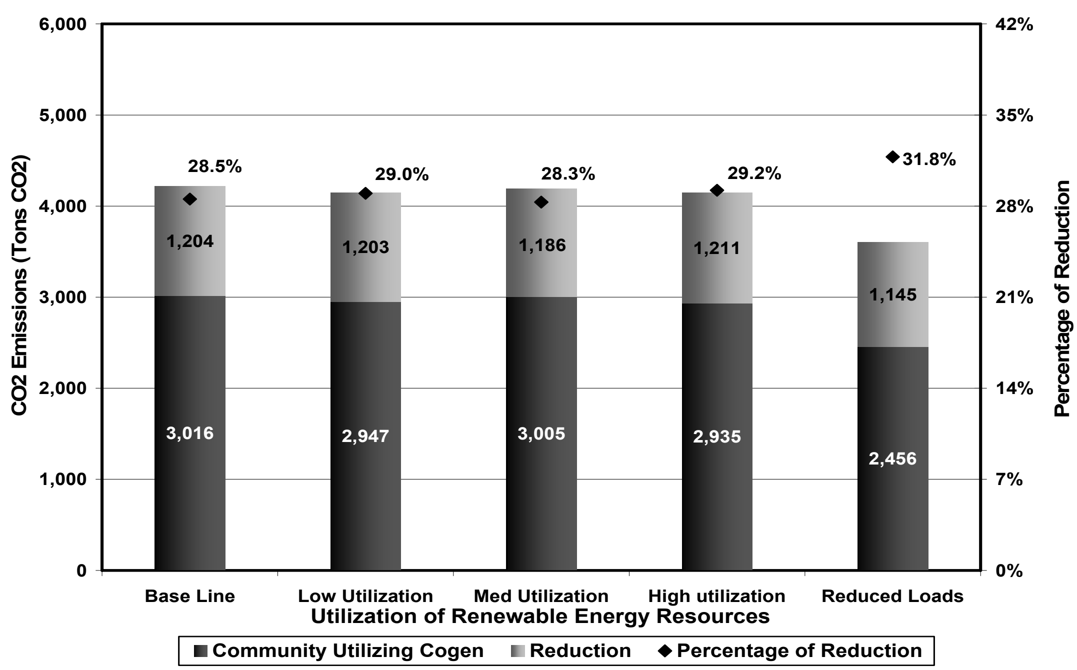


Figure 5-53 Impact of Utilization of Renewable Energy Resources on CO_2 Emissions – Decentralized Approach

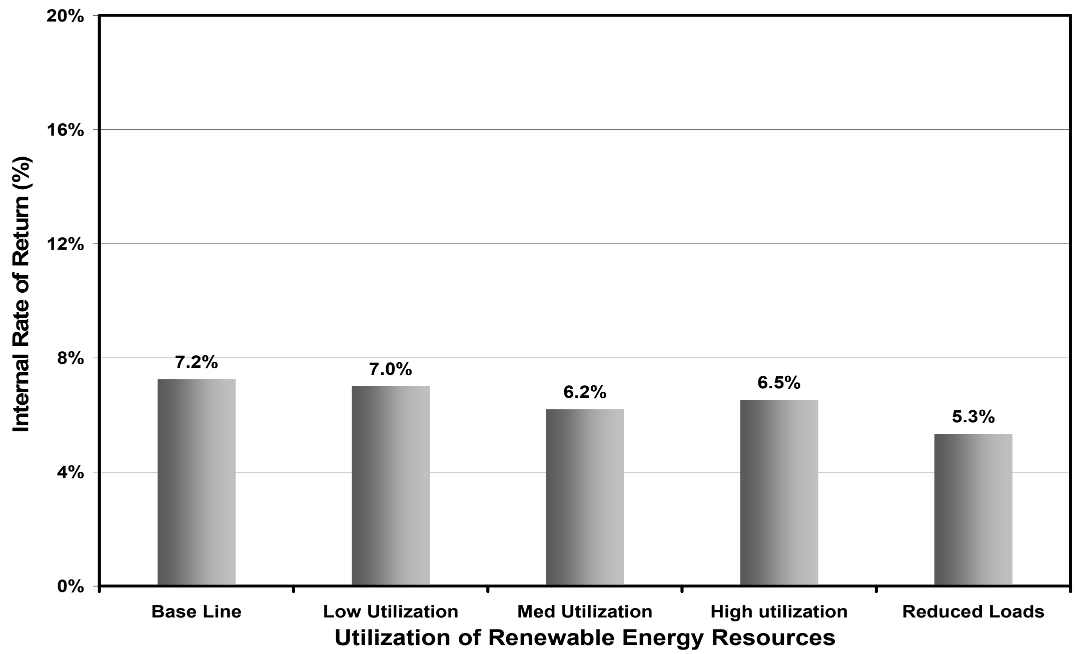


Figure 5-54 Impact of Utilization of Renewable Energy Resources on Internal Rate of Return – Decentralized Approach

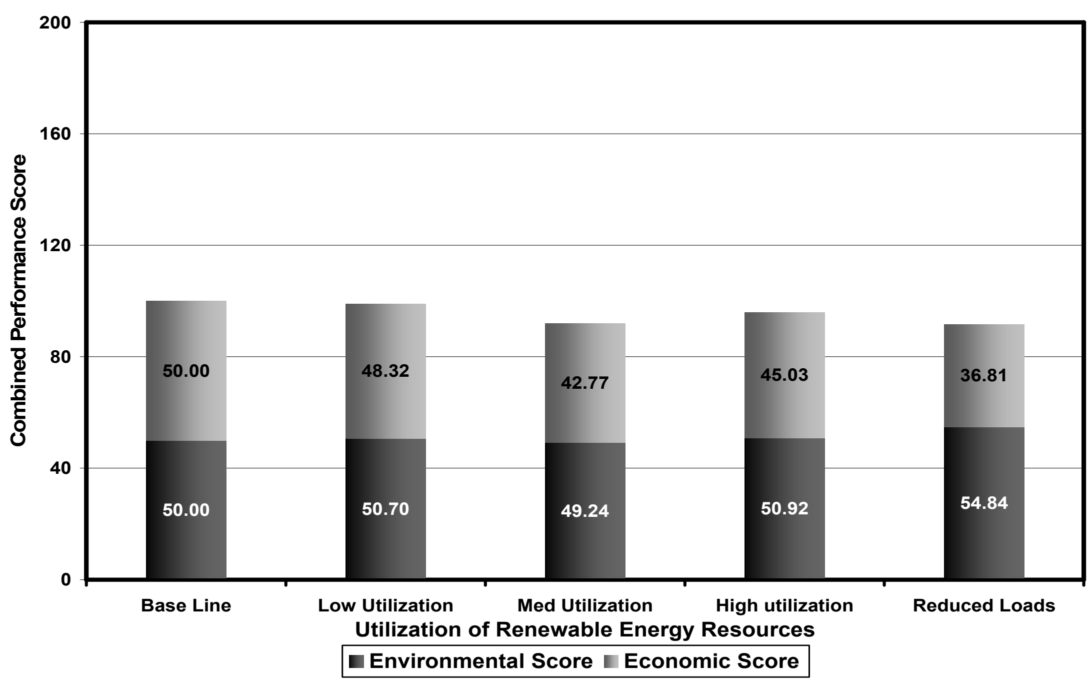


Figure 5-55 Impact of Utilization of Renewable Energy Resources on Combined Performance – Decentralized Approach

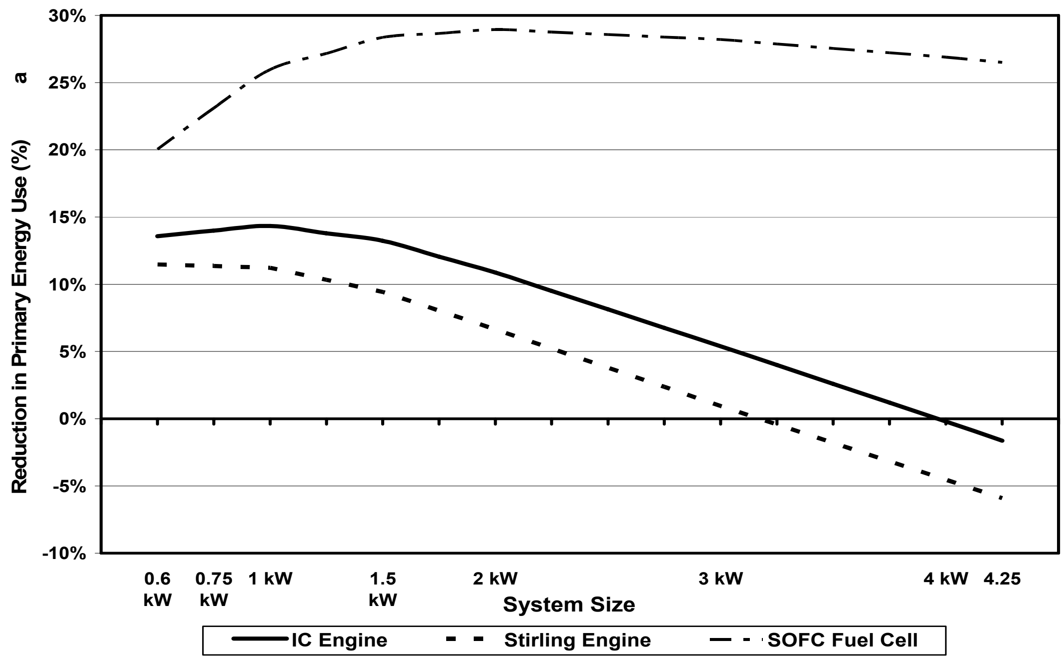


Figure 5-56 Impact of Cogeneration System Type on Primary Energy Use– Decentralized Approach

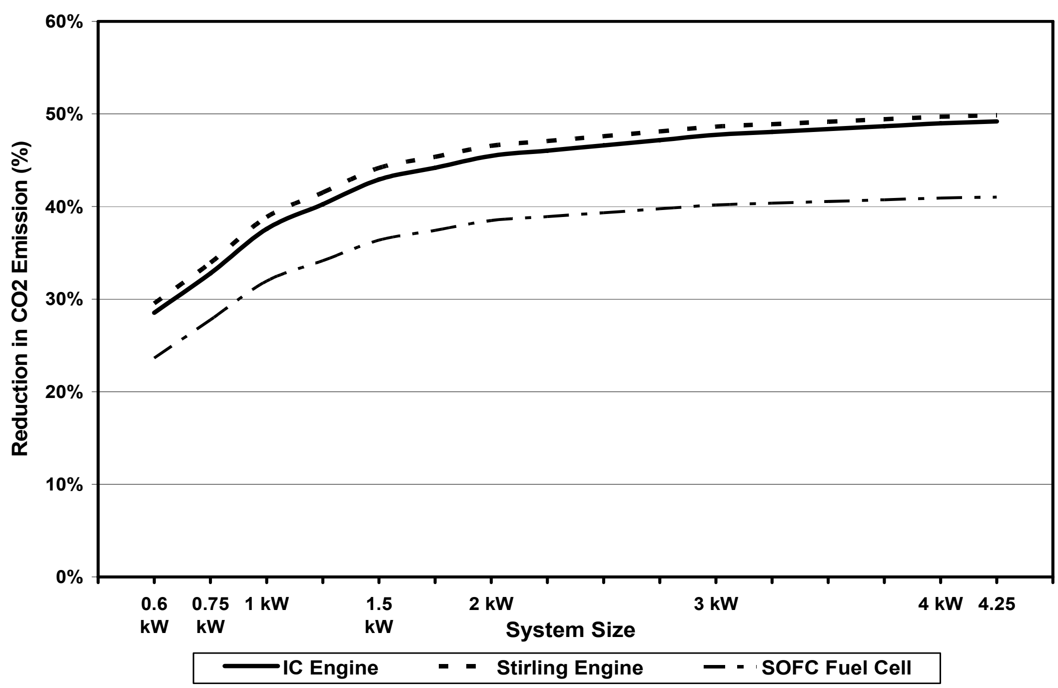


Figure 5-57 Impact of Cogeneration System Type on CO_2 Emissions – Decentralized Approach

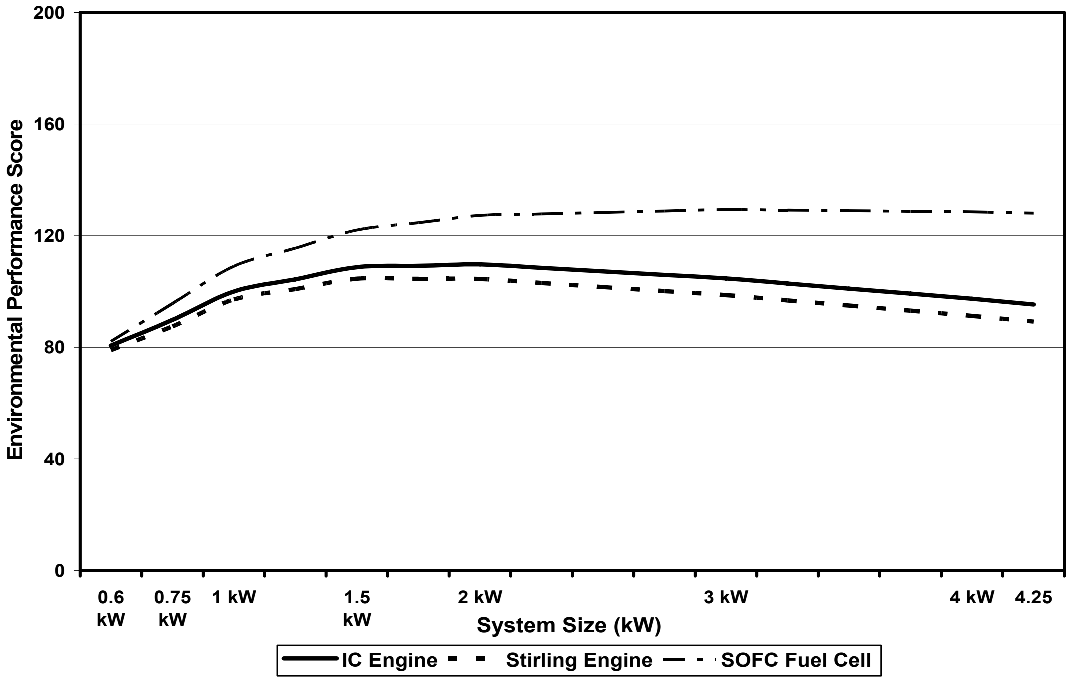


Figure 5-58 Impact of Cogeneration System Type on Environmental Performance – Decentralized Approach

Table 5-1 Internal Rate of Return for Different Cogeneration System Types & Sizes – Decentralized Approach

System type	0.6 kW	0.75 kW	1.0 kW	1.5 kW	2.0 kW	3.0 kW	4.0 kW	4.25 kW
Reciprocating engine	7.25%	1.10%	-4.75%	-13.71%	-8.24%	N/A*	N/A*	N/A*
Stirling engine	-3.73%	-8.34%	-13.88%	N/A*	N/A*	N/A*	N/A*	N/A*
SOFC fuel cells	-3.65%	-6.29%	-9.51%	-14.21%	-14.21%	-17.93%	N/A*	N/A*

* N/A indicates that the IRR could not be calculated because there were no annual savings.

Figures 5-56 shows that fuel cell systems result in the largest reductions in primary energy use especially for larger system sizes because of their good part load efficiencies. While they do not result in high CO_2 emissions reductions, they perform the best with regard to the overall environmental performance, as shown in figure 5-58, with IC and Stirling engines achieving comparable performances. Additionally, initial increases in system sizes, for all system types, result in significant improvements in environmental performance; however, sizes larger than 2 kW do not result in any improvements in the case of fuel cells and result in reduction in performances for the other two types. On the other hand, with regard to economic performance, table 5-1 shows that only the 0.6 kW and, to a much lesser extent, the 0.75 kW IC engine systems result in a positive IRR, while all other alternatives result in negative IRR's or, in many cases, do not result in any annual savings making the calculation of an IRR impossible. Because of this, it was not possible to calculate a combined score for all the alternatives being evaluated. However, the large decline in IRRs shown in table 5-1 indicates that only the two alternatives previously mentioned are possible under the conditions of this study.

5.4.3.2. Cogeneration system size and operation strategy

Figures 5-59 to 5-61 show the impact of system size and operation strategy on the performance of micro-cogeneration systems. Figure 5-59 shows the reductions in annual community primary energy use for different sizes and operation strategies, figure 5-60 shows the same information with regard to the reduction in CO_2 emissions, and figure 5-61 shows the environmental performance score resulting from those two indicators. Table 5-2, on the other hand, shows the resulting IRR for various operation strategies and sizes.

From figures 5-59 & 5-60, it can be seen that, for small system sizes, both net metering and electric load matching result in comparable performances. However, as sizes increase, net metering results in increasingly larger reductions especially in CO_2 emissions. The environmental performance shown in figure 5-61 also shows similar results. With regard to economic performance, table 5-2 shows that only the smaller system sizes, 0.6 kW & 0.75 kW resulted in a positive IRR, and that increases in system size have a significant negative impact on the IRR. It can also be seen that net metering does not result in an economic advantage even with the assumption that electricity buying and sell back prices are equal. This indicates that the increase in the consumption of natural gas, and the resulting increase in costs, for the net metering alternatives outweigh the income resulting from selling back electricity to the grid.

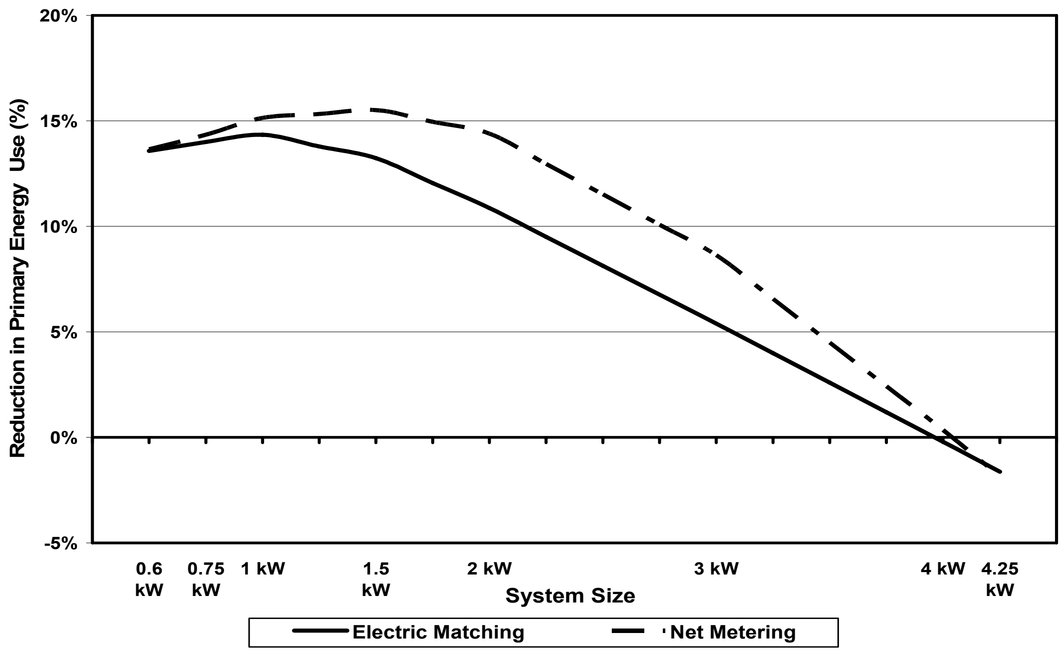


Figure 5-59 Impact of Cogeneration System Size & Operation Strategy on Primary Energy Use – Decentralized Approach

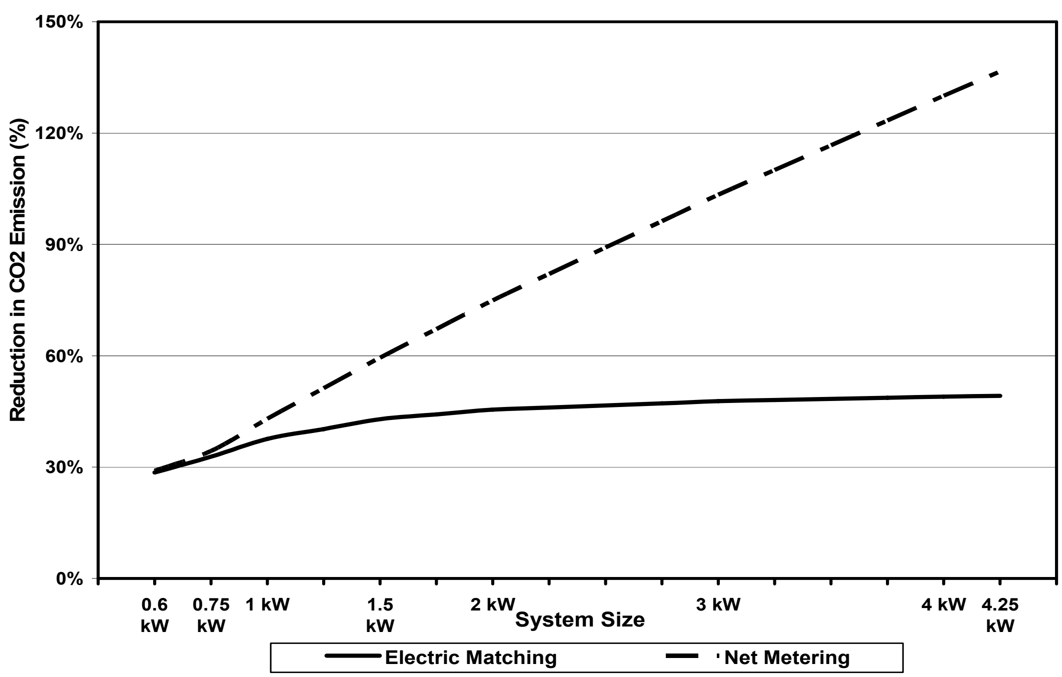


Figure 5-60 Impact of Cogeneration System Size & Operation Strategy on CO_2 Emissions – Decentralized Approach

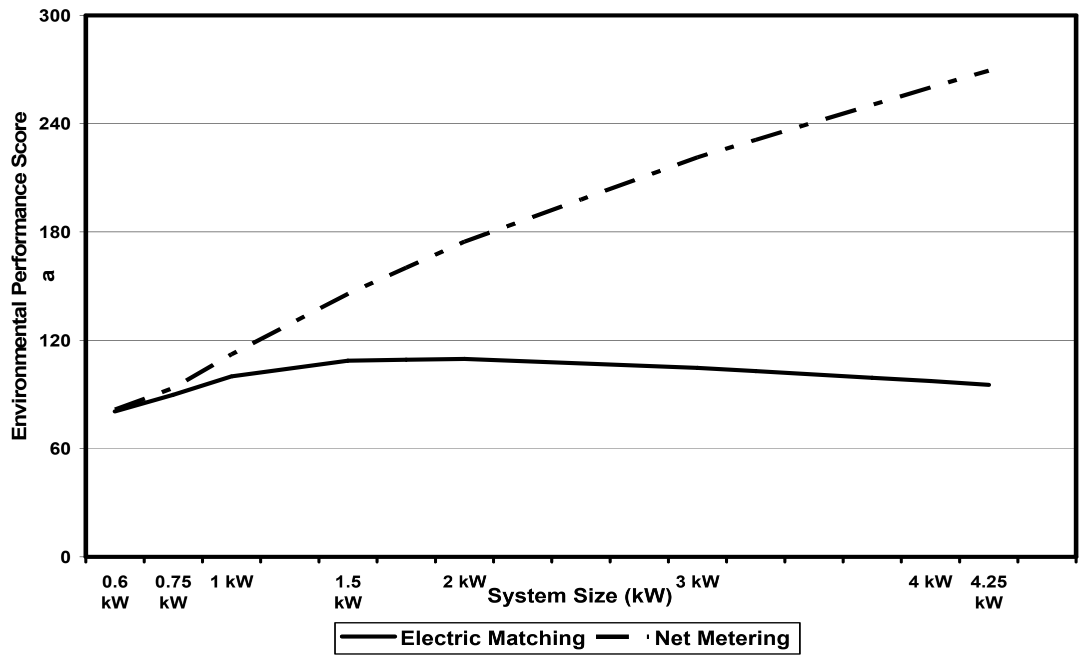


Figure 5-61 Impact of Cogeneration System Size and Operation Strategy on Environmental Performance - Decentralized Approach

Table 5-2 Internal Rate of Return for Different Cogeneration System Sizes and Operation Strategies – Decentralized Approach

System type	0.6 kW	0.75 kW	1.0 kW	1.5 kW	2.0 kW	3.0 kW	4.0 kW	4.25 kW
Electric Load-Matching	7.25%	3.43%	-3.16%	- 8.24%	-5.70%	-8.24%	N/A*	N/A*
Net metering	17.32%	3.11%	-5.31%	N/A*	N/A*	N/A*	N/A*	N/A*

* N/A indicates that the IRR could not be calculated because there were no annual savings.

5.4.4 Summary of Design Parameters' Impacts – Decentralized Approach

Similar to the centralized approach, the results of the individual assessments of the impacts of the community design parameters on the performance of cogeneration systems in the decentralized integration approach were compared and the results shown in figure 5-62. The outcome of this comparison will form the basis of the design optimization process described in chapter VI. These outcomes include the following:

1) Only small size IC engine systems (0.6 kW to 0.75 kW) are economically feasible under the conditions of the study. All other system types and sizes are economically unfeasible because of their high initial costs. The 0.6 kW IC engine system achieves the best performance following an electric load matching operation strategy.

2) The impacts of community design parameters on the performance of the cogeneration systems in the decentralized approach are considerably less than for the centralized approach.

3) Similar to the centralized approach, higher densities achieve the largest improvements in combined performance relative to he base-line case. In addition to that, only the large single family houses alternative resulted in an increase in combined performance. This indicates that the micro-cogeneration systems investigated n this study perform better in design alternatives with high thermal loads and vice versa.

4) Some housing typologies, e.g. multi-family homes and single-family attached houses, show some potential for improved combined performance in higher density communities.

5) Reductions in community energy consumption either through increases in envelope and building systems' efficiencies or through increasing the utilization of renewable energy resources generally result in reductions in the combined performance of the cogeneration system.

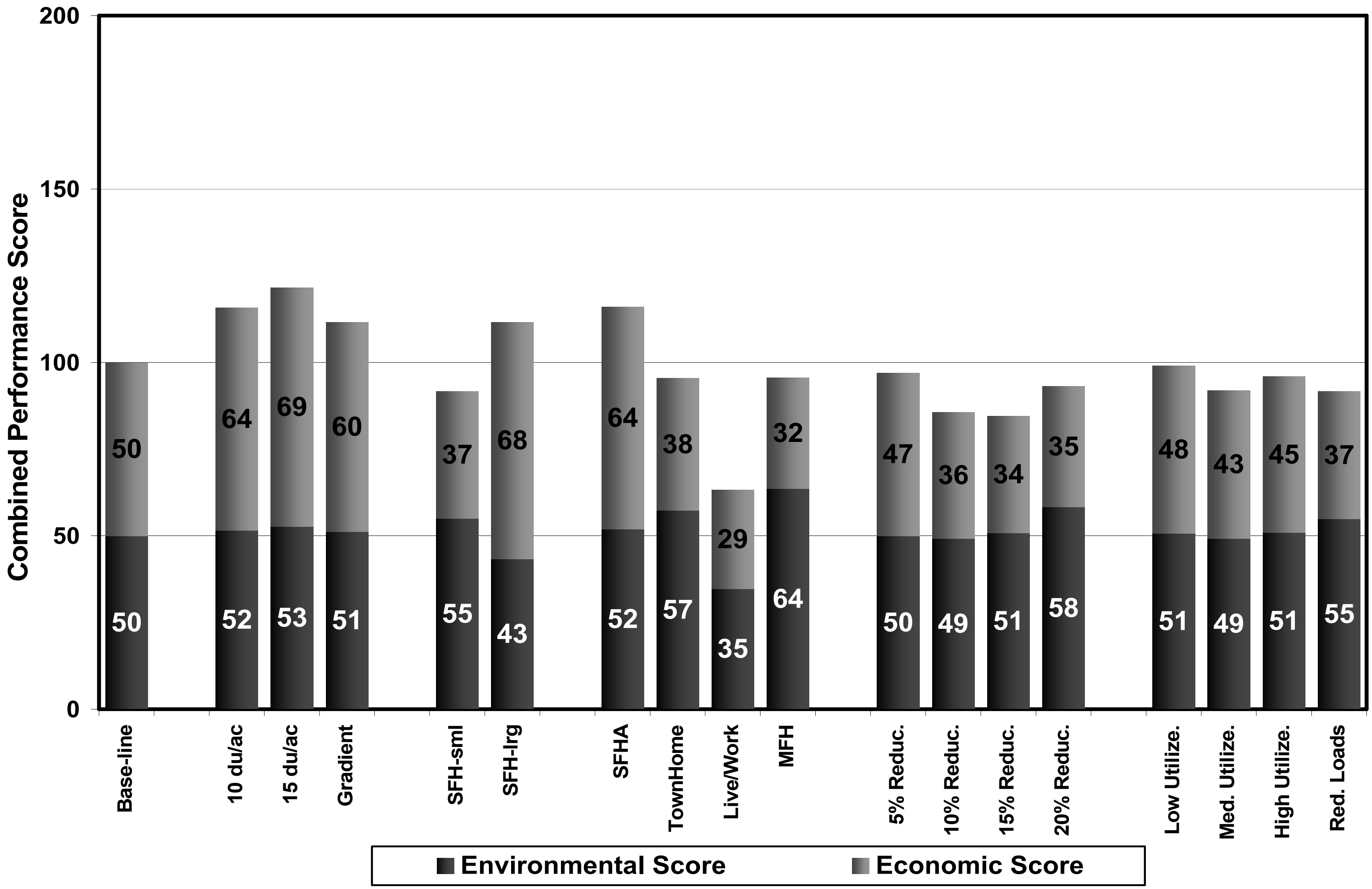


Figure 5-62 Summary of Impacts of Design Parameters on Combined Performance – Decentralized Approach

5.5 SUMMARY

This chapter described the results of the performance assessment procedures conducted to determine the impact of each of the community design parameters on the environmental and economic performances of the residential cogeneration systems for both the centralized and the decentralized integration approaches. This assessment will form the basis for the community design optimization presented in the following chapter.

First, the cogeneration system performance in the base-line community was determined for both integration approaches and the two approaches were contrasted. Subsequently, the impacts of each design parameter on the percentages of reduction in primary energy use and CO_2 emissions due to the use of cogeneration, the IRR of the cogeneration system, and the resulting combined environmental and economic performance were presented and discussed. Then, for each integration approach, the impacts of all design parameters were compared and the parameters having the most impact identified. The results described in the chapter show that, under current conditions, the centralized integration approach for residential cogeneration achieves better environmental and economic performances than the decentralized one. Analysis of the impacts of the design parameters also show that the centralized approach is affected more than the decentralized approach by variations in community design thus offering a higher potential for performance improvements.

For the centralized approach, it was shown that higher densities and mixing of uses achieve the largest performance improvements relative to the base-line case. Several housing typologies also offer potential for improvements in performance when utilized within communities with high densities and/or high mix of uses. On the other hand, all changes in street configuration from the base-line interconnected network alternative resulted in reductions in performance. Finally, increasing envelope and building systems' efficiencies as well as increasing the utilizations of renewable energy resources resulted in small improvements in environmental performance combined with larger reductions in economic performance. For the decentralized approach, only higher densities and larger single family houses result in improving the combined performance of the cogeneration systems. All other design parameters result in minimal or negative impacts.

CHAPTER VI
OPTIMIZATION OF COMMUNITY DESIGN

6.1 INTRODUCTION

In this chapter, the results of the assessment of the individual impact of the selected community design parameters on the performance of the cogeneration system was used to identify the combination of community design characteristics that would achieve optimum and minimum acceptable cogeneration system performances for both the centralized and decentralized integration approaches. For each approach, the chapter will describe and justify the selected design characteristics and report the resulting environmental and economic cogeneration system performances in each scenario. The sensitivity of the resulting system performances to changes in a number of economic and environmental parameters will also be evaluated and, finally, the resulting cogeneration system performances for both integration approaches will be contrasted and compared to the system performance in the base-line community.

6.2 DESIGN OPTIMIZATION – CENTRALIZED APPROACH

6.2.1 Optimum Design Scenario

6.2.1.1 Community design characteristics

Comparing the impact of the selected planning and architectural parameters on the performance of the cogeneration system for the centralized approach clearly shows that density of urban form, mix of uses, and housing typology have the most impact on the system performance (see section 5.3.4 and figure 5-37). The analysis also showed that changes in street configurations, from the base-line configuration, resulted in a clear negative impact on the system performance, while increases in envelope and building systems' efficiencies and in the utilization of renewable energy resulted in a mixed impact on that performance. Based on this, and according to the procedures detailed in section 3.3.5, the characteristics of the optimized design were identified. These characteristics, for both the optimum and minimum acceptable design scenarios, are summarized in table 6-1, while an aerial view of the community design included in Appendix C.

Table 6-1 Design Characteristics for the Two Optimization Scenarios – Centralized Approach

Design parameter	Optimum system performance	Minimum acceptable system performance
Planning parameters		
Density of built form	Density gradient from 4 du/ac to 15 du/ac – average density of 10 du/ac	Density gradient from 2 du/ac to 6 du/ac – average density of 4 du/ac
Mix of uses	Optimized mix of uses*	Low mix of uses*
Street configuration	Interconnected/grid.	Interconnected/grid.
Architectural parameters		
Housing typology	32 detached SFH, 16 detached SFH – small, 28 attached SFH, 30 town homes, 10 live work units, 48 multi-family houses.	64 detached SFH – large, 100 detached SFH, 80 attached SFH, 36 multi-family houses
Envelope and building systems efficiencies	Base-Line (compliant with IECC 2003). Sensitivity of cogeneration performance to increases in efficiency evaluated.	Base-Line (compliant with IECC 2003). Sensitivity of cogeneration performance to increases in efficiency evaluated.
Utilization of renewable energy	Base-line value	Base-line value
Cogeneration system parameters		
Cogeneration system type	Reciprocating engine based system.	Reciprocating engine based system.
Cogeneration system size	100 kW to 700 kW.	100 kW to 700 kW
Operation strategy	al load-matching	al load-matching

* see table 4-2 for detailed description of commercial building typologies in both the optimized and low mix of uses alternatives.

While the 15 du/ac density alternative achieved the best system performance, this alternative would limit the range of housing typologies that could be incorporated into the optimized design and was therefore excluded and the optimized design was assumed to have an average density of 10 du/ac. As density gradients were shown to result in a performance comparable to their average density, the optimized design was assumed to have a density gradient ranging from 15 du/ac in the center to 4 du/ac at the edges. The optimized scenario also included a range of housing typologies including detached single family houses, both average and small sizes, attached single family houses, town homes, live-work units, and multi-family houses; as well as a variety of commercial and civic building types (see table 4-2). Al non-residential building types were assumed to be concentrated in the center of the community.

As reductions in residential energy use, resulting from increasing the envelope and building systems' efficiencies of the base-line community, caused improvements in the environmental performance of the cogeneration system combined with larger reductions in its economic performance, the optimized design did not assume any increases in envelope and system efficiencies. However, the sensitivity of the cogeneration system performance to changes in these efficiencies within the optimized design was evaluated. On the other hand, with regard to the utilization of renewable energy, the results also showed that increasing this utilization, while resulting in reducing the overall community energy use and a small increase in the environmental performance of the cogeneration system also resulted in a larger decrease in its economic performance. Based on these results, and because the higher densities identified as very favorable for the cogeneration system performance would inevitably reduce the solar access to the buildings, no utilization of renewable energy resources was assumed in the optimized design and the base-line building configuration was used instead.

With regard to cogeneration system characteristics, while fuel cells achieved a higher environmental performance, their current high initial and maintenance costs make them economically unfeasible. Reciprocating engines, on the other hand, have a clear advantage with regard to the combined system performance. Subsequently, they were selected for both scenarios. With regard to system size and operation strategy, the electric load matching operation strategy was used and a range of system sizes was evaluated to identify the best size.

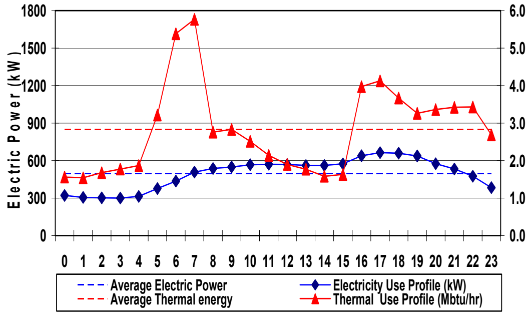
6.2.1.2 Community energy use profiles

The graphs in figure 6-1 show the average daily seasonal electrical and thermal energy use profile for the community in the optimum design scenario, while figure 6-2 shows the average hourly monthly energy needs of the community in this scenario compared to the average output of its centralized cogeneration systems. The impact of the community design optimization process on the community's energy use profile can be seen by comparing these two figures to the corresponding profiles developed for the base-line community and included in figures 5-1 and 5-2a respectively. From the comparison, the following can be concluded:

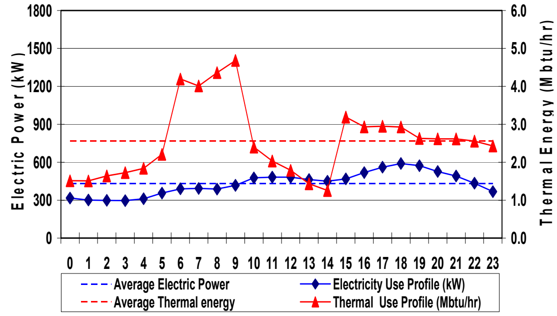
1) The design optimization process resulted in clear reductions in the daily variations of the community's electricity use profile for all seasons. The resulting profiles show considerably less variations from the base-line case. While the summer profile still shows a large evening increase, the variations in the profile are also smaller than the base-line case. These improvements in energy use profiles result in improving the performance of the cogeneration system through allowing it to operate at or close to full power and maximum efficiency for longer periods.

2) While the thermal energy use profiles for the optimum design scenario are generally similar in form to their counterparts in the base-line community, their magnitude is considerably smaller especially with regard to summer and fall morning and evening peaks which show a reduction of more than 30% compared to the base-line community. These reductions reduce the required size of the auxiliary heater as well as the fuel needed for it.

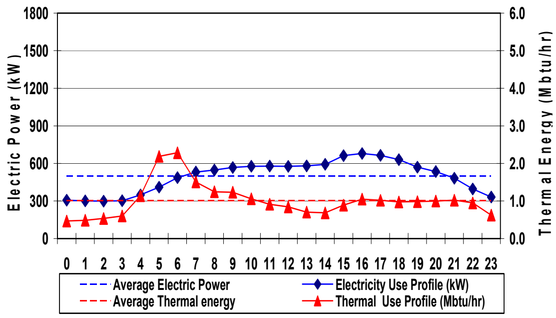
3) Figure 5-2 shows that, because of these improvements in energy use profiles, the cogeneration system in the optimum design scenario is, on average, very successful in meeting the majority of the community's electrical and thermal needs for most of the months of the year. The figure, however, shows that the cogeneration system results in considerable excess thermal energy for most of the year (March through November) and especially in summer months (June through September) in which the average unutilized thermal output of the system reaches an average of 1.75 MBtu/hr. This excess thermal energy shows an even higher potential for the use of thermally activated cooling technologies than in the base-line case. Alternatively, it can be utilized for other thermal end uses either within or near to the community thus potentially resulting in further improvements in the cogeneration system's economic performance.



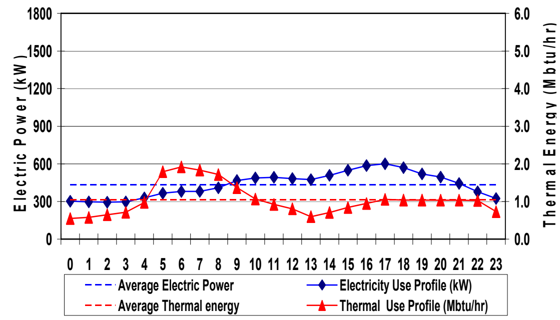
a) Average daily winter weekday energy use profile



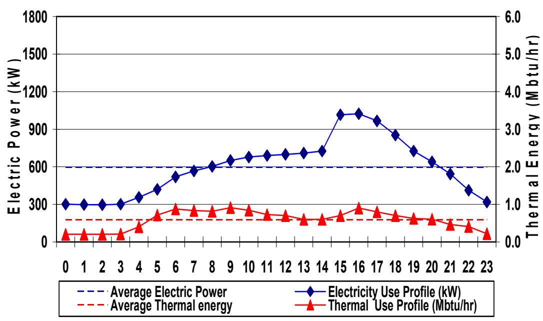
b) Average daily winter weekend energy use profile



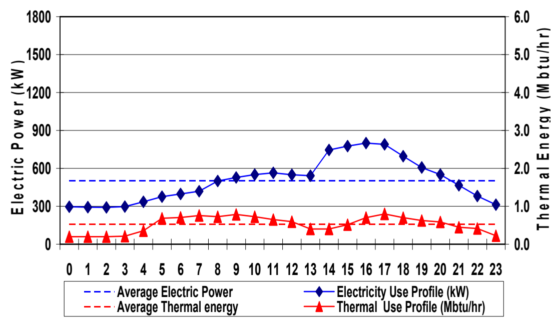
c) Average daily spring weekday energy use profile



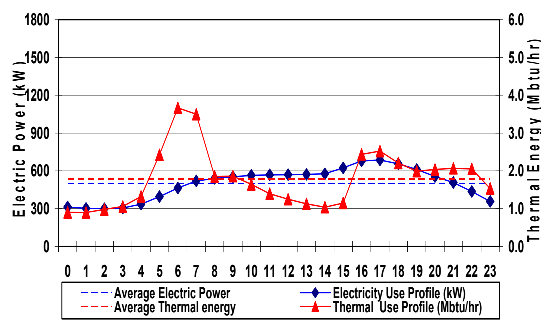
d) Average daily spring weekend energy use profile



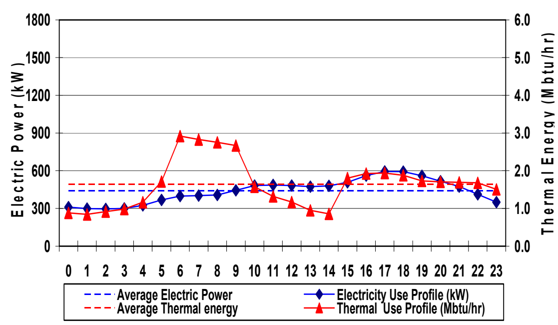
3) Average daily summer weekday energy use profile



f) Average daily summer weekend energy use profile



g) Average daily fall weekday energy use profile



h) Average daily fall weekend energy use profile

Figure 6-1 Average Daily Seasonal Weekday and Weekend Community Energy Use Profiles – Optimum Design Scenario

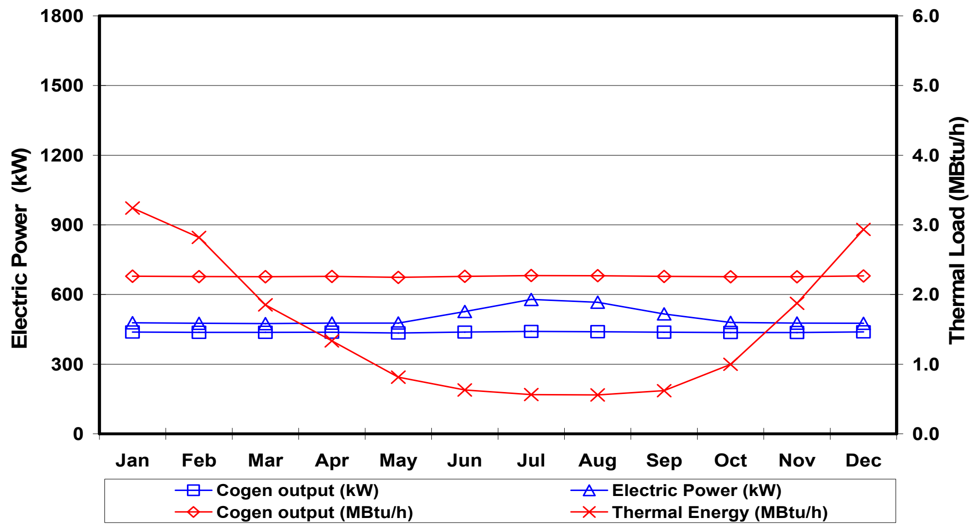


Figure 6-2 Average Hourly Monthly Electrical and Thermal Community Needs Compared to Average Hourly Output of Cogeneration System - Optimum Design Scenario

6.2.1.3 Cogeneration system performance

The performance of the centralized cogeneration system within this scenario was assessed for a range of system sizes and the results shown in figures 6-3 through 6-6. Figure 6-3 shows the magnitude and percentage of reduction in primary energy use due to the cogeneration; figure 6-4 shows the same information with regard to reduction in CO_2 emissions; figure 6-5 shows the resulting IRRs for the various system sizes; while figure 6-6 shows the combined performances for all centralized system sizes relative to the base-line case.

The figures show that for the same system size of 250 kW, the cogeneration system in the optimized design achieves an improvement in economic performance of more than 250%, compared to the base-line community, combined with no noticeable reduction in environmental performance. This substantial improvement in economic performance allows for the use of larger cogeneration system sizes, which achieve more improvements in environmental performance while in the same time maintaining an acceptable economic one, thus indicating the success of the optimization process. However, it can also be seen that increases in system size result in larger reductions in economic performance than increases in environmental performance, and that the rate of increase in environmental performance drops significantly for system sizes larger than 500 kW as the impact of the lower cogeneration part-load efficiencies increases.

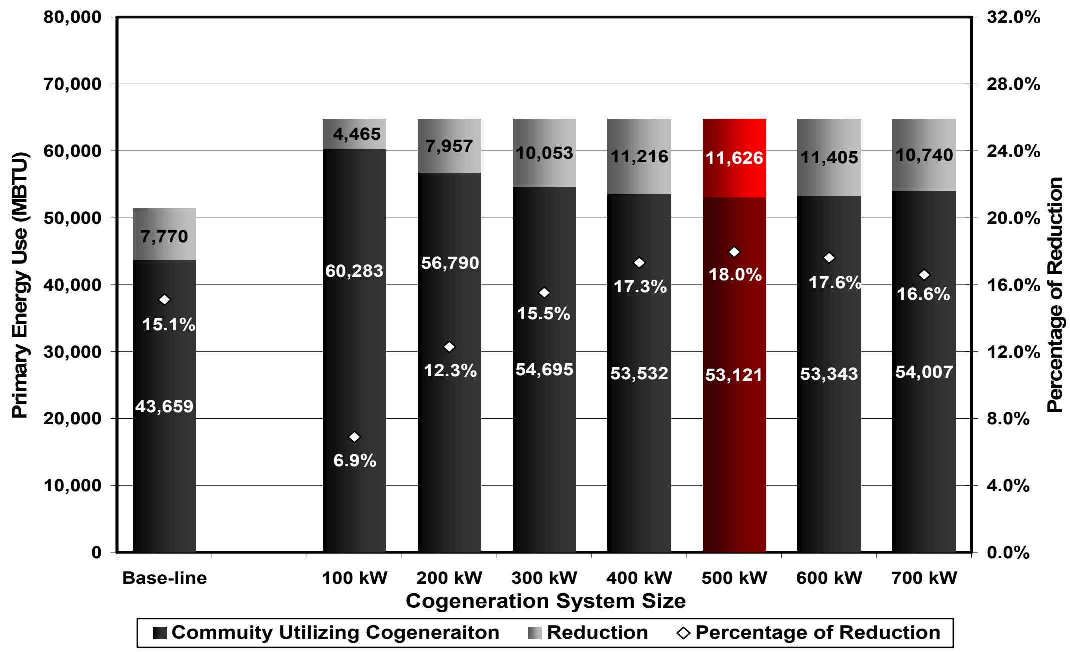


Figure 6-3 Magnitude and Percentage of Reduction in Primary Energy Use for Optimum Design Scenario – Centralized Approach

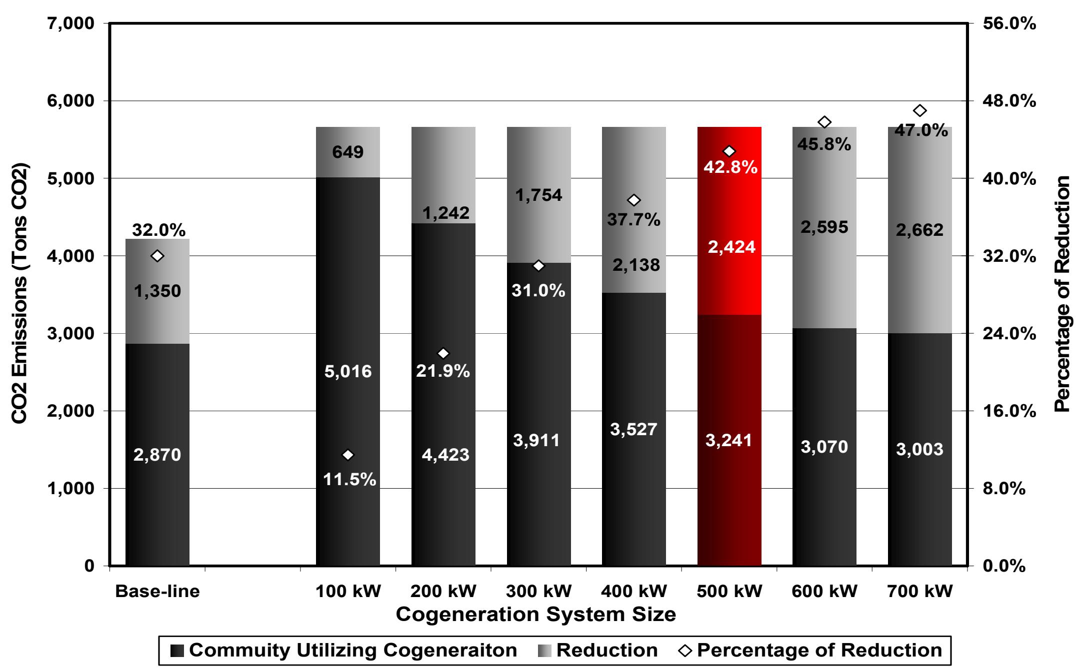


Figure 6-4 Magnitude and Percentage of Reduction in CO_2 Emissions for Optimum Design Scenario – Centralized Approach

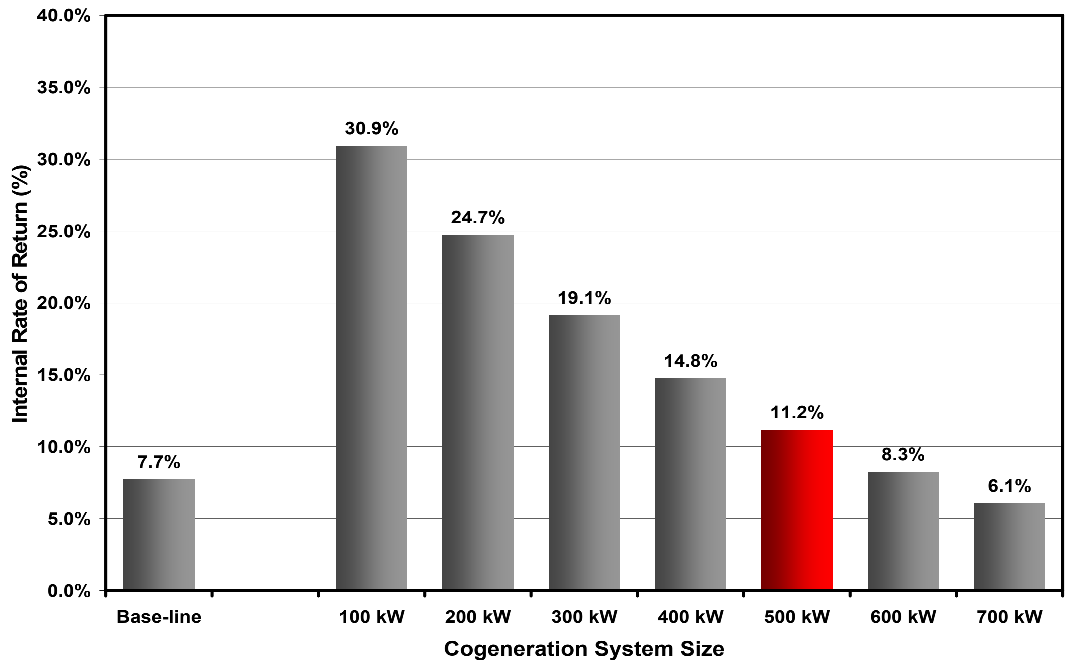


Figure 6-5 Internal Rate of Return for Cogeneration System in Optimum Design Scenario – Centralized Approach

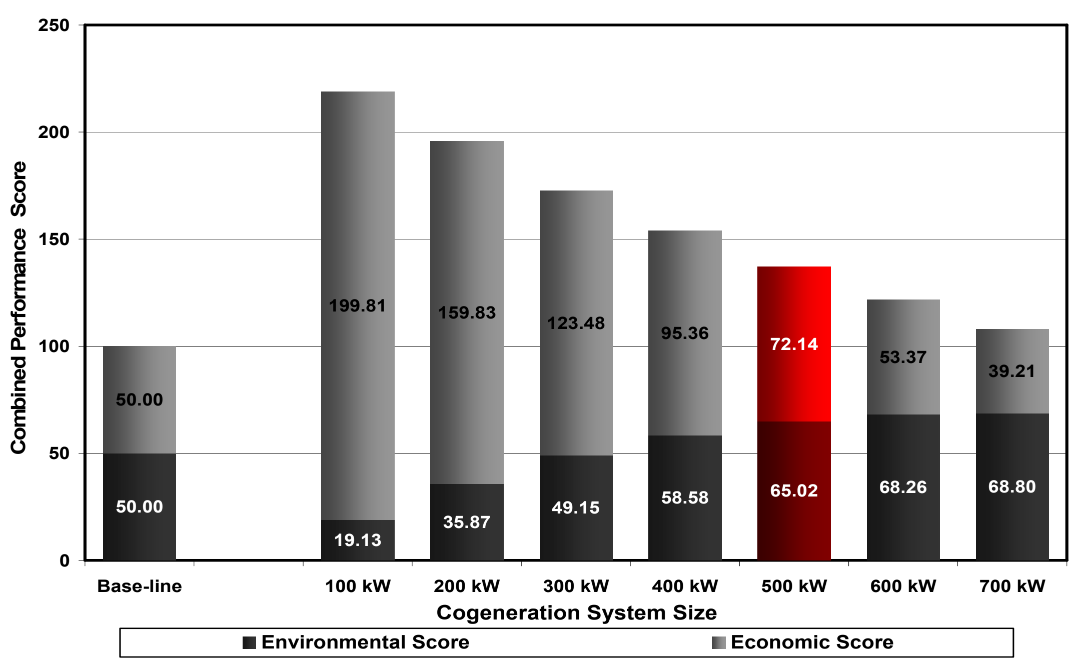


Figure 6-6 Combined Cogeneration System Performance for Optimum Design Scenario – Centralized Approach

As figure 6-5 also shows that cogeneration system sizes up to 500 kW achieve adequate IRRs (based on a minimum acceptable IRR of 10% identified according to previous studies of cogeneration system performance (e.g. Caton, 2003; and NREL-GRI, 2003)), the 500 kW cogeneration system was selected as the optimum system size for this scenario. Using this system size results a reduction of 18% in the annual primary energy use of the community and a much more significant reduction of 42.8% in its annual CO_2 emissions. Additionally, this system supplies 87.4% of the electrical needs of the community as well as 80.3% of its thermal needs. These results indicate the large potential for cogeneration systems in effectively meeting the energy needs of residential communities, with suitable design characteristics, while in the same time achieving significant reductions in their CO_2 emissions. On the other hand, only 53.8% of the thermal output of the cogeneration system is utilized within the residential community thus representing a clear potential for utilizing the excess thermal energy for other end uses. The cogeneration system also achieves an IRR of 11.2%, thus indicating its economic feasibility. While using a slightly larger system would still result in an IRR above the 10% minimum, the corresponding improvements in environmental performance were minimal. Finally, compared to the base-line case, the system performance in the optimized design shows an improvement of 30% in environmental performance, and 45% in economic performance.

6.2.1.4 Parametric sensitivity analysis

In this section, the sensitivity of the cogeneration system performance to changes in a number of parameters was evaluated and the resulting trends analyzed and described. First, the sensitivity of the performance to increases in building envelope and systems' efficiencies was evaluated to assess the potential of using cogeneration systems in residential communities requiring a higher energy efficiency level than the code-compliant one assumed in the optimized design. In this analysis, the performance of the system assuming a 5% reduction in residential energy use, from the code-compliant base-line, was calculated and compared to its performance in the optimized design. The combined performance results are shown in figure 6-7.

Following this, the sensitivity of the combined system performance to variations in a number of economic and environmental parameters assumed within the study was investigated. The economic parameters evaluated included: electricity rate, natural gas rates, cogeneration system initial cost, and annual maintenance cost; while the environmental parameters included the utility emissions rate, and the utility electricity generation efficiency. Both of these environmental parameters vary according to the fuel mix used by the utilities and impact the reductions in primary energy use and emissions resulting from the cogeneration system. Each assessment was performed by varying the investigated parameter ± 25 from its value in the base-line and optimized designs and the resulting percentage of change in the combined cogeneration system performance was calculated. The results of this analysis are shown in figure 6-8.

From figure 6-7, it can be seen that the impact of increasing envelope and building systems' efficiencies in the optimum design are similar to their impact in the previous chapter, i.e. a small increase in environmental performance combined with a slightly larger decrease in economic performance. The combined impact of this is, however, minimal for small cogeneration system sizes and only increases slightly for larger sizes. Additionally, the small reduction in economic performance do not cause the IRR to drop significantly, and the resulting IRRs for system sizes up to 500 kW are still larger than the identified 10% minimum (e.g. the IRR for the 500 kW system size is 10.9 %). Based on all of this, it can be concluded that residential communities with energy efficiency standards exceeding code requirements are still suitable for the integration of centralized residential cogeneration systems especially taking into consideration that, in these communities, the resulting magnitude of primary energy use and CO_2 emissions are less than the code-compliant ones.

Figure 6-8, on the other hand, shows that the combined performance of the cogeneration system is most sensitive to changes in electricity rates, with decreases in rates having an even larger negative impact than the positive impact of rate increases (up to -60% compared to +40%), while changes in natural gas rates have the next most significant impact (approximately ± 20%). In general, changes in economic parameters had a more significant impact on the combined performance than environmental ones further indicating the higher sensitivity of the economic performance to changes in design parameters. This higher sensitivity was also seen in the sensitivity of the economic performance to changes in cogeneration system size. This high sensitivity of the system performance to changes in energy rates should be taken into consideration when applying the results of the study to other location with different energy rates.

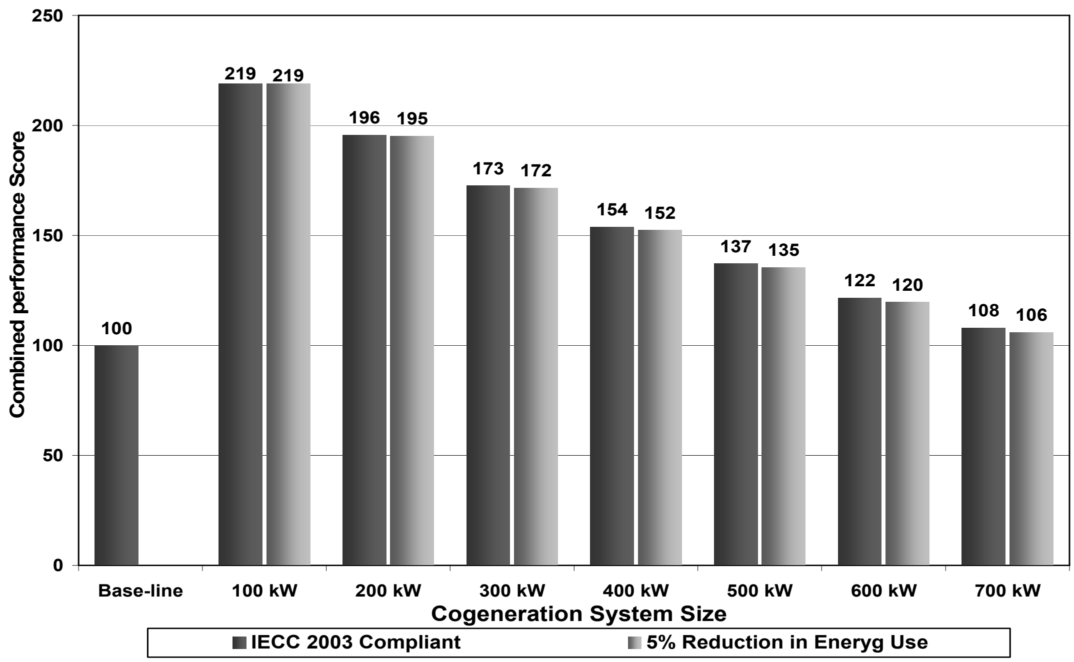


Figure 6-7 Impact of Increased Envelope & Building Systems' Efficiencies on Combined Performance in Optimum Design Scenario – Centralized Approach

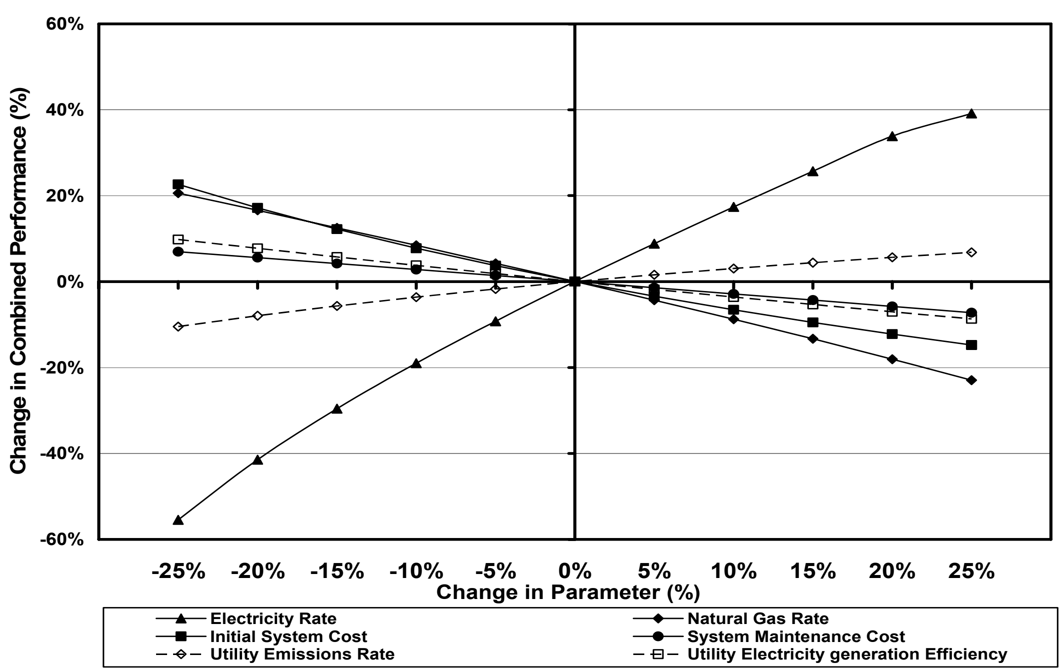


Figure 6-8 Sensitivity of Combined System Performance to Changes in Selected Parameters for Optimum Design Scenario – Centralized Approach

6.2.2 Minimum Acceptable Design Scenario

From the previous section and chapter V, it can be seen that the design characteristics having the largest positive impact on the performance of the cogeneration system are high density, and high mix of uses. These characteristics, however, are typically found only in urban residential communities (e.g. urban redevelopment and revitalization projects), and can be difficult to achieve in suburban areas. The purpose of this section, therefore, is to identify the potential of integrating centralized cogeneration systems in communities where high density and high mix of uses are not possible, and to identify the combination of community design characteristics that would achieve a minimum acceptable cogeneration system performance under those circumstances. As previous results showed that residential cogeneration systems typically achieves a better environmental than economic performance, and as previous studies, see section 2.4.3.3, indicate that economic performance typically plays a more important role in project feasibility decisions, the minimum acceptable performance for the cogeneration system in this scenario was identified as the combination of community design characteristics that achieve a minimum IRR of 10%. These design characteristics are summarized in table 6-1, and detailed below. A layout of the community is included in Appendix C.

6.2.2.1 Community design characteristics

Based on the assumptions of this scenario, the community in the scenario had an average density of 4 du/ac (in the form of a density gradient ranging from 6 du/ac in the center to 2 du/ac at the edges), and a low level of mix of uses (including a small community center, a child care center, and a small corner store). Additionally, similar to the previous scenario, the community was assumed to have a mix of housing typologies. However, the typologies selected for this scenario were more suitable for the low-density circumstances and therefore included a higher number of detached single family houses (64 large SFHs and 100 average sizes SFHs), attached single family houses (80 units), a lower number of multi-family houses (only 36 units), and did not include town homes or live-work units. No increases in envelope and building systems' efficiencies or in renewable energy utilization, from the base line values, were assumed in this scenario as well. However, a sensitivity analysis was also conducted for the impact of increasing envelope and system efficiencies on the performance of the cogeneration system. Finally, the cogeneration system characteristics in this scenario were the same as those in the previous scenario: a reciprocating engine based system using an electrical load-matching operation strategy evaluated over a range of system sizes from 100 kW to 700 kW.

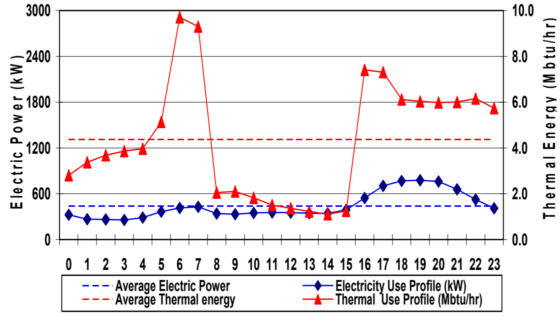
6.2.2.2 Community energy use profiles

The graphs in figure 6-9 show the average daily seasonal electrical and thermal energy use profiles for the community in the minimum acceptable design scenario, while figure 6-10 shows the average hourly monthly energy needs of the community in this scenario compared to the average output of its centralized cogeneration systems. The impact of the design optimization process in this scenario on the community's energy use profile can be seen by comparing the profiles to the corresponding profiles developed for the base-line community (figures 5-1 and 5-2a respectively) as well as those developed for the optimum design scenario (figure 6-1 and 6-2 respectively). From the comparison, the following can be concluded:

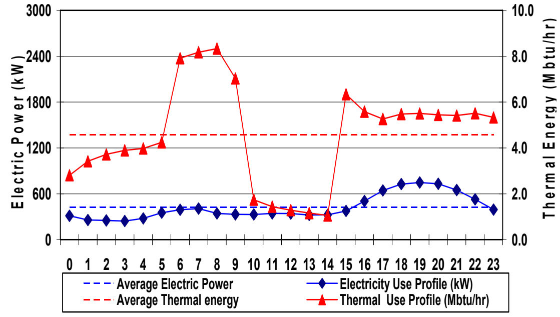
1) Compared to the base-line community, the electricity use profiles for the minimum acceptable design scenario do not show the same level of improvements as the ones for the optimum design scenario. However, the average electricity use for this scenario is still considerably higher than the base-line community. While the percentage of increase is about 32% for summer, it ranges between 40% and 48% for the other three seasons therefore reducing the seasonal differences in energy use to some extent.

2) The thermal energy use profiles for this scenario are similar in shape to their counterparts for the base-line community. However, their magnitude is noticeably higher especially with regard to morning and evening peaks in fall and winter.

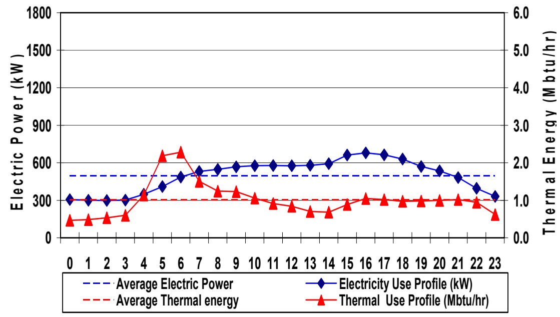
3) Figure 6-10 shows that the cogeneration system in this scenario is less successful than the one in the optimum design scenario in meeting the energy needs of the community especially with regard to thermal energy (it meets 76.8% of the electrical needs and only 54.3% of the thermal needs). This, combined with the larger thermal needs in this scenario, results in the need for a larger auxiliary heater as well as in increases in annual fuel costs. On the other hand, 72.3% of the thermal output of the cogeneration system in this scenario is utilized within the community thus resulting in much less excess thermal energy than the optimized scenario. While this reduces the potentials for utilizing this excess energy discussed earlier, it does improve the economics of the system if these potentials are not utilized.



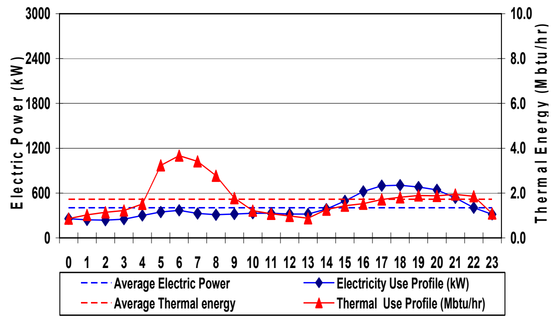
a) Average daily winter weekday energy use profile



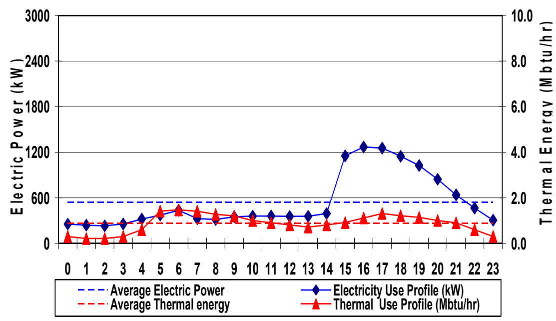
b) Average daily winter weekend energy use profile



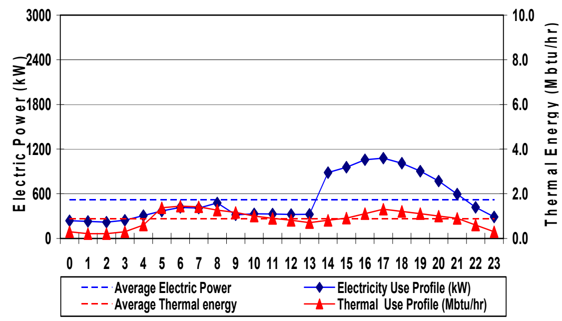
c) Average daily spring weekday energy use profile



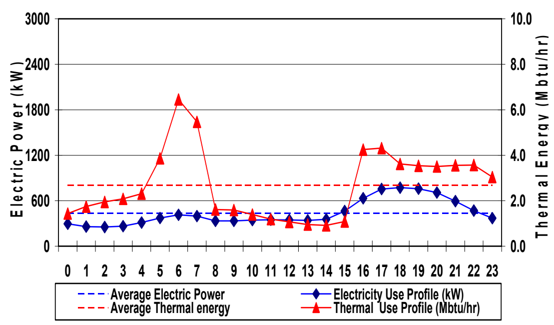
d) Average daily spring weekend energy use profile



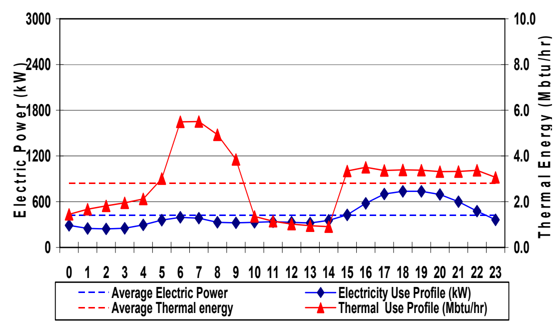
3) Average daily summer weekday energy use profile



f) Average daily summer weekend energy use profile



g) Average daily fall weekday energy use profile



h) Average daily fall weekend energy use profile

Figure 6-9 Average Daily Seasonal Weekday and Weekend Community Energy Use Profiles – Minimum Acceptable Design Scenario

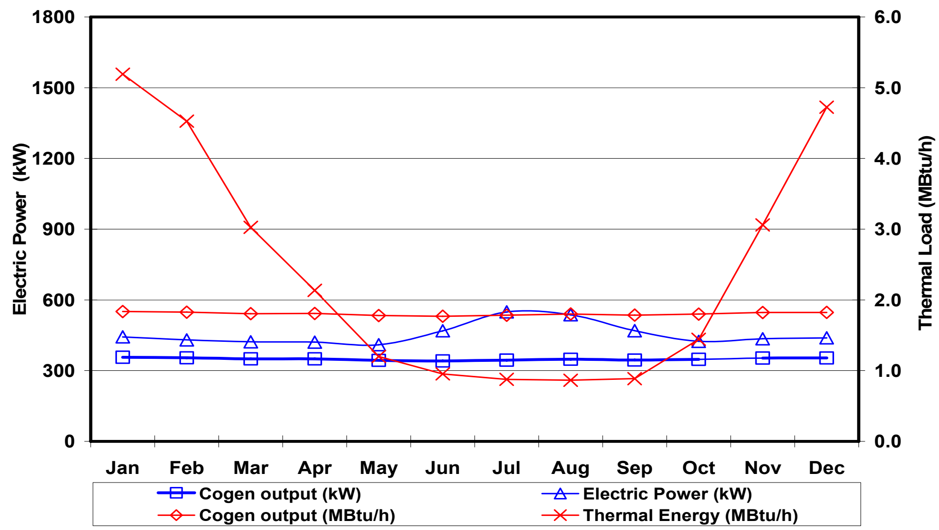


Figure 6-10 Average Hourly Monthly Electrical and Thermal Community Needs Compared to Average Hourly Output of Cogeneration System – Minimum Acceptable Scenario

6.2.2.3 Cogeneration system performance

The performance of the centralized cogeneration system within the minimum acceptable design scenario was assessed and the results shown in figures 6-11 through 6-14. Figure 6-11 shows the magnitude and percentage of reduction in primary energy use due to the use of the cogeneration system; figure 6-12 shows the same information with regard to reduction in CO_2 emissions; figure 6-13 shows the resulting IRRs for the various system sizes; and figure 6-14 shows the combined, environmental and economic, performances of the centralized cogeneration system for each size relative to the base-line case.

The figures show that both the economic and environmental performances of the system in this scenario are considerably lower than their counterparts in the optimized design one. The reduction in economic performance, however, is more significant especially for small system sizes. However, it can also be seen that the cogeneration system within this scenario still achieves a better performance than the base-line community for all system sizes. The figures also shows similar trends in performance including an increase in economic performance for smaller system sizes, an increase in environmental performance for larger system sizes, and a higher sensitivity of the economic performance to changes in system size.

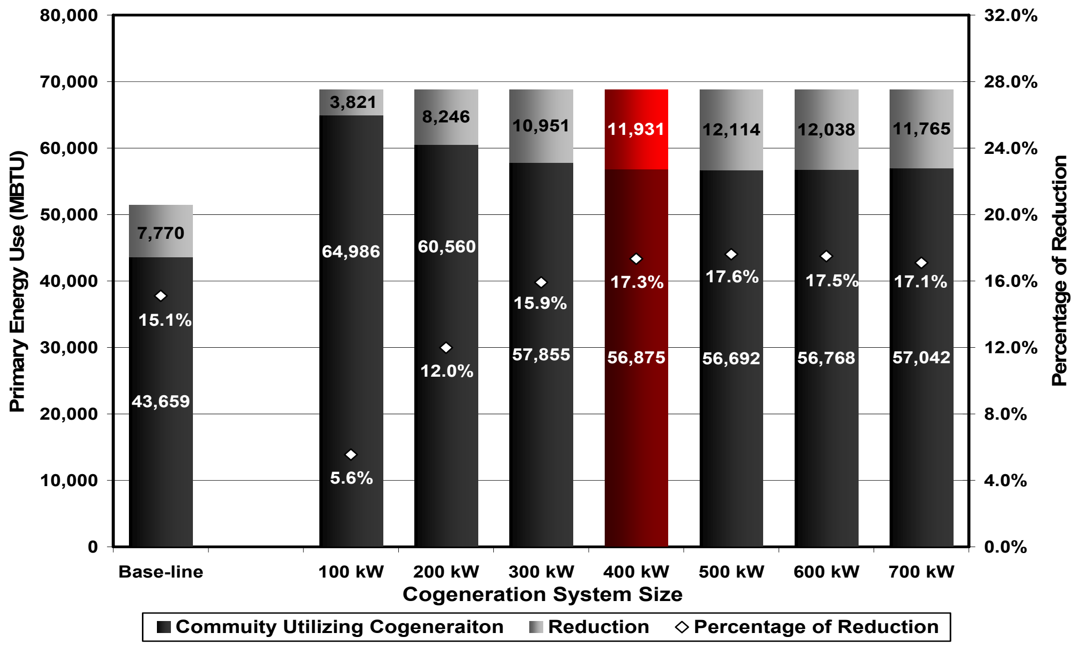


Figure 6-11 Magnitude and Percentage of Reduction in Primary Energy Use for Minimum Acceptable Design Scenario – Centralized Approach

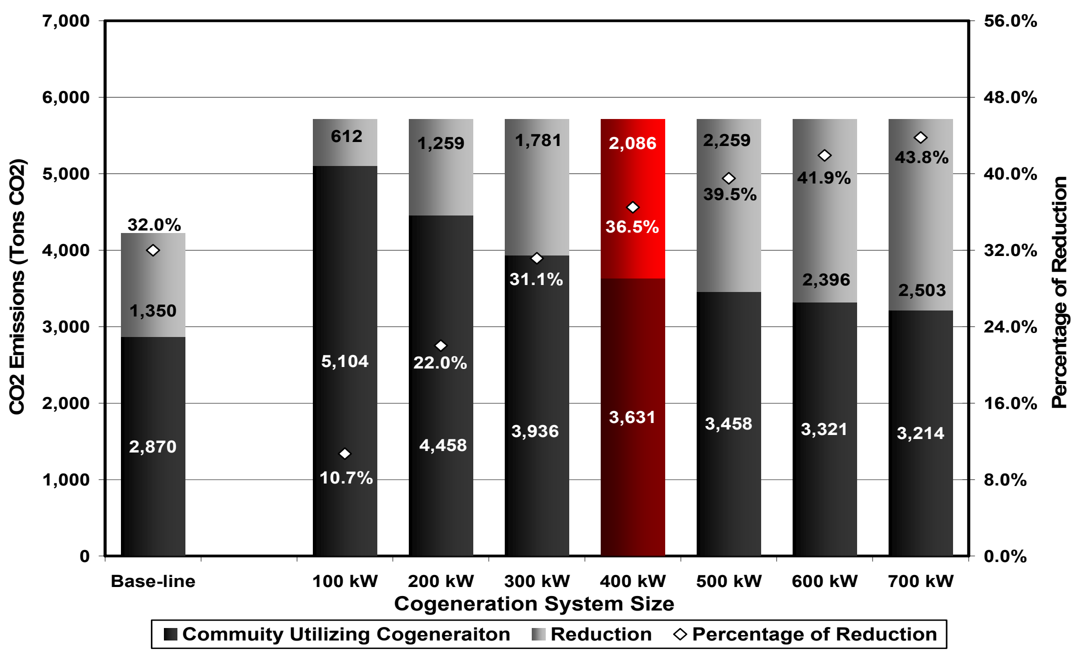


Figure 6-12 Magnitude and Percentage of Reduction CO_2 Emissions for Minimum Acceptable Design Scenario – Centralized Approach

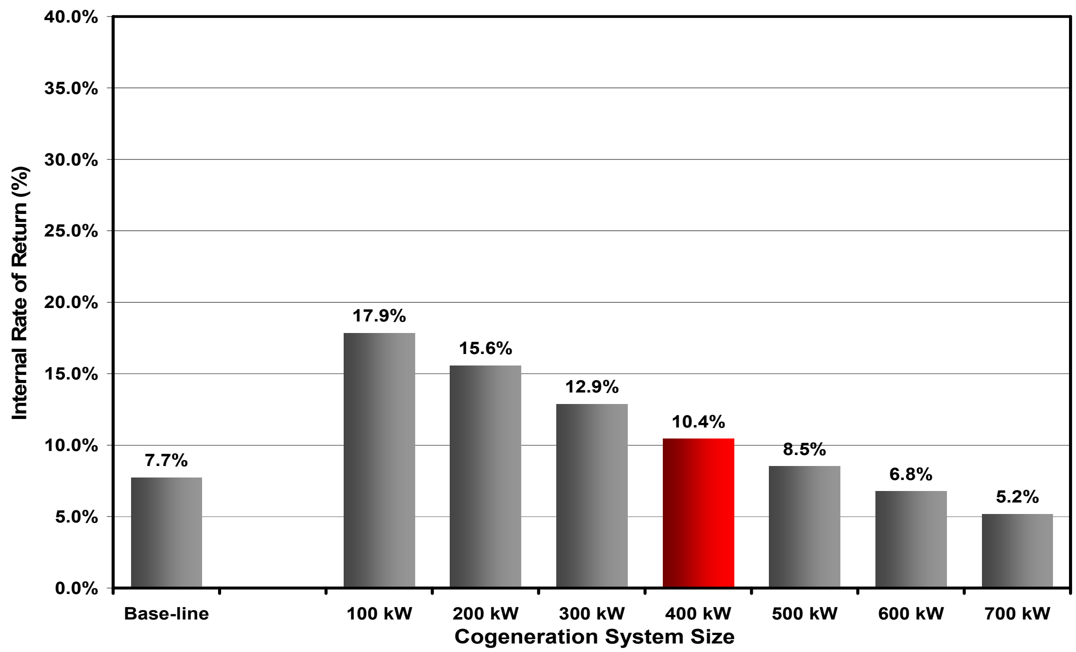


Figure 6-13 Internal Rate of Return for Cogeneration System for Minimum Acceptable Design Scenario – Centralized Approach

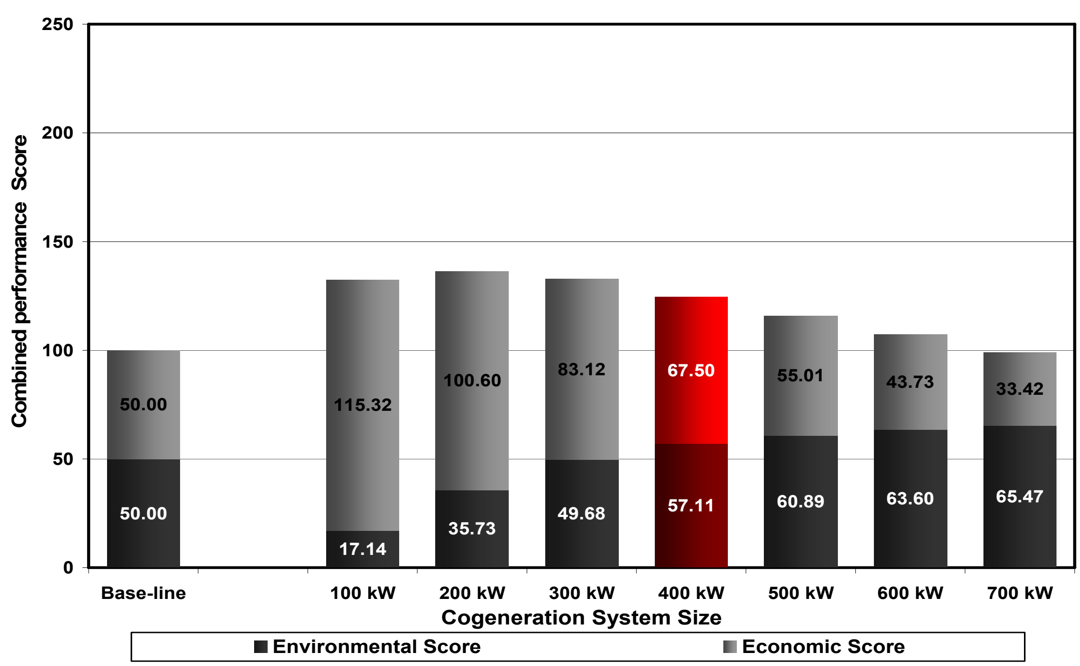


Figure 6-14 Combined Cogeneration System Performance for Minimum Acceptable Design Scenario – Centralized Approach

Figure 6-13 also shows that the maximum system size achieving an IRR above the minimum acceptable level of 10% is 400 kW, and, therefore, this system size was selected as the optimum size for this scenario. This system size achieves a reduction in primary energy use of 17.3%, a reduction in CO_2 emissions of 36.5%, and, as discussed earlier, the system also meets 76.8% of the electrical needs of the community and 54.3% of its thermal needs. Additionally, compared to the base-line case, the system in this scenario achieves an improvement of 15% in environmental performance and 35% in economic performance. All of these results indicate that, although the performance of the centralized cogeneration systems in this scenario, which corresponds with low density suburban residential communities, is less than its performance in their high-density urban counterparts represented by the optimum design scenario, the use of cogeneration in these circumstances can still achieve relatively high reductions in primary energy use and CO_2 emissions while in the same time being economically feasible.

6.2.2.4 Parametric sensitivity analysis

Similar to the optimum design scenario, the sensitivity of the combined cogeneration system performance to variations in several parameters was evaluated. First, the sensitivity of the combined performance to increases in building envelope and systems' efficiencies was assessed and the results were almost identical to those in the case of the optimum design scenario and included a small increase in environmental performance combined with a slightly larger decrease in economic performance, both combining in a minimal negative impact on the system performance. In this case also, the small reduction in economic performance does not cause the IRR to drop significantly, and the resulting IRRs for system sizes up to 400 kW are larger than 10% (e.g. the IRR for the 400 kW system size is 10.2 %). Therefore, here too, it can be concluded that residential communities with energy efficiency standards exceeding code requirements are still suitable for the integration of centralized residential cogeneration systems even in densities as low as 4 du/ac.

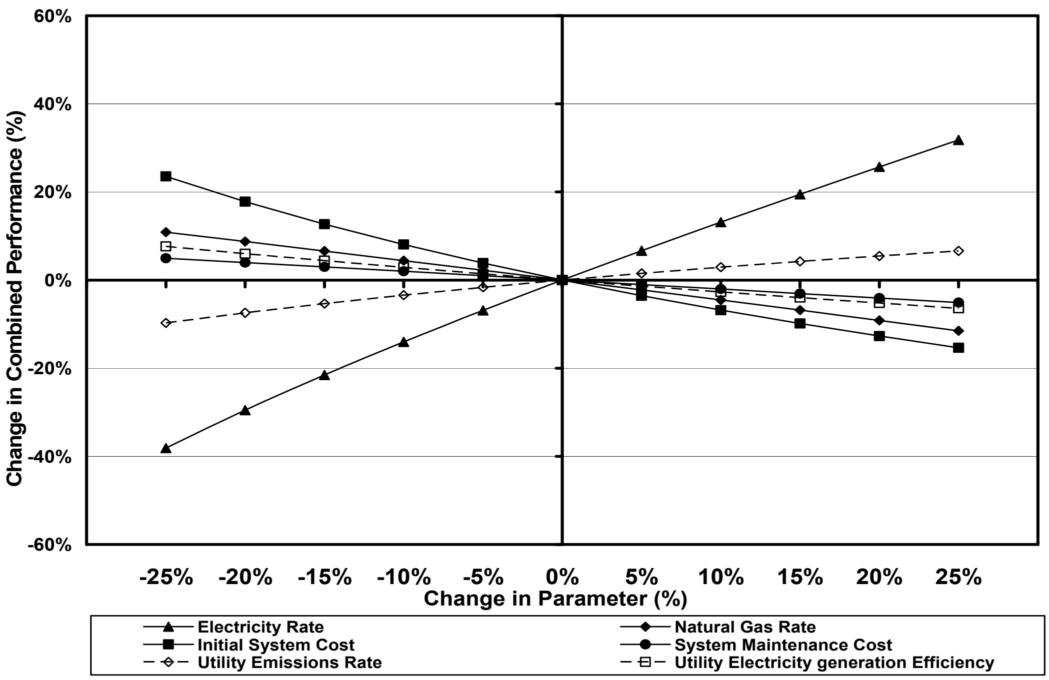


Figure 6-15 Sensitivity of Combined System Performance to Changes in Selected Parameters for Minimum Acceptable Design Scenario – Centralized Approach

Following this, the sensitivity of the combined system performance to variations in the same economic and environmental parameters evaluated in the previous scenario was investigated. The parameters evaluated included: electricity rate, natural gas rates, cogeneration system initial cost, annual maintenance cost, utility emissions rate, and utility electricity generation efficiency. The results of this analysis, shown in figure 6-15, indicate trends similar to those found in the optimum design scenario with changes in electricity rates having the most impact followed by changes in natural gas rates and with economic parameters having a higher impact than environmental ones. The magnitude of the impact is, however, smaller in this scenario than the previous one. For example, a ±25% change in electricity rates in this scenario resulted in a - 38% to + 32% change in combined system performance compared to a – 56% to + 39% change for the optimum design scenario. This is likely due to both the smaller system size in this scenario as well as to the fact that the improvement in economic performance in the optimum design scenario is related to the increased use of electricity, because of the high mix of uses, and therefore, the performance is more sensitive to changes in its rates.

6.3 DESIGN OPTIMIZATION – DECENTRALIZED APPROACH

6.3.1 Introduction

Contrary to the centralized approach, where identification of the optimum design characteristics showed a clear trend towards urban, high-density communities with high mix of uses; analyzing the impact of the design parameters on the cogeneration system performance for the decentralized approach, see section 5.4.4 & figure 5-62, showed different and potentially conflicting trends. While higher density also had a similar, though smaller, positive impact on the system performance as in the centralized approach, the only other design parameter having a positive impact was the use of alternative housing typology especially large detached single family houses, a typology associated mostly with lower density suburban communities. Also, the generally small magnitude in the improvements for the decentralized approach combined with the lower IRRs of the base-line case (7.2%) indicated that the critical part of the design optimization process for this approach would be achieving the identified minimum acceptable IRR of 10%. Therefore, instead of identifying an optimum design scenario and a minimum acceptable design scenario, as was the case in the centralized approach, the design optimization process for this approach aimed to explore both trends, high density urban and low-density suburban, and to identify the combination of design characteristics that would achieve the identified minimum acceptable IRR of 10% in each case.

6.3.2 High Density Scenario

In this scenario, the required economic performance was achieved through a combination of higher densities and a mix of housing typologies. A layout of the community is included in Appendix C, while descriptions of its design characteristics are summarized in table 6-2. The community included both detached and attached SFHs, however, the majority of the residential units were multifamily houses. This was because of the high targeted average density as well as the fact that micro-cogeneration systems in multi-family houses and attached SFHs achieve a relatively high IRR for smaller system sizes, and therefore can offset the lower IRRs of the micro-cogeneration systems in the detached SFHs. No town homes or live-work units were included. To select the optimum system size for each housing typology, a number of system sizes were tested for each typology as will be discussed in detail in section 6.3.4. The analysis resulted in selecting a 5.5 kW system for multifamily houses, a 1 kW system for the attached SFHs, and a 0.6 kW system for detached SFHs.

Table 6-2 Design Characteristics for the Two Optimization Scenarios – Decentralized Approach

Design parameter	High density scenario	Low density scenario
Planning parameters		
Density of built form	Density gradient from 4 du/ac to 20 du/ac – average density of 10 du/ac	Density gradient from 2 du/ac to 6 du/ac – average density of 4 du/ac
Mix of uses	Single use - residential	Single use - residential
Street configuration	Interconnected/grid.	Interconnected/grid.
Architectural parameters		
Housing typology	48 detached SFH, 60 attached SFH, 192 multi-family houses.	64 detached SFH – large, 100 detached SFH, 100 attached SFH, 36 multi-family houses
Envelope and building systems efficiencies	Base-line (compliant with IECC 2003).	Base-line (compliant with IECC 2003).
Utilization of renewable energy	Base-line value	Base-line value
Cogeneration system Parameters		
Cogeneration system type	Reciprocating engine based system.	Reciprocating engine based system.
Cogeneration system size	Detached single family: 0.6 kW Attached single family: 1.0 kW Multi-family house: 5.5 kW	Detached single family: 0.6 kW large detached SFH: 0.6 kW Attached single family: 1.0 kW Multi-family house: 5.5 kW
Operation strategy	Electrical load-matching	Electrical load-matching

6.3.3 Low-Density Scenario

In this scenario, the required economic performance was achieved primarily through the mixing of housing typologies achieving a high IRR, i.e. large SFHs, attached SFHs, and a small number of multi-family houses, with the base line detached SFHs to offset their lower IRR. A layout of the community is included in Appendix C while descriptions of its design characteristics are summarized in table 6-2. The same micro-cogeneration system sizes used for the high-density scenario were also used for this scenario. These included a 5.5 kW for multifamily houses, a 1 kW for the attached single family houses, and a 0.6 kW for detached single family houses (both average and large sizes).

6.3.4 Cogeneration System Performance

The performance of the decentralized cogeneration systems for both scenarios was evaluated by first assessing the performance of individual micro-cogeneration systems in each of the housing typologies taking into consideration the effect of external shading on the annual energy use. To determine the optimal system size for the attached SFH and the multi-family house typologies, a sensitivity analysis was conducted in which several system sizes were evaluated. Similar to the performance of micro-cogeneration systems in detached SFHs (the base-line case), the IRR of the micro-cogeneration systems in both alternative typologies decreased significantly with small increases in system size. The selected 5.5 kW system size for the multi-family housing resulted in an IRR of 9.95% and a reduction in CO_2 emissions of 32%; while the 1 kW system size selected for the attached SFHs resulted in an IRR of 15% and a reduction in CO_2 emissions of 22%. While this IRR is higher than the minimum required IRR of 10%, a small increase in the system size to 1.2 kW resulted in significant drop in IRR to 9%, and was therefore unsuitable.

To assess the overall performance of the micro-cogeneration systems within the community, the total reduction in primary energy use and CO_2 emissions for the whole community was calculated by adding the reductions in each building. In the case of economic performance, the overall IRR was calculated by adding the total costs and revenues for all buildings and calculating the resulting IRR. The performance of the decentralized systems for both scenarios is shown in figures 6-16 through 6-19. Figure 6-16 shows the magnitude and percentage of reduction in primary energy use due to the use of the cogeneration system; figure 6-17 shows the same information with regard to reduction in CO_2 emissions; figure 6-18 shows the resulting IRRs for the two approaches; and figure 6-19 shows the combined system performances for each scenario relative to the base-line case.

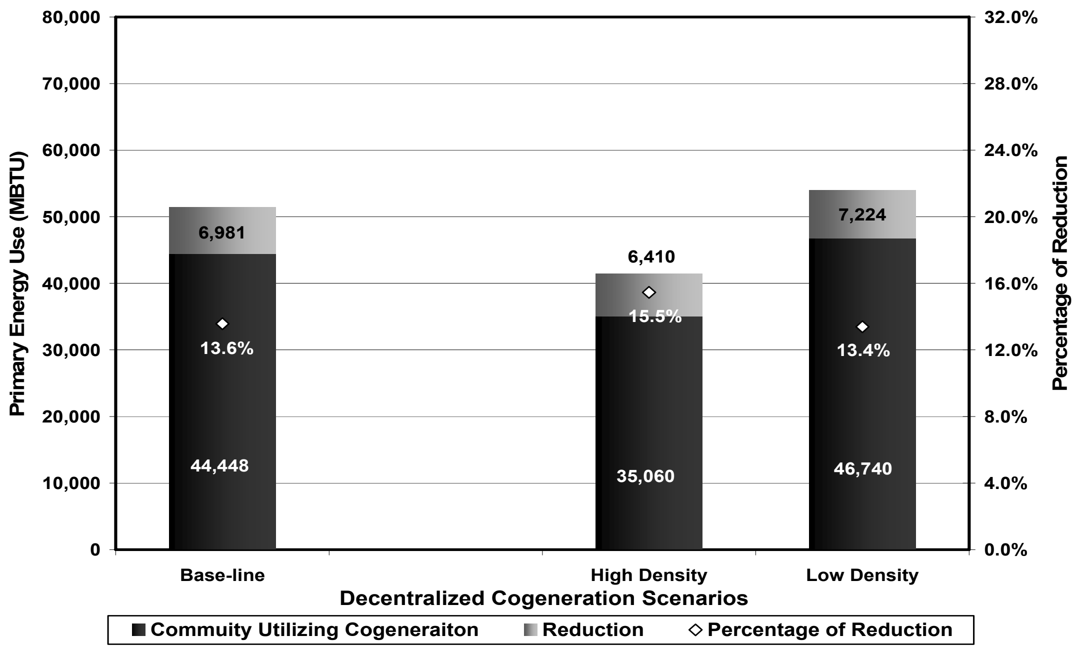


Figure 6-16 Magnitude and Percentage of Reduction in Primary Energy Use for High and Low-Density Scenarios – Decentralized Approach

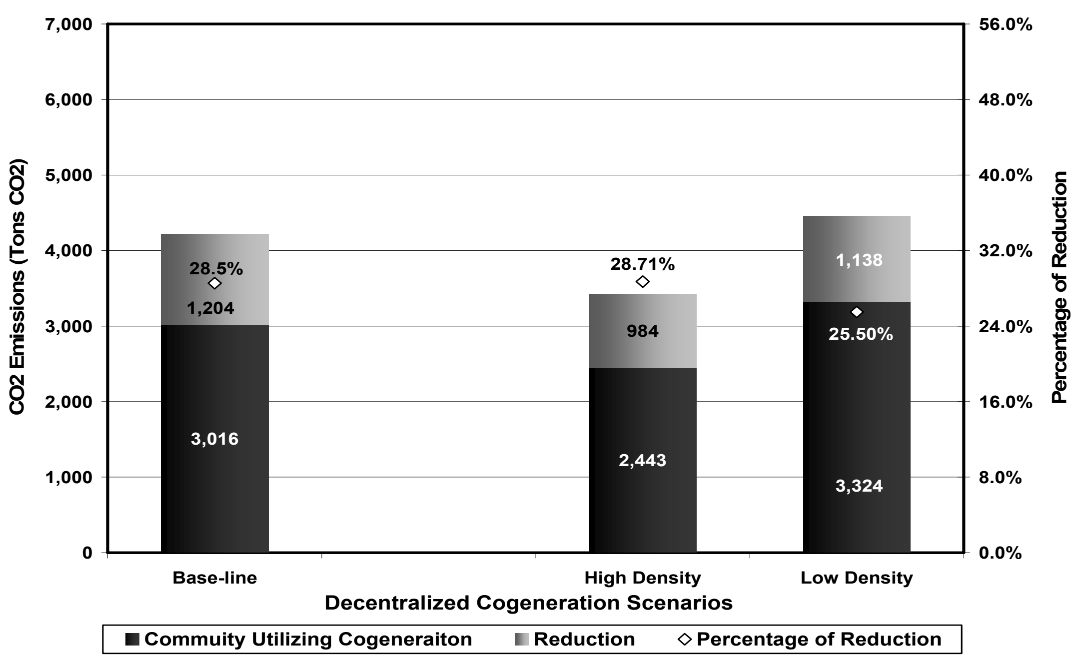


Figure 6-17 Magnitude and Percentage of Reduction in CO_2 Emissions for High and Low-Density Scenarios – Decentralized Approach

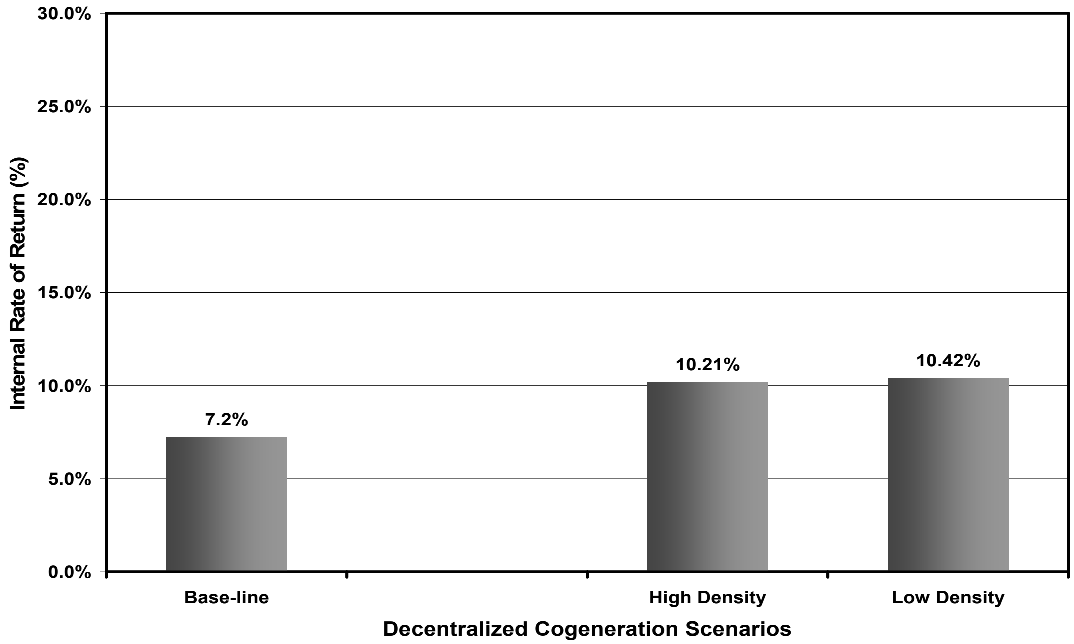


Figure 6-18 Internal Rate of Return for Cogeneration System for High and Low Density Scenarios – Decentralized Approach

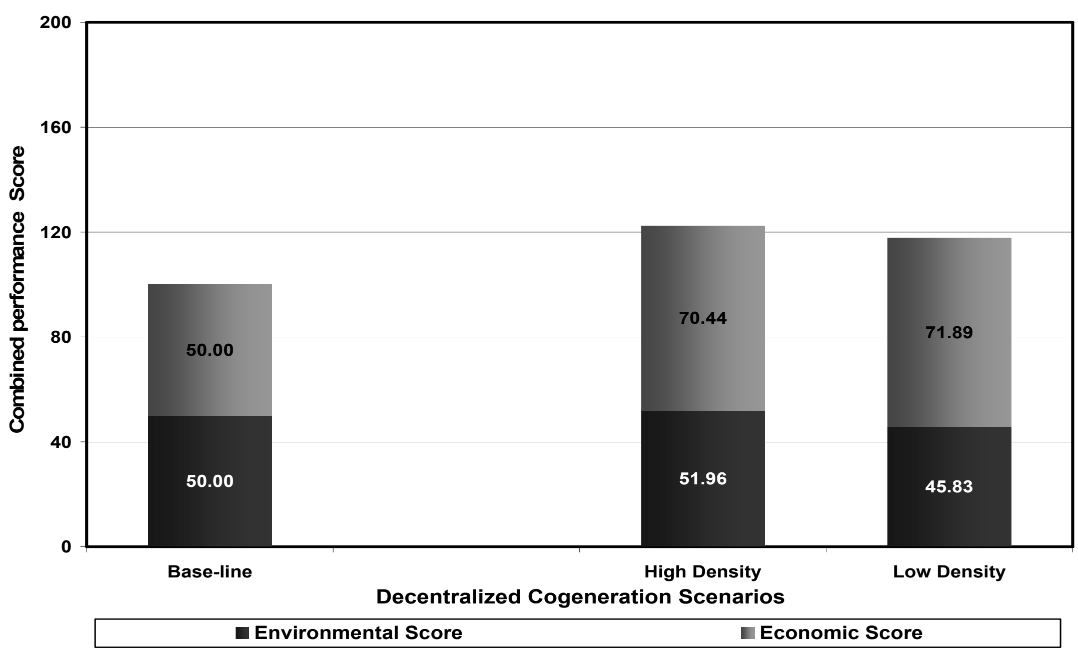


Figure 6-19 Combined Cogeneration System Performance for High and Low Density Scenarios – Decentralized Approach

The figures show that, for both the high and low-density scenarios, the average IRR for all buildings within the community exceeded the identified minimum IRR of 10% (10.2% and 10.4% respectively), thus indicating the economic feasibility of the projects. However, the high density scenario was more successful with regard to environmental performance achieving a reduction in primary energy use of 15.5% and a reduction in CO_2 emissions of 28.7% thus resulting in a small improvement, of less than 5%, in environmental performance compared to the base-line case. The cogeneration system in the low-density scenario, on the other hand, was less successful achieving only 13.4% reduction in primary energy use and 25.5% reduction in CO_2 emissions, thus resulting in a reduction of approximately 8% in environmental performance compared to the base-line case. The combined performance for both scenarios, however, showed a clear improvement due to the improvement in economic performance.

The results of the assessment indicate that, while decentralized cogeneration systems are not economically feasible in all housing typologies under current circumstances, they can be economically feasible on the level of the overall community if suitable mixes of housing typologies were identified. The mixes of housing typologies used in this assessment are, however, not the only combinations that would produce such a result and other mixes are possible that combine typologies achieving a high IRR with ones achieving a lower IRR. For individual typologies, micro-cogeneration systems in multi-family houses and in attached SFHs, are shown to be economically feasible and result in high reductions in energy use and emissions. Finally, the use of micro-cogeneration in high density residential communities results in higher percentages of reductions in energy use and emissions than low-density ones.

6.3.5. Parametric Sensitivity Analysis

Similar assessments of the sensitivity of the combined system performance to variations in selected economic and environmental parameters were investigated for both the high density and the low density scenarios. The parameters evaluated included: electricity rate, natural gas rates, cogeneration system initial cost, maintenance cost, utility emissions rate, and utility electricity generation efficiency. The results of this analysis are shown in figures 6-20 & 6-21. The figures show similar trends as those found for the centralized approach with changes in electricity rates having the most impact followed by changes in natural gas rates. The low density scenario is, however, more sensitive to changes in electricity rates and especially to reductions in these rates which result in a reduction of 76% in combined performance.

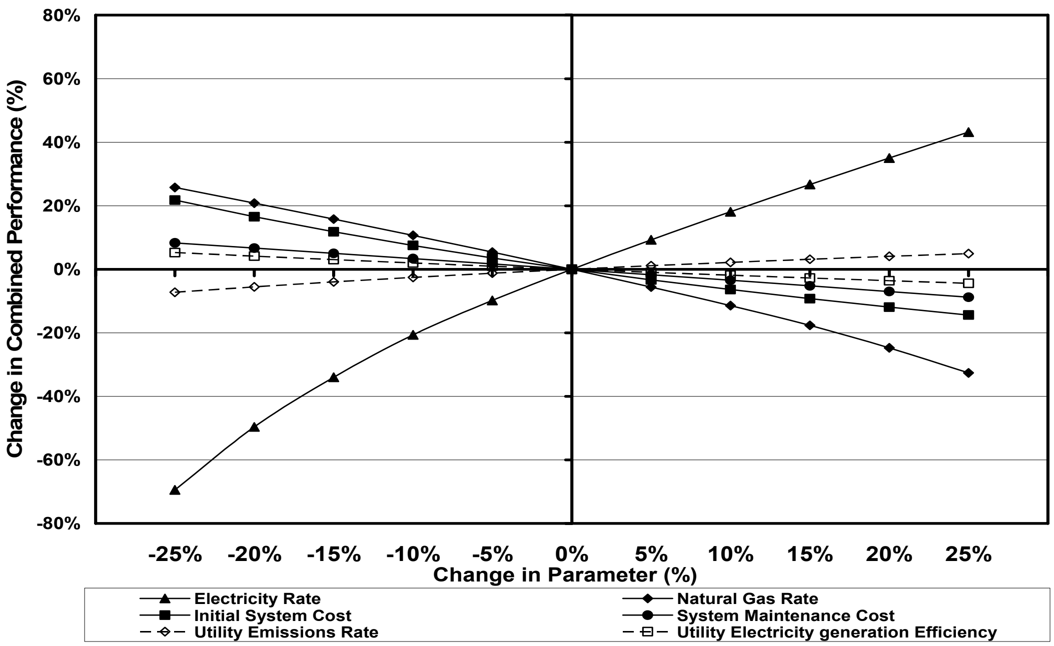


Figure 6-20 Sensitivity of Combined System Performance to Changes in Selected Parameters for High-Density Scenario – Decentralized Approach

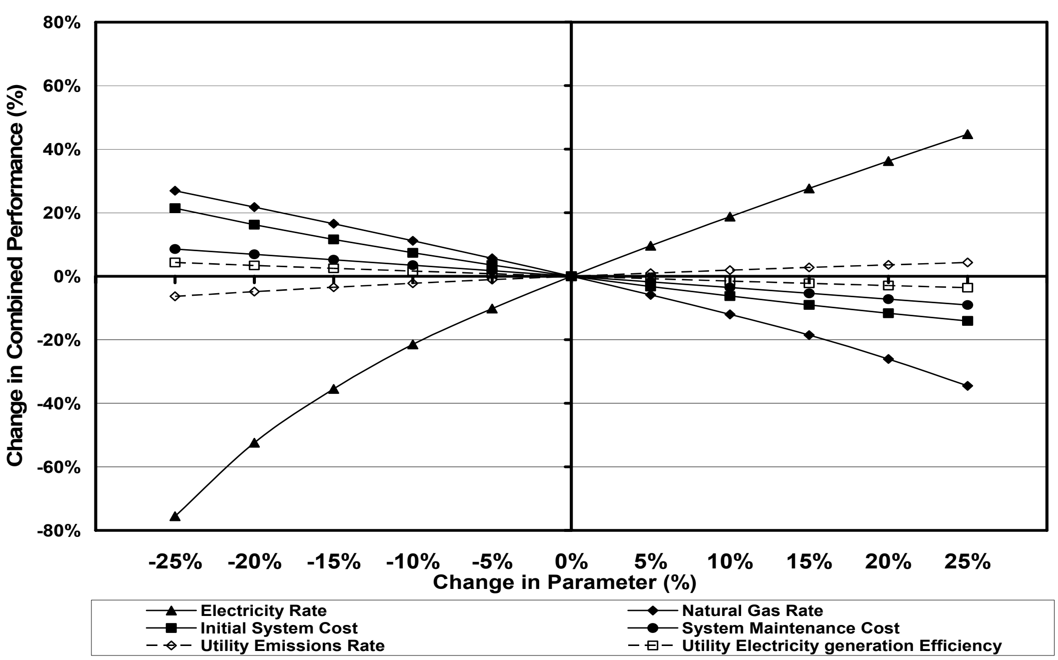


Figure 6-21 Sensitivity of Combined System Performance to Changes in Selected Parameters for Low-Density Scenario – Decentralized Approach

6.4 CENTRALIZED VS. DECENTRALIZED INTEGRATION APPROACHES

In sections 6-2 & 6-3, two optimization scenarios were evaluated for each of the two cogeneration approaches. Figure 6-22 shows the resulting combined performance of the cogeneration systems in each of the four scenarios compared to the base-line case in both approaches. Comparing the centralized and decentralized approaches shows that both optimization scenarios of the centralized approach achieve higher economic and environmental performances than their counterparts in the decentralized one, and that the optimized design scenario of the centralized approach, representing high-density communities, achieves the best performance. Additionally, high-density design optimization scenarios for both approaches perform better than their low-density counterparts achieving both adequate economic performances and significant reductions in primary energy use (18% and 15.5%) and in CO_2 emissions (42.8% and 28.7%) indicating a higher potential for cogeneration systems in high-density urban locations than in low-density suburban ones. However, cogeneration systems in low-density communities, while resulting in lower performances, still achieve adequate economic performance (an IRR equal to or higher than 10%) and reductions in CO_2 emissions of 36.5%, for the centralized approach, and 25.5%, for the decentralized one, thus indicating their feasibility and potentially high environmental benefits in these locations as well.

6.5 SUMMARY

In this chapter, the assessment of the impact of each community design parameter on the cogeneration system performance was used to identify the combination of community design characteristics that would achieve optimum and minimum acceptable cogeneration system performance for both the centralized and the decentralized integration approaches. For each approach, two design optimization scenarios were developed. For the centralized approach, the first scenario represented the design characteristics achieving the optimum system performance, while the second represented those characteristics achieving a minimum acceptable system performance. For the decentralized approach, on the other hand, the scenarios represented the design characteristics achieving a minimum acceptable performance in both high-density and low-density locations. For each of the four scenarios, the chapter included a description of its corresponding community design characteristics, an assessment of the resulting environmental and economic performance of the cogeneration system, and an analysis of the sensitivity of this performance to changes in several economic and environmental parameters.

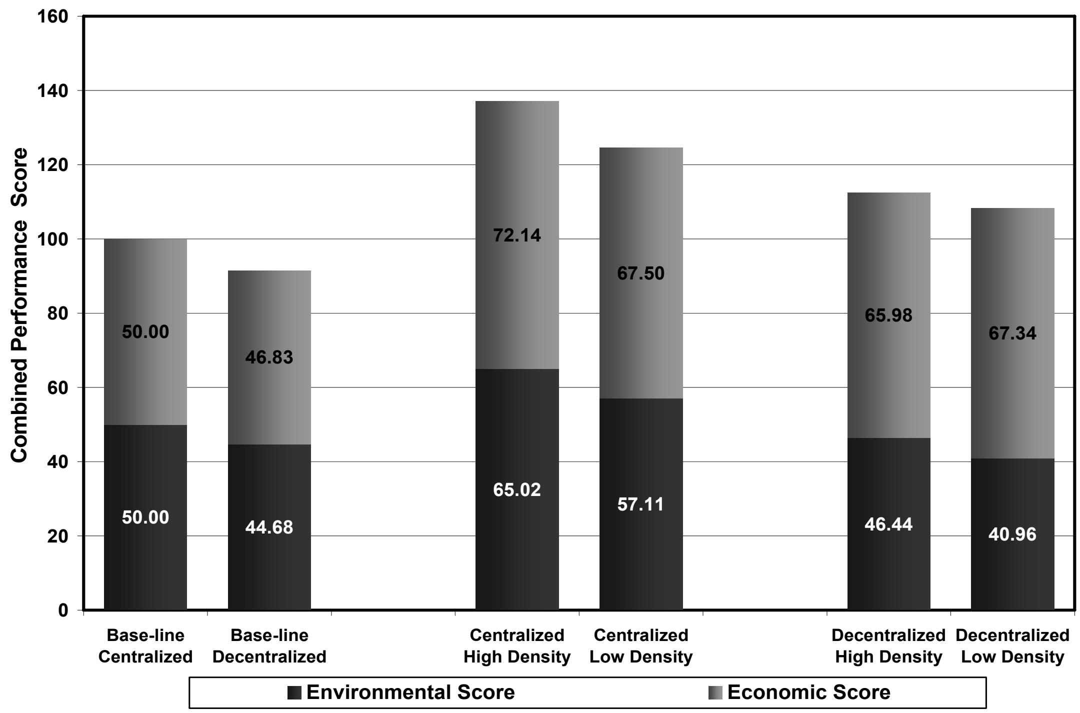


Figure 6-22 Combined System Performance for the Four Design Optimization Scenarios, Centralized and Decentralized Approaches, Compared to Base-Line Cases

For the centralized approach, the cogeneration system in the optimized design scenario, whose primary design characteristics were high density, high mixing of uses, and a mixing of housing typologies; achieved considerably high reductions in annual community primary energy use and CO_2 emissions (18% and 42% respectively) combined with a good internal rate of return of 11.2%. In the minimum acceptable design scenario, which represented residential communities in low-density suburban areas, the cogeneration system achieved lower, though still significant, reductions in energy use and emissions (17.3% and 36.5% respectively) also combined with an acceptable IRR of 10.4%. For the decentralized approach, while both optimization scenarios, achieved lower reductions in energy use and emissions than the centralized one, the resulting reductions were still high (15.5% & 13.4% for energy use, and 28.7% & 25.5% for CO_2 emissions. An acceptable IRR (above 10%) was also achieved in both scenarios. All four scenarios achieved noticeable improvements in environmental and economic performances compared to the base-line cogeneration system performance.

Based on this, it can be concluded that the centralized approach achieves a better environmental and economic performances for both high and low-density locations. The centralized approach, however, is more suitable for communities with a certain level of mixes of uses. The decentralized approach, on the other hand, while achieving lower performances, is still economically feasible provided that a suitable mix of housing typologies is achieved, and as it does not benefit from mixing of uses, it can be suitable for single-use residential communities. Both approaches achieved better performances in higher density residential communities, suggesting that such communities can represent the most suitable market entry point for these emerging technologies. Decreases in residential energy use resulting from increases in envelope and system efficiencies from code requirements resulted in a small drop in the performance of the cogeneration system. However, this drop was very small and therefore, communities with these design characteristics are still suitable for the integration of cogeneration systems and would result in a lower magnitude of the community's energy use and emissions.

Sensitivity analyses showed that the performance of the cogeneration system, in both approaches, improves significantly with increases in electricity rates and declines even more significantly with decreases in these rates. A reverse, and smaller, impact results from changes in natural gas rates. Such high sensitivity of the cogeneration system performance to energy rates is typical and must be taken into consideration when applying the results of this study to any locations with different energy rates. Changes in the other parameters investigated, including system cogeneration system capital and maintenance cost, utility electricity generation efficiency and emissions rates, had smaller impacts on the performance of the cogeneration system.

In conclusions, this chapter demonstrated the economic feasibility and potential significant environmental benefits that could result from the integration of cogeneration systems in residential communities in general and those with favorable design characteristics such as high density, high mix of uses, interconnected street configurations, and mix of housing typologies, in particular. The chapter also established that, under the current performance and economic characteristics of the cogeneration systems suitable for both the centralized and decentralized approaches, the centralized cogeneration approach achieves a better performance.

CHAPTER VII
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 INTRODUCTION

This chapter presents a summary of the study, including a summary of its objectives, methodology, and an overview of its main findings. Following this, the conclusions of the study are presented focusing on two main issues: the first is a discussion of the impact of the optimization of community design characteristics on the performance of residential cogeneration systems, while the second is a discussion of the potential for cogeneration systems in U.S. residential communities, in light of the findings of this study, and an identification of possible market entry points for these emergent technologies. The two cogeneration integration approaches are then discussed and contrasted. Finally, several recommendations are presented for future research directions that aim to either address the identified limitations of this study or to build on its findings.

7.2 SUMMARY OF STUDY

7.2.1 Summary of Study Objectives

This study aimed to investigate how selected community design parameters, on the planning, architecture, and cogeneration system scales, can impact the environmental and economic performance of cogeneration systems integrated into residential communities in cold climates following either a centralized or a decentralized integration approach. This investigation was performed as a basis for identifying the combination of design characteristics that would achieve an optimum system performance for each approach. To achieve this, the study aimed to identify the key community design parameters on the three identified scales; determine the impact of each design parameters on the environmental and economic performance of the cogeneration system; utilize these individual impacts in identifying optimization scenarios for each integration approach; determine the potential environmental and economic benefits resulting from the use of residential cogeneration systems in each scenario; and finally, compare the two integration approaches form the point of view of their current economic feasibility and potential environmental benefits.

7.2.2 Summary of Methodology

To achieve its objectives, the study followed a mixed research design model composed of two phases: the first was a qualitative phase, in which studies of sustainable residential community design as well as three selected case studies of sustainable residential communities in the U.S. and Europe were analyzed as a means of identifying the key community design parameters on the planning, architecture, and cogeneration system scales; while the dominant second phase was a quantitative one, in which building energy simulation and cogeneration system performance simulation tools were utilized to investigate the impact of the selected design parameters on the performance of the cogeneration systems and subsequently to optimize the design the residential community to improve the performance of the system.

Procedures for assessing the impact of the selected design parameters on the cogeneration system performance included developing a base-line model representing the typical design characteristics of U.S. residential communities. Then, the cogeneration system performance within this base-line community was assessed, for each integration approach, using three performance indicators: the reduction in annual community primary energy use due to the use of cogeneration, the subsequent reduction in annual community CO_2 emissions; and the internal rate of return. The impact of each design parameter on the performance of the cogeneration system was then assessed through developing 46 design variations of the base-line residential community model representing selected assessment values for each design parameter. The same three environmental and economic performance indicators were then assessed for each of these design variations and a multi-attribute decision analysis methodology was used to calculate the environmental, economic, and combined performances of the cogeneration system in each of these design variations relative to its performance within the base-line community. These results were then used to evaluate the relative impact of each of the design parameters on the cogeneration system performance.

Finally, for each integration approach, two design optimization scenarios were developed. For the centralized integration approach, the first scenario included the design characteristics achieving the optimum cogeneration system performance, while the second scenario included the design characteristics achieving a minimum acceptable system performance. For the decentralized approach, both scenarios represented combinations of design characteristics achieving a minimum acceptable system performance for a high-density and a low-density residential community. In each case, the minimum acceptable system performance was based on economic feasibility and defined as the combination of design characteristics resulting in an internal rate of return of at least 10% for the cogeneration system.

7.2.3 Summary of Findings

7.2.3.1 Community design parameters

Based on the analysis of relevant literature and the three selected case studies, the following community design parameters were selected for investigation: 1) density of urban form, 2) mix of uses, and 3) street configuration, on the planning scale; 4) housing typology, 5) envelope and building systems' efficiencies, and 6) utilization of renewable energy resources, on the architecture scale; and 7) cogeneration system type, 8) system size, and 9) operation strategy, on the cogeneration system scale. For the planning scale, the selected parameters were identified as being important to describe a residential community's development patterns, while in the same time having considerable influence on its sustainability and on the performance of the cogeneration system within it. For the architecture scale, mixing of housing typologies was also identified as being influential on the energy consumption, social sustainability, and economic vitality of a residential community; while the other two parameters represented two different approaches of reducing the energy consumption of a residential community either through increased efficiencies of building systems or through increasing the utilization of renewable energy resources. Finally, on the cogeneration system scale, the selected parameters represented issues typically considered in initial cogeneration systems' feasibility studies.

7.2.3.2 Impact of community design parameters

Assessing the impact of the selected design parameters on the cogeneration system performance revealed a number of significant findings. For the centralized cogeneration approach, variations in density and mix of uses clearly had the most impact on the system performance each resulting in up to 50% improvement in combined performance. First, a direct relationship was found between increasing the mixing of non-residential uses within residential communities and improvements in the cogeneration system performance. Out of all the design parameters investigated within this study, increasing the mix of uses resulted in the most improvements in the cogeneration system's economic performance (up to 125%) and its combined performance (up to 53%). These significant improvements are primarily due to the improved daily electric and thermal load profiles of the community through increasing the availability of day-time and all-night loads to balance the morning and evening loads typical of residential communities. The largest increase in economic performance was achieved through providing a high level of use mix combined with an optimization of non-residential building typologies within the community. While increasing the mix of uses resulted in some reduction in environmental performance (up to 20% for the optimized use mix alternative), the considerable increase in economic and combined performances indicate the potential for using larger cogeneration system sizes which would improve this environmental performance while still achieving an acceptable economic one. Based on the optimization process, the largest improvements in system performance were achieved by: first, providing day-time electrical loads from commercial building types such as retail, and office buildings; second, providing day-time non-seasonal thermal loads through the use of fast food and sit-down restaurants and a laundry, which increase the utilization of the thermal output of the cogeneration system in the day time; and third, providing all-night electrical and thermal loads through the use of a grocery and a bakery with 24 hour working schedules.

Similarly, increases in density were shown to have a significant positive impact on the system performance especially with regard to improving its economic performance resulting in up to 84% increase in IRR. This positive economic impact was primarily caused by reductions in the initial cost of the district heating network in the higher density design alternatives. Additional, though much smaller, environmental improvements were also achieved with higher densities primarily due to the reduced thermal energy losses in the same network. Based on these results, a density of 8 du/ac would result in the minimum acceptable IRR of approximately 10%. This positive impact of higher density on system performance, however, is reduced as the community density increases. Finally, a density gradient was found to result in a cogeneration system performance comparable to one with the average density of this gradient.

For other design parameters, several alternative housing typologies also resulted in improved cogeneration system performance the most notable of which are multi-family houses and live-work units. Multi-family houses performed the best resulting in an improvement in environmental performance of 24%, a smaller improvement in economics of 6%, both resulting in a 15% increase in combined performance. While live-work units resulted in larger economic improvements (46%) combined by a 26% drop in environmental performance, thus resulting in an improvement of only 10% in combined performance. However, both of these typologies were evaluated with the base-line density of 4 du/ac, which is lower than the densities typically found for them. This indicates a clear potential for further performance improvements under actual conditions. The SFH size had a varied impact on the system performance with large sizes resulting in better economics and smaller sizes resulting in better environmental performance. However, both impacts were not significant (within 10%) and the resulting combined performance for both sizes showed no noticeable change from the base-line.

With regard to street configuration, the base-line interconnected configuration resulted in the best performance especially with regard to economics because of the impact of the increased network lengths in the other configuration alternatives. On the other hand, increases in either envelope and building systems' efficiencies or the utilization of renewable energy within the buildings of the community resulted in a reduction in economic performance due to the reduced availability of thermal loads and the subsequent increasing mismatch between the fuel to electricity ratio of the buildings and the heat to power ratio of the reciprocating engine based cogeneration system used in assessment.

Finally, with regard to cogeneration system parameters, reciprocating engines achieved the best combined performance for a 250 kW system size. While fuel cells achieved a much better environmental performance especially for large system sizes, their high costs gave the overall advantage to reciprocating engines. Expected future decreases in these costs, however, would clearly make fuel cells the preferred option especially as their heat to power ratio is more favorable to that of residential communities especially the more energy efficient ones. Electric load matching strategy was also showed to result in a better performance than net-metering.

For the decentralized approach, the selected design parameters generally had a similar, though smaller, impact on the cogeneration system performance. As the mixing of uses does not impact the performance of building integrated micro-cogeneration systems and was therefore not investigated, density emerged as the most influential design parameter followed by housing typology. Increases in density resulted in improvements of up to 22% in combined performance and up to 38% in economic performance relative to the base-line case. However, the resulting IRRs were generally low and only at the highest density of 15 du/ac was an acceptable IRR of 10% achieved. With regard to housing typology, and assuming a single cogeneration system serving multiple residential units, only attached single family houses performed better than the base-line case achieving a 16% improvement in combined performance. Multi-family houses, however, resulted in a considerable, 28%, improvement in environmental performance. Also, increasing the single family house size resulted in a large improvement in economic performance of 36% clearly outweighing the 14% drop in environmental performance, thus making larger sized SFHs more favorable for micro-cogeneration systems. This was due to the increased availability of heating loads which allow for the better utilization of the cogeneration systems.

With regard to cogeneration system parameters, reciprocating engines also achieved better economic and overall system performances while fuel cells had a clear advantage with regard to environmental performance. Additionally, for the base-line case only very small IC engines (less than 0.75 kW) achieved a positive IRR. In general, the economic performance of micro-cogeneration systems was both low and highly sensitive to changes in system size with very small changes in size resulting in significant changes in IRR. However, this high sensitivity indicated the potential for improving the economic performance of the micro-cogeneration systems in alternative housing typologies, such as multi-family housing, while maintaining a good environmental performance, by using a smaller system sizes. Finally, electric load-matching was also found to be the best operation strategy with regard to combined system performance.

7.2.3.3 Community design optimization

For each of the two integration approaches, two design optimization scenarios were developed. For the centralized approach, the first scenario, optimum design, represented the combination of design characteristics achieving the optimum cogeneration system performance. This scenario was characterized by high average density (10 du/ac), high mix of uses, interconnected street network, and a mix of housing typologies. No increase in envelope and system efficiencies or in the utilization of renewable energy, from their base-line values, was assumed. The scenario utilized a reciprocating engine cogeneration system with an electrical load matching operation strategy. An assessment of the performance of several cogeneration system sizes indicated that the 500 kW system size achieved the best environmental performance combined with an acceptable economic performance (an IRR above 10%). This system resulted in a reduction of 18% in annual primary energy use and 42.3% in annual CO_2 emissions combined with an IRR of 11.2%.

The second scenario for the centralized approach represented situations in which high density and high mix of uses, the most influential design parameters, can not be achieved.

Therefore, the purpose of the scenario was to identify the combination of design characteristics that would achieve the minimum acceptable economic performance under these circumstances. This scenario was characterized by an average density of 4 du/ac, a low mix of uses, a mix of housing typologies, suitable for low-densities, and an interconnected street configuration. No increases in envelop and building systems' efficiencies or in the utilization of renewable energy resources, from their base-line values, was included; and the cogeneration system characteristics were similar to the first scenario. The optimum system size for this scenario was 400 kW. This system size achieved smaller, though still significant, reductions in primary energy use (17.3%) and CO_2 emissions (36.5%), and also achieved an acceptable IRR of 10.4%. An investigation of the impact of increasing envelope and system efficiencies on the cogeneration system performance, for both scenarios, indicated that this increase resulted in small increases in the environmental performance combined with a slightly larger decrease in economic performance. These two impacts add into a minimal reduction in combined performance, which does not reduce the potential of using cogeneration systems in low-energy residential communities.

An analysis of the seasonal and annual community energy use profiles as well as the cogeneration system output for both scenarios compared to their base-line values showed that the optimization process did result in improvements in the community's energy use profiles. These improvements were more significant for the optimum design scenario and included clear reductions in the daily variations in electricity use as well as more than 30% reductions in the peak thermal energy use. Subsequently, the cogeneration system in this scenario was successful in meeting 87.4% of the electrical needs of the community as well as %80.3 of its thermal needs. However, the system also resulted in considerable excess thermal energy for most of the year peaking in summer months at an average 1.75 MBtu/hr), thus indicating a potential for the use of thermally activated cooling technologies or for the utilization of this excess energy in other thermal end uses inside or outside the community. The minimum acceptable design scenario did not result in the same level of improvement in energy use profiles although its electric use profiles did show some improvements. Daily variations in thermal energy use were, however, larger in this scenario thus indicating a higher potential for thermal storage. The system in this scenario was less successful in meeting the community's energy needs meeting only 76.8% of the electrical needs and 54.3% of the thermal needs. However, the systems' thermal output was more utilized in this scenario resulting in less excess thermal energy (a maximum of approximately 0.95 MBtu/hr in summer months). While both thermally activated cooling technologies and thermal storage were not investigated within this study, they both represent clear directions for further research as well be discussed in section 7-4.

For the decentralized approach, as assessing the impacts of individual parameters showed that achieving an acceptable IRR was a critical issue for most design alternatives, the optimization scenarios explored the possibility of achieving this acceptable IRR in both high and low-density situations and the resulting environmental benefits in each. The high density scenario had an average density of 10 du/ac and a mix of housing typologies including a high percentage of multi-family housing; while the low-density one had an average density of 4 du/ac and a mix of housing typologies with a high percentage of large detached and attached SFHs. In both cases, no increase in envelope and building systems' efficiencies or utilization of renewable energy was assumed. Reciprocating engine based cogeneration systems using an electric load matching strategy were used in both scenarios. A sensitivity analysis was conducted for each housing typology to determine the optimum system size. Both high and low density scenarios achieved an acceptable IRR (10.2% and 10.4% respectively); however, they both resulted in lower reductions in energy use and emissions than the centralized approach. The high-density scenario performed better resulting in a reduction in primary energy use of 15.5% and in CO_2 emissions of 28.7%. Compared to that, the low-density scenario resulted in reductions of 13.4% in primary energy use and 25.5% in CO_2 emissions.

An analysis of the sensitivity of the cogeneration system performance, in each of the four optimization scenarios, to changes in a number of environmental and economic parameters including: electricity rate, natural gas rate, cogeneration system initial and maintenance costs, utility electricity generation efficiency, and utility CO_2 emissions rate showed that changes in electricity rate had the most impact on the performance of the cogeneration system, followed by changes in the natural gas rate. From the four scenarios, the system performance in the decentralized low-density scenario was the most sensitive to changes in electricity rate with a 25% increase in electricity rate resulting in a 45% increase in performance, while a 25% decrease resulted in a 75% decrease in performance. Natural gas rates had an opposite impact with a 25% increase in rates, also for the low-density decentralized scenario, resulting in a 35% decrease in performance, while a 25% decrease in rates resulted in a 27% increase in performance. In general, the combined performance of the cogeneration system was more sensitive to economic parameters than to environmental ones in all four optimization scenarios.

7.3 CONCLUSIONS

This study represents an attempt to conduct a performance-based optimization of the design characteristics of residential communities that aims to improve the potential of using cogeneration systems in these communities thus achieving, and increasing, the environmental benefits that can result from it. The results of this study can be utilized in one of two methods. On the one hand, they can be used to inform designers of new residential communities aiming to integrate cogeneration systems in their designs of the most suitable cogeneration integration approaches for their project, the design parameters having the most impact on the cogeneration system performance, as well as the combinations of design characteristics achieving an optimum cogeneration system performance and those achieving a minimum acceptable one. On the other hand, the results can also be used to assess the potential for integrating cogeneration systems in residential communities with a certain set of design characteristics and therefore identify potential market entry point for these emergent technologies. The following sections summarize the major conclusions that were reached in each case.

7.3.1 Cogeneration and Community Design

1) The design of residential communities has a significant impact on the performance of cogeneration systems for both the centralized and decentralized approaches. Design optimization causes improvements in system performance as high as 200% for economic performance, and 40% for environmental performance. With regard to combined performance, design optimization can cause improvements of up to 119% for the centralized approach, although the improvements for the decentralized approach only reach approximately 22.5% mainly due to its lower economic performance compared to the centralized approach. These results indicate the significant role that designers of residential communities can play in increasing the potential for utilizing cogeneration in their communities through optimization of the community design.

2) Through community design optimization, existing cogeneration technologies, for both the centralized and decentralized approaches, can be both economically feasible and result in considerable reductions in both primary energy use and CO_2 emissions. Cogeneration systems investigated in this study resulted in up to 42.3% reduction in CO_2 emissions for the centralized approach and up to 28.7% for the decentralized one. Reductions in primary energy use were lower primarily due to the use of reciprocating engine based cogeneration systems which are characterized by low part-load performances. However, considerable reductions of up to 18%, for the decentralized approach, and up to 15.5%, for the decentralized one, were still achieved. All optimization scenarios investigated in this study resulted in an IRR higher than 10%.

3) The centralized cogeneration integration approach showed a larger potential for improvements through design optimization and resulted in larger environmental benefits. Both the optimum and minimum acceptable design scenarios for the centralized approach showed larger improvements in environmental, economic, and combined performances relative to the base-line case than their decentralized counterparts in. In combined performance, the two centralized scenarios resulted in 37% and 25% improvements in performance compared to 12.5% and 8.3% for the two decentralized ones. The magnitudes of reductions in primary energy use and CO_2 emissions were also larger for the centralized approach than the decentralized one as discussed in the previous point.

4) Planning parameters generally had a larger impact on cogeneration system performance than architectural parameters especially for the centralized approach. Increases in mix of uses and density resulted in the highest improvements in performance for the centralized approach, while density had the most impact on the decentralized one. With regard to architectural parameters, variations and mixing of housing typologies offered the most potential for system performance improvements in both approaches. For the decentralized approach, the mixing of housing typologies was the primary optimization tool in achieving an acceptable overall economic performance for the community through the balancing of housing typologies with good economic performances (e.g. large SFHs, multi-family houses, and attached SFHs), and the base-line SFH, which does not result in acceptable economics.

5) *Reciprocating engines, for both approaches, currently have a clear advantage over other available technologies mainly because of their lower costs*. However, the economic performance or reciprocating engine cogeneration systems is much more sensitive to increases in system size than their environmental performance. This outcome is even more pronounced in the case of the decentralized approach where minor changes in system size (less than 0.5 kW) can result in IRR changes of up to 5%. This is mainly due to the lower part load efficiencies of reciprocating engines, which impact negatively the environmental and, to a much larger extent, economic performance of large system sizes. This reduction in economic performance for large system sizes results in limiting the potential of using these large systems and achieving the

higher environmental benefits they have been shown to result in. A similar conclusion can be reached with regard to system operation strategy, where net metering offers a better potential for environmental benefits for larger system sizes yet its economics are adversely affected by the corresponding drop in economic performance. It should be noted, however, that the economic performance of net-metering strategies is also affected by high natural gas prices and would improve in locations where the ratio of electric rates to natural gas rates is higher. Based on the previous, it can be concluded that fuel cells, through their higher electrical efficiency and better part load performance, offers a considerably higher potential for large cogeneration system sizes in both approaches, provided that the expected future reductions in their initial and maintenance costs are achieved, thus making them economically competitive.

7.3.2 Cogeneration in U.S. Sustainable Residential Communities

1) A strong correlation exists between design characteristics identified as favorable for cogeneration system performance and the characteristics of sustainable residential communities. Design characteristics shown to be favorable to the performance of the cogeneration system included high density, high mix of use, interconnected street configurations, and mixing of housing typologies, all of which were shown by the analysis of the case studies and the literature to also be characteristics of sustainable residential communities. This indicates the higher potential for integrating cogeneration systems in sustainable residential communities compared to conventional ones.

2) The centralized approach is the preferred choice for integrating cogeneration systems in residential communities under current conditions especially in high-density, high mix of uses situations. Centralized cogeneration system resulted in higher environmental and economic performances in both high and low-density locations. However, design characteristics resulting in the most environmental benefits for this approach, high density and high use mix, are more typical of urban infill and redevelopment projects although they are also found in central areas of larger suburban projects. As the mixing of uses offers considerable potential for improvements in cogeneration system performance for the centralized approach, communities with this characteristic can be considered as its most suitable market.

3) The decentralized approach can be economically feasible and represents a suitable alterative for certain design situations where a centralized one is not possible. While the decentralized approach generally resulted in lower system performance, it has been shown to be economically feasible, for the overall community, provided that a suitable mix of housing typologies is used. As the performance of the decentralized approach is not affected by the lack of mixing of uses, this approach, therefore, presents a suitable alternative for communities having only residential uses. It can also offer a good alternative for communities with very low densities or with low-connectivity street configurations where the high cost of the district heating network makes the centralized approach economically unfeasible. The higher flexibility of the decentralized approach can also be an advantage in circumstances where a community electric cooperative and a district energy network are not possible. As the micro-cogeneration technologies of the decentralized approach are mostly still in the R&D or early commercialization stages, future improvements in efficiencies and, more importantly, in economics are possible. Such improvements can significantly increase the potential of using this approach compared to the centralized one.

4) Reductions in residential building energy use generally had a small negative impact on the cogeneration system performance. For both integration approaches, increases in both envelope and building systems' efficiencies or in the utilization of renewable energy resources generally had a negative impact on the cogeneration system economics that outweighed the corresponding increase in environmental performance. However, this impact was minimal for lower percentages of reductions in building energy consumption, and therefore communities with these levels of reduction still represent a suitable market for cogeneration and would result in lower magnitudes of primary energy use and CO_2 emissions. However, an obvious mismatch can be seen between the fuel to power ratio of energy efficient communities, in cold climates, and the heat to power ratio of existing reciprocating engine based cogeneration systems, which increases with higher levels of building energy efficiency. A cogeneration system with a more suitable heat to power ratio would be more effective in such circumstances. Fuel cells offer a clear potential in this regard provided that their economics are considerably improved.

7.3.3 Generalizability of Findings

The results of this study are based on a number of assumptions related to energy use patterns of residential communities, efficiencies and costs of cogeneration systems, as well as other external parameters such as energy rates and utility fuel mixes. While the study provides a suitable initial assessment of the potential for using cogeneration in various circumstances with a level of accuracy and detail appropriate for early design stages, the interpretation and/or generalization of the study results should take into consideration the complex and dynamic relationships between the different parameters involved in the study and the fact that the study assumptions were mostly derived from average or prevailing values of their respective parameters and that many of them can be impacted, sometimes significantly, by the local conditions of the residential community such as local climate, topography, social factors, etc.

For example, with regard to climate, the study was based on the U.S. cold-dry zone (zone 6B) (Briggs et al., 2003). The Helena, MT climate used in this study was identified by Briggs et al. as representative of this zone and as suitable for the development of performance based guidelines applicable to it. The results of the study are, therefore, only applicable to locations (or counties) with this climate including counties in the states of Colorado, Idaho, Montana, Utah, Washington, and Wyoming. Also, the base-line community model in the study is base on compliance with the requirements of the IECC 2003, and communities with lower energy efficiency standards can result in different cogeneration system performances.

The parametric sensitivity analyses conducted in chapter VI also indicate that the results of the study, especially with regard to economic performance, are significantly impacted by electricity rates and, to a lesser extent, by natural gas rates. While the study utilized average state-wide energy rates, these rates, and consequently the resulting economic performance, can vary significantly between utilities. These variations must be taken into consideration when applying the results of the study to specific locations. However, the sensitivity analyses conducted in the study can provide a general estimate of the expected change in performance due to changes in these rates. Generally, increases in electricity rates and/or reduction in natural gas rates will improve the performance of cogeneration systems and vice versa. The specific utility rate structure (i.e. service fees, demand rates, back-up rates, etc) should also be considered.

7.4 RECOMMENDATIONS & FUTURE RESEARCH

The complexity of the issues involved in this study, both with regard to the estimation of community energy use as well as the assessment of cogeneration system performance, resulted in a number of limitations for the study as discussed previously in section 1-5. These imitations, therefore, need to be addressed by future studies. Also, the study represented an exploration of the impact of a relatively large number of deign parameters on the performance of residential cogeneration systems, and therefore, a need exists for further and/or more detailed studies of several of these parameters as well as other issues identified by the study. The following represents a discussion of suggested future research direction to address both of these categories:

1) This study was limited to only one of the 17 U.S. climate zones included in the classification developed by Briggs et al. (2003a & b). As climate can significantly affect the energy use patterns of the residential community especially with regard to its fuel to electricity ratio, a more detailed study is required that investigates the impact of community design optimization on cogeneration system performance in each of these climate zones. Such a study would utilize the representative cities identified by Briggs et al. for each of these zones.

2) The assessment of environmental performance in this study was based on two major environmental indicators, primary energy use and CO_2 emissions. However, other environmental impacts can be significant or even critical in certain locations, e.g. localized increases in NOx emissions in locations with existing high level of these emissions. In such cases, a more comprehensive assessment of the environmental impact of the system would be required.

3) While this study assumed a fixed residential community size of 300 dwelling units, sizes of residential communities vary considerably. As this study indicated that the initial costs of the district heating network, which is proportional to the community size, significantly impacts the economics of centralized cogeneration system for a certain density, a more detailed study is required to investigate this relationship for various residential densities.

4) The assessment of community energy use in this study was based on assumptions of building systems and fuels (electric air conditioning and natural gas furnaces and domestic water heaters). While these assumptions represent the more common systems in residential buildings according to EIA and U.S. Census Bureau data, other combinations of buildings systems and fuels are also used in residential communities and the performance of cogeneration systems in these communities should also investigated.

5) While the study investigated the overall impact of combinations of energy efficiency measures (either with regard to building systems efficiencies or building form), more detailed analyses are required to investigate the impact of individual energy efficiency measures on system performance especially with regard to the impact of these individual measures on the fuel to electricity ratio of the building loads. Examples of such measures include increasing the

efficiency of each building system (air conditioning, furnaces, or domestic water heaters), changes in building form or percentage of glazing, increased lighting efficiencies, etc.

6) The study results showed a clear potential for micro-cogeneration technologies in housing typologies were the system serves multiple dwelling units compared to the case where it serves only one unit (i.e. detached single family homes). Therefore, a more detailed study is needed which investigates the optimum number of units to be served by a cogeneration system as well as the optimum size of a cogeneration system serving a certain number of units. In addition to the housing typologies investigated in this study, other potential typologies that can offer considerable potential for residential cogeneration systems on these bases include high-rise residential buildings and buildings with multiple uses (residential and commercial).

7) Because of the limitations of the simulation tool used to assess the performance of cogeneration systems in this study (HOMER), the impact of thermal storage on this performance could not be investigated for both the centralized and decentralized approaches. As thermal storage has been identified in previous studies as having a positive impact on the performance of cogeneration systems, especially in the case of micro-cogeneration technologies, an investigation of this impact is needed for the decentralized approach. The use of thermal storage in the centralized approach also represents a potential for improved system performance.

8) Similarly, only one cogeneration system configuration was investigated in this study, including a packaged cogeneration system (with a prime mover and a heat exchanger), grid-connection, and an auxiliary heater. Other configurations, identified in the previous studies, should be explored such as using cogeneration to meet hot water loads only, and the use Tri-generation (i.e. the production of electricity, heating, and cooling) either through the use of thermally activated cooling technologies such as absorption chillers, or the use of electric heat pumps to provide both heating and cooling. These configurations vary in potential according to the climate and the resulting characteristics of the community electrical and thermal loads.

9) This study was based on state-wide averages of energy prices. A more detailed economic study is required which investigates the impacts of various utility rate structures, such as demand rate, back-up rates, net-metering rates, time-of-use schedules, and service charges) on the economics of the cogeneration system. The study also does not addresses monthly variations in natural gas prices, an issue that also merits further investigation.

REFERENCES

Akbari, H.; Eto, J.; Konopacki, S.; Afzal, A.; Heinemeier,K.; and Rainer, L. (1993) *Integrated Estimation of Commercial Sector End Use Load Shapes and Energy Use Intensities in the PG&E Service Area*, Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

ANE (Al Nichols Engineering Inc.) (2003) *Energy Use in Civano and Tucson Residences*, Al Nichols Engineering Inc., Tucson, AZ.

ANE (Al Nichols Engineering Inc.) (2004) *Energy Use in Civano Residences - Prepared for the Community of Civano,* Al Nichols Engineering Inc., Tucson, AZ.

Anderson, J., Shiers; D, and Sinclair, M. (2000) *The Green Guide to Housing Specification: An Environmental Profiling System for Building Materials and Components*, Blackwell Science, Oxford, UK.

Anderson, R. (2003) Energy innovations in america's housing, U.S. DOE Building Technology Program, A Presentation in *the National Micro-CHP Technologies Roadmap Workshop*, 11-12 June, Greenbelt, MD [http://www.eere.energy.gov/der/micro_chp_workshop .html]

Anderson, R.; Christensen, C.; Horowitz, S.; Courtney, A.; Givler, T.; et al. (2004) *Analysis of System Strategies Targeting Near-Term Building America Energy-Performance Goals for New Single-Family Homes*, FY 2004 Fourth-Quarter Building America Milestone Report. Report number NREL/TP-550-36920, National Renewable Energy Laboratories, Golden, CO.

APA (American Planning Association) (1999) *Planning Communities for the 21st Century*, A Special Report of the American Planning Association's Growing Smart Project. The American Planning Association. [http://www.planning.org/growingsmart/pdf/planning communities21st.pdf].

ASHRAE (2000) *ASHRAE Handbook: HVAC Systems and Equipment*, American Society of Heating, Ventilation, and Air-Conditioning Engineers, Atlanta, GA.

ASHRAE (2003) *ASHRAE Handbook: HVAC Applications*, American Society of Heating, Ventilation, and Air-Conditioning Engineers, Atlanta, GA.

Avin, U. and Bayer, M. (2003) Right sizing urban growth boundaries. *Planning*, **69**(2), 22-27.

Ayres, J. M. and Stamper, E. (1995) Historical development of building energy calculations. *ASHRAE Journal*, **37**, 44-55.

Bailey, O.; Creighton, C.; Firestone, R.; Marnay, C.; and Stadler, M. (2003) *Distributed Energy Resources in Practice: A Case Study Analysis and Validation of LBNL's Customer Adoption Model*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Balcomb, J. D. & Beeler, G. (1998) Designing low-energy building with energy-10, *23rd National Passive Solar Conference*, June, American Solar Energy Society, Albuquerque, NM.

Barton, H. (ed.) (2000) *Sustainable Communities, The Potential for Eco-Neighborhoods*, Earth Scan Publications Limited, London, UK.

Barton, H.; Grant, M.; & Guise, R. (2003) *Shaping Neighborhoods, A Guide for Health, Sustainability and Vitality*, Spon Press, London, UK.

Baxter, G. R. (1997) Development and use of an interactive computer simulation for generalized technical and economic assessments of cogeneration systems. MS thesis, Texas A&M University, College Station, TX.

BCHP (2004) Cooling, Heating, and Power for Buildings Program, US Department of Energy [http://www.chpb.net/index.html].

Beasley, R.G. (1999) A methodology for baselining the energy use at large campus utility plants for the purpose of measuring energy savings from energy conservation retrofits. MS thesis, Texas A&M University, College Station, TX.

Beatley, T. (1995) Planning and sustainability, the elements of a new (improved?) paradigm. *Journal of Planning Literature,* **9**(4), 383-395.

BEQUEST (2004) BEQUEST Toolkit, European Commission Project for Building, Environmental Quality for Sustainability through Time [http://research.scpm.salford.ac.uk/bqtoolkit/index2.htm].

Berke, P. R. (2002) Does sustainable development offer a new direction for planning? Challenges for the twenty-first century. *Journal of Planning Literature*, **17**(1), 21-36.

Beyard, M. D.; O'Mara, W. P. et al. (1999) *Shopping Center Development Handbook,* 3rd Edn ULI-The Urban land Institute, Washington, DC.

BLAST Support Office (1992) *BLAST 3.0 Users Manual*, BLAST Support Office, University of Illinois, Department of Mechanical and Industrial Engineering, Urbana-Champaign, IL.

Boarnet, M. and Sarmiento, S. (1998) Can land-use policy really affect travel behavior? a study of the link between non-work travel and land-use characteristics. *Urban Studies,* **35**(7),1155-1169.

Borbely, A. M. and Kreider, J. F. (eds) (2001) *Distributed Generation, The Power Paradigm of the New Millennium*, CRS Press, Boca Raton, FL.

Braun, R.J.; Klien, S.A.; and Reindl, D.T. (2004) Considerations in the design and application of solid oxide fuel cell energy systems in residential markets. *ASHRAE Transactions,* **110**(1), 14-24.

Breheny, M. J. (ed.) (1992) *Sustainable Development and Urban Form*, European Research in Regional Science 2, Pion Limited, London.

Breheny, M. (1996) Centrists, decentrists and compromisers: views on the future of urban form, in M. Jenks, E. Burton, and K. Williams (eds): *The Compact City, a Sustainable Urban Form?*, E & FN Spon, London, pp. 13-35.

Briggs, R. S., Lucas, R. G., and Taylor, Z. T. (2003a) Climate classification for building energy codes and standards: Part 1: Development process. *ASHRAE Transactions*, **109**(1), 109-121.

Briggs, R. S., Lucas, R. G., and Taylor, Z. T. (2003b) Climate classification for building energy codes and standards: Part 2: Zone definitions, maps, and comparisons. *ASHRAE Transactions*, **109**(1), 122-130.

Burchell, R. et al. (2002) *The Costs of Sprawl – 2000,* National Academy Press, Washington, DC.

Calthorpe, P. (1993) *The Next American Metropolis, Ecology, Community and the American Dream*, Princeton Architectural Press, New York, NY.

Calthorpe, P. (1994) The region, in: P. Katz (ed.): *The New Urbanism: Toward an Architecture of Community*, McGraw-Hill, New York, NY.

Calthorpe, P. and Fulton, W. (2001) *The Regional City*, Island Press, Washington, DC.

Caton, J. (2003) *Cogeneration Systems*. Lecture notes, TAMU, College Station, TX.

CDA (Community Design Associates Inc.) (1998) *CIVANO, Neighborhood 1 Planned Area Development*, Revised 12 October 1998, Community Design Associates Inc., City of Tucson, Tucson, AZ.

Chambers, A.; Schnoor, B.; & Hamilton, S. (2001) *Distributed Generation, a Non-Technical Guide*, Penn Well Corporation, Tulsa, OK.

CIBSE (Chartered Institution of Building Services Engineers) (1998) *Energy Efficiency in Buildings*. CIBSE Guide, Chartered Institution of Building Services Engineers, Yale Press Ltd, London.

City of Hannover (2000) *Modell Kronsberg: Sustainable Building for the Future*, City of Hannover, Hannover, Germany.

City of Hannover (2004) *Hannover Kronsberg Handbook: Planning and Realisation*, City of Hannover, Hannover, Germany.

City of Tucson (2003) *City Of Tucson Guidelines for Developers and Builders*, *The Revised Impact System (Integrated Method of Performance And Cost Tracking),* City of Tucson, Tucson, AZ.

City of Tucson (2005) *CIVANO, Master Planned Area Development, District PAD's Include: Sierra Morado Pad Pavilions PAD Neighborhood 1 PAD*, City of Tucson, Tucson, AZ.

Clarke J. A. (2001) *Energy Simulation in Building Design*, Butterworth-Heinemann, Oxford, UK.

CNU (Congress for the New Urbanism) (2000) *Charter of the New Urbanism*, Congress for the New Urbanism, McGraw-Hill, New York.

Cole, R.J. (2004) Changing context for environmental knowledge. *Building Research & Information*, **32**(2), 91–109.

Cole, R.J. and Larsen, N. (2002) *GBTool User Manual*, Green Building Challenge 2002, NRCan (Natural Resources Canada), Ottawa, ON.

Cooper, I. (2002) Transgressing discipline boundaries: is BEQUEST an example of 'the new production of knowledge'? *Building Research & Information,* **30**(2), 116–129.

Corbett, J. and Corbett, M. (2000) *Designing Sustainable Communities, Learning From Village Homes*, Island Press, Washington, DC.

Corrigan, M. B., et al. (2004) *Ten Principles for Smart Growth on the Suburban Fringe*, ULI–The Urban Land Institute, Washington, DC.

Cox, R. L. (1993) An analysis of grocery store energy use. MS thesis, Texas A&M University, College Station, TX.

Cox, R. L.; Haberl, J. S.; and Claridge, D. E. (1993) A study of energy use in grocery stores. *ASHRAE Transaction*, **99**(1), 1301-1314.

Crawley, D.B.; Hand, J.W.; Kummert, M.; and Griffith, B.T. (2005) *Contrasting the Capabilities of Building Energy Performance Simulation Programs*, Version 1.0. A joint report by the US Department of Energy, University of Strathclyde, and University of Wisconsin [http://www.eere.energy.gov/buildings/tools_directory/pdfs/contrasting_the_capabilities_of_building_energy_performance_simulation_programs_v1.0.pdf]

Crawley, D. B., Pedersen, C. O., Lawrie. L. K., and Winkelmann, C. F. (2000) EnergyPlus: Energy Simulation Program. *ASHRAE Journal*, **42**, 49-56.

Crawley, D. B.; Winkelmann, F. C.; Lawrie, L. K.; and Pedersen, C. O. (2001) EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, **33**, 319-331.

Creswell, J.W. (2003) *Research Design, Qualitative, Quantitative, and Mixed Methods Approaches*, 2nd Edn, Sage Publications, Thousand Oaks, CA.

CRISP (2004) *Network on Construction & City Related Sustainability Indicators*, The European Commission Funded Thematic Network [http://crisp.cstb.fr/default.htm].

Curwell, S. and Cooper, I. (1998) The implications for urban sustainability. *Building Research & Information,* **26**(1), 17-28.

Day, K. (2003) New urbanism and the challenges of designing for diversity. *Journal of Planning Education and Research*, **23**, 83-95.

Dixon, J., Scura, L., Carpenter, R., and Sherman, P. (1997) *Economic Analysis of Environmental Impacts*, 2nd Edn, Earthscan Publications Ltd, London, UK.

Duany, A. and Plater-Zyberk, E. (1994) The neighborhood and the district, in P. Katz (ed.): *The New Urbanism: Toward an Architecture of Community*, McGraw-Hill, New York.

Duany, A. and Plater-Zyberk, E. (2005) *Smart Code, a Comprehensive Form-Based Planning Ordinance*, v-6.5, Duany Plater-Zyberk & Company, Miami, FL.

Duany, A., Plater-Zyberk, E. and Speck, J. (2000) *Suburban Nation, The Rise of Sprawl and the Decline of the American Dream*, North Point Press, New York.

Duffie, J. A. and Beckman, W. A. (1991) *Solar Engineering of Thermal Processes*, John Wiley and Sons Inc., New York.

Edwards, B. and Du Blessis, C. (2001) Snakes in utopia - A brief history of sustainability (Tracing the preoccupation with nature in architecture back to the 19th Century, an overview of the green movement). *Architectural Design*, **152**, 8-19.

EERE (2005) *Distributed Energy Program*, Office of Energy Efficiency and Renewable Energy, US Department of Energy [http://www.eere.energy.gov/de/].

EERE (2006) Building America Performance Analysis Resources, Office of Energy Efficiency and Renewable Energy, US Department of Energy [http://www.eere.energy.gov/buildings/building_america/pa_resources.html].

EIA (Energy Information Administration) (2002) *Commercial Buildings Energy Consumption Survey (CBECS), 1999 Detailed Tables*, Energy Information Administration [http://www.eia.doe.gov/emeu/cbecs/contents.html].

EIA (Energy Information Administration) (2004a) *Emissions of Green House Gases in the United States 2003*, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC.

EIA (Energy Information Administration) (2004b) *Residential Energy Consumption Survey (RECS)*, *2001 Data Tables*, Energy Information Administration [http://www.eia.doe.gov/emeu/recs/ contents.html].

EIA (Energy Information Administration) (2005a) *Annual Energy Outlook 2005, with Projections Till 2025*, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC.

EIA (Energy Information Administration) (2005b) *Annual Energy Review 2004*, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (Energy Information Administration) (2005c) *Electric Power Annual 2004*, Energy Information Administration, U.S. Department of Energy, Washington, DC.

EIA (Energy Information Administration) (2005d) *Natural Gas Annual 2004*, Energy Information Administration, U.S. Department of Energy, Washington, DC.

Elkin, T. and McLaren, D. (1991) *Reviving the City, Towards Sustainable Urban Development*, Friends of the Earth, London, UK.

Ellis, C. (2002) The new urbanism: critiques and rebuttals. *Journal of Urban Design*, **7**(3), 261–291.

Ellis, M. W. (2002) *Fuel Cells for Building Applications*, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta, GA.

EPA (Environmental Protection Agency) (1995) *Compilation of Air Pollutant Emission Factors*, AP-42 Volume I: Stationary Point and Area Source, 5th Edn, Environmental Protection Agency, Washington, DC.

EPA (Environmental Protection Agency) (2001) *Framework for Responsible Environmental Decision-Making (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products*, Environmental Protection Agency, Washington, DC.

EPA (Environmental Protection Agency) (2003) *User Manual, Emissions and Generation Resource Integrated Database, eGRID, Data Years 1996-2000*, Environmental Protection Agency Office of Atmospheric Programs, Washington, DC.

EPA (Environmental Protection Agency) (2004) Combined heat and power partnership, U.S. Environmental Protection Agency [http://www.epa.gov/chp/]

EPA (Environmental Protection Agency) (2005) *Investing in Our Future*. Energy Star and Other Voluntary Programs 2004 Annual Report, Environmental Protection Agency, Washington, DC.

Ewing, R. (1997) Is Los Angeles-style sprawl desirable? *Journal of the American Planning Association*, **63**(1), 107-125.

Fainstein, S. S. (2000) New directions in planning theory. *Urban Affairs Review*, **35**(4), 451-478.

Fathy, H. (1986) *Natural Energy and Vernacular Architecture, with Reference to Hot Arid Climates*, edited by Walter Shearer and Abd-el-rahman Ahmed Sultan, University of Chicago Press, Chicago, IL.

Firestone, R. and Marnay, C. (2005) *Energy Manager Design for Microgrids*, prepared for California Energy Commission, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA.

Fischer, S. (2003) Micro-CHP in the United States, A presentation *in the National Micro-CHP Technologies Roadmap Workshop*, 11-12 June, 2003, Greenbelt, MD [http://www.eere.energy.gov/der/micro_chp_workshop.html]

Fleming, J.G. (1997) Simplified thermoeconomic approach to cost allocation in a combined cycle cogeneration and district energy system. MS thesis, Texas A&M University, College Station, TX.

Frank, L. (2000) Land use and transportation interaction implications on public health and quality of life. *Journal of Planning Education and Research,* **20**, 6-22.

Fuller, S. K. and Peterson, S. R. (1995) *Life Cycle Costing Manual for the Federal Energy Management Program*, U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology, Gaithersburg, MD.

GARD Analytics (2000) *Assessing Combined Cooling, Heating and Power Systems in Northeast Wisconsin*, Energy Center of Wisconsin, Madison, WI.

Garde-Bentaleb, F.; Miranville, F.; Boyer, H.; and Depecker, P. (2002) Bringing scientific knowledge from research to the professional fields: the case of the thermal and air-flow design of buildings in tropical climates. *Energy and Buildings,* **34**, 511-521.

Givoni, B. (1969) *Man, Climate and Architecture*, Elsevier Publishing Co. Ltd, New York, NY.

Givoni, B. (1976) *Man, Climate and Architecture*, 2nd Edn, Applied Science Publishers Ltd., London, UK.

Givoni, B. (1981) Cooling of buildings by passive systems, in A. Bowen, E. Clark, and K. Labs (eds), *Proceedings of the International Passive and Hybrid Cooling Conference*, American Section of the International Solar Energy Society, 6-16 November, Miami Beach, FL.

Givoni, B. (1994) *Passive and Low Energy Cooling of Buildings*, Van Nostrand Reinhold, New York, NY.

Givoni, B. (1998) *Climate Considerations in Building and Urban Design*, Van Nostrand Reinhold, New York, NY.

Gordon, J. (2001) *Solar Energy, the State of the Art, ISES Position Papers*, International Solar Energy Society, James & James, London, UK.

Grant, J. (2002) Mixed use in theory and practice: Canadian experience with implementing a planning principle. *Journal of the American Planning Association,* **68**(1), 70-84.

Groat, L. and Wang, D. (2003) *Architectural Research Methods*, JohnWiley & Sons inc., New York, NY.

Groberg, B. (2003) CHP for Housing and Community Development, *A Presentation in the 4th National CHP Roadmap Workshop*, 22-24 September, 2003, Chicago, IL [http://www.energetics.com/4thchpworkshop/]

Grumman, D.L. (ed.) (2003) *ASHRAE Green Guide*, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA.

Gunes, M.B. and Ellis, M.W. (2003) Evaluation of energy, environmental, and economic characteristics of fuel cell combined heat and power systems for residential applications. *Transactions of the ASME,* **125**, 208-220.

Guy, G.B. and Kibert, C.J. (1998) Developing indicators of sustainability: US experience. *Building Research & Information.* **26**(1), 39-45.

Guy, S. and Farmer, G. (2001) Reinterpreting sustainable architecture, the place of technology. *Journal of Architectural Education*. **54**(3), 140-148.

Haberl, J.S.; Bronson, D.J.; and O'Neal, D.L. (1995) Impact of using measured weather data vs. TMY weather data in a DOE simulation. *ASHRAE Transactions,* **101**(2), 558-576.

Haberl, J. & Cho, S. (2004) *Literature Review of Uncertainty of Analysis Methods (DOE-2 Program).* Report to the Texas Commission on Environmental Quality. Report number: ESL-TR-04/11-01. Energy Systems Laboratory, Texas A&M University System, College Station, TX. [http://esl.tamu.edu/sb5/documents/DOE-2 11-01.pdf]

Haberl, J. S., Im, P., Culp, C., Yazdani, B., Fitzpatrick, and Turner, D. (2003) Calculation of NOx emissions reductions from implementation of the 2000 IECC/IRC Conservation Code in Texas, in *Proceedings of the 2003 IBPSA Conference,* 11-14 August, Eindhoven, Netherlands.

Haberl, J., Sreshthatputra, A., Claridge, D., and Turner, D. (2001) Measured energy indices for 27 office buildings, in *Proceedings of the 1st International Conference for Enhanced Building Operations*, Austin, Texas, pp. 185-199

Hart, M. (1999) *Guide to Sustainable Community Indicators*, 2nd Edn, Hart Environmental Data, North Andover, MA.

Haughey, R. (2003) *The Case for Multifamily Housing*, 2nd Edn ULI–The Urban Land Institute, Washington, DC.

Haughey, R. (2005) *Higher-Density Development: Myth and Fact*. ULI–The Urban Land Institute, Washington, DC.

Hebbert, M. (2003) New urbanism-the movement in context. *Built Environment*. **29**(3), 193-209.

Hendron, R. (2005) *Building America Research Benchmark Definition*, Updated 29 December 2004. Report number: NREL/TP-550-37529, National Renewable Energy Laboratories, Golden, CO.

Hendron, R.; Anderson, R.; Judkoff, R.; Christensen, C.; Eastment, M.; et al. (2004) *Building America Performance Analysis Procedures*, Revision 1. Report Number: NREL/TP-550-35567, National Renewable Energy Laboratories, Golden, CO.

Higbee, C. V. (1998) Engineering cost analysis, in J. Lund (ed.): *Geothermal Direct Use Engineering and Design Handbook*, 3rd Edn, Geo-heat Center, Klamath Falls, OR.

Hirsch, J. J. (2003) *eQUEST, Quick Energy Simulation Tool: Introductory Tutorial*. James J. Hirsch and Associates [http://www.doe2.com/download/equest/eQUESTv3-40_Tutorial.exe].

Hirschenhofer, J.H. et al. (1998) *Fuel Cell Handbook*, 4th Edn. A report by Parsons Corporation for the US Department of Energy, Federal Energy Technology Center (DOE/FETC-99/1076) [http://www.seca.doe.gov/pubs/4-fuelcell.pdf]

Houghton, T. (2000) The community energy utility, in H. Barton (ed.): *Sustainable Communities, The Potential for Eco-Neighbourhoods*, Earth Scan Publications Limited, London.

Huang, J.; Akbari, H.; Rainer, L.; and Ritschard, R. (1991) *481 Prototypical Commercial Buildings for 20 Urban Market Areas, Technical Documentation of Building Loads Data Base Developed for the GRI Cogeneration Market Assessment Model*. Lawrence Berkeley Laboratory, Applied Science Division, Berkeley, CA

Huang, Y.J. and Crawley, D.B. (1996) Does it matter which weather data you use in energy simulations, in *Proceedings of 1996 ACEEE Summer Study on Energy Efficiency in Buildings*, **4**, 4.183-4.192.

Hudson, R. (2003) *Survey of DER/CHP Software*, Oak Ridge National Laboratory, Springfield, IL [http://www.chpb.net/pdfs/20040206_ORNL_der_chp_software_survey_HudsonR.pdf]

Hyde, R. (2000) *Climate Responsive Design, a Study of Buildings in Moderate and Hot-Humid Climates*, UJ: E&F Spon, London, UK.

IBACOS Consortium (Integrated Building and Construction Solutions) (2003) *IBACOS 2001 Final Technical Report: Building-Scale Project Results*. Report Number: NREL/SR-550-31506, National Renewable Energy Laboratory, Golden, CO.

ICC (International Code Council) (2003) *International Energy Efficiency Code, 2003*, International Code Council, Club Hills, IL.

ICC (International Code Council) (2005) *International Energy Efficiency Code, 2004*, Supplement Edn, International Code Council, Club Hills, IL.

IDHA (International District Heating Association) (1983) *District Heating Handbook*, 4th Edn, Vol. 1, A Design Guide. International District Heating Association, Washington, DC.

IEA (International Energy Agency) (1994) *Passive Solar Commercial and Institutional Buildings*, *A Source Book of Examples and Design Insights*, International Energy Agency, Solar Heating and Cooling Programme, John Wiley & Sons, West Sussex, UK.

IEA (International Energy Agency) (1996) *World Energy Outlook*, 1996 Edn, IEA/OECD, Paris, France.

IEA (International Energy Agency) (1997) *World Energy and Climate Change*, OECD/IEA, Paris, France.

IEA (International Energy Agency) (1998) *World Energy Prospects to 2020*. Paper presented by the IEA for the G8 energy ministers' meeting, Moscow, International Energy Agency, Paris, France.

IEA (International Energy Agency) (2002) *Distributed Generation in Liberalized Electricity Markets*, International Energy Agency, Paris, France.

IEA (International Energy Agency) (2003) *The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems*. A proposal for a new IEA/ECBCS annex, International Energy Agency, Energy Conservation in Buildings and Community Systems Program, May [http://cogen-sim.net/]

IEA (International Energy Agency) (2004) *Survey of Tools & Methods*, Resources of IEA-BCS task 31: energy related environmental impacts of buildings [http://www.uni-weimar.de/scc/PRO/survey.html].

IPCC (Intergovernmental Panel on Climate Change) (1995) *IPCC Second Assessment, Climate Change 1995*. A Report of the Intergovernmental Panel on Climate Change [http://www.ipcc.ch/pub/sa(E).pdf].

IPCC (Intergovernmental Panel on Climate Change) (2001) Climate change 2001: synthesis report, in R.T. Watson and the Core Writing Team (eds): *A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, pp. 1-398.

IUCN/UNEP/WWF (1991) *Caring for the Earth, A Strategy for Sustainable Livin*g, Gland, Switzerland.

Jackson, H. and Svensson, K. (eds) (2002) *Ecovillage Living, Restoring the Earth and Her People*, Green Books Ltd, Devon, UK.

Jenks, M.; Burton, E., and Williams, K. (eds) (1996) *The Compact City, A Sustainable Urban Form?*, E & FN Spon, London, UK.

Johansson, T.B.; and Goldemberg, J. (eds) (2002) *Energy for Sustainable Development, A Policy Agenda*, United Nations Development Program, New York, NY.

Johansson, T.B.; and Goldemberg, J. (eds) (2004) *World Energy Assessment: Overview 2004 Update*, United Nations Development Program, New York, NY.

Judkoff, R. and Neymark, J. (1995a) *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method*, National Renewable Energy Laboratories, Golden, CO.

Judkoff, R. and Neymark, J. (1995b) *Home Energy Rating System Building Energy Simulation Test (HERS BESTEST*, Volume 1, Tier 1 and Tier 2 Tests User's Manual, National Renewable Energy Laboratories, Golden, CO.

Katz, P. (ed.) (1994) *The New Urbanism: Toward an Architecture of Community*, McGraw-Hill, New York, NY.

Kirk, S.J. and Dell'isola, A.J. (1995) *Life Cycle Costing for Design Professionals*, 2nd Edn, McGraw-Hill, New York, NY.

Kleiner, D. and Barton, H. (2000) Survey of eco-neighborhoods world-wide, in H. Barton (ed.): *Sustainable Communities, The Potential for Eco-Neighborhoods*, Earth Scan Publications Limited, London, NY, pp. 253-267.

Knight, I. and Ugursal, I. (eds) (2005) *Residential Cogeneration Systems: A Review of the Current Technologies*. A Report of Subtask A of FC+COGEN-SIM, The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems, Annex 42 of the International Energy Agency, Energy Conservation in Buildings and Community Systems Programme.

Kreider, J. F. and Rabl, A. (1994) *Heating and Cooling of Buildings: Design for Efficiency*, McGraw-Hill, New York, NY.

Kreith, F. and Kreider, J. F. (1978) *Principles of Solar Engineering: Series in Thermal and Fluids Engineering*, Hemisphere Publishing Corporation, Washington, DC.

Krizek, K. (2003) Operationalizing neighborhood accessibility for land use – travel behavior research and regional modeling. *Journal of Planning Education and Research,* **22**, 270-287.

Kusuda, T. (1999). Early history and future prospects of building system simulation, in *The Sixth International Building Performance Simulation Association Conference (IBPSA)*, September, Kyoto, Japan.

Lambert, T., Gilman, P., and Lilienthal, P. (2006) Micropower system modeling with HOMER, in: F. A. Farret, and Simões (eds): *Integration of Alternative Sources of Energy*, Wiley-IEEE Press, pp. 379-418 [http://www.mistaya.ca/products/homer.htm].

LBNL and James J. Hirsch & Associates (1998) *Overview of DOE-2.2.* Lawrence Berkeley National Laboratories & James J. Hirsch & Associates, Berkeley, CA [http://www.doe2.com/Download/Docs/22_oview.pdf].

LBNL and James J. Hirsch & Associates (2004) *DOE-2.2, Building Energy Use and Costs Analysis Program*, *Volume 1, Basics,* Lawrence Berkeley National Laboratories & James J. Hirsch & Associates, Berkeley, CA.

Lechner, N. (2001) *Heating, Cooling, Lighting: Design Methods for Architects*, 2nd Edn, John Wiley & Sons Inc., New York, NY.

Lippiatt, B.C. (2002) *BEES® 3.0, Building for Environmental and Economic Sustainability Technical Manual and User Guide*, National Institute of Standards and Technology, Gaithersburg, MD.

LOGANEnergy Corp (2004) *Residence of Lieutenant Colonel Jeffrey Jackson PEM Demonstration Program Shaw Air Force Base*, Sumter, South Carolina Final Report, Proton Exchange Membrane (PEM) Fuel Cell Demonstration of Domestically Produced PEM Fuel Cells in Military Facilities. Report for the US Corps of Engineers, ERDC/CERL [http://www.dodfuelcell.com/res/ShawAFB_FinalReport.pdf]

Marion, W. and Urban, K. (1995) *User's Manual for TMY2s Typical Meteorological Years*, derived from the 1961-1990 National Solar Radiation Data Base, National Renewable Energy Laboratory, Golden, CO.

Marsk, A. and Raines, C. (1998) *Software, Square One*, Square One Research and the Welsh School of Architecture, Cardiff University, Cardiff, UK [http://www.squ1.com/site.html].

Matson, J.; Sparks, R.; Spadaro, J.; and Haberl, J. (1991) *Documentation Manual for COLROW3D*, Version 4.0, Texas Engineering Experiment Station, College Station, TX.

Mazouz, S. and Zerouala, M. S. (2001) The integration of environmental variable in the process of architectural design, the contribution of expert systems. *Energy & Buildings*, **33**, 699-710.

Mazria, E. (1979) *The Passive Solar Energy Book: A Complete Guide to Passive Solar Home, Greenhouse, and Building Design*, Rodale Press, Emmaus, PA.

McQuiston, F. C.; Parker, J. D.; and Spitler, J.D. (2005) *Heating, Ventilation, and Air Conditioning, Analysis and Design*, 6th Edn, John Wiley & Sons, Inc., New York, NY.

Meadows, D. (1972) *The Limits to Growth*, Universe, New York, NY.

Means, R. S., Co. (2004) *Mechanical Cost Data*, 27th annual Edn. 2004, Reed Construction Data, Kingston, MA.

Milne, M. and Givoni, B. (1979) Architectural design based on climate, in D. Watson (ed.): *Energy Conservation through Building Design*, McGraw-Hill, New York.

Mitchell, G.; May, A.; & McDonald, A. (1995) BICABUE: A methodological framework for the development of indicators of sustainable development. *International Journal of Sustainable Development & World Ecology,* **2**, 104-123.

Morbitzer, C.A. (2003) Towards the integration of simulation into the building design process, PhD dissertation, University of Strathclyde, Glasgow.

Mulholland J., Sheahen T. and B. McConnell, (2003) *Analysis of Future Prices and Markets of High Temperature Superconductors,* U.S. Department of Energy (DOE), Washington, DC.

Naess, A. (ed.) (1989) *Ecology, Community and Lifestyle. Outline of an Ecosophy*, (Rothenberg, D. Trans. & Ed.), Cambridge University Press, Cambridge, UK (Original work published 1976).

NAHB (National Association of Home Builders) (1999) *A Guide to Developing Green Builder Programs*, NAHB Research Center, Upper Marlboro, MD.

NAHB (National Association of Home Builders) (2002a) *Building Greener Building Better, the Quiet Revolution*, The National Association of Home Builders and the NAHB Research Center, Washington, DC.

NAHB (National Association of Home Builders) (2002b) *Smart Growth, Smart Choices*, National Association of Home Builders, Washington DC. [http://www.nahb.org/publication_details.aspx?publicationID=15& sectionID=155].

NAHB (National Association of Home Builders) (2002c) *Summary of Green Building Programs. Prepared for National Renewable Energy Laboratory*, NAHB Research Center, Upper Marlboro, MD.

NAHB (National Association of Home Builders) (2004) *Model Green Home Building Guidelines*, NAHB Research Center, Upper Marlboro, MD.

NASEO/RESNET (2002) *Mortgage Industry National Home Energy Rating Systems Accreditation Standards*, Residential Energy Services Network, Oceanside, CA. [http://www.natresnet.org/standards/standards.pdf].

Neuman, M. (2005) *The Compact City Fallacy*. Sustainable Urbanism Working Papers no. 1, Center for Housing and Urban Development, Texas A&M University, College Station, TX.

Neymark, J. and Judkoff, R. (2002) *International Energy Agency Building Energy Simulation Test and Diagnostic Method for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST) Volume 1: Cases E100–E200*, National Renewable Energy Laboratories, Golden, CO.

Neymark, J. and Judkoff, R. (2004) *International Energy Agency Building Energy Simulation Test and Diagnostic Method for Heating, Ventilating, and Air-Conditioning Equipment Models (HVAC BESTEST) Volume 2: Cases E300–E545*, National Renewable Energy Laboratories, Golden, CO.

NIST (National Institute of Standardsandztechnology) (2002) *BEES® 3.0, Building for Environmental and Economic Sustainability Technical Manual and User Guide*, National Institute of Standards and Technology, Gaithersburg, MD.

Norris, G. A. and MarShall, H. E. (1995) *Multiattribute Decision Analysis Method for Evaluating Buildings and Building Systems*, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.

NRCan (National Resources Canada) (2005) *RETScreen Software Online User Manual*, Combined Heat & Power Project Module, National Resources Canada, Ottawa, ON.

NRDC (Natural Resources Defense Council) (2003) *Environmental Characteristics of Smart Growth Neighborhoods, Phase II: Two Nashville Neighborhoods*, Natural Resources Defense Council, New York.

NREL (2003) *HOMER, the Optimization Model for Distributed Power, Getting Started Guide, Version 2.0* [http://www.nrel.gov/homer/].

NREL and GRI (2003) *Gas-Fired Distributed Energy Resource Technology Characterizations.* A joint project of the Gas Research Institute (GRI) and the National Renewable Energy laboratories (NREL), The Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, Washington, DC.

Olgyay, V. (1963) *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Princeton University Press, Princeton, NJ.

O'Neill, D. (1999) *Smart Growth: Myth and Fact*, ULI–The Urban Land Institute, Washington, DC.

ONSITE (1999) *Review of Combined Heat and Power Technologies*. Report by ONSITE SYCOM Energy Corporation, for the Office of Energy Efficiency and Renewable Energy (EERE), US Department of Energy, Washington, DC.

ONSITE (2000) *The Market and Technical Potential for Combined Heat and Power in the Commercial/Institutional Sector*. A report by ONSITE SYCOM Energy Corporation, for the U.S. Department of Energy, Energy Information Administration, Washington, DC.

Orlando, J. A. (1996) *Cogeneration Design Guide*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc., Atlanta, GA.

Orlando, J. A. (1997) *Cogeneration Planner's Handbook*, PennWell Publishing Company, Tulsa, OK.

ORNL (1993) *1992 National Census for District Heating, Cooling, and Cogeneration*, Oak Ridge National Laboratories, Oak Ridge, TN.

ORNL (2003a) *Emissions Benefits of Distributed Generation in the Texas Market*, Oak Ridge National Laboratories, Oak Ridge, TN.

ORNL (2003b) *Quantitative Assessment of Distributed Energy Resource Benefits*, Oak Ridge National Laboratories, Oak Ridge, TN.

Owens, S. (1986) *Energy, Planning and Urban From*, Pion Limited, London, UK.

Owens, S. (1992) Energy, environmental sustainability and land-use planning, in M. J. Breheny, (ed.): *Sustainable Development and Urban Form*, European Research in Regional Science 2, Pion Limited, London, UK.

Oyarza´bal B., Ellis M.W., and von Spakovsky M.R. (2004) Development of thermodynamic, geometric, and economic models for use in the optimal synthesis/design of a PEM fuel cell cogeneration system for multi-unit residential applications. *Journal of Energy Resources Technology*, **126**, 21-29.

Phetteplace, G. (1995a) *Efficiency of Steam and Hot Water Heat Distribution Systems*. CRREL Report 95-18, Cold Regions Research & Engineering Laboratory, US Army Corps of Engineers, Hanover, NH.

Phetteplace, G. (1995b) *Optimal Design of Piping System for District Heating*. CRREL Report. 95-17, Cold Regions Research & Engineering Laboratory, US Army Corps of Engineers, Hanover, NH.

Plug Power, Inc. (2004) *Final Project Report – FY02 PEM Fuel Cell Demonstration Proton Exchange Membrane (PEM) Fuel Cell Demonstration of Domestically Produced PEM Fuel Cells in Military Facilities*. Report for the US Corps of Engineers, ERDC/CERL [http://www.dodfuelcell.com/res/NSU_FinalReport.pdf].

Rafferty, J. D. (1996) *Selected Cost Considerations for Geothermal District Heating in Existing Single-Family Residential Areas*, Geo-heat Center, Klamath Falls, OR.

Rafferty, J. D. (1998) Piping, in J. Lund (ed.): *Geothermal Direct Use Engineering and Design Handbook,* 3rd Edn, Geo-heat Center, Klamath Falls, OR, pp. 241-259.

RDC (Resources Dynamic Corporation) (2002) *Integrated Energy Systems (IES) for Buildings: A Market Assessment*. Final report prepared for Energy Efficiency and Renewable Energy, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN.

Reddy, A.K.N.; William, R.H., and Johansson, T.B. (1997) *Energy after Rio, Prospects and Challenges*, Executive Summary, United Nations Development Program, New York, NY.

RESNET (Residential Energy Services Network) (2004) *Adopted Enhancements to the Mortgage Industry National Home Energy Rating Standards*, Residential Energy Services Network, Oceanside, CA. [http://www. natresnet.org/standards/Enhancements_to_National_Rating_Standards.pdf].

Rickaby, P. (1985) *Towards a Spatial Energy Model, A Theoretical Comparison of Accessibility and Energy-Use in Regional Settlement Patterns*. Final Report of a Research Project conducted by P. Rickaby and P. Steadman*,* Centre for Configurational Studies, The Open University, Milton Keynes, UK.

Rittelmann, W. (2004) *Field Investigation of 18 Solar-Assisted Domestic Hot Water Systems With Integral Collector Storage*, IBACOS Inc., Pittsburgh, PA.

RMI (Rocky Mountain Institute) (1995) *A Primer on Sustainable Building*, Rocky Mountain Institute Green Development Services, Snowmass, CO.

Roaf, S., Fuentes, M. and Thomas, S. (2001) *Ecohouse, A Design Guide*, Architectural Press, Oxford, UK.

Rothenberg, D. (1989) Ecosophy: from intuition to system, in A. Naess (ed.): *Ecology, Community and Lifestyle, Outline of an Ecosophy*, Rothenberg, D. Trans. & Ed., Cambridge University Press, Cambridge, UK (Original work published 1976).

Sachs, W. (1999) *Planet Dialectics, Explorations in Environment and Development*, Zed Books, London, UK.

Sachs, W. (2000) Being and buying. *New Perspectives Quarterly*, **17**(4), 14-26.

Sachs, W.; Loske, R.; & Linz, M. (1996) *Greening the North, A Post-Industrial Blue Print for Ecology and Equity*, Zed Books, London, UK.

Santamouris, M. & Allard, F. (eds) (1998) *Natural Ventilation in Buildings*, *a Design Handbook*, James & James Science Publishers, London, UK.

SCN (Smart Communities Network) (2005a) *Creating Energy Smart Communities*, *Measuring Progress-Indicators in Action*, U.S. Department of Energy [http://www.sustainable.doe .gov/measuring/meaction.shtml].

SCN (Smart Communities Network) (2005b) *Green Development Success Stories*, *Smart Communities Network* [http://www.sustainable.doe.gov/management/sstoc.shtml].

SCN (Sustainable Communities Network) (2005) *Sustainable Communities Case Studies* [http://www.sustainable.org/casestudies/studiesindex.html].

Shaviv, E.; Yezioro, A., Capeluto, I.G., Peleg, U.J., and Kalay, Y.E. (1996) Simulations and knowledge-based computer-aided architectural design (CAAD) systems for passive and low energy architecture. *Energy & Buildings*, **23**, 257-296.

Shultz, L. I.; Rushing, A. S.; and Fuller, S. K. (2004) *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis - April 2004*. Annual Supplement to NIST Handbook 135 and NBS Special Publication 709, U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology, Gaithersburg, MD.

Sick, F. & Erge, T. (1996) *Photovoltaics in Buildings, A Design Handbook for Architects and Engineers*, International Energy Agency, Solar Heating and Cooling Programme, Task 16, IEA, Paris, France.

Siddiqui A.S.; Firestone, R.; Ghosh, S.; Stadler, M.; Edwards, J. L.; et al. (2003) *Distributed Energy Resources with Combined Heat and Power Applications*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Siddiqui, A.S.; Marnay, C.; Bailey, O. and LaCommare, K.H. (2004) *Optimal Selection of On-Site Generation with Combined Heat and Power Applications*, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA.

Socolow, R.; Hotinski, R.; Greenblatt, J.; & Pacala, S. (2004) Solving the climate problem, Technologies available to curb CO_2 emissions. *Environment.* **46**(10), 8-19.

Southworth, M. (1997) Walkable suburbs? An evaluation of neotraditional communities at the urban edge. *Journal of the American Planning Association,* **63**(1), 28-45.

Southworth, M. (2003) New urbanism and the American metropolis. *Built Environment*. **29**(3), 210-226.

Southworth, M. and Ben-Joseph, E. (1997) *Streets and the Shaping of Towns and Cities*, McGraw Hill, New York, NY.

Southworth, M. and Owens, P. (1993) The evolving metropolis, studies of community, neighborhood, and street form at the urban edge*. Journal of the American Planning Association*, **59**(3), 271-287.

Spiewak, S. and Weiss, L. (1994) *Cogeneration & Small Power Production Manual*, 4th Edn, The Fairmont Press, Lilburn, GA.

Steel, J. (1997) *Sustainable Architecture, Principles, Paradigms, and Case Studies*, McGraw-Hill, New York, NY.

Steuteville, R. and Langdon, P. (2003) *New Urbanism, Comprehensive Report & Best Practices Guide*, 3rd Edn, New Urban News, Ithaca, NY.

Sung, Y. H. (2004) Development of a comprehensive community NOx emission reduction toolkit (CCNERT). Ph.D. dissertation, Texas A&M University, College Station, TX

SwRI (2004) *Brooks Residential Fuel Cell Demonstration Program Final Report*, prepared for the US Corps of Engineers, ERDC/CERL, South West Research Institute Project No. 05118, Champagne, IL [http://www.dodfuelcell.com/res/BrooksFinalReport.pdf].

Tabb, P. (1984) *Solar Energy Planning.* McGraw-Hill, New York, NY.

Tabb, P. and Gee, B. (1990) *Jerome, Arizona: A Study of Coherence, Relationships, Energy and Form*, Arizona State University, Tempe, AR.

Tabb P. J. and Kreider, J. F. (2000) Sustainable community design and energy analysis, in *Passive and Low Energy Association Conference*, Cambridge, UK.

Tashakkori, A., and Teddlie, C. (1998) *Mixed Methodology: Combining Qualitative and Quantitative Approaches*, Applied Social Research Methods Series (Vol. 46), Sage Publications, Thousand Oaks, CA.

Tashakkori, A. and Teddlie (eds) (2003) *Hand Book of Mixed Methods in Social and Behavioral Research*, Sage Publications, Thousand Oaks, CA.

Teed, J. and Condon, P. (2002) *Sustainable Urban Landscapes, Urban Neighborhood Typologies*, the University of British Columbia James Taylor Chair in Landscape and Liveable Environments [http://www.sustainable-communities.agsci.ubc.ca/projects /typology.htm].

Trouche, L. (2003) EPA's role in reaching our goal of 46 GW new CHP, A Presentation in the 4th National CHP Roadmap Workshop, 22-24 September, Chicago, IL [http://www. energetics.com/4thchpworkshop/].

UNDP (United Nations Development Program) (1996) *UNDP Initiative for Sustainable Energy*, Energy and Atmosphere Program, Bureau for Policy and Programme Support, UNDP, Sustainable Energy and Environment Division, New York, NY.

U.S. Census Bureau (2004) *American Housing Survey for the United States: 2003*. Current Housing Reports, Series H150/03, U.S. Government Printing Office, Washington, DC.

U.S. Census Bureau. (2005) *Characteristics of New Housing: 2004*, US Census Bureau, Washington, DC [http://www.census.gov/const/www/charindex.html].

U.S. DOE (U. S. Department of Energy) (2000) *Technical Support Document: Energy Efficiency Standards for Consumer Products: Residential Water Heaters, Including: Regulatory Impact Analysis*, U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Building Research and Standards Office, Washington, DC. [http://www.eere.doe.gov/buildings/ appliance_standards/residential/waterheat_0300_r.html].

U.S. DOE (U. S. Department of Energy) (2003) *The Micro-CHP Technologies Roadmap, Meeting 21st Century Residential Energy Needs*, U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Distributed Energy Program, Greenbelt, MD.

U.S. DOE (U. S. Department of Energy) (2004) *Technical Support Document: Energy Efficiency Program for Consumer Products: Energy Conservation Standards For Residential Furnaces and Boilers*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program, Appliances and Commercial Equipment Standards, Washington, DC. [http://www.eere.doe.gov/buildings/appliance_standards/residential/furnaces_ boilers_1113_r.html].

U.S. GBC (U.S. Green Building Council) (2003) *Leadership in Energy & Environmental Design (LEED)™, Green Building Rating System for New Construction & Major Renovations (Version 2.1),* U.S. Green Building Council, San Francisco, CA.

US GBC (U.S. Green Building Council) (2005) *Rating System for Pilot Demonstration of LEED® for Homes Program*, U.S. Green Building Council, Washington, DC. [https://www.usgbc.org/FileHandling/show_general_file.asp?DocumentID=855].

Vale; B. and Vale, R. (2000) *The New Autonomous House: Design and Planning for Sustainability*, Thames & Hudson, London, UK.

WADE (World Alliance for Decentralized Energy) (2003) *Guide to Decentralized Energy Technologies,* World Alliance for Decentralized Energy, Edinburgh, UK.

Watson, D. and Labs, K. (1983) *Climatic Building Design: Energy- Efficient Building Principles and Practice,* McGraw-Hill, New York, UK.

WCED (World Commission on Environment & Development) (1987) *Our Common Future*, Oxford University Press, Oxford, UK.

White, M. K.; Halcomb, F. H.; Josefik, N. M.; Lux. S. M.; and Binder, M. J. (2004) *DOD Residential Proton Exchange Membrane (PEM) Fuel Cell Demonstration Program*, Volume I – Summary of the Fiscal Year 2001 Program, Construction Engineering Research Laboratory, U.S. Army Corps of Engineers, Champaign, IL.

Williams, K.; Burton, E.; and Jenks, M. (eds) (2000) *Achieving Sustainable Urban Form*, E&FN Spon, London, UK.

Willis, H. Lee, H., and Scott, W. G. (2000) *Distributed Power Generation, Planning and Evaluation*, Marcel Dekker Inc., New York, UK.

Winkelmann, F. C., Birdsall, B. E., Buhl, W. F., Ellington, K. L., and Erdem, A. E. (1993) *DOE-2 Supplement: Version 2.1 e*, Lawrence Berkeley National Laboratory, Berkeley, CA.

Wuppertal Institute (2002) *Bringing Energy Efficiency to the Liberalized Electricity and Gas Markets, How Energy Companies and Others Can Assist End-Users in Improving Energy Efficiency, and How Policy Can Reward Such Action*, Wuppertal Institute for Climate, Environment, Energy and Partners, Wuppertal, Germany.

York, D. A. and Tucker, E. F. (1980) *DOE-2 Reference Manual,* Part I & Part II: Version 2.1, May, Lawrence Berkeley National Laboratory, Berkeley, CA.

APPENDIX A

ENERGY SIMULATION SOFTWARE: DOE-2.1e, DOE-2.2, & eQUEST

A.1 INTRODUCTION

This appendix presents an overview of the main differences between the building energy simulation tool used in this study, eQUEST / DOE-2.2, and the DOE-2.1e version, which is the latest official, U.S. DOE supported, version of the DOE-2 energy simulation software. The overview is summarized from a description of the changes in the DOE-2.2 version prepared jointly by LBNL and J. J. Hirsch and Associates (LBNL & J. J. Hirsch, 1998).The appendix also describes the advantages and disadvantages of using eQUEST and DOE-2.2 for this study instead of the more widely used and accepted DOE-2.1e. Finally, the results of the IEA HVAC BESTEST, with regard to both DOE-2.1e & DOE-2.2, are also described.

A.2 BACKGROUND

DOE-2 is a computer simulation program used to analyze the energy performance and associated operation costs of buildings, and is considered the most widely recognized, accepted, and respected whole building energy simulation and analysis program in use today. Haberl & Cho (2004) report that the first version of DOE-2 was released by the Lawrence Berkeley Laboratory, later renamed Lawrence Berkeley National Laboratory (LBNL), in 1978 and was based on earlier simulation tools and methods developed and funded by ASHRAE, NASA, the U.S. Postal Service, and the electric and gas utility industries. Since then, the program has been continually updated by LBNL until the most recent version, DOE2.1e, was released in 1993 (Buhl et al., 1993). Following this, several updates and improvements have been added to DOE-2.1e with versions up to DOE-2.1e-121.

DOE-2.2, on the other hand, was initially developed in a collaborative effort between LBNL and J. J. Hirsch & Associates, with support from the U.S. DOE and the Electric Power Research Institute, with the following purposes: 1) to make improvements to the simulation portions of DOE-2.1 to provide more accurate and flexible simulations of windows, lighting, and HVAC systems; 2) to make the Building Description Language (BDL) processor more capable of being used in an interactive environment, which will allow integration with interactive user interfaces (LBNL & J. J. Hirsch, 1998). As the initial U.S. DOE support for DOE-2.2 was discontinued, DOE-2.2 was not released as an official version of the DOE-2 software and is currently supported only by J. J. Hirsch and Associates. However, DOE-2.2 has been certified by the California Energy Commission (CEC) for use in demonstrating compliance with California's Title 24 energy code. Additionally, the performance analysis procedures developed by the Building America program (Hendron et al. (2004) recommend the use of DOE-2.2 (with or without eQUEST) in its performance analysis procedure.

eQUEST is a simulation software, produced and supported by J. J. Hirsch and Associates (Hirsch, 2003), which incorporates an enhanced DOE-2.2 engine with schematic and design development model creation wizards, industry standard input defaults, an energy efficiency measures wizard, and a graphical results display module. Hirsch (2003) describes eQUEST as "*sophisticated, yet easy-to-use building energy use analysis tool which provides professional-level results with an affordable level of effort*". The eQUEST version used in this study is version 3.55, which utilizes version 44c of the DOE-2.2 software.

A.3 DIFFERENCES BETWEEN DOE-2.1E & DOE-2.2

The following description of the differences between DOE-2.1e and DOE-2.2 is a summary of an overview of the changes in DOE-2.2 from DOE-2.1e version 087 (released in 1995) prepared by LBNL and J. J. Hirsch and Associates (LBNL & J. J. Hirsch, 1998). Based on this overview, it can be seen that DOE-2.2 has two major structural differences from DOE-2.1e. The first difference is combining of the SYSTEMS and PLANT subprograms of DOE-2.1e into a single "HVAC" program, with the aim of improving the connectivity between the loads incurred by the secondary HVAC systems (air handler coils, reheat coils, etc.), and the primary HVAC equipment (boilers, chillers, etc.); while the second difference is conducting the LOADS and HVAC calculations together in single time step loop, compared to the previous running order of DOE-2.1e, in which LOADS was calculated for the run period, then SYSTEMS, then PLANT, then ECONOMICS. Another major addition to DOE-2.2 is the concept of circulation loops. A summary of the main changes in the Building Description Language (BDL), LOADS, and HVAC programs in DOE-2.2, compared to DOE-2.1e version 087, is presented next.

A.3.1 BDL Changes

Name lengths: all symbols in DOE-2.2 can be up to 32 characters compared to a maximum of 16 characters in DOE2.1e.

TYPE keyword: a new class of commands is included in DOE-2.2 called the TYPE commands, which require a TYPE keyword as the first keyword in the input. This keyword is used to designate the keywords and defaults that are to be utilized for the object being defined.

Schedules: All DOE-2.2 schedules must specify the keyword TYPE and the type specified must be compatible with the keyword that refers to the schedule. The TYPE must be specified in the DAY-SCHEDULE, WEEK-SCHEDULE, and the SCHEDULE commands.

A.3.2 LOADS Changes

Geometry: Exterior and interior walls can be described as polygons with 3 to 12 sides. Windows and building shades, however, must still be entered as rectangles. Spaces and walls, can "inherit" geometry from their parents by use of LOCATION keywords.

Space conditions: The keywords used to describe area lighting and equipment in the SPACE-CONDITIONS command can now accept lists (within parenthesis) of up to five values or a single value (without parenthesis.).

Glass type: The GLASS-TYPE-CODE (G-T-C) values of 1 - 11 are no longer valid in DOE-2.2 and the G-T-C must be defined in the window library. The library identifier designation is a u-name (32 characters max). The alternative method of specifying GLASS-COND and SHADING-COEF can still be used. Panes are incorporated into the G-T-C library entry, and the GLASS-TYPE command requires the specification of the TYPE keyword: GLASS-TYPE-CODE or SHADING-COEF.

Window Layers: A new command, WINDOW-LAYER, and a new WINDOW keyword, STRUCTURE, allow windows to be built up from glass, gap, and blind layers. The program calculates the overall properties of the window from the user-specified properties of each layer.

Lighting Systems: The new LIGHTING-SYSTEM command allows electric lighting systems to be specified in terms of number of luminaires, and luminaire, lamp, and ballast types.

Floor: A new FLOOR command allows spaces to be grouped floor by floor. Although this does not effect the thermal calculation, it allows floor-by-floor visual display of a building.

Daylighting: Calculation of interior daylight illuminance for windows with blinds was added. Improvements were made to the calculation of exterior direct and diffuse illuminance.

A.3.3 HVAC Changes

As mentioned previously, DOE-2.2 has a new HVAC program that replaces the SYSTEMS and PLANT programs of DOE-2.1e. Some of the features found in DOE-2.2 were first developed and released in DOE-2.1e versions 100 and higher. In DOE-2.2, however, new simulation models were developed for all primary equipment and merged, along with the DOE-2.1e-100 SYSTEMS program, into a single new HVAC program (LBNL & J. J. Hirsch, 1998). The main changes in the HVAC program are as follows:

Circulation Loops: A circulation loop allows a thermal load to be connected to a thermal supply. Different reheat coils may be connected to the same or different loops, and each loop may serve an entire system, multiple systems, or only a portion of a system. Loops aim to improve the connectivity between secondary HVAC systems and primary HVAC equipments. A variety of loop types are incorporated into DOE-2.2 including chilled water, hot water, two-pipe, condenser water, water-loop heat pump, domestic hot water. A single loop can directly deliver energy from the central plant equipment to the end-uses, or two or more loops can be arranged in a primary/secondary fashion, where a primary loop serves one or more secondary loops.

CHILLER command: A new CHILLER command replaced the PLANT-EQUIPMENT command in DOE-2.1e, which contains all the performance specifications in the PART-LOAD-RATIO, PLANT-PARAMETERS, and EQUIPMENT-QUAD commands. Types of chillers include ELEC-OPEN-CENT, ELEC-OPEN-REC, ELEC-HERM-CENT, ELEC-HERM-REC, ELECHTREC, ABSOR-1, ABSOR-2, GAS-ABSOR, and ENGINE. This command allows for the specification of the efficiency, off-design performance characteristics, etc. for each chiller.

ELEC-METER command: A new ELEC-METER command allows for defining many meters to which electrical equipment could be attached. Three TYPEs of ELEC-METERs can be defined: UTILITY, the highest, BUILDING, the middle, and SUB-METER, the lowest.

Other new HVAC commands: Other new or enhanced HVAC commands in DOE-2.2 include: an enhanced PUMP command; new BOILER, DW-HEATER, HEAT-REJECTION, HEAT RECOVERY in DOMESTIC WATER SYSTEMS, FUEL-METER, STEAM-METER, CHW-METER, THERMAL-STORAGE, and HEAT-EXCHANGER commands; as well as a hydronic heating option added to all air-system models systems; and an expansion of the single-fan dual-duct algorithm of DOE-2.1e to permit the modeling of dual-fan dual duct systems.

A.4 ADVANTAGES AND DISADVANTAGES OF USING EQUEST/DOE-2.2

This study involved the development of a considerably large number of building prototypes, which were evaluated in a variety of conditions based on the design alternatives investigated. In total, seven residential prototypes and 21 commercial prototypes of different building typologies and sizes were developed in addition to 25 community design variations, for the planning and architectural design parameters, and four optimization scenarios, some of which required modifying the prototypes to account for variables such as increased system efficiencies, changes in envelope characteristics, and/or external shading. The use of eQUEST's design development model creation wizard as a starting point for developing the models in this study followed by using eQUEST's detailed mode graphical user interface (GUI) allowed for the development of this large number of models in a relatively short timeframe compared to the use of DOE-2.1e. The incorporation of user-friendly GUI's is increasing in building energy simulation software and many of the latest tools either include a GUI (e.g. ECOTECT, ESP-r, & IES Virtual Environment, ENERGY 10) or have independently developed GUI's (e.g. Design Builder software, an interface developed for EnergyPlus). Clarke (2001) argues that having a more accessible user interface is a characteristic of the fourth generation of simulation tools. For this study, the time savings provided by eQUEST's GUI were extremely helpful in developing the required number of models in a suitable timeframe.

While eQUEST creation wizards represented a good starting point for creating the models epically with regard to building geometry and initial assignment of envelope elements and systems to their respective spaces and zones, they only provide access to a limited number of commands and include a large number of default values. Therefore, all models, following their creation in the wizard, were developed in eQUEST's detailed mode. While the study did not investigate all DOE-2.2 commands, the detailed mode provided access to all the command required for developing the prototypes in this study. However, for some commands (e.g. schedules) editing the text input file and then re-opening the file in eQUEST represented a better option than editing in the detailed mode. In addition to the creation wizard and the GUI, other features of eQUEST/DOE-2.2 were also useful in this study including the graphical results display, parametric analysis capabilities, detailed output viewer, and formatted hourly results. The graphical results display allowed for a quick method of testing the impact of changes in the model on resulting energy consumption, however, only hourly data were used in the subsequent stages of the assessment procedures; the parametric run capabilities of eQUEST also allowed for the relatively quick development and simulation of prototype variations (such as changes in orientation and external shading); the detailed simulation output viewer allowed for the easy navigation of the variety of reports generated by eQUEST's DOE-2.2 engine; while the formatted hourly output reduced the processing time for the results used in subsequent tasks.

On the other hand, the study acknowledges a number of disadvantages associated with using eQUEST/DOE-2.2 instead of DOE-2.1e in this study. These disadvantages can be summarized as follows:

1) While both eQUEST and DOE-2.2 have available and detailed documentations, this documentation does not include the equations and algorithms used to develop the different models used within the software, which are considered proprietary. In contrast, the equations and algorithms used in the DOE-2.1e software are publicly available in an "*Engineers Manual*", although this manual dates back to version 2.1a. The source code for DOE-2.1e is also publicly available while that for DOE-2.2 is not. This potential for public review of the algorithms and source code for DOE-2.1 gives it an advantage over the privately owned DOE-2.2.

2) DOE-2.1e is the latest official version of the DOE-2 software, and is therefore fully supported by LBNL. DOE-2.2, on the other hand, while initially developed by both LBNL and J. J. Hirsch and Associates, is not an official version of DOE-2 and is not supported by LBNL or U.S. DOE. However, it has to be mentioned that, during the use of DOE-2.2 and eQUEST in this study, support from J. J. Hirsch and Associates was readily available when needed.

3) DOE-2.1e is the more recognized and accepted version of DOE-2 and has been in use for a much longer time. DOE-2.2, on the other hand, has only been available for a short time period although its use in the commercial sector appears to be increasing.

4) Considerably more validation activities have been conducted for the official versions of DOE-2 (including DOE-2.1e) compared to the much newer DOE-2.2. Haberl and Cho (2004) present a summary of validation activities for DOE-2 that includes comparative studies, analytical studies, and 47 empirical studies. In comparison, much less validation activities have been conducted for DOE-2.2. However, both DOE-2.1e and DOE-2.2 have been tested using the IEA HVAC BESTEST volume 2 (cases E300-E545) (Neymark & Judkoff, 2004) and the results of this activity will be described in the following section.

A.5 COMPARATIVE VALIDATION OF DOE2.1E & DOE-2.2

Neymark & Judkoff (2004) present the results of a comparative validation of six simulation tools using the second set of the IEA's HVAC BESTEST (cases E300-E545). These tests are designed to test a program's modeling capabilities on the working-fluid side of the coil in an hourly dynamic context over an expanded range of performance conditions. In addition to DOE-2.1e & DOE-2.2, the study also evaluated and compared the following software: EnergyPlus, CODYRUN, HOT3000, and TRNSYS. Results reported by Neymark & Judkoff show that both DOE-2.1e & DOE-2.2 2 exhibits a good level of agreement with the other programs for annual energy use, loads, and other annual average results. They conclude that, for both software, the annual summed or averaged results for system performance and zone conditions appear satisfactory when compared with other programs.

On the other hand, similar disagreements are mentioned in the report for both DOE-2.1e and DOE-2.2 compared to the other software evaluated within the study. In the case of DOE-2.1e, the report relates these disagreements to the inability of software to iterate systems and loads calculations within a time step, and its inability to apply sub-hourly time steps. Neymark & Judkoff, however, report that DOE-2.2 code authors are planning to examine remaining disagreements and revise their software if necessary; while for DOE-2.1e, they report that the code authors do not plan to rewrite the HVAC calculations for DOE-2.1e. The results show that, with regard to annual energy use, the use of DOE-2.2 does not result in noticeable differences compared to DOE-2.1e as well to the other software investigated in the report.

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APPENDIX B
PROTOTYPES' INPUTS AND MODEL VALIDATIONS

B.1 INTRODUCTION

This appendix includes summaries of the model inputs for each of the residential and commercial prototypes developed within this study. The characteristics of each prototype are summarized in a table including building form, shell characteristics, internal loads, system types, zone divisions and descriptions. The results of the validation of each prototype, by comparing the resulting annual energy use to average values of the EIA's CBECS & RECS surveys (EIA 2002 & 2004b), are also included.

B.2 RESIDENTIAL PROTOTYPES

B.2.1 Single Family House Prototypes

Table B-1 includes a summary of the model inputs for the large and small sized SFH prototypes compared to the inputs for the base-line average-sized SFH. Figure B-1 shows a comparison of the annual energy consumption for each of the prototypes to the average energy consumption values derived from the 2001 EIA RECS survey (EIA, 2004b).

Table B-1 Model Inputs for Single-Family House Prototypes

Parameter	Small SFH	Base-line	Large SFH
Building form	Square – garage on south side	Square – garage on south side	Square – garage on south side
Dimensions (ft)	37*37 + 22*15 garage	42.4 x 42.4 + 22*15 garage	50*50 + 22*25 garage
No. of floors	1	1	1
Conditioned floor are (ft^2)	1370	1800	2500
Garage area (ft^2)	330	330	550
Total floor area (ft^2)	1700	2130	3050

Table B-1 Continued

Parameter	Small SFH	Base-line	Large SFH
Shell Characteristics			
Wall R-value	R-25.	R-25.	R-25.
Roof R-Value	R-49	R-49	R-49
Floor R-Value	R-10 & 4 ft	R-10 & 4 ft	R-10 & 4 ft
Infiltration (ACH)	0.5073	0.5073	0.5073
Percentage of Glazing	18% of gross area	18% of gross area	18% of gross area
Distribution of glazing	Equal on 4 facades	Equal on 4 facades	Equal on 4 facades
Window U-value	0.33	0.33	0.33
Glass-type-code	2634	2634	2634
External shading	N/A	N/A	N/A
Internal loads			
No. of occupants	2	3	4
Internal lighting density (W/ft^2.day)	3.10235	2.88509	2.69014
Garage lighting density (W/ft^2.day)	0.83022	0.83022	0.49813
External lighting (kW/day)	0.68493	0.68493	0.68493
Refrigeration loads (W/ft^2.day)	1.33884	1.01940	0.73315
Washer/dryer loads (W/ft^2.day)	1.56799	1.43234	1.20164
Cooking loads (W/ft^2.day)	1.55218	1.23410	0.92515
Plug appliances (W/ft^2.day)	4.57534	4.57534	4.57534
Hot water usage (gal/person. day)	25	20	17.5
System characteristics			
System type	RESYS2	RESYS2	RESYS2
Heating source	NG Furnace	NG Furnace	NG Furnace
Heating efficiency (AFUE)	78%	78%	78%
Cooling source	Air-cooled AC	Air-cooled AC	Air-cooled AC
Cooling efficiency (SEER)	10	10	10
Domestic water heater type	Natural Gas	Natural Gas	Natural Gas
Water heater efficiency (EF)	61.3%	59.4%	57.5%
Storage volume	30	40	50
Water heater capacity(kBtu)	36	36	38
Water heater setpoint (F)	120	120	120
Thermostat settings			
Cooling setpoint (F)	78	78	78
Heating setpoint (F)	68	68	68
Setback (F)	5 for 6 hours	5 for 6 hours	5 for 6 hours

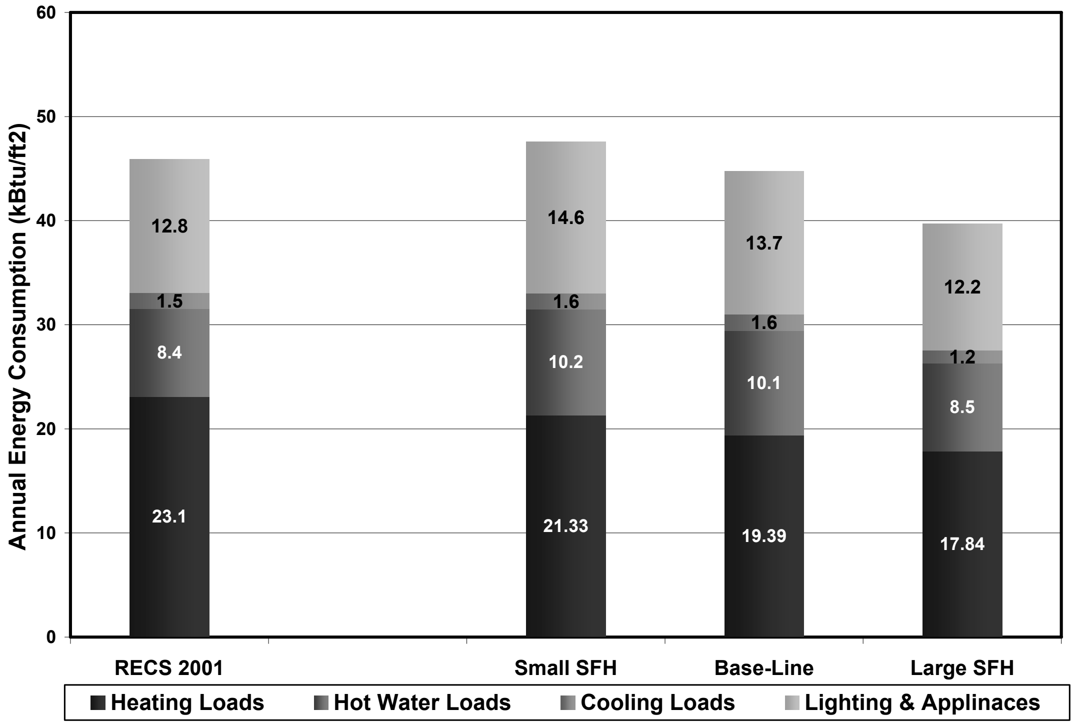

Figure B-1 Annual Energy Consumption per Unit Area for the Three Single-Family House Prototypes Compared to Average 2001 RECS Values for Different End Uses

B.2.2 Alternative housing typologies Prototypes

Table B-2 includes a summary of the model inputs for several alternative housing typologies prototypes including attached single family house, town home, live-work unit, and multi-family home. Figures B-2 through B-4 show a comparison of the annual energy consumption for each of the prototypes to the corresponding average energy consumption values derived from the 2001 EIA RECS survey (EIA, 2004b). RECS values for the attached SFH prototype were based on energy use per unit area for new construction (2000-2001) adjusted to account for housing typology (single family attached with 3 bedrooms); climate region (> 7000 HDD); heated floor area (1,600 – 1,999); and heating fuel (natural gas). The same values were used for the town homes and multi-family homes prototypes except that the housing typologies used in the adjustment were: single family attached < 3 bedrooms for the town home prototype, and the apartments (5 or more units) for the multi-family houses.

Table B-2 Model Inputs for Alternative Housing Typologies

Parameter	Attached SFH	Town Homes	Live Work	Multi-family
Number of dwelling units	2	5	5	12
Unit dimensions (ft)	42.4 x 42.4 + 22*15 garage	30 x 50	25 x 40 (per floor)	33.15 x 33.15
No. of floors	1	1	2	3 (4 per floor)
Conditioned floor are/unit (ft^2)	1800	1500	2000	1100
Garage area/unit (ft^2)	330	N/A	N/A	N/A
Total floor area (ft^2)	2130	1500	2000	1100
Shell Characteristics				
Wall R-value	R-25.	R-16	R-16	R-16
Roof R-Value	R-49	R-38	R-38	R-38
Floor R-Value	R-10 & 4 ft	R-9 & 4 ft	R-9 & 4 ft	R-9 & 4 ft
Infiltration (ACH)	0.5073	0.5073	0.5073	0.5073
Percentage of Glazing	18% of gross wall area	25% of gross wall area	25% of gross wall area	25% of gross wall area
Distribution of glazing	Equal on 4 facades	Equal on 2 external facades	Equal on 2 external facades	Equal on 2 external facades
Window U-value	0.33	0.33	0.33	0.33
Glass-type-code	2634	2634	2634	2634
External shading	N/A	N/A	N/A	N/A
Internal loads				
No. of occupants	2	2	2	2
Internal lighting density (W/ft^2.day)	3.10235	3.02283	3.43836	3.32503
Garage lighting density (W/ft^2.day)	0.83022	N/A	N/A	N/A
External lighting (kW/day)	0.68493	0.68493	0.68493	0.68493
Refrigeration loads (W/ft^2.day)	1.33884	1.22192	1.83288	1.66625
Washer/dryer loads (W/ft^2.day)	1.56799	1.43105	2.14658	1.95143
Cooking loads (W/ft^2.day)	1.55218	1.41662	2.12493	1.93176
Plug appliances (W/ft^2.day)	4.57534	4.57534	4.57534	4.57534
Hot water usage (gal/per. day)	25	25	25	25

Table B-2 Continued

Parameter	Attached SFH	Town Homes	Live Work	Multi-family
System characteristics				
System type	RESYS2	RESYS2	RESYS2	RESYS2
Heating source	NG Furnace	NG Furnace	NG Furnace	NG Furnace
Heating efficiency (AFUE)	78%	78%	78%	78%
Cooling source	Air-cooled AC	Air-cooled AC	Air-cooled AC	Air-cooled AC
Cooling efficiency (SEER)	10	10	10	10
Domestic water heater type	Natural gas	Natural gas	Natural gas	Natural gas
WH efficiency (EF)	59.4%	61.3%	61.3%	61.3%
Storage volume	40 (per unit)	30 (per unit)	30 (per unit)	306
Heater capacity (kBtu)	36 (per unit)	36 (per unit)	36 (per unit)	331
Water heater setpoint (F)	120	120	120	120
Thermostat settings				
Cooling setpoint (F)	78	78	78	78
Heating setpoint (F)	68	68	68	68
Setback (F)	5 for 6 hours	5 for 6 hours	5 for 6 hours	5 for 6 hours

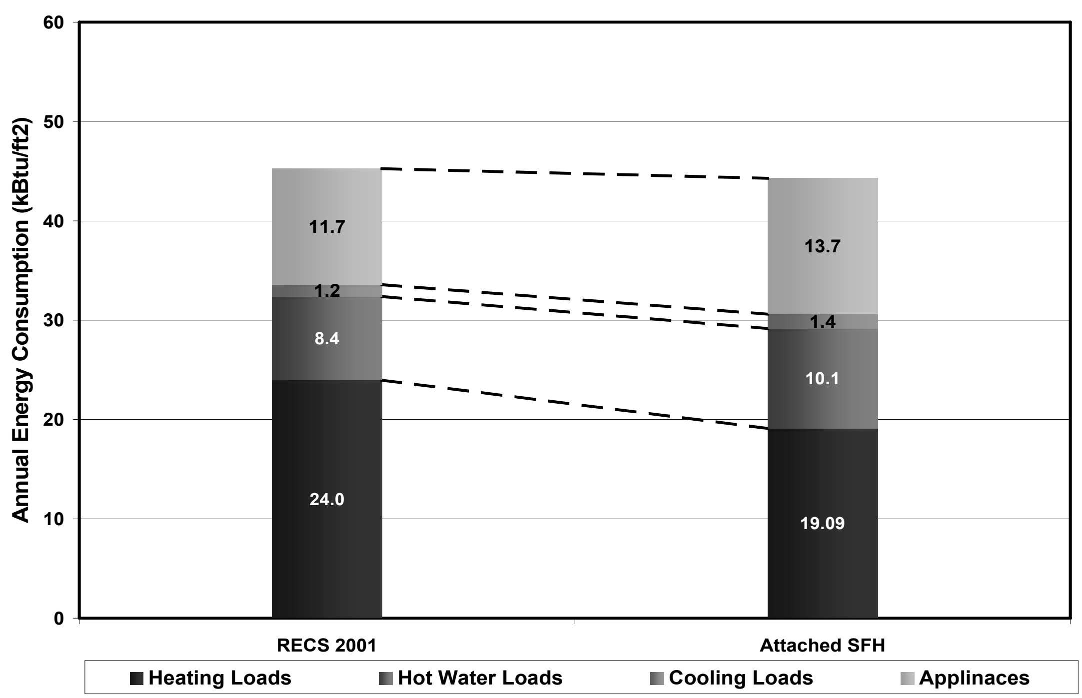

Figure B-2 Annual Energy Consumption per Unit Area for the Attached Single-Family House Prototypes Compared to Average 2001 RECS Values for Different End Uses

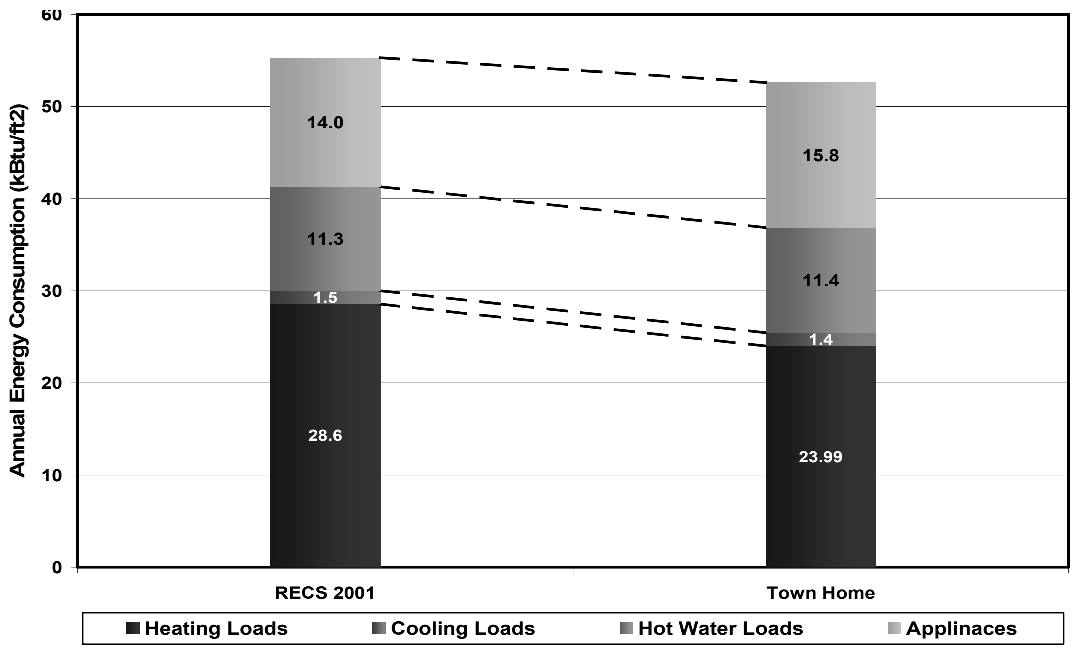

Figure B-3 Annual Energy Consumption per Unit Area for the Town Home Prototype Compared to Average 2001 RECS Values for Different End Uses

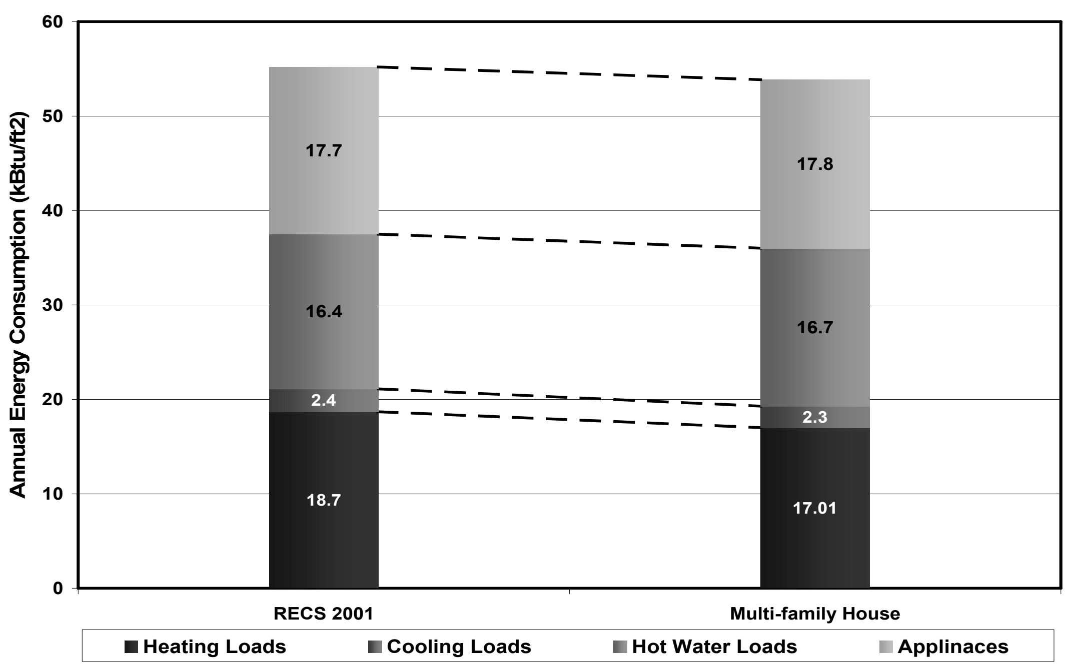

Figure B-4 Annual Energy Consumption per Unit Area for the Multi-Family House Prototype Compared to Average 2001 RECS Values for Different End Uses

B.3 COMMERCIAL PROTOTYPES

B.3.1 Retail Prototypes

Table B-3 includes a summary of the model inputs for the three retail prototypes developed for this study (for the low use mix, medium use mix, and high us mix design alternatives). The table also includes the fuel to electricity ratio of the prototype compared to fuel to electricity ratios resulting from retail prototypes developed by Huang et al. (1991) for Detroit, MI. Figure B-5, however, shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity (mercantile – enclosed and strip malls), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

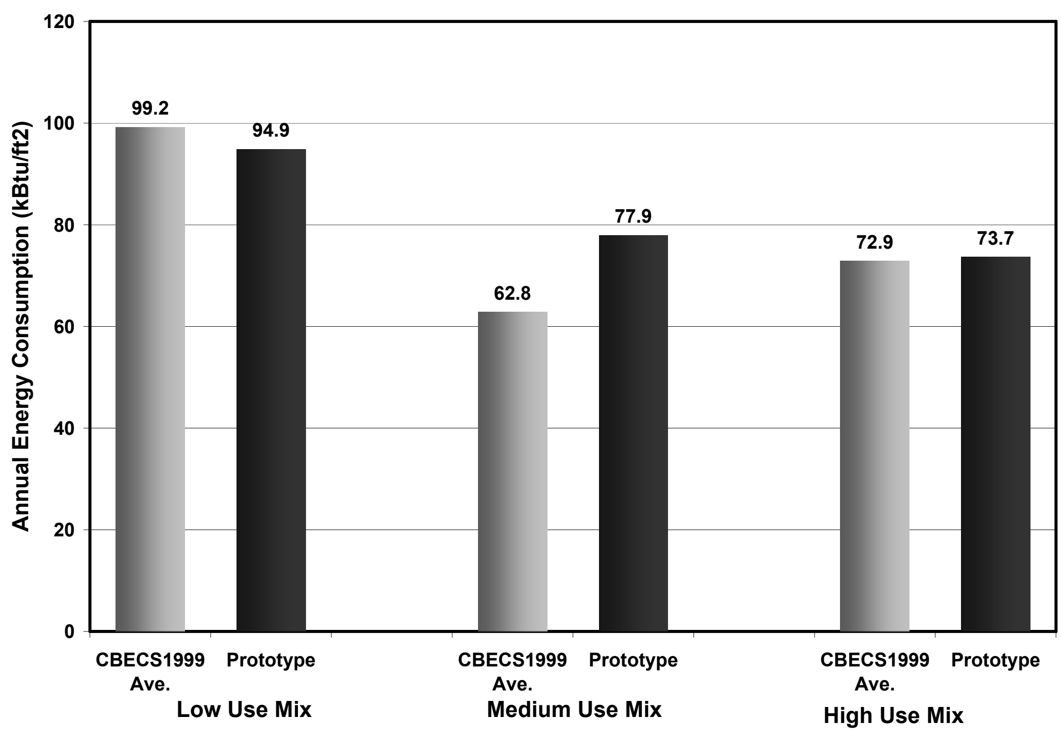

Figure B-5 Annual Energy Consumption per Unit Area for the Retail Prototypes Compared to Average 1999 CBECS Values

Table B-3 Model Inputs for the Retail Prototypes

Parameter	Low use mix	Medium use mix	High use mix
Building form	Square	Rectangle (0.5 aspect ration)	Rectangle (0.5 aspect ration)
Dimensions (ft)	70.7*70.7 ft	100 x 200	100*200
No. of floors	1	1	1
Floor area (ft^2)	5,000	20,000	40,000
Building height (ft)	15 (11 flr to ceiling)	15 (11 flr to ceiling)	15 (11 flr to ceiling)
Shell Characteristics			
Construction type	Metal frames	Metal frames	Metal frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)			
Perimeter	0.5	0.5	0.5
Core	0.2	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4	0.4
Glass-type-code	2641	2641	2641
External shading PF	50%	50%	50%
Internal loads			
Zone descriptions	Perimeter & core	Perimeter & core	Perimeter & core
Occupancy (ft/person)	135	135	135
General lighting (W/ft^2.day)	1.5	1.5	1.5
Task lighting (W/ft^2)	1.6 (16% of area)	1.6 (8% of area)	1.6 (8% of area)
External lighting (W/ft^2)	0.5757	0.4554	0.4554
Equipment loads (W/ft^2)	0.4	0.4	0.4
Refrigeration loads (W/ft^2)	0.06	0.06	0.06
Cooking loads (W)	0.01	0.01	0.01
Hot water load (btu/hr.ft^2)	0.2	0.148	0.148

Table B-3 Continued

Parameter	Low use mix	Medium use mix	High use mix
System characteristics			
System type	PSZ	PSZ	PSZ
Heating source	Furnace	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX	Air-cooled DX
Cooling efficiency (SEER)	10	10	10
Outside air (CFM/person)	15	15	15
Domestic water heater type	Natural gas	Natural gas	Natural gas
Thermostat settings			
Cooling setpoint (F)	72	72	72
Heating setpoint (F)	74	78	78
Heating setback temp. (F)	60	60	60
Cooling setback temp (F)	85	85	85

B.3.2 Office Prototypes

Table B-4 includes a summary of the model inputs for the two office prototypes developed for this study (for the medium use mix, and high use mix design alternatives); while figure B-6 shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity (office), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

Table B-4 Model Inputs for the Office Prototypes

Parameter	Medium use mix	High use mix
Building form	Square	Rectangle (0.5 aspect ratio)
Dimensions (ft)	100 x 100	100 x 200
No. of floors	1	1
Floor area (ft^2)	10,000	20,000
Building height (ft)	12 (9 floor to ceiling)	12 (9 floor to ceiling)
Shell Characteristics		
Construction type	Metal Frames	Metal Frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)		
Perimeter	0.5	0.5
Core	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4
Glass-type-code	2641	2641
External shading projection factor	50%	50%
Internal loads		
Zone descriptions	Perimeter & core	Perimeter & core
Occupancy (ft/person)	189	189
General lighting (W/ft^2.day)	1.0	1.0
Task lighting (W/ft^2)	0.35 (64% of floor area)	0.35 (33.6%)
External lighting (W/ft^2)	0.1638	0.1338
Equipment loads (W/ft^2)	0.7	0.7
Refrigeration loads (W/ft^2)	0.02	0.02
Cooking loads (W)	0.05	0.05
Hot water load (btu/hr.ft^2)	2.0	2.0

Table B-4 Continued

Parameter	Medium use mix	High use mix
System characteristics		
System type	PSZ	PSZ
Heating source	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX
Cooling efficiency (SEER)	10	10
Outside air (CFM/person)	15	15
Domestic water heater type	Natural gas	Natural gas
Thermostat settings		
Cooling setpoint (F)	74	71
Heating setpoint (F)	78	78
Heating setback temp. (F)	65	65
Cooling setback temp (F)	85	85

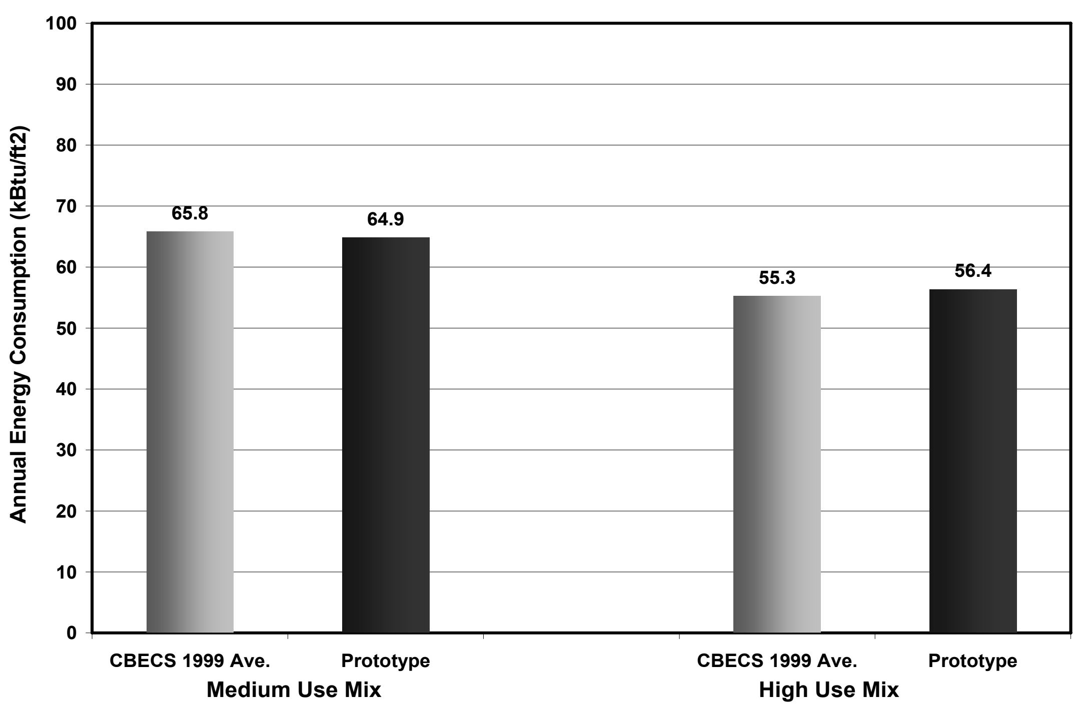

Figure B-6 Annual Energy Consumption per Unit Area for the Office Prototypes Compared to Average 1999 CBECS Values

B.3.3 Community Center Prototypes

Table B-5 includes a summary of the model inputs for the two community center prototypes developed for this study (for the low use mix, and high use mix design alternatives); while figure B-7 shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity (pubic assembly), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

Table B-5 Model Inputs for the Community Center Prototypes

Parameter	Low use mix	High use mix
Building form	Square	Rectangle (0.5 aspect ratio)
Dimensions (ft)	100 x 100	100 x 200
No. of floors	1	1
Floor area (ft^2)	10,000	20,000
Building height (ft)	12 (9 floor to ceiling)	12 (9 floor to ceiling)
Shell Characteristics		
Construction type	Metal Frames	Metal Frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)		
Perimeter	0.5	0.5
Core	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4
Glass-type-code	2641	2641
External shading PF	50%	50%

Table B-5 Continued

Parameter	Low use mix	High use mix
Internal loads		
Zone descriptions	Convention & meetings (49.5%); Gym (25.5%); Office (12.5%); Lobby (12.5%).	Convention & meetings (52%); Gym (24%); Office (15.6%); Lobby (8.2%).
Occupancy (ft/person)	Convention & meetings: 100; Gym: 50; Office: 189; Lobby: 100.	Convention & meetings: 100; Gym: 50; Office: 189; Lobby: 100.
General lighting (W/ft^2.day)	Convention & meetings: 1.3; Gym : 1.4; Office: 1.1; Lobby: 1.3	Convention & meetings: 1.3; Gym : 1.4; Office: 1.1; Lobby: 1.3
Task lighting (W/ft^2)	Convention & meeting: 0.2; Office: 1.35.	Convention & meeting: 0.2; Office: 1.35.
External lighting (W/ft^2)	0.3	0.3
Equipment loads (W/ft^2)	Convention & meetings: 0.25; Gym : 0.1; Office: 0.7;	Convention & meetings: 0.25; Gym : 0.1; Office: 0.7
Refrigeration loads (W/ft^2)	Office: 0.02	Office: 0.02
Cooking loads (W)	Office: 0.05	Office: 0.05
Hot water load (btu/hr.ft2)	0.5	0.5
System characteristics		
System type	PSZ	PSZ
Heating source	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX
Cooling efficiency (SEER)	10	10
Outside air (CFM/person)	Convention & meetings: 20; Gym : 20; Office: 15; Lobby: 15	Convention & meetings: 20; Gym : 20; Office: 15; Lobby: 15
Domestic water heater type	Natural gas	Natural gas
Thermostat settings		
Cooling setpoint (F)	68	68
Heating setpoint (F)	78	78
Heating setback temp. (F)	55	55
Cooling setback temp (F)	85	85

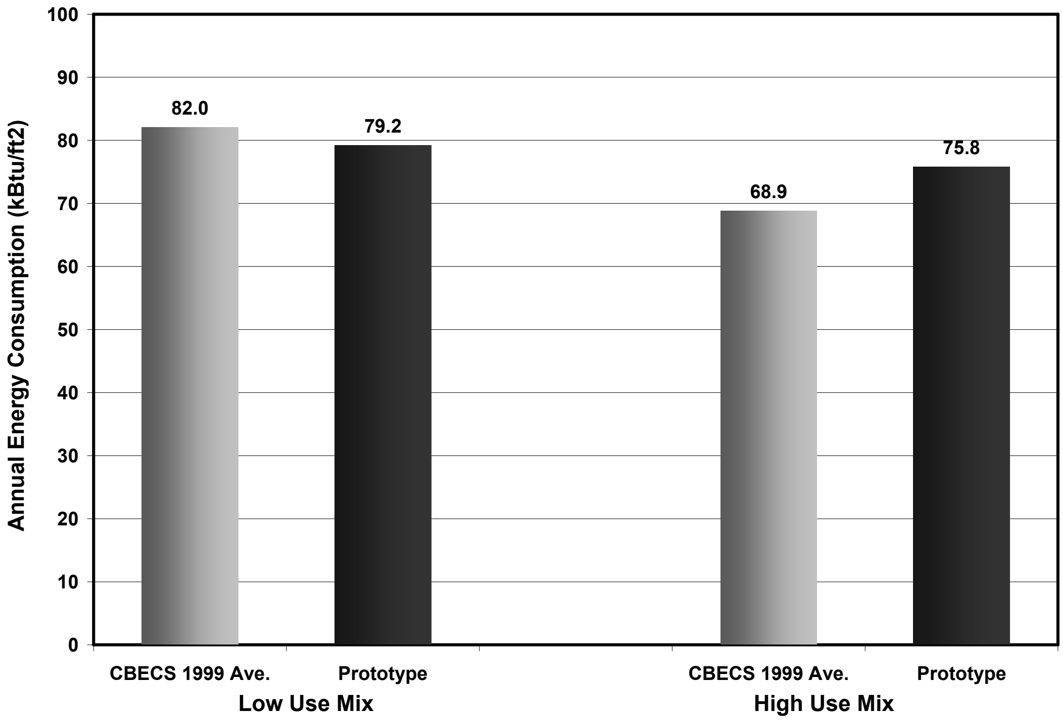

Figure B-7 Annual Energy Consumption per Unit Area for the Community Center Prototypes Compared to Average 1999 CBECS Values

B.3.4. Child Care Center Prototypes

Table B-6 includes a summary of the model inputs for the two child care center prototypes developed for this study (for the low use mix, and high use mix design alternatives); while figure B-8 shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity (education), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

Table B-6 Model Inputs for the Child Care Center Prototypes

Parameter	Low use mix	High use mix
Building form	Square	Rectangle (0.5 aspect ratio)
Dimensions (ft)	77.45*77.45	77.45*154.9
No. of floors	1	1
Floor area (ft^2)	6,000	12,000
Building height (ft)	12 (9 floor to ceiling)	12 (9 floor to ceiling)
Shell Characteristics		
Construction type	Metal Frames	Metal Frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)		
Perimeter	0.5	0.5
Core	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4
Glass-type-code	2641	2641
External shading PF	50%	50%
Internal loads		
Zone descriptions	Classes (68.8%); Reading area (15.6%); Office (5.6%); Kitchen (10%).	Convention & meetings (66.9%); Gym (16.5%); Office (7.8%); Lobby (9%).
Occupancy (ft/person)	Classes: 90; Reading area: 80; Office: 189; Kitchen: 200.	Classes: 90; Reading area: 80; Office: 189; Kitchen: 200.
General lighting (W/ft^2.day)	Classes: 1.4; Reading area: 1.7; Office: 1.1; Kitchen: 1.2	Classes: 1.4; Reading area: 1.7; Office: 1.1; Kitchen: 1.2
Task lighting (W/ft^2)	Office: 1.35.	Office: 1.35.
External lighting (W/ft^2)	0.2283	0.1865

Table B-6 Continued

Parameter	**Low use mix**	**High use mix**
Equipment loads (W/ft^2)	Classes: 0.5; Reading area: 0.5; Kitchen: 25	Classes: 0.5; Reading area: 0.5; Kitchen: 25
Cooking loads (W/ft^2)	Kitchen: 10	Kitchen: 10
Process Loads (Btu/ft. hr)	Kitchen: 150	Kitchen: 140
Hot water load (Gal/per. day)	Classes: 0.6	Classes: 0.6
System characteristics		
System type	PSZ	PSZ
Heating source	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX
Cooling efficiency (SEER)	10	10
Outside air (CFM/person)	Classes: 15; Reading area: 15; Office: 15; Kitchen: 50	Classes: 15; Reading area: 15; Office: 15; Kitchen: 50
Domestic water heater type	Natural gas	Natural gas
WH Efficiency (EF)	0.634	0.5997
Thermostat settings		
Cooling setpoint (F)	71	71
Heating setpoint (F)	74	74
Heating setback temp. (F)	55	55
Cooling setback temp (F)	85	85

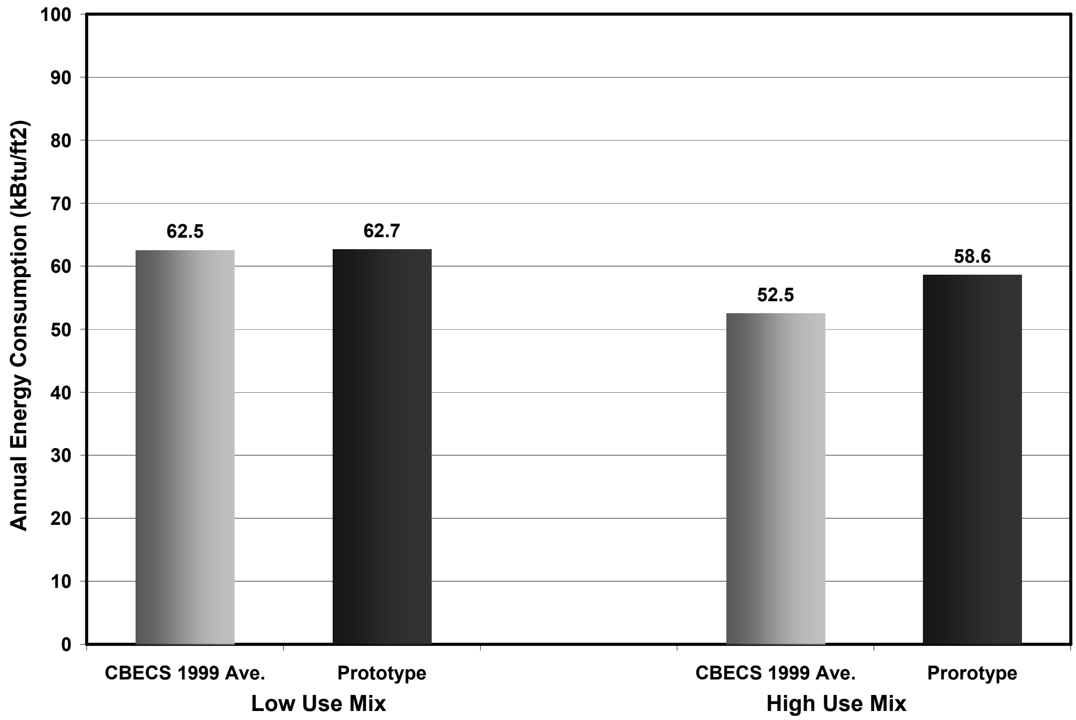

Figure B-8 Annual Energy Consumption per Unit Area for the Child Care Center Prototypes Compared to Average 1999 CBECS Values

B.3.5 Restaurant Prototypes

Table B-7 includes a summary of the model inputs for the two restaurant prototypes developed for this study (fast food restaurant and sit-down restaurant); while figure B-9 shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity (food services), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

Table B-7 Model Inputs for Restaurant Prototypes

Parameter	Fast Food Restaurant	Sit Down Restaurant
Building form	Square	Square
Dimensions (ft)	50x50	70.7x70.7
No. of floors	1	1
Floor area (ft^2)	2,500	5,000
Building height (ft)	12 (10 floor to ceiling)	12 (9 floor to ceiling)
Shell Characteristics		
Construction type	Metal Frames	Metal Frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)		
Perimeter	0.5	0.5
Core	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4
Glass-type-code	2641	2641
External shading projection factor	50%	50%
Internal loads		
Zone descriptions	Dining (58%); Kitchen (42%).	Dining (70%); Kitchen (30%).
Occupancy (ft/person)	Dining 35; Kitchen 115.	Dining: 50 Kitchen: 50.
General lighting (W/ft^2.day)	Dining 0.9; Kitchen 1.2.	Dining: 0.9 Kitchen: 1.2.
Task lighting (W/ft^2)	Dining: 1.0.	Fast Food: 0.5
External lighting (W/ft^2)	0.3672	0.2333
Equipment loads (W/ft^2)	N/A.	Dining: 0.1 Kitchen: 7.2.
Refrigeration loads (W/ft^2)	Dining 1.4; Kitchen 1.4.	Dining: 0.9 Kitchen: 0.9.

Table B-7 Continued

Parameter	Fast Food Restaurant	Sit Down Restaurant
Cooking loads (W/ft^2)	Dining 0.0; Kitchen 10.	Dining: 0.1 Kitchen: 10.
Process Loads (Btu/ft. hr)	Kitchen 90.	Kitchen: 68.
Hot water load (Gal/per. day)	Dining 0.7; Kitchen 0.7.	Dining: 0.7 Kitchen: 0.7.
System characteristics		
System type	PSZ	PSZ
Heating source	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX
Cooling efficiency (SEER)	10	10
Outside air (CFM/person)	Dining 15; Kitchen 135 (7 ACH).	Dining: 15 Kitchen: 45 (6 ACH)
Domestic water heater type	Natural gas	Natural gas
WH Efficiency (EF)	0.6364	0.6035
Thermostat settings		
Cooling setpoint (F)	68	70
Heating setpoint (F)	75	78
Heating setback temp. (F)	55	55
Cooling setback temp (F)	85	85

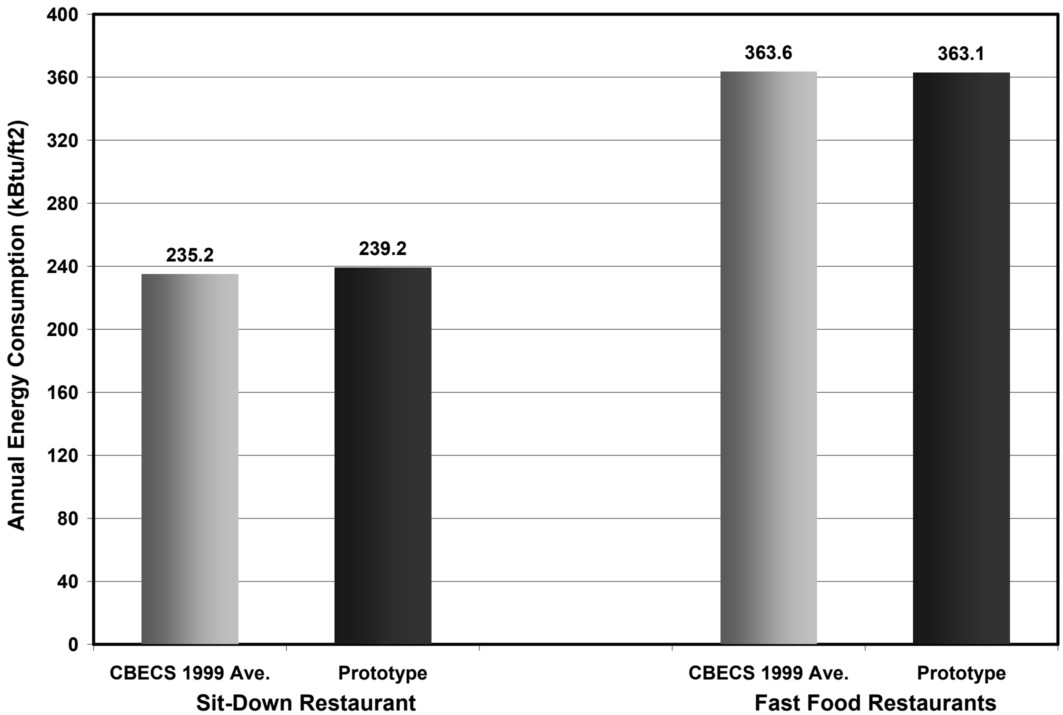

Figure B-9 Annual Energy Consumption per Unit Area for the Restaurants Prototypes Compared to Average 1999 CBECS Values

B.3.6 Food Store & Grocery Prototypes

Table B-8 includes a summary of the model inputs for the food store & grocery prototypes developed for this study; while figure B-10 shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity (food sales), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

Table B-8 Model Inputs for the Food Store and Grocery Prototypes

Parameter	Food Store	Grocery
Building form	Square	Square
Dimensions (ft)	70.7x70.7	141.4x141.4
No. of floors	1	1
Floor area (ft^2)	5,000	20,000
Building height (ft)	15 (11 floor to ceiling)	18 (14 floor to ceiling)
Shell Characteristics		
Construction type	Metal Frames	Metal Frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)		
Perimeter	0.5	0.5
Core	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4
Glass-type-code	2641	2641
External shading PF	50%	50%
Internal loads		
Zone descriptions	Sales (60%); Dry storage (20%); Bakery (12%); Deli (5%); Office (3%).	Sales (72%); Dry storage (14%); Bakery (6%); Deli (6%); Office (2%).
Occupancy (ft/person)	Sales 325; Dry storage 880; Bakery 220 Deli 220; Office 130.	Sales 325; Dry storage 880; Bakery 220 Deli 220; Office 130.
General lighting (W/ft^2.day)	Sales: 1.6; Dry storage: 0.8; Bakery: 1.6 Deli: 1.6; Office: 1.1.	Sales: 1.6; Dry storage: 0.8; Bakery: 1.6 Deli: 1.6; Office: 1.1...

Table B-8 Continued

Parameter	Food Store	Grocery
Task lighting (W/ft^2)	Sales: 0.4.	Sales: 0.4.
External lighting (W/ft2)	0.552	0.476
Equipment loads (W/ft^2)	Sales: 0.4; Dry storage: 0.4; Bakery: 7.5 Deli: 3.8; Office: 0.5.	Sales: 0.5; Dry storage: 0.5; Bakery: 10 Deli: 5; Office: 0.6.
Refrigeration loads (W/ft^2)	Sales: 5.5	Sales: Freezer: 1.172 (4 Btu/ft^2) Meet: 3.224 (11 Btu/ft^2) Produce: 2.638 (9 Btu/ft^2)
Cooking loads (W/ft^2)	Kitchen: 5.0.	Kitchen: 5.0.
Hot water load	4 Btu/hr. ft^2	50 Btu/person .hr
System characteristics		
System type	PSZ	PSZ
Heating source	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX
Cooling efficiency (EER)	10.1	10.1
Outside air (CFM/person)	Sales: 15; Dry storage: 15; Bakery: 180 (5 ACH) Deli: 15; Office: 15.	Sales: 15; Dry storage: 15; Bakery: 280 (5 ACH) Deli: 15; Office: 15...
Domestic water heater type	Natural gas	Natural gas
Thermostat settings		
Cooling setpoint (F)	70	70
Heating setpoint (F)	76	76
Heating setback temp. (F)	60	60
Cooling setback temp (F)	85	85

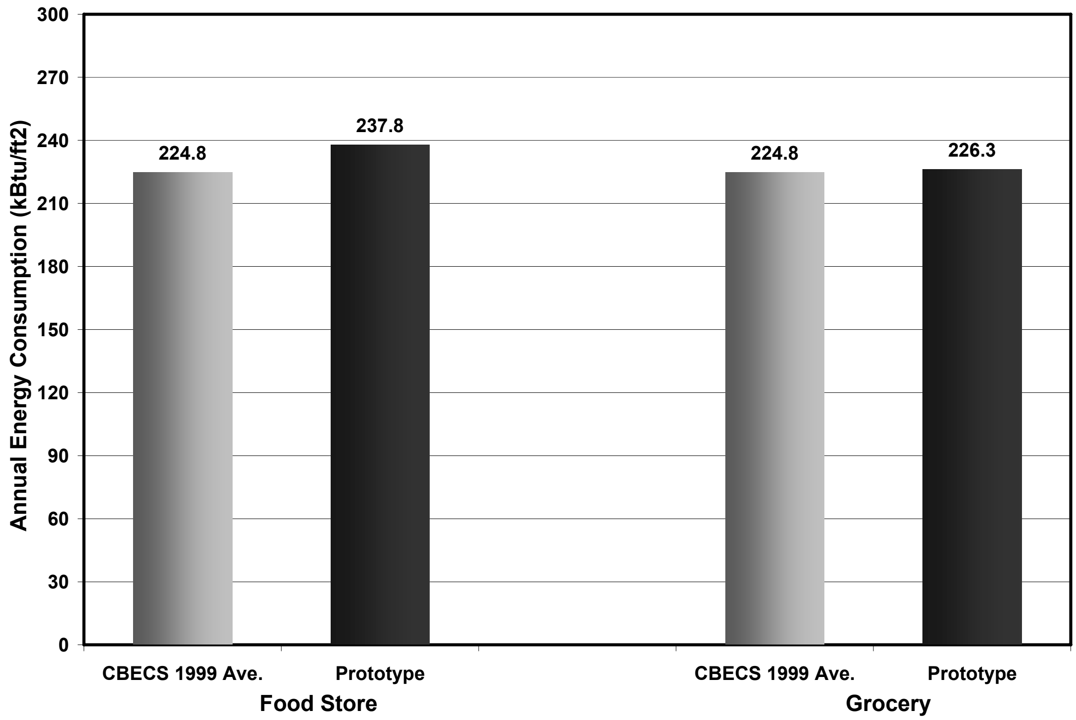

Figure B-10 Annual Energy Consumption per Unit Area for the Food Store & Grocery Prototypes Compared to Average 1999 CBECS Values

B.3.7 Bakery & Laundry/Dry Cleaner Prototypes

Table B-9 includes a summary of the model inputs for the bakery & laundry/dry cleaner prototypes developed for this study; while figure B-10 shows a comparison between the annual energy consumption of each of the prototypes compared to average values derived from the EIA's CBECS 1999 survey (EIA, 2002). CBECS values were based on total consumption and gross energy intensity values for new construction (1990 – 1999) adjusted to account for building floor space range, principal building activity ("food sales" for the bakery prototype, and "services" for the laundry/dry cleaners), climate zone (> 7000 HDD), space heating fuel (natural gas), cooling energy source (electricity), and heating equipment (furnace).

Table B-9 Model Inputs for the Bakery and Laundry/Dry Cleaner Prototypes

Parameter	**Small Bakery**	**Large Bakery**	**Laundry**
Building form	Square	Square	Square
Dimensions (ft)	50x50	70.7x70.7	100x100
No. of floors	1	1	1
Floor area (ft^2)	2,500	5,000	10,000
Building height (ft)	15 (11 floor to ceiling)	15 (11 floor to ceiling)	10 (8 floor to ceiling)
Shell Characteristics			
Construction type	Metal Frames	Metal Frames	Metal Frames
Wall R-value	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.	R-13 batt + R-3 ext. Sheet.
Roof R-Value	R-24 Ext.	R-24 Ext.	R-24 Ext.
Floor R-Value	R-8 & 4 ft	R-8 & 4 ft	R-8 & 4 ft
Infiltration (ACH)			
Perimeter	0.5	0.5	0.5
Core	0.2	0.2	0.2
Percentage of Glazing	35% of gross wall area.	35% of gross wall area.	35% of gross wall area.
Distribution of glazing	Equal on all facades	Equal on all facades	Equal on all facades
Window U-value	0.4	0.4	0.4
Glass-type-code	2641	2641	2641
External shading projection factor	50%	50%	50%
Internal loads			
Zone descriptions	Sales (60%); Kitchen (40%).	Sales (60%); Kitchen (40%).	Laundry (82.5%); Lobby (17.5%).
Occupancy (ft/person)	Sales 325; Kitchen 220.	Sales 325; Kitchen 220.	Laundry 140; Lobby 400.
General lighting (W/ft^2.day)	Sales 1.7; Kitchen 1.2.	Sales 1.7; Kitchen 1.2.	Laundry 1.2; Lobby 1.3.
Task lighting (W/ft^2)	Sales: 0.4.	Sales: 0.4.	N/A
External lighting (W/ft2)	0.428	0.276	0.276
Equipment loads (W/ft^2)	Sales 0.1; Kitchen 7.5.	Sales 0.1; Kitchen 5.0.	Laundry 3.0; Lobby 0.0.

Table B-9 Continued

Parameter	**Small Bakery**	**Large Bakery**	**Laundry**
Cooking loads (W/ft^2)	Kitchen: 5.0.	Kitchen: 5.0.	
Hot water load	4 Btu/hr. ft^2	4 Btu/hr. ft^2	20 Btu/hr.ft^2
System characteristics			
System type	PSZ	PSZ	PSZ
Heating source	Furnace	Furnace	Furnace
Heating efficiency (AFUE)	78%	78%	78%
Cooling source	Air-cooled DX	Air-cooled DX	Air-cooled DX
Cooling efficiency	10 (SEER)	10 (SEER)	10.1 (EER)
Outside air (CFM/person)	Sales 15; Kitchen 180 (5 ACH).	Sales 15; Kitchen 180 (5 ACH).	Laundry 54 (1 ACH); Lobby 15.
Domestic water heater type	Natural gas	Natural gas	Natural gas
Thermostat settings			
Cooling setpoint (F)	72	70	72
Heating setpoint (F)	74	74	76
Heating setback temp. (F)	60	60	60
Cooling setback temp (F)	85	85	85

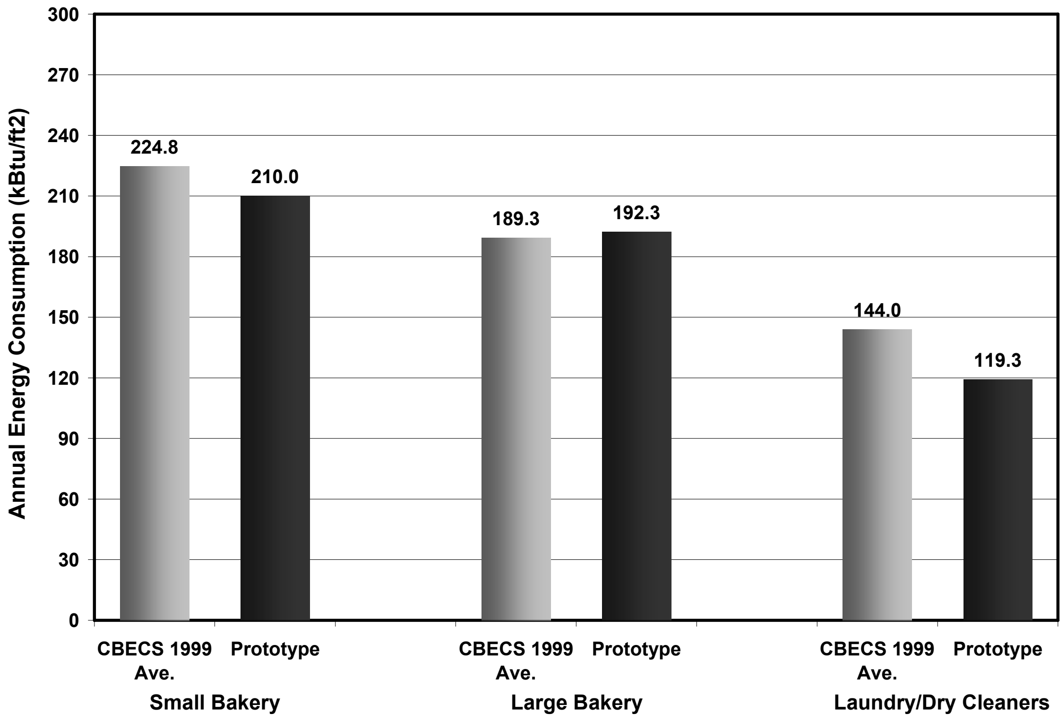

Figure B-11 Annual Energy Consumption per Unit Area for the Bakery & Laundry/Dry Cleaners Prototypes Compared to Average 1999 CBECS Values

APPENDIX C
COMMUNITY DESIGN VARIATIONS

This appendix presents the community design variations & optimization scenarios investigated in this study. The appendix includes isometric views of the design variation within five of design parameters: 1) density of urban form; 2) mix of uses; 3) street configuration; 4) hosing typology; and 5) utilization of renewable energy resources. As design variations for the "envelope and systems' efficiencies" parameter and the three cogeneration system parameters do not result in changes to the isometric view of the community, they are not included. The appendix also includes isometric views of the four optimization scenarios developed in the study. Finally, tables C-1 through C-4 present a summary of the community design & energy use characteristics for all design variations and optimization scenarios.

C.1 COMMUNITY DESIGN VARIATIONS

C.1.1 Density of Urban Form

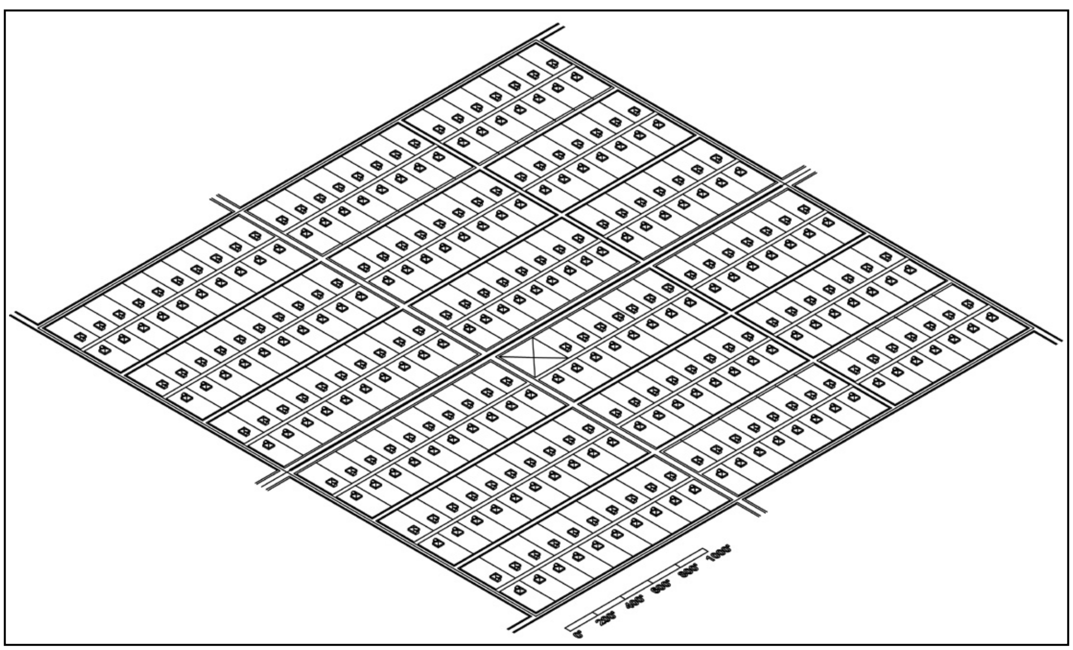

Figure C-1 Isometric View of the 1 du/ac Density Design Alternative

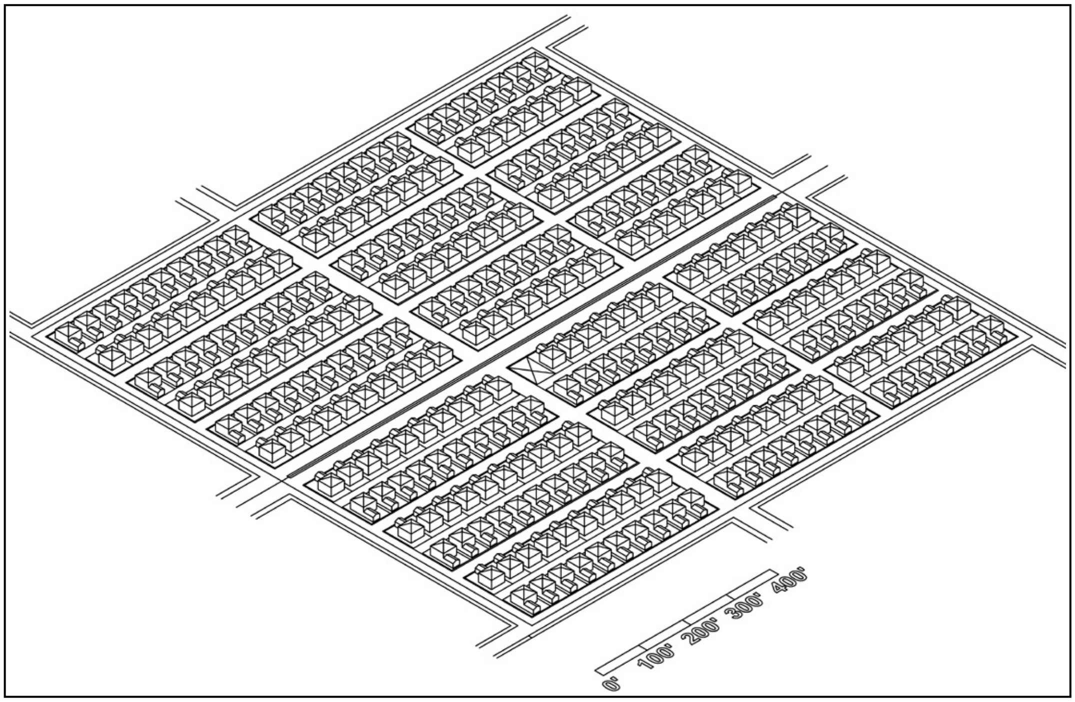

Figure C-2 Isometric View of the 10 du/ac Density Design Alternative

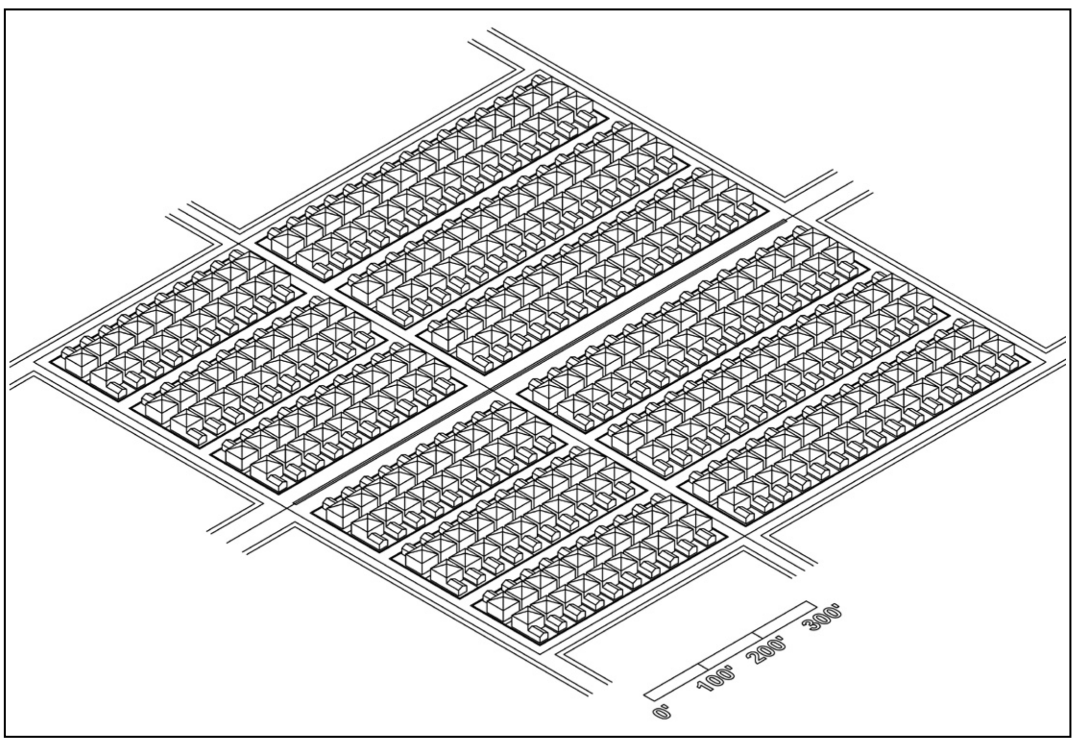

Figure C-3 Isometric View of the 15 du/ac Density Design Alternative

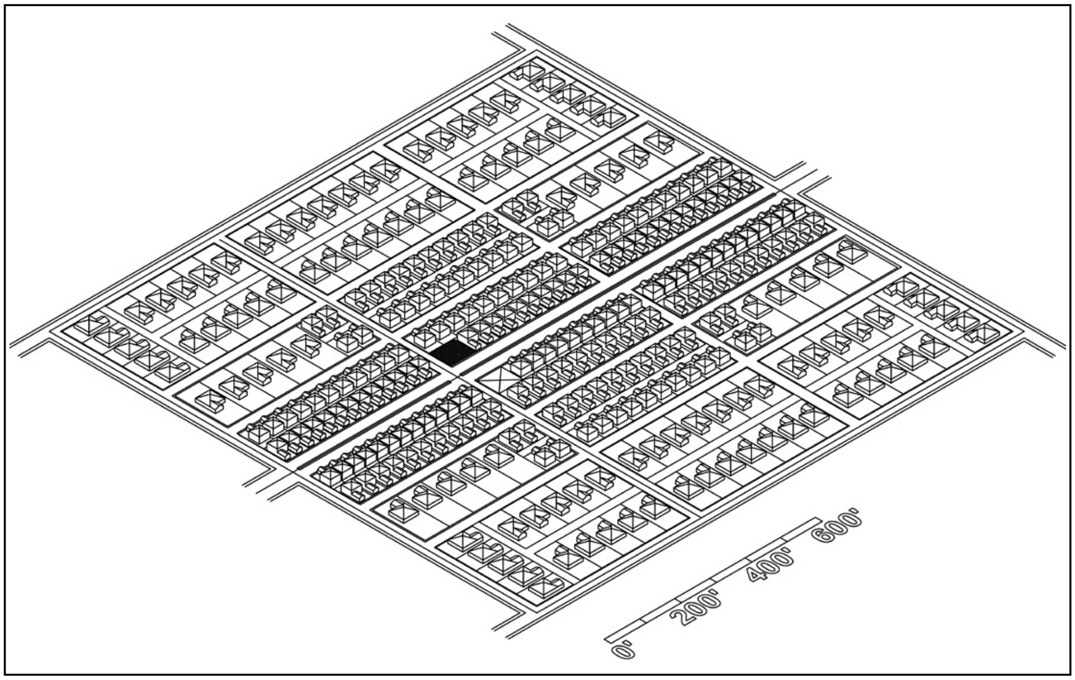

Figure C-4 Isometric View of the Density Gradient Design Alternative

C.1.2. Mix of Uses

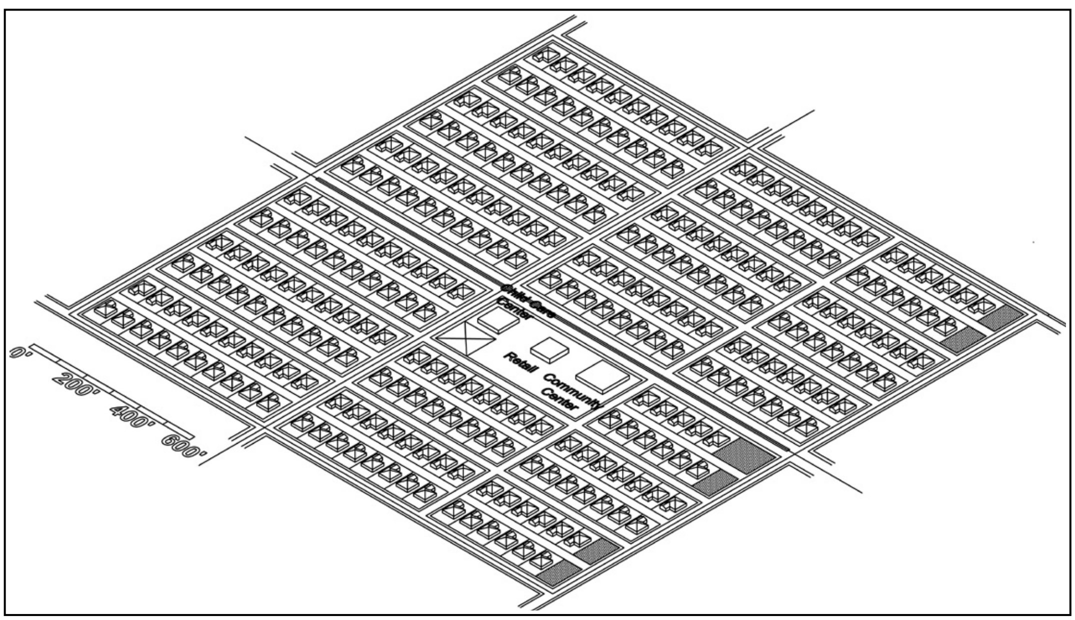

Figure C-5 Isometric View of the Low Use Mix Design Alternative

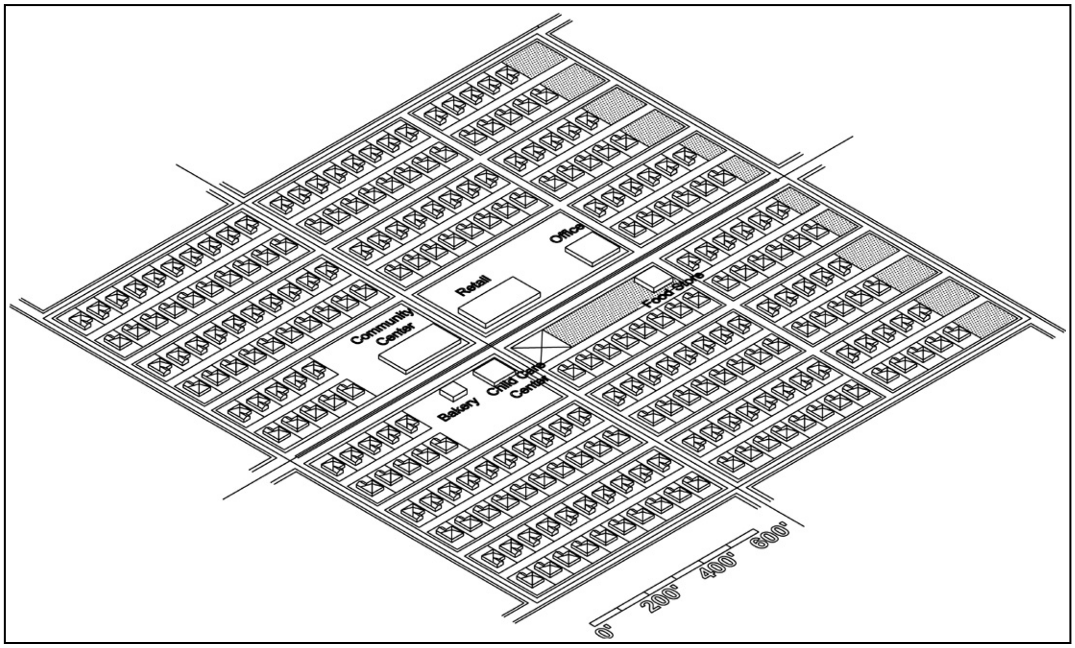

Figure C-6 Isometric View of the Medium Use Mix Design Alternative

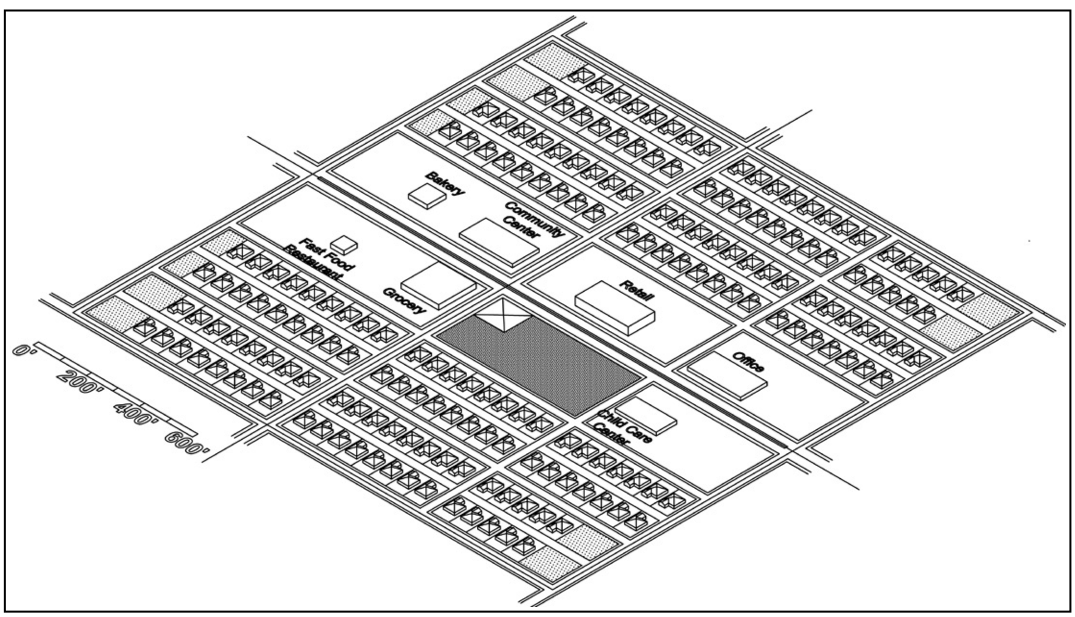

Figure C-7 Isometric View of the High Use Mix Design Alternative

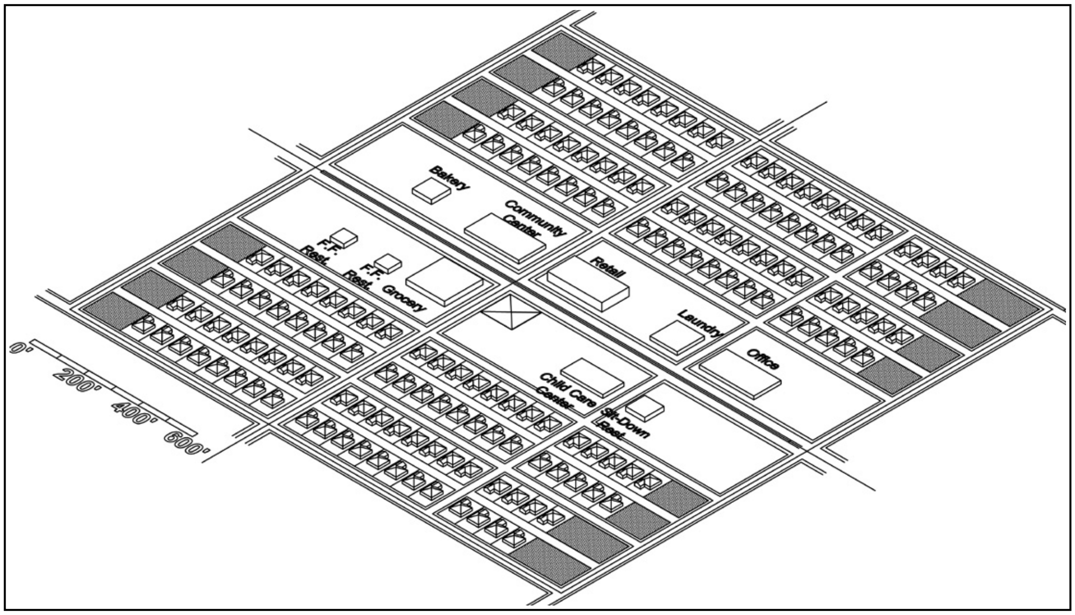

Figure C-8 Isometric View of the Optimized Use Mix Design Alternative

C.1.3 Street Configuration

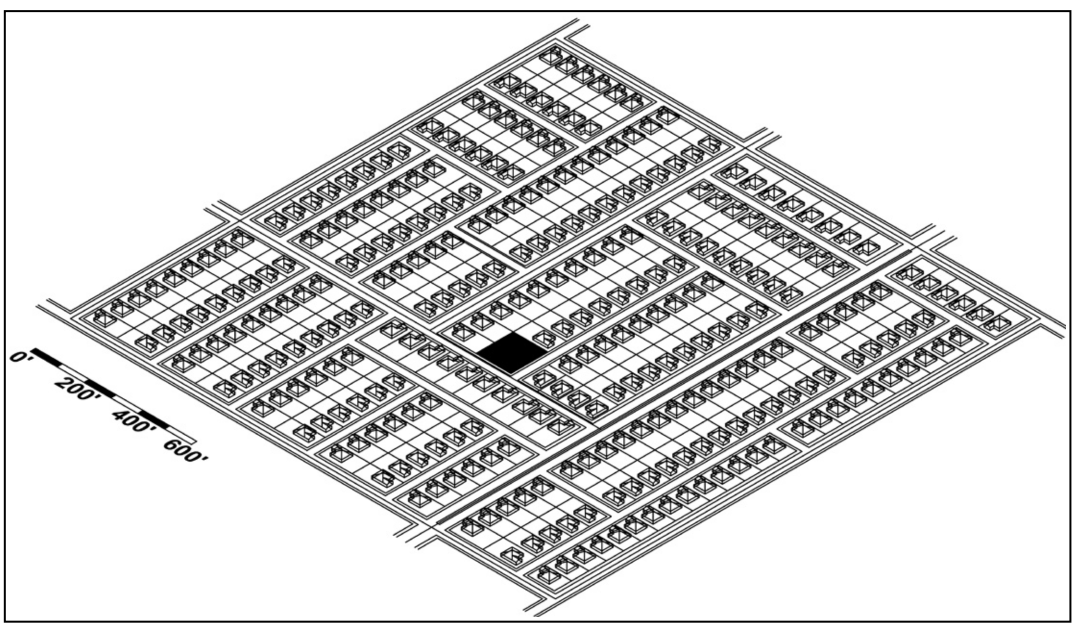

Figure C-9 Isometric View of the Fragmented Street Configuration Design Alternative

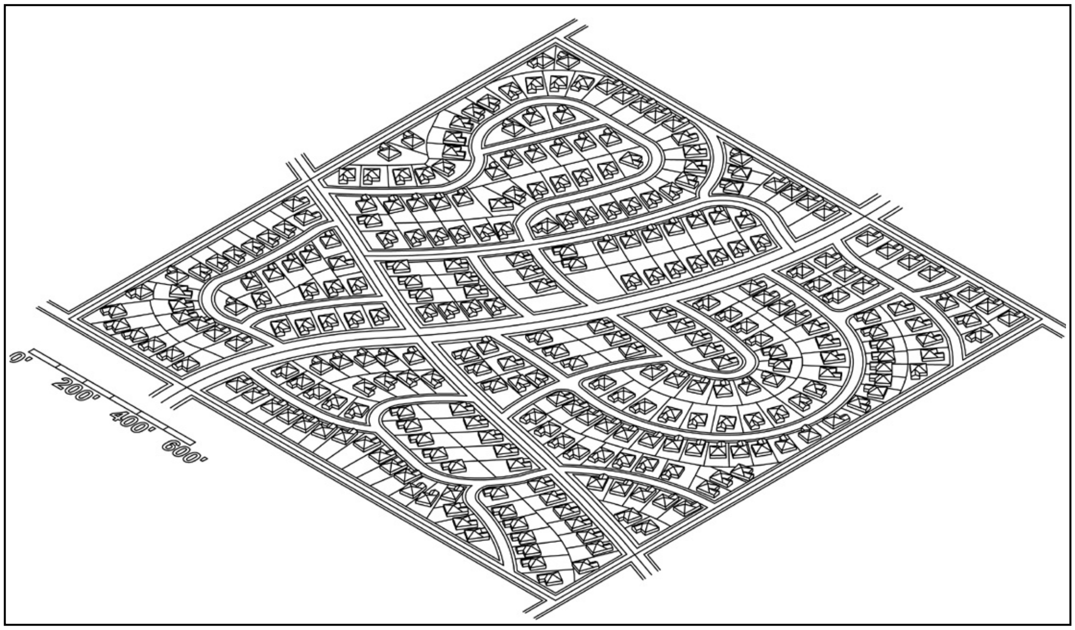

Figure C-10 Isometric View of the Landscape Street Configuration Design Alternative

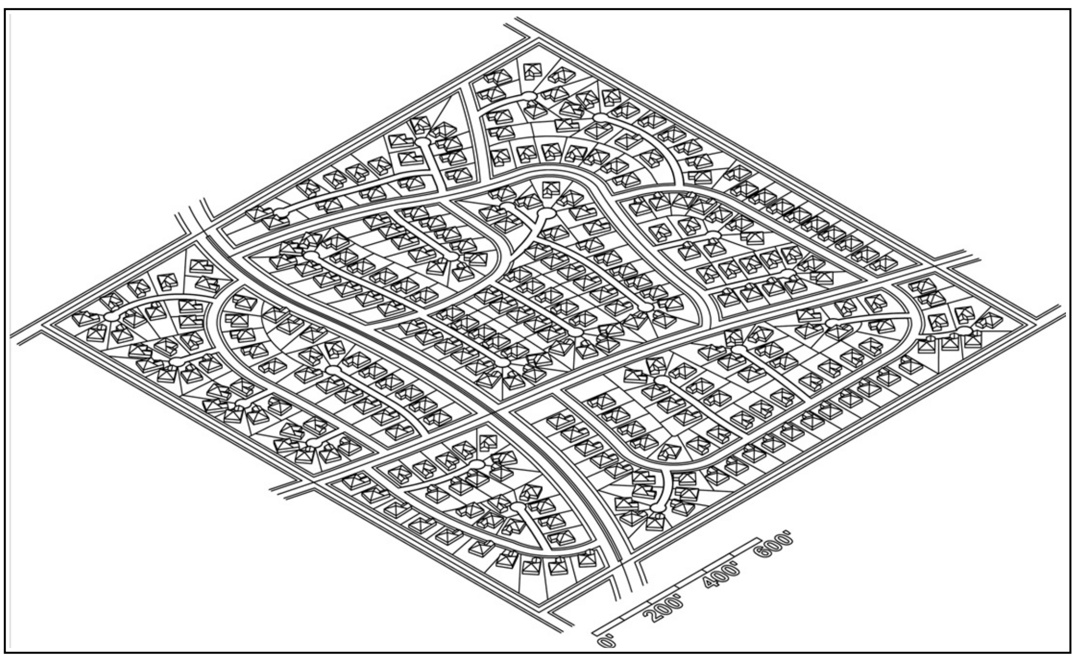

Figure C-11 Isometric View of the Loops & Cul-de-Sacs Street Configuration Design Alternative

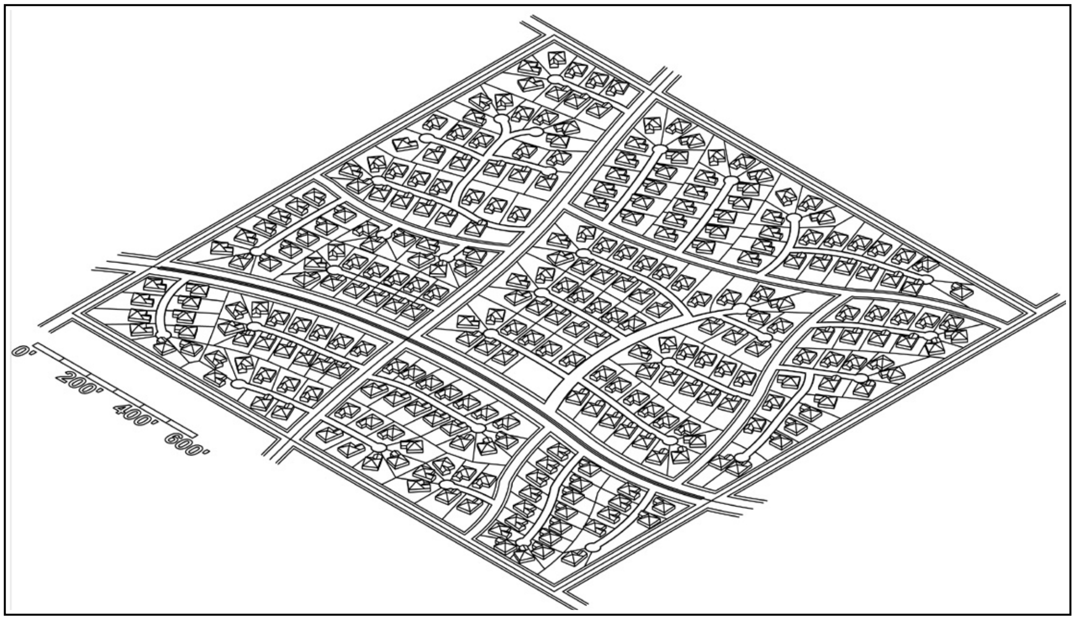

Figure C-12 Isometric View of the Dendritic Street Configuration Design Alternative

C.1.4 Housing Typology

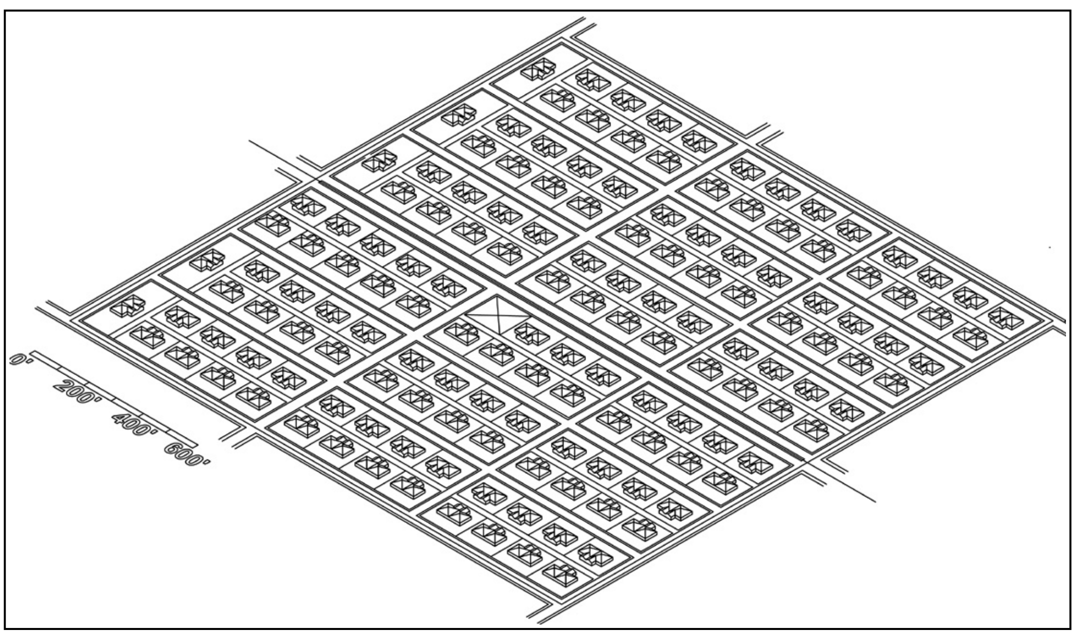

Figure C-13 Isometric View of the Attached Single Family Houses Design Alternative

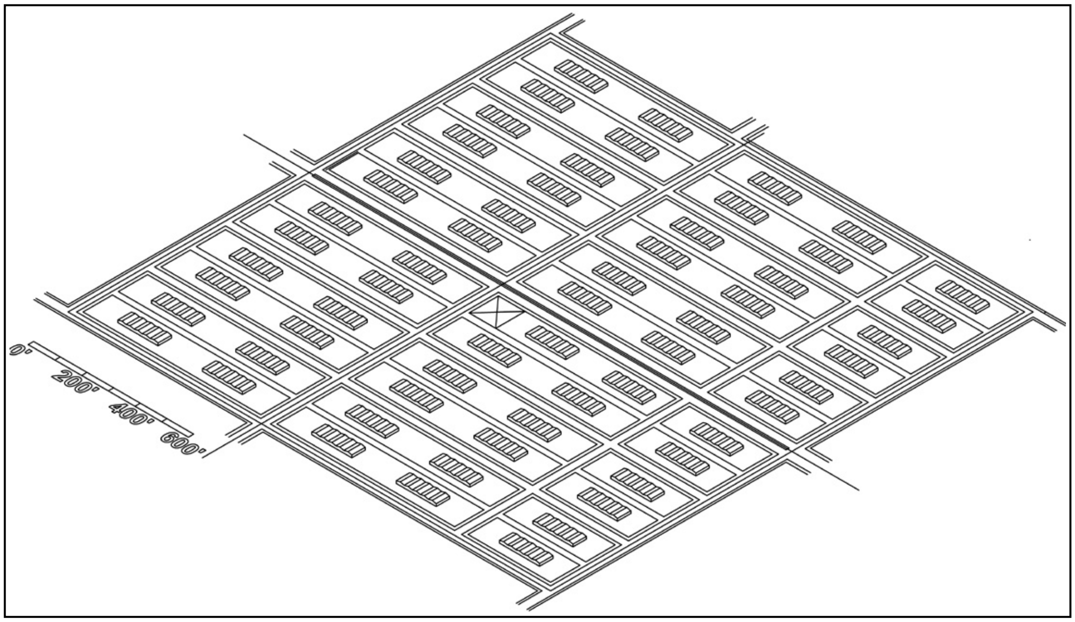

Figure C-14 Isometric View of the Town Homes Design Alternative

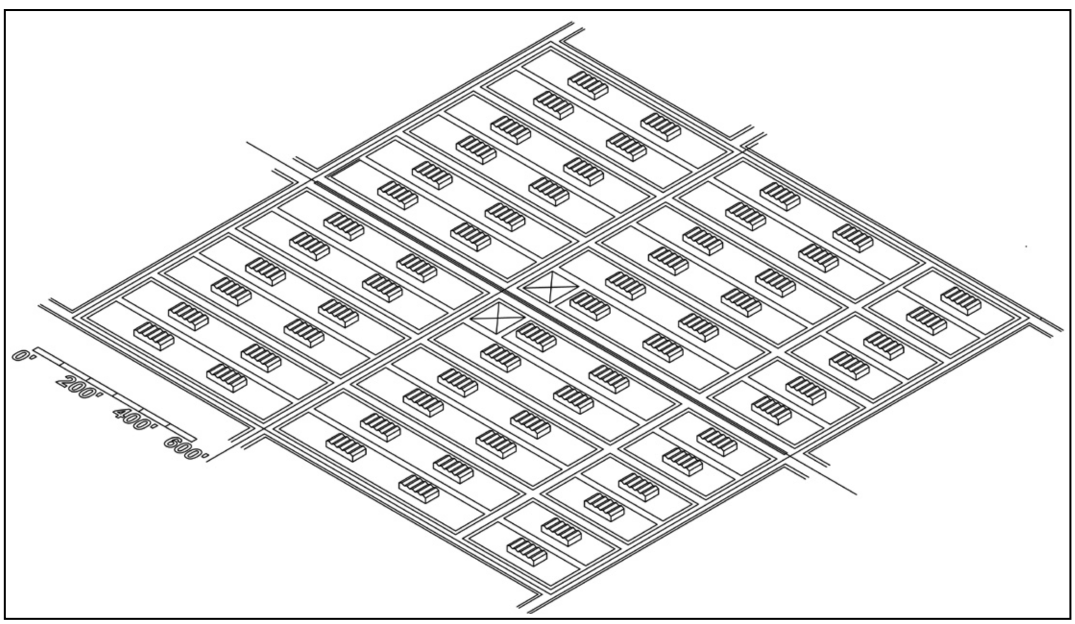

Figure C-15 Isometric View of the Live-Work Units Design Alternative.

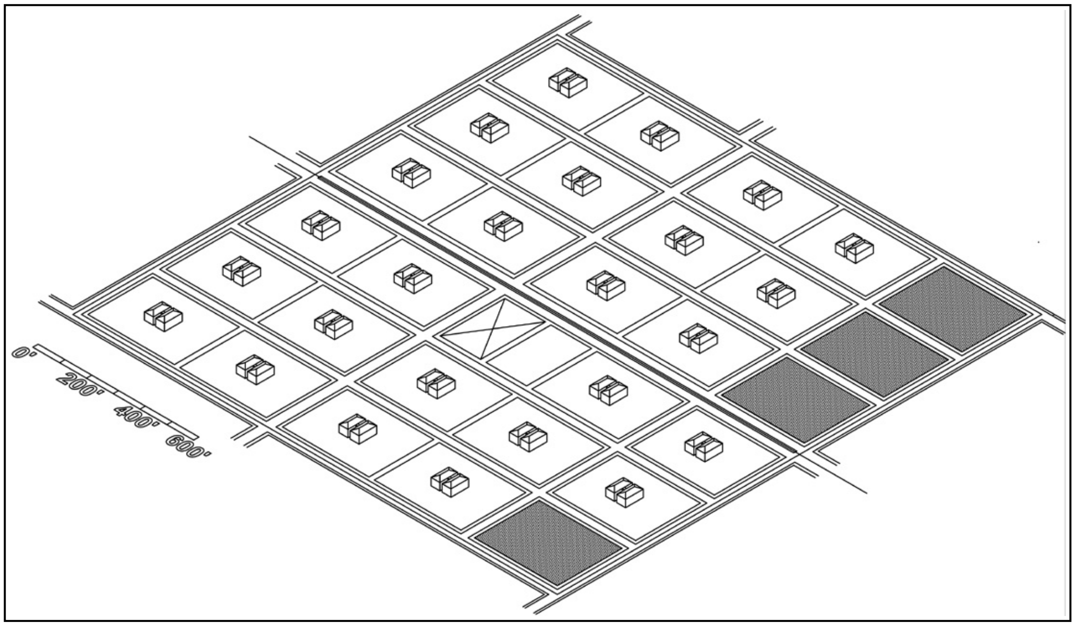

Figure C-16 Isometric View of the Multi-Family Houses Design Alternative

C.1.5 Utilization of Renewable Energy Resources

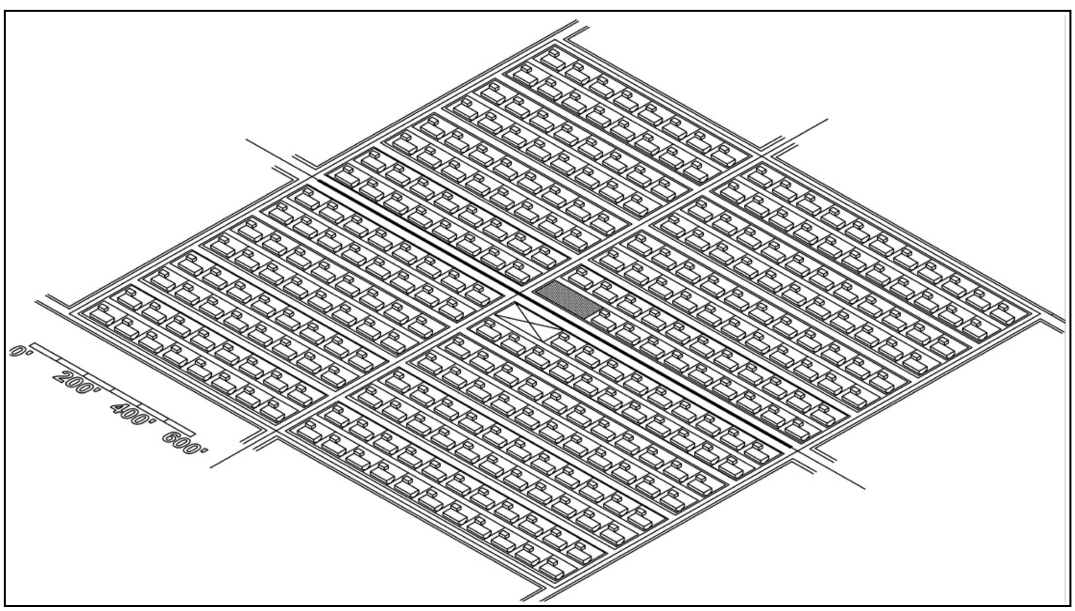

Figure C-17 Isometric View of the Renewable Energy Utilization Design Alternatives

The isometric view included for this design parameter (figure C-17) represents the change in building form from square to rectangular (with an east/west axis). This building form was used for all 4 design alternatives in this parameter.

C.2 DESIGN OPTIMIZATION SCENARIOS

C.2.1 Centralized Integration Approach

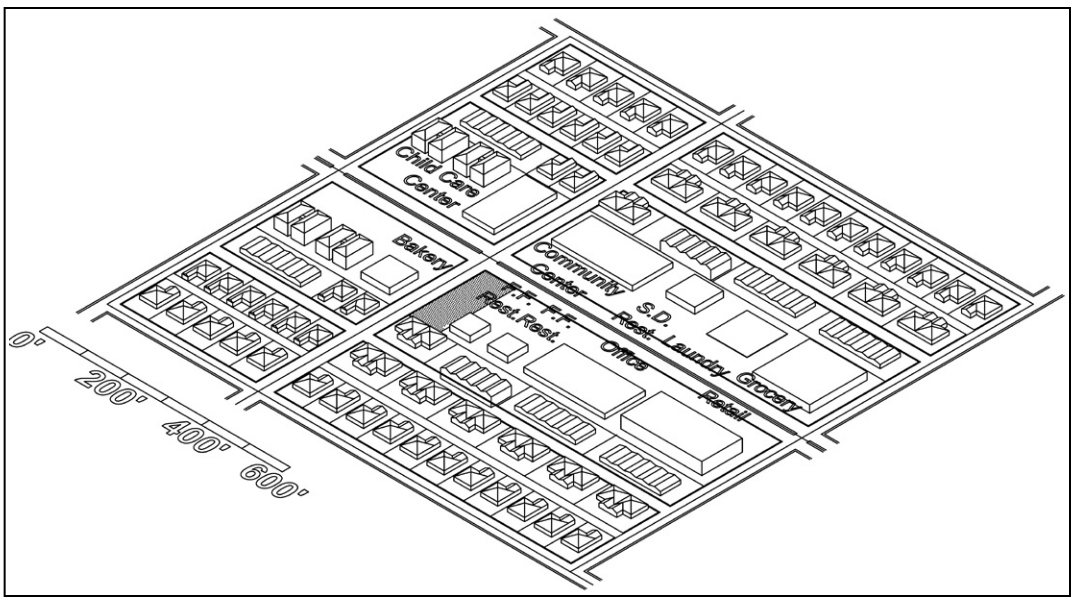

Figure C-18 Isometric View of the Optimized Design Optimization Scenario – Centralized Approach

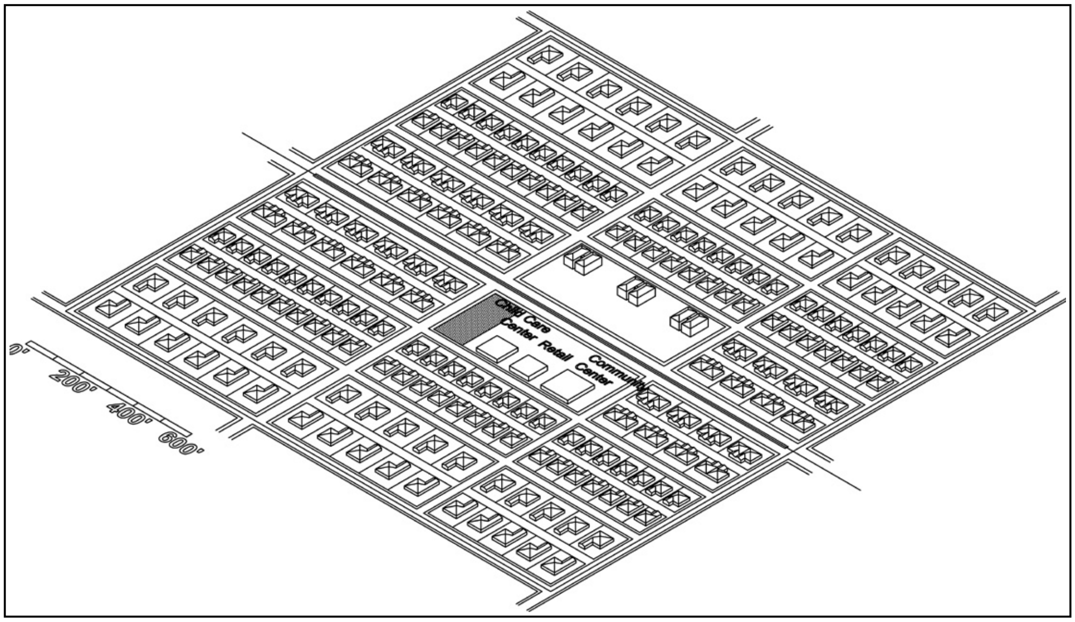

Figure C-19 Isometric View of the Minimum Acceptable Design Optimization Scenario – Centralized Approach

C.2.2 Decentralized Integration Approach

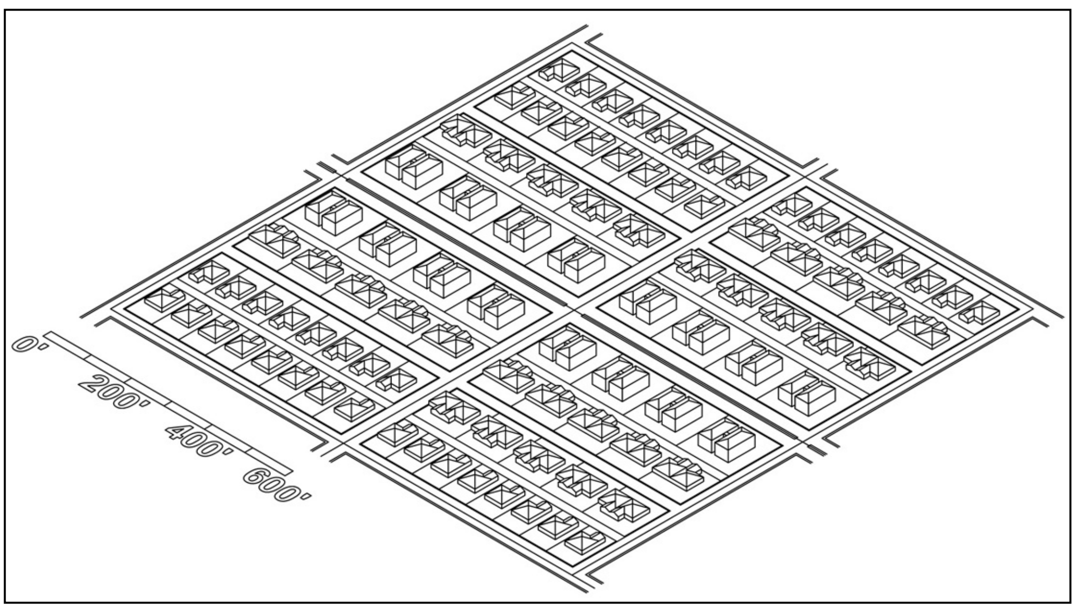

Figure C-20 Isometric View of the High-Density Design Optimization Scenario – Decentralized Approach

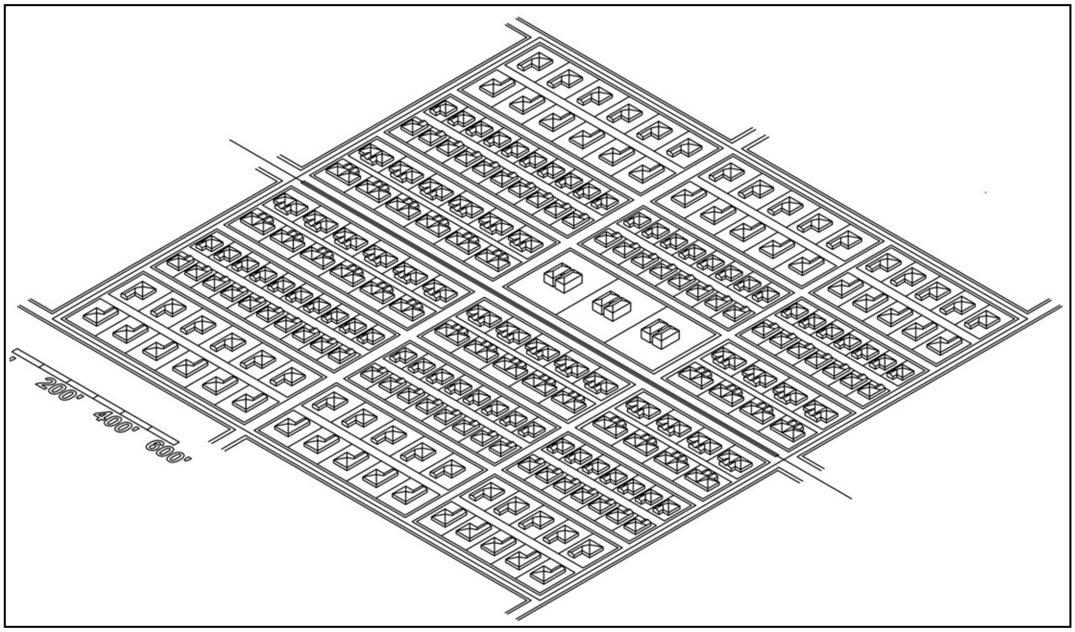

Figure C-21 Isometric View of the Low-Density Design Optimization Scenario – Decentralized Approach

Table C-1 Community Design Characteristics for Design Variations

Design parameters/variations	Area (acres)	Density (du/ac)	Community Buildings		District Heating Network		
			Residential	Commercial	Network length (mile)	Design Load (gpm)	Head Loss (ft)
Base-line	***75***	4	300 SFH	Non	4.17	315.2	739
Density of built form							
1 du/ac	300	1	300 SFH	Non	8.34	315.2	1452.3
10 du/ac	30	10	300 SFH	Non	2.64	325.3	530.4
15 du/ac	20	15	300 SFH	Non	2.32	310.	487.5
Density gradient	44	4 – 15 (7.8 ave.)	300 SFH	Non	4.4	317.7	912
Mix of uses							
Low use mix	75	4	279 SFH	Small community center; child care center; corner store.	4.01	326.4	787.8
Medium use mix	75	4	246 SFH	Small community center; child care center; food store, retail, office, small bakery.	3.72	355.75	790.9
High use mix	75	4	180 SFH	Community center; child care center; grocery, retail, office, bakery; fast food restaurant.	3.06	342.98	600.99
Optimized use mix	75	4	164 SFH	Community center; child care center; grocery, retail, office, bakery; 2 fast food restaurants; sit-down restaurant; laundry.	2.86	343.4	608.99
Street configuration							
Fragmented	75	4	300 SFH	Non	5.38	315.2	1171.3
Landscape	757	4	300 SFH	Non	6.17	315.2	1555.7
Loops & cul-de-sacs	75	4	300 SFH	Non	5.74	315.2	1153.09
Dendritic	757	4	300 SFH	Non	5.73	315.2	1217.6

Table C-1 Continued

Design parameters/variations	Area (acres)	Density (du/ac)	Community Buildings		District Heating Network		
			Residential	Commercial	Network length (mile)	Design Load (gpm)	Head Loss (ft)
Housing typology							
Small SFH	75	4	300 small SFH	Non	4.17	246.13	693.5
Large SFH	75	4	300 large SFH	Non	4.17	417.6	931.8
Attached SFH	75	4	150 attached SFH (2 unit each)	Non	4.01	302.88	1266.1
Town homes	75	4	60 town homes (5 units each)	Non	3.91	242.07	635.16
Live-work units	75	4	60 live work unit (5 unit each)	Non	3.88	395.04	1402.04
Multi-family houses	75	4	25 multi-family units (12 units each)	Non	1.94	195.34	1061.53
Envelope & building systems' efficiencies							
5% reduction	75	4	300 SFH	Non	4.17	301.03	978.16
10% reduction	75	4	300 SFH	Non	4.17	278.82	851.73
15% reduction	75	4	300 SFH	Non	4.17	251.68	718.05
20% reduction	75	4	300 SFH	Non	4.17	255.38	720.68
Utilization of renewable energy							
Low utilization	75	4	300 SFH	Non	4.81	297.33	1220.72
Medium utilization	75	4	300 SFH	Non	4.81	314.6	1249.56
High utilization	75	4	300 SFH	Non	4.81	308.43	1220.72
Reduced loads	75	4	300 SFH	Non	4.81	308.43	1220.72

Table C-2 Community Design Characteristics for Design Optimization Scenarios

Design parameters/variations	Area (acres)	Density (du/ac)	Community Buildings		District Heating Network		
			Residential	Commercial	Network length (mile)	Design Load (gpm)	Head Loss (ft)
Base-line	***75***	4	300 SFH	Non	4.17	315.2	739
Design optimization – centralized approach							
Optimized design scenario	30	4 – 15 (10 ave.)	32 detached SFH, 16 detached SFH – small, 28 attached SFH, 30 town homes, 10 live work units, 48 multi-family houses.	Community center; child care center; grocery, retail, office, bakery; 2 fast food restaurants; sit-down restaurant; laundry.	1.82	312.03	450.55
Minimum acceptable design	75	2 -6 (4 ave.)	64 detached SFH – large, 100 detached SFH, 80 attached SFH, 36 multi-family houses	Small community center; child care center; corner store.	3.72	227.44	765.84
Design optimization – decentralized approach							
High-density scenario	30	4 – 20 (10 ave.)	48 detached SFH; 60 attached SFH; 192 multi-family houses.	N/A	N/A	N/A	N/A
Low-density scenario	75	2 – 6 (4 ave.)	64 detached SFH – large; 100 detached SFH; 100 attached SFH; 36 multi-family houses	N/A	N/A	N/A	N/A

Table C-3 Community Energy Use & CO_2 Emissions for Design Variations

Design parameters/variations	District heating network		Average annual loads			Primary energy use			CO_2 emissions		
	Plant load (MBtu)	Thermal losses	Electrical (kW)	Thermal (MBtu/hr)	H/P	Cogen system (MBtu)	Auxiliary boiler (MBtu)	Utility use (MBtu)	Cogen system (tons CO_2)	Auxiliary boiler (MBtu)	Utility (tons CO_2)
Base-line	17,740.7	14.69%	326.2	2.03	2.03	21970.1	10,987.8	9,793.6	1,273.9	646.3	949.8
Density of built form											
1 du/ac	20,343.9	25.61%	326.2	2.32	2.36	21,970.1	12,617.1	9,793.6	1,273.9	742.2	949.8
10 du/ac	18,969.1	8.72%	323.6	2.17	2.33	22,077.5	12,712.8	9,420.2	1,280.9	747.8	913.6
15 du/ac	19,709.9	7.65	341.3	2.24	2.42	22,070.0	13,533.8	8510.1	1,280.4	796.1	825.3
Density gradient	19,264.83	12.84%	321.77	2.20	2.32	22,049.6	12,501.9	9271.7	1,279.1	735.4	899.19
Mix of uses											
Low use mix	17,205.3	14.35%	330.8	1.96	1.95	22,108.6	10.421.5	10,095.9	1,282.9	613.0	979.1
Medium use mix	16,162.8	14.37	364.5	1.90	1.70	22,581.6	9,383.4	13,512.8	1,311.9	551.9	1,310.5
High use mix	14,425.6	13.7%	480.2	1.64	1.10	23,595.3	7,713.4	23,106.7	1,379.8	453.7	2,240.9
Optimized use mix	15,337.4	11.92%	519.9	1.75	1.05	23,979.4	8,120.5	26,569.2	1,404.9	477.7	2,567.7
Street configuration											
Fragmented	18,135.2	16.55%	326.2	2.07	2.08	21,970.1	11,198.2	9,793.6	1,273.9	658.7	949.8
Landscape	18,477.7	18.09%	326.2	2.1	2.12	21,970.1	11,390.9	9,793.6	1,273.9	670.1	949.8
Loops & cul-de-sac	18,426.9	17.87%	326.2	2.1	2.12	21,970.1	11,361.3	9,793.6	1,273.9	1,336.6	949.8
Dendritic	18,204.2	16.86%	326.2	2.08	2.09	21,970.1	11,235.9	9,793.6	1,273.9	1,321.9	949.8
Housing typology											
Small SFH	15,429.4	16.20%	274.7	1.76	2.13	20,412.5	9,109.7	6,511.7	1,172.3	535.9	631.5
Large SFH	22,117.7	12.40%	411.4	2.52	1.95	23,272.6	15,269.3	16,698.4	1,358.8	898.2	1,619.4
Attached SFH	17,386.3	13.83%	322.7	1.98	2.05	22,055.2	10,470.9	9,356.04	1,279.4	615.9	907.4
Town homes	15,163.5	15.41%	258.8	1.73	2.28	19,946.0	8,913.8	5,479.3	1141.8	524.4	531.4
Live-work units	14,260.1	17.93%	505.8	1.63	1.09	22,971.4	7,522.5	26,334.5	1,339.1	442.5	2,553.9
Multi-family houses	10,378.6	13.66%	222.03	1.18	1.76	18,082.6	4,526.0	3,991.3	1,020.2	266.2	387.1

Table C-3 Continued

Design parameters/variations	District heating network		Average annual loads			Primary energy use			CO_2 emissions		
	Plant load (MBtu)	Thermal losses	Electrical (kW)	Thermal (MBtu/hr)	H/P	Cogen system (MBtu)	Auxiliary boiler (MBtu)	Utility use (MBtu)	Cogen system (tons CO_2)	Auxiliary boiler (MBtu)	Utility (tons CO_2)
Envelope & building systems' efficiencies											
5% reduction	16,500.1	15.20%	326.02	1.88	1.88	21,968.1	9,672.3	9,779.5	1,273.8	568.9	948.4
10% reduction	15,162.8	16.48%	326.00	1.73	1.73	21,968.4	8,430.3	9,778.9	1,273.8	495.9	948.4
15% reduction	14,279.8	17.50%	315.2	1.63	1.64	21,959.1	7,528.7	8,731.2	1,273.2	442.9	846.8
20% reduction	14,804.2	16.88%	254	1.69	2.09	19,774.5	8,408.9	5,198.5	1,130.6	494.6	504.2
Utilization of renewable energy											
Low utilization	16,374.4	14.20%	327.1	1.87	2.00	22,196.7	9,550.7	9,629.0	1,288.7	561.8	933.8
Medium utilization	15,729.9	14.77%	338.6	1.76	1.87	22,250.3	8,571.5	10,691.6	1,292.2	504.2	1,036.9
High utilization	13,639.2	17.03%	347.6	1.56	1.62	22,94.5	6,603.9	11,535.4	1,295.1	388.5	1,118.7
Reduced loads	14,155	16.41%	286.6	1.62	2.06	20,189.1	7,540.0	7,932.6	1,157.7	443.5	769.3

Table C-4 Community Energy Use & CO_2 Emissions for Design Optimization Scenarios

Design parameters/variations	**District heating network**		**Average annual loads**			**Primary energy use**			**CO_2 emissions**		
	Plant load (MBtu)	**Thermal losses (%)**	**Electrical (kW)**	**Thermal (MBtu)**	**H/P**	**Cogen system (MBtu)**	**Auxiliary boiler (MBtu)**	**Utility use (MBtu)**	**Cogen system (tons CO_2)**	**Auxiliary boiler (MBtu)**	**Utility (tons CO_2)**
Base-line	17,740.7	14.69%	326.2	2.03	2.03	21970.1	10,987.8	9,793.6	1,273.9	646.3	949.8
Design optimization – centralized approach											
Optimized design scenario	13,256.0	8.64%	500.6	1.51	0.94	42,607.6	3,066.3	6,189.1	180.4	2,460.2	600.2
Minimum acceptable design	21,003.2	10.22%	454.4	2.4	1.67	33,980.0	11,280.5	10,368.6	1,961.8	663.6	1,005.6
Design optimization – decentralized approach											
High-density scenario	N/A	N/A	269.1	1.40	N/A	15,262.8	6,660.4	12,533.5	835.5	391.8	1,215.5
Low-density scenario	N/A	N/A	350.8	1.73	N/A	17,778.1	9,671.9	16,105.2	957.5	568,9	1,561.9

APPENDIX D
COGENERATION SYSTEMS PART LOAD PERFORMANCES

This appendix presents normalized electrical part load performance characteristics for the different cogeneration system types investigated in this study (reciprocating engines; micro turbines, fuel cells, and Stirling engines). Part load performance characteristics for reciprocating engines and micro- turbines are based on NREL & GRI (2003), while those for Stirling engines are based on Knight and Ugursal (2005). Both references showed similar performance data for fuel cells. These performance characteristics represent average characteristics of commercially available technologies for each of the system types investigated within the study.

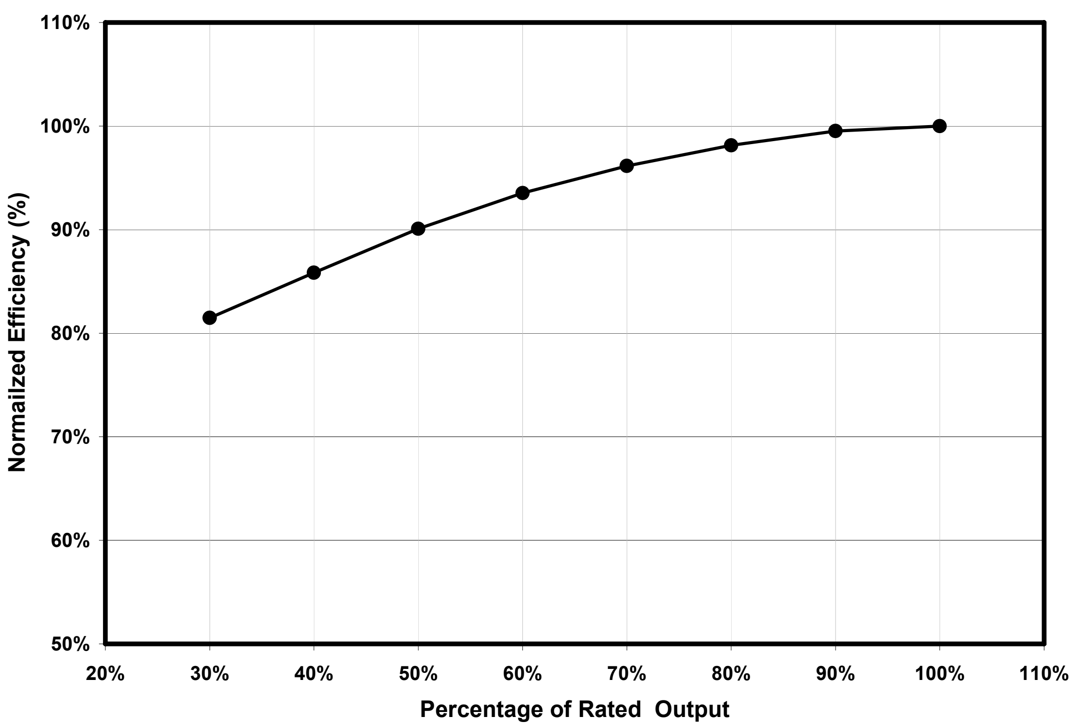

Figure G-1 Normalized Electrical Part Load Efficiencies for Reciprocating Engines

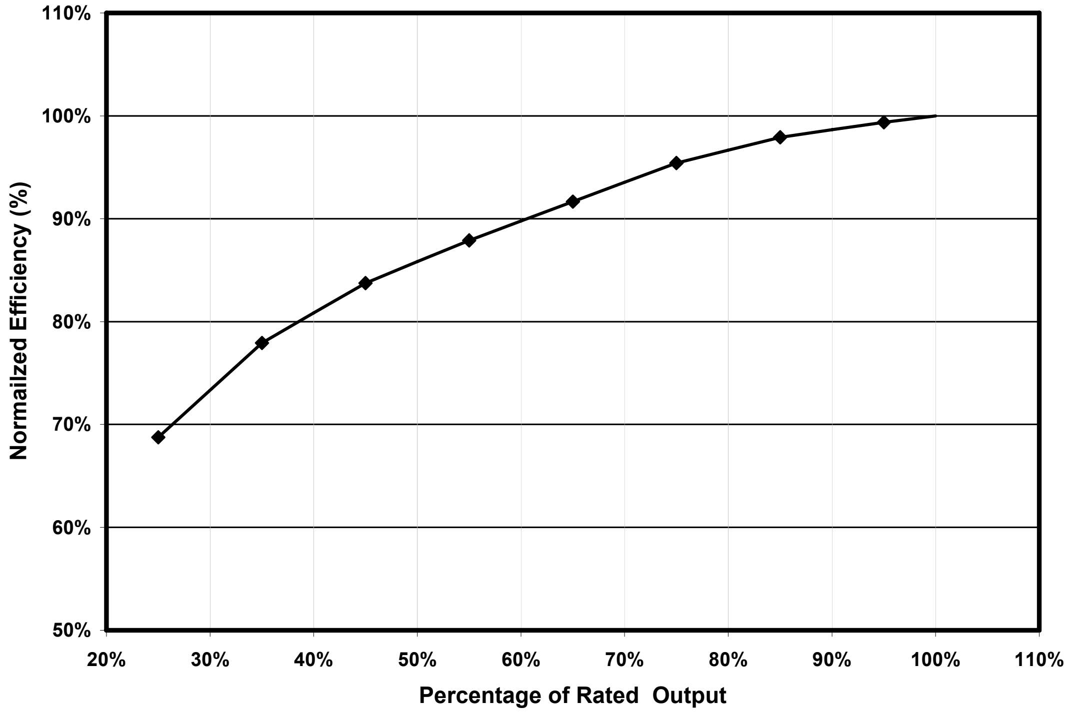

Figure G-2 Normalized Electrical Part Load Efficiencies for Microturbines

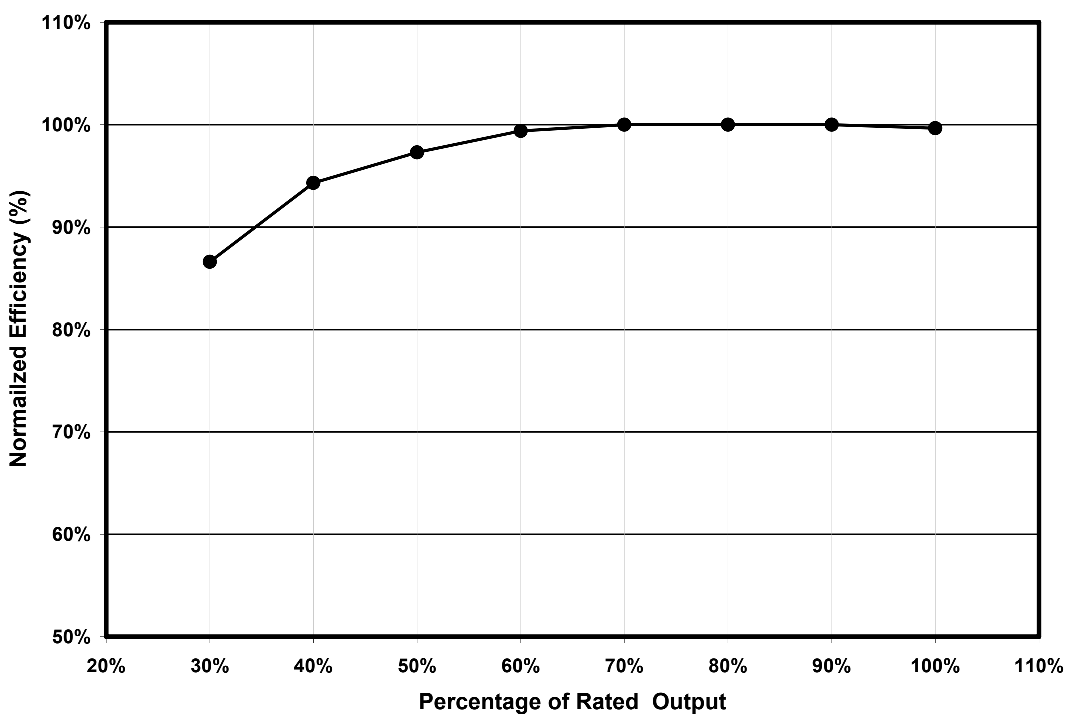

Figure G-3 Normalized Electrical Part Load Efficiencies for Fuel Cells

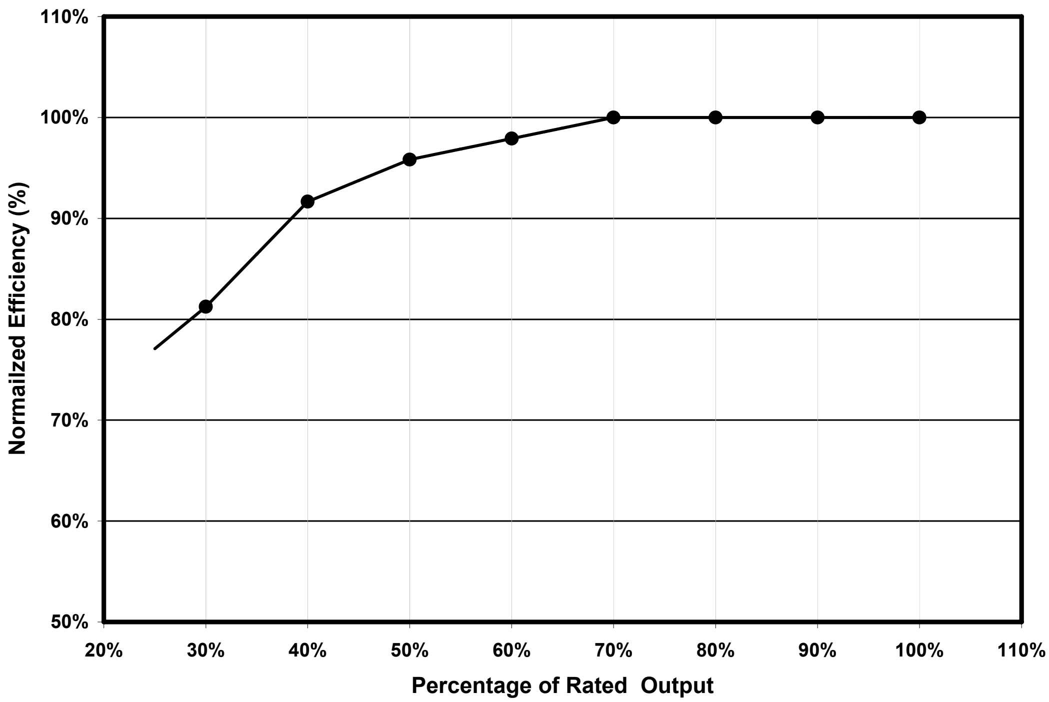

Figure G-3 Normalized Electrical Part Load Efficiencies for Stirling Engines

APPENDIX E
PROTOTYPES INPUT FILES

This digital appendix includes the digital “*.inp*” input files for all the residential and commercial building prototypes developed within this study. Table F-1 lists the names of these files and the corresponding prototype or design variation. The appendix also includes a “*schdl.dat”* file which contains the details of the occupancy, lighting, and equipment schedules referenced within these input files. For the input files to run correctly, these schedules need to be pasted into the “*Bdllib.dat”* library file of included in eQUEST. Additionally, the input files were developed using version 3.55 of eQUEST, and would therefore only function correctly using this version.

Table F-1 Input file names and corresponding prototypes and design variations

File name	Prototype
Residential prototypes:	
base-line.inp	Base-line single family home.
sfh-l.inp	Large detached single family house.
sfh-s.inp	Small detached single family house.
sfha.inp	Attached single family houses.
townhome.inp	Town homes.
livework.inp	Live-work units.
mfh.inp	Multi family houses.
Commercial prototypes:	
retail-sml.inp	Small retail building – low use mix alternative.
retail-med.inp	Medium retail building – medium use mix alternative.
retail-lrg.inp	Large retail building – high & optimized use mix alternatives.
office-sml.inp	Small office building – medium use mix alternative.
office-lrg.inp	Large office building - high & optimized use mix alternatives.

Table F-1 Continued

File name	Prototype
Commercial prototypes - continued	
childcare-sml.inp	Small child care building – low and medium use mix alternatives.
childcare-lrg.inp	Large child care building –high and optimized use mix alternatives.
comcenter-sml.inp	Small Community center – low use mix alternative.
comcenter-med.inp	Medium community center – medium use mix alternative.
comcenter-lrg.inp	Large community center – high and optimized use mix alternative.
rest-sd.inp	Sit-down restaurant – high and optimized use mix alternative.
rest-ff.inp	Fast-food restaurant – high and optimized use mix alternative.
fdstr.inp	Food store – medium use mix alternative.
grocery-18.inp	Grocery store – 18 hours working schedule – high use mix alternative.
grocery-24.inp	Grocery store – 24 hours working schedule – optimized use mix alternative.
bakery-sml.inp	Small bakery – medium use mix alternative.
bakery-lrg.inp	Large bakery - high use mix alternative.
bakery-night.inp	Bakery, night working schedule - optimized use mix alternative.
laundry.inp	Laundry/dry cleaning - optimized use mix alternative.

APPENDIX F
ENERGY USE & COGENERATION OUTPUT PROFILES

This digital appendix includes the digital seasonal and annual energy use profiles for each of the residential and commercial building prototypes and the community design variations developed within this study. First, for each prototype, a digital excel file s included which contains graphs showing the average daily electrical and thermal energy use profiles for weekdays and weekends in each of the four seasons (winter, spring, summer, and fall); the average daily electrical and thermal energy use profiles for weekdays and weekends for the whole year; as well as the average hourly electrical and thermal load for each month of the year. In addition, the appendix also includes excel files showing the same information for the base line community as well as each of the community design variations investigated within the study. For each variation, a graph is also included showing a comparison between the average hourly electrical and thermal load of the community and the average hourly electrical and thermal output of the cogeneration system for each month of the year for the centralized cogeneration approach. Finally, the appendix includes similar seasonal and annual energy use profiles, average hourly loads for each month, and average hourly output of the cogeneration system for the two optimization scenarios developed for the centralized approach.

VITA

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