Evaluation of the use of wind power to satisfy various electric and heating energy demand scenarios

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The goal of this research is to develop and evaluate a methodology to determine feasibility and economics of several wind energy systems (energy pathways) that make use of available and advanced technologies for a variety of uses. Fraction of supplied energy (FSE) is defined as the yearly supplied energy by the system divided by the yearly energy demand. A model has been developed to simulate energy demand for various communities as a function of outside temperature, population, and fraction of commercial versus industrial employment. The demand for low grade and high grade energy is per 1,000 persons modeled for each hour for typical meteorological years. Each demand is divided by the energy network's efficiency and matched to the supply of wind generated energy. The energy network (path) efficiency and cost are found using pathway analysis.

Fuel cells and lead acid batteries are evaluated for storage of energy and heat pumps are considered for reducing the consumption of electric energy for low grade energy applications. This research also evaluates energy supply from a series of diesel generators and the utility grid as an auxiliary energy source. This research evaluates the fraction of supplied energy and economics of the modeled systems.

Each scenario has three means of supplying low grade energy: electric furnaces, gas furnaces, and district heating and cooling using heat pumps. This research has evaluated five energy pathways: wind-utility, wind-batteries, wind-diesel, wind-hydrogen, and wind-diesel/batteries. Three regions have been simulated due to their climatic variations: Iowa, Hawaii, and Alaska. For both fraction of supplied energy and economy studies, wind turbines that use gas furnaces and lead acid batteries for energy storage show the best results.

Environmentally, the use of the hydrogen-fuel cell pathway is the best, with practically zero pollution, but the cost is high compared to other current technologies. Sometimes in the next century, the cost of fossil fuel combined with improved alternative technology efficiencies and cost reductions should make renewable energy technologies economically more attractive.

1 INTRODUCTION

The objectives of this study are twofold. The first objective is to develop a method to determine demand and cost of wind turbines as an energy source combined with different storage and auxiliary energy systems. The second objective is to determine the fraction of energy demand matched by energy supply and the economics of the systems supplying the energy.

Some significant features of the models used in the simulations for this research include:

1. An emphasis has been placed on the difference of modeling end consumption of high[1] and low[2] grade energy.

2. Energy production is related to the cube of wind-speed, rendering that the daily average wind speed does not give an accurate picture of the daily energy production and its match to electrical demand. The simulation time intervals have been reduced to more accurately model this effect, and thus hourly wind power production is simulated.

3. The cost of renewable energy is usually too high to be cost effective in comparison to already existing non-renewable energy sources. The cost of long term hidden effects of non-renewable energy sources on the environment are addressed and given approximate costs where feasible, in order to more fairly compare the total costs of renewable and non-renewable energy technologies.

There are three groups of models: energy supply, energy demand, and energy storage/distribution models. The energy supply is found from simulating the operation of wind-turbines, diesel generators, and utility power. Demand models are found from using physical principles, and various statistical data obtained from different sources. Storage/distribution models include lump models of electrolysis of water, fuel cell operation, lead acid batteries, district heat and cooling, and heat pumps.

Introduction

In 1990, about eighty percent of the world's total average energy consumption of 100 PW (10^{17} W) was from burning fossil fuels (Yurum 1994). The United States alone was responsible for consuming

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[1] Energy that can easily be converted into work

[2] Energy that cannot easily be converted into work

more than one fourth of the world's total energy consumption the same year (Dept. of Commerce 1995). Of the total energy consumption of 25,922 billion kWh in the United States in 1994, 85.7% originated from fossil fuels and non-renewable energy sources, 6.6% was generated utilizing renewable energy sources, and nuclear power plants generated the rest of the consumed energy (EIA 1994).

Residential and commercial sectors accounted for 35.6% of the end-use, the industrial sector 38.1%, and 26.5% of the total energy consumption was used in the transportation sector (EIA 1994). 19.8% was lost in energy distribution systems, distributed approximately equally in the industrial, residential and commercial, and transportation sectors. Of the total energy consumption in the United States 37% was used to generate electricity (EIA 1994).

Research shows that there is a correlation between consumption of fossil fuels and increased levels atmospheric carbon-dioxide (Winteringham 1992). Increased levels of carbon-dioxide have been related to the greenhouse effect and global warming (Winteringham 1992). Combustion of fossil fuels also produces SO_x, NO_x, and volatile organic compounds (VOC's), compounds harmful to the environment. Research also shows that the economic growth of a country is strongly related to the energy consumption (Alam et al. 1991) and particularly the consumption of electricity which is expected to be a significant fraction of total future energy consumption (Starr 1993). Thus the future production of electric energy will significantly influence the growth of a country's economy. The literature also indicates a strong relation between energy consumption and the standard of living (Alam et al. 1991), an increase in standard of living is therefore related to an increase in energy consumption. This will most likely result in a slow increase of energy consumption in the developed countries, whereas developing and underdeveloped countries' energy consumption will increase at a faster rate.

Electric energy consumption is expected to be at least four times greater than present consumption by early in the next century (Starr 1993). The total energy consumption of the world is expected to be between two and four times today's consumption by 2050 (Starr 1993, EIA 1994), depending on conservation, energy efficiencies, legislative and environmental restrictions, and depletion of fossil fuels.

There are several ways to slow down the increase in consumption. Consumers can make better use of current energy sources or increase the availability of electricity. Improving energy efficiencies has a maximum yield of the total energy potential of the supplier. There is much more to gain by improving the philosophies and attitudes in regards to the consumption of energy relating to how, when and where to utilize the different kinds of energy. One way to improve the use of energy is to reduce the use of electric energy for low grade energy applications such as space heating and cooling. By using a larger fraction of geo-thermal and solar energy for space heating and in some industrial processes, the availability of high grade energy where it is needed can be substantially increased. In the United States approximately one fourth of space heating and ninety percent of space cooling is accomplished by electric appliances (EIA-MECS 1991, EIA-RECS 1993). Fifty percent of the energy consumption in the commercial sector and two thirds in the residential sector is used for space heating, space cooling, and water heating (EIA 1994).

Due to concerns about global climate changes caused by human intervention in the ecological balance, renewable non-polluting energy sources and increased energy efficiency have become attractive. California legislatures are requiring that 2% of all new vehicles offered for sale in California in 1998 must be zero-polluting, and 10 % of new vehicles offered for sale in 2003 must be zero polluting (NREL 1995). The Los Angeles - Long Beach area is currently experiencing air pollution levels above the national ambient air quality standard (NAAQS, McKee 1990) more than one fourth of the year (Dept. of Commerce 1995), possibly harming residents in the area. A search for continued economic growth has therefore increased attention on renewable energy technologies such as photo-voltaic cells, fuel cells, and wind power generation.

Photo-voltaic cells may be used in the future, but today's technology is not generally cost effective. Current commercial photo-voltaic cells have a relatively low efficiency of about 12-18 % and are expensive to produce (NREL 1992, Ogden 1989). The cheapest electricity production from PV technology in 1987 was $0.28/kWh; the goal is to reduce this cost to $0.02-0.035 per kWh by the turn of the century (Ogden 1989). Energy suppliers utilizing PV-technology would also need vast surfaces in order to generate sufficient amounts of energy, because of the current low efficiencies of PV-cells. Capital costs of photo-voltaic cell systems are high, mostly above $ 5000/installed kW (NREL 1992). Wind generated energy on the other hand costs $1100 per installed kW (NREL 1992).

Wind generated energy on the other hand has become less expensive ($0.05/kWh) and is expected to become cheaper than energy production from fossil fuels in the next three decades due to the depletion of fossil fuels. The location of the consumer is a deciding factor for the price of wind generated energy. For remote sites with an average wind speed higher than 4 m/s, cost per kWh of wind generated electricity is usually less than other energy sources.

The cost of fossil fuel generated electricity ranges from $ 0.015/kWh to $ 0.10/kWh depending on the location, the fuel (Table 1.1), local legislation on emissions, and energy taxes.

Wind generated electricity does not impact the global environment; wind power has a great future as a potential energy source. Energy suppliers wanting to use wind as their source have one great disadvantage. The wind is usually not very flexible or adaptable to the demand load, so a storage system for surplus wind energy from windy periods becomes necessary.

Fuel cells are a promising storage system and energy converter that can be used with wind generated electricity. Capital investments in fuel cell electricity/energy are high, but not as high as for photo-voltaic cells. Fuel cells can utilize both hydrocarbons and pure hydrogen (Yildiz & Pekmez 1995). Hydrogen can be produced by electrolysis of water with efficiencies up to 100 % under ideal circumstances, and the hydrogen can be used in fuel cells with efficiencies up to 75% (NREL 1995). The cost of producing hydrogen by reforming hydrocarbons is $ 0.035/kWh or $10-18/GJ (Yurum 1995). This is equivalent to a gasoline price of $1.68-$2.35 /gallon. Producing hydrogen requires large amounts of electricity, 60-70 % of the cost of energy generated in fuel cells stems from production costs of hydrogen. Power plants utilizing fuels cells are also expensive, but stacks of fuel cells are capable of converting many megawatts of energy.

Table 1.1 Estimated Energy Costs (NREL 1992).

Source	Current	2010
	$/kWh	$/kWh
Coal	0.008	0.009
Oil	0.034	0.043
Natural Gas	0.017	0.035

Another storage system is lead acid batteries. Batteries can provide cyclical loads as well as emergency loads and peak leveling. Batteries used in large power plants has shown to be beneficial to the operation. In a real life scenario, even utilizing wind energy and a storage system, the demand might be larger than the systems' energy supply. In that case there are two methods of supplying supplemental energy. The most efficient and stable method to meet the peak demand is to buy the energy from another utility. In remote areas, a second option is to have a diesel generator match the peak loads.

Past analysis of the energy market has not taken into consideration the global effects of greenhouse and ozone depleting gases. On a global basis these pollutions cause an increase in the number of skin cancer incidents, rise in sea-levels, decrease in fertile land, change in local and global climates, change agricultural yields, increase in lung diseases, and the destruction of habitats and eco-systems. All these effects will impact the economy one way or another. The United States spends $ 474 billion on energy related expenditures, $ 101 billion of this was related to abatement and control of environmental pollution (Dept. of Commerce 1995). The cost of social and environmental effects have yet to be determined accurately. This research attempts to establish a more complete accounting of the monetary costs of current energy consumption and it's consequences to the global society.

The rest of this introduction will discuss each individual topic considered in this thesis. These topics are wind power, fuel cells, batteries, wind-diesel systems, heat pumps, district heating and cooling, and finally an assessment of the long term effects and costs on the environment using non-renewable energy versus renewable energy.

Wind Power

Wind energy has been utilized for a long time. Ancient warriors and travelers reached their destinations across the oceans using sails to catch the winds. History books show that the Babylonian emperor Hammurabi, seven hundred years B.C, planned to use wind turbines to irrigate land (Johnson 1985). Wind turbines were used for pumping water (Gipe 1993), grinding corn (Johnston 1985) and sawing lumber (Hunt 1981) long before electricity was ever discovered by scientists. In 1890, Denmark built the first wind turbine converting wind into electrical energy (Hunt 1981, Johnston 1985), and since then a lot of research and development has been conducted on wind power conversion systems and related topics.

Wind, like many other energy sources, is a result of solar radiation. Solar radiation, better known as sunlight, contains much energy. When sunlight reaches earth about 43 percent is reflected directly back to space, approximately 17 percent is absorbed in the lower atmosphere, and much of the remaining 40 percent which reaches the surface is reflected back to space (Hunt 1981). Even though most of the energy is reflected, some of it is absorbed in the air-layers and make a contribution to the earth's energy reservoir.

Wind Energy

When air is heated, it becomes less dense, which causes pressure differences in the air layers. The pressure differences cause the air to start moving towards thermal and pressure equilibrium. This motion in air is what we call wind. When the wind moves past a surface, it creates a pressure gradient, which can cause the blades of a wind generator to turn. Two percent of the total solar energy incident on the earth is converted into wind energy (Hunt 1981). If all available wind would be harnessed, the United States would be able to produce more than 30 times the energy consumption of the United States (Hunt 1981). In all practicality, with current technologies, it is not cost effective to attempt utilizing wind at these levels. It is anticipated that renewable energy will be supplying less than 20 percent of the energy demand for the next 15-20 years (Winteringham 1992).

There are two types of wind energy conversion systems (WECS): horizontal axis and vertical axis. Both systems are highly compatible to already established energy generating systems.

Horizontal Axis Wind Collectors

Horizontal axis WECS have towers rising into the sky. The height of these towers is determined by local values of wind availability, and the size of the turbine. Most turbines are higher than 10 meters, but experience from Altamont Pass in California has shown decreasing wind speeds with increasing height above 60 meters above ground (Gipe 1993).

On the top of the tower is an engine house (nacelle) with all electric conversion systems and controls. Facing into the wind attached to the house are the blades. The blades are attached to the rotor which is connected to the transmission and converter, located in the engine house on the top of the tower, also called the hub.

Horizontal axis turbines must face the wind in order to harness it, and it is therefore necessary to have a system to change the direction of the blades when the direction of the wind changes. This can be achieved several ways. For small turbines, a simple tail vane directs the blades in the needed direction. For wind farms, automatic control might be required. A person or control system can monitor the direction of the wind and, using wired controls, direct the position of the blades.

Most horizontal axis wind turbines have two or three blades. With only two blades there is a dynamic imbalance in the harnessing process which causes unnecessary stress on the system (Hunt 1981). Three-bladed wind generators are more common than two-bladed wind collectors. Horizontal axis wind turbines are most common today and they receive the most interest from both designers and buyers.

Vertical Axis Wind Collectors

The most common Vertical axis wind generators are the Darrieus' type. Darrieus wind generators do not have to face the wind, they operate independent of the wind direction. Most Darrieus' wind generators are located on the ground and suffer from less wind potential compared to the horizontal axis wind turbines. Darrieus' have inexpensive blades and because they do not need the same height as horizontal axis wind turbines, they are easier to construct and maintain. Darrieus wind generators are almost as efficient as horizontal axis wind generators, but they have two rather large problems. The first one is that they can not start on their own, unless they are aligned exactly with the incoming wind, so a motor has to initiate the harnessing of the wind. Second the Darrieus wind generators are very sensitive to high winds, and there has been some problems with stopping the generators before they break in strong winds. Darrieus blades have different configurations depending on their geometrical shape (Gipe 1993). The first large Darrieus wind turbine was built in Quebec, Canada in 1977. While operating it was rated at 230 kW (Johnson 1985).

There are other innovative wind energy conversion available described in the literature (Gipe 1993, Hunt 1981), but they are very expensive and not recommended with the current low costs for both horizontal and vertical axis wind turbines (Johnson 1985).

Wind energy conversion systems can either convert wind energy into mechanical energy to run saw mills, water pumps, etc, or to generate either AC or DC electricity. AC can be utilized by a utility grid and applications, while DC power can be used for local applications.

The most significant problem with wind energy is it's availability. We have all been exposed to weather variations. There is no model that can predict weather perfectly and forecast wind speed and wind energy potential. Weather is affected by a multitude of factors, some difficult to evaluate, which makes the regional wind energy potential difficult to predict accurately. Models therefore try to use collected weather data to predict wind energy potentials. These models are more conservative than the real life picture and can be used for simulation of fractions of supplied energy and cost analysis.

Physical problems occurring because of the location of the wind turbine(s)s will be briefly discussed in this thesis. Not covered here are topics related to the details of the actual wind harnessing procedure such as aerodynamics of the rotors, wake effects, and pitch control to mention a few. Several extended research papers and text books have been written on these topics and are available from many sources (Gipe 1993, Hunt 1981, Johnson 1985). A very extensive history of wind turbines can be found in the literature (Hills 1994).

Turbulence

Turbulence is caused by ground surface roughness and barriers. Turbulence causes a decrease in harnessed wind power. Because of the unequal load on the rotor blades, vibrations that might cause long term damage to the WECS may occur (Hunt 1981).

Extreme Winds

Most of the sensitive systems in WECS are protected against extreme winds, but a major factor in designing wind turbines is the tower. The weight and cost of the tower are proportional. Stronger towers cost more, but will also withstand more extreme winds (Hunt 1981).

Tower Height

Turbines with higher towers are less affected by turbulence or turbulent layers and have better power production. The increased power production is somewhat offset by increased weight and initial cost and maintenance. Most of today's towers are not taller than 50 meters (Gipe 1993), because there is no cost efficient increase in power production above 60 meters over the ground (Gipe 1993).

Elevation above sea level

The elevation above sea level impacts the power production because an increase in elevation decreases the atmospheric pressure and therefore the regional density of the air. Table 1.2 shows the impact of elevation above sea level on the change of wind power potential.

Table 1.2 Change in Air Density Relative to Elevation (Gipe 1993).

Elevation [m]	Relative change
0	100%
152	99 %
610	94 %
1220	88 %
1829	85 %
2134	79 %
2744	73 %
3049	70 %

Density

The density of the air directly affects the wind power generation, in most areas the seasonal change in air-density is not negligible (Gipe 1993, Hunt 1981). The maximum and minimum temperatures in climatic regions with extreme temperature differences (e,g. Iowa), changes the density and thus the power generation by up to 35% (Iowa).

Wind Shear

Wind shear is caused by a large change in wind speed over a short distance as in a boundary layer. Larger blades are more susceptible to wind shear, and the effect is more dominant where the wind turbine is located such that the blades are close to a surface, such as the ground or a mountain, that might interrupt the flow of the wind (Hunt 1981).

Snow

Snow does not affect the power generation directly, but might cause difficulties for maintenance staff to perform routine checkups on the turbines during the heavy snow periods of the year (Hunt 1981).

Icing

Icing can cause great damage to wind turbine blades. Ice can accumulate from either fog or rain, or freezing rain which can cause the blades to break and the system controls to fail. In remote areas flying blades will usually not cause a safety problem, but in populated areas a failing blade might create dangerous situations to surrounding people and equipment (Hunt 1981).

Extreme Temperatures

Extreme temperature does not directly affect the power production but it does effect the lubricants which are important to maintain a long life cycle. Extreme temperature will adversely affect the life time and the need for increased maintenance, and therefore down periods for the turbine (Hunt 1981).

Salt/Dust Spray

Siting of the wind turbine makes a difference in what will be hurled up from the surface or surrounding areas. If the turbine is located by the ocean, which will improve wind availability, there will be a drawback due to salt spray on the equipment which causes corrosion. Dust in desert areas will increase chances for fatigue failure along with higher levels of maintenance which demands down time of the turbine (Hunt 1981).

Small Wind Turbines (SWECS)

WECS' are usually referred to by their size: small, medium, or large wind turbines (Hunt 1981). Small wind turbines have a rated production up to about 100 kW, and are mostly utilized for individual homes, farms, remote communities, and small industry (Twidell 1987). There are very small wind turbines with a rated production of 50 - 500 watts, mostly used for charging batteries and supplying energy to small remote installations. These wind collectors are also small in size and their blades are usually in the range from 1-7 meter in diameter (Gipe 1993).

Another set of small wind turbines are used for pumping water. These turbines do not produce electricity at all, but convert the wind potential into mechanical work. These wind turbines are different because instead of the usual 2-3 blades horizontal axis wind collectors they have many blades. These wind-mills are capable of producing a large amount of mechanical energy in low winds, but are less efficient for electricity production (Gipe 1993).

Small wind turbines will, throughout their lifetime, rotate several million times in order to meet demand, which will cause a larger chance for fatigue failure. Engineers have to be very careful about the design of the blades for that reason. Because the turbines are small they are very delicate in regards to the wind speed, and their rotational speed is proportional to the wind speed at all times. For larger wind turbines this might not be true due to the larger inertia in the larger blades. Because the small wind turbines have less inertia they are also can operate in lower wind speeds.

Small wind generators are easy to control, and they need little supervision resulting in low maintenance expenditures. The drawback is of course that the production is low, including a low voltage in the range of 12-24 volts (Gipe 1993). Siting of these turbines has to be close to the end user because of this low voltage, otherwise loss through distribution could be too large for the wind turbine to be cost effective (Twidell 1987).

Medium Wind Turbines (MWECS)

Medium wind turbines have a rated production between 100 kW and 1000kW, and are mostly utilized for commercial electricity production. Medium or intermediate wind turbines are also used for water pumping, heating and cooling in small/medium clusters of buildings (Hunt 1985).

A large wind turbine system utilizing primarily medium WECS has been operating at Altamont Pass, California since 1984. The Altamont Pass facility is a wind farm with 75 units and a rated output of 26 MW (Gipe 1993)

Large Wind Turbines (LWECS)

Large wind turbines have a rated production above 1000 kW, and are mostly experimental turbines for industry, grid connections, and power plants. Most conventional wind turbines range up to a rated output of 500kW, larger turbines are not economically compatible on the market. Installation costs are up to 4-6 times higher for large wind turbines compared to smaller/medium WECS (Hau et al. 1993). The world's largest wind turbine ever built was German and had a rated output of 2-3MW at 12 m/s. Sweden is operating two large wind turbines WTS-3 and WTS-4 for the purpose of evaluating their potential (Hau et al. 1993). These two turbines have operated for at least ten thousand hours. The world's largest Darrieus-rotor is Canadian. It is rated at 4 MW and has been under test since 1987 (Hau et al. 1993). The problem that occurs for large wind turbines is the increased weight of the tower and the rotor, which increases the initial cost to a point where it is no longer beneficial, even considering the increased power output and more stable winds. Several countries, including the United States, Sweden, Germany, Denmark, Canada, Holland, and Italy, have been involved in a project called WEGA. In 1984, WEGA had three major systems planned operating or operating (Hau et al. 1993):

1. Tjaereborg, Denmark
    - Estimated Cost - $ 11,751,820.00 (9,355,800 ECU)
    - Rated power - 2 MW
    - Rated voltage - 6kV
    - Total mass - 889,600 kg
    - Wind speeds - 5/15/25 m/s (Cut-in/Rated/Cut-off)
    - Unit Cost 5,875.91 $/kW
2. Richborough, United Kingdom
    - Estimated Cost - $ 5,585,751.10 (4,446,900 ECU)
    - Rated power - 1 MW
    - Rated voltage - 3.3kV
    - Total mass - 159,900 kg
    - Wind speeds - 5/12/25 (Cut-in/Rated/Cut-off)
    - Unit Cost 5,585.75 $/kW
3. AWEC-60, Spain
    - Estimated Cost - $ 17,535,156.00 (13,960,000 ECU)
    - Rated power - 1.2 MW
    - Rated voltage - 6.3kV
    - Total mass - 281,600 kg
    - Wind speeds - 5.2/12/24 (Cut-in/Rated/Cut-off)
    - Unit Cost 14,612.63 $/kW

In general large wind turbines are considered to be not competitive, and for that reason research is conducted to try to improve their cost-effectiveness in order to establish better ways to harness more wind.

For the reminder of the thesis, the term the Wega turbine refers to turbine number one, with a rated power production of 2 MW, and a cost of \$5,800 per kW.

Fuel Cells

Fuel cells have received increased attention in the past ten years. There is a yearly conference on hydrogen as an energy carrier (Block & Veziroglu 1994), where research on fuel cells are a vital part of the conference. Countries like Brazil, Canada, Japan and several European countries are in the forefront of fuel cell R & D. The United States has for a long time utilized fuel cell technology in NASA's space programs and the space shuttles, where fuel cells provide water for drinking and cooling purposes secondary to energy production (Yildiz & Pekmez 1995). The use of fuel cells for power plants is now being seriously considered by several industrial countries (Block & Veziroglu 1994). Japan has the largest operating fuel cell power plant in the world with a production of 11 MW (Appleby & Foulkes 1989).

Utilizing fuel cells in an energy system provides several benefits: high efficiencies, low to zero emissions, low noise levels, fast response to demand/load, adaptability to either low local production or power plant production using multiple cells(stacks). The ideal fuel cells operate on pure hydrogen. The content of hydrogen gas in the atmosphere is relatively low, so for commercial and industrial purposes it must be manufactured. Hydrogen can be produced from either electrolysis of water, reforming hydrocarbons, or from a mixture of both. The energy requirement for reforming hydrocarbons is lower than for electrolysis of water (Yurum 1995). Electrolysis of water is an efficient procedure and can achieve efficiencies up to 92% (NREL 1992). Most systems operate with efficiencies in the range 60-80% (Yurum 1995). Using renewable energy, the total cost of electrolysis of water can be decreased by decreasing consumption of fossil fuels for electricity generation and therefore decrease emissions of green-house gases, reducing the total global cost of energy.

Steam reforming of natural gas is one source of hydrogen, at approximately \$ 6/GJ and 65-75% efficiency[3] it is the most efficient and economical method of producing hydrogen (Yurum 1995). Hydrogen from coal gasification costs on the average \$12-14/GJ, and is thus less cost efficient (Yurum 1995). Hydrogen can be produced using several other methods, most of them having drawbacks or expenses

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[3] 25-35 % of the energy is lost in the process

too large to be cost efficient. Some of these methods are water thermolysis, water radiolysis, and water photolysis (Yurum 1995). The last one is direct cleaving of water by solar radiation. A photon with the exact energy of 2.458 eV will cleave the water molecule into hydrogen and oxygen. This process is difficult to obtain with high efficiencies, bacteria do it regularly with an efficiency of 1-2%[4] (Yurum 1995).

There are a few problems related to hydrogen's ease of ignition both under storage and transportation, but they can be overcome. The United Stated already has an extensive network of gas lines for natural gas, which is primarily methane, another highly explosive gas. There are few accidents with natural gas, and initial research and operation of hydrogen pipelines in Germany, Northern France and Belgium (Pottier 1994) indicate that there should be few problems adjusting the distribution net of natural gas to transportation and storage of pure hydrogen gas. The cost of a distribution system to handle hydrogen gas is estimated to be 1.5-2 times higher than the cost of a natural gas distribution system (Pottier 1994).

Fuel cells are simple applications, in most combustion processes all the energy is converted into molecular motion or heat which is harnessed in some shape or form. Instead of harnessing random molecular motion, a fuel cell produces a steady stream of electrons at a low voltage. Fuel cells also generate heat, and when using fuel cells in combination with cogeneration, and in large power plants, efficiencies in the range of 75-80% can be achieved (NREL 1992). Higher operating temperatures would reduce the need for expensive metal catalysts and reduce both capital and operating costs (Yildiz & Pekmez 1995). The most effective commercial fuel cells include:

Alkaline Fuel Cells - AFC

Alkaline fuel cells produce the highest ratio of volts per cell, higher then 0.5 V per cell, they operate at room temperature and are utilized most for military and space applications. AFC's have a high initial cost and use pure hydrogen gas as fuel. Their cell life has proven to be between 10,000 to 15,000 hours. Capital cost related to their fuels and operation makes it inefficient to utilize AFC's for large scale use (Yildiz & Pekmez 1994).

Proton Exchange Membrane Fuel Cells - PEMFC

Proton Exchange Membrane Fuel Cells are very attractive in both transportation and stationary applications. These fuels cells have no moving parts and operate with minimum noise levels. PEMFC's

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[4] 98 % of the energy is lost in the process

have a high efficiency up to 50 %. Ballard Power System has built a 35 cell stack utilizing pure hydrogen and oxygen as fuels that produced over 10kW of power over a period of 2000 hours. Production costs for PEMFC stacks are today $ 3,200/kW for a 10 kW power plant. Increased research on membrane and electrolyte is expected to reduce the cost to $ 500 /kW by year 2000 for systems up to 50kW (Barbir 1995).

Molten Carbonate Fuel Cells - MCFC

Molten carbonate fuel cells have initial low expenses, operate at about 500 C- 700 C, and have a limited life cycle of about 5000 hours. MCFC's are utilized mostly in small power plants (Yildiz & Pekmez 1995).

Phosphoric Fuel Cells - PAFC

Phosphoric fuel cells are the most utilized. They work on reformed hydro-carbons and at a temperature of 170 C - 200 C. They have a relatively low cost, and their life cycle has reached as much as 40,000 working hours. Stacks of PAFC's can be utilized in all ranges of demand such as oil fueled, 1-5 kW cells for military purposes and natural gas, 40 kW - 5 MW stacks for power plants (Yildiz & Pekmez 1995).

Batteries

Due to legislation requiring vehicles to have partial zero-emissions in Los Angeles by 1997, and low-emission requirements in other regions of the United States by the end of this century (Cairns & McLarnon 1993), much research has been done on electric cars and re-chargeable batteries. Batteries also provide means for meeting peak demands in the utility grid, also referred to as load-leveling (Cairns & McLarnon 1993), and can be combined in or with power plants. The Electric Power Research Institute (EPRI) was, in 1987, operating a 10 MW rechargeable battery powered plant in Palo Alto, California, a supplement to the southern California utility grid.

There are two primary types of batteries, lead-acid cells and nickel-cadmium cells that have been around since 1900 (Berndt 1993). The nickel-cadmium cell provides less cell voltage and therefore nickel-cadmium batteries require more cells than lead-acid cells to provide the same capacity. A problem that appears with the nickel-cadmium batteries is that cadmium is an environmental toxic waste, and thus a problem occurs with disposal of used nickel-cadmium cells. It is therefore expected that nickel-cadmium cells soon will be replaced by non-toxic cells (Berndt 1993).

Tables 1.3 and 1.4 give a brief view of some of the batteries on available or currently researched with some of their most important characteristics.

Nickel hydrogen batteries tested in Philips Laboratories have set records in cell life (35,000 cycles) in a simulated low-orbit testing on the ground, they have improved battery characteristics but are still on the developing table.

There are different ways to charge these batteries and thus differences in how to discharge them as well. Low discharge rates result in high energy but low power output. High discharge rates result in the opposite, high power output and low energy output. Batteries can be used in two ways; emergency use only (floating) or repeated charge/discharge on an irregular base or in regular cycles. Table 1.5 shows the different characteristics of the two applications of the two most common batteries.

Table 1.3 New and Advanced Batteries (Cairns & McLarnon 1993)

	Lead-acid	Fe-Ni	Ni-Z	Ni-Hybrid[5]	Zn-Air[6]
Specific Energy [Wh/kg]	40	50	55-85	80	110
Specific Power [W/kg]	200	100	200	200	140
Life Cycle [hr]	2000	1000	600	500	600
Efficiency [%]	80	60	70	80	60
Cost [$/Wh]	0.1-0.3	-	0.15-0.5	1.0-3.0	$20/kg

Table 1.4 New and Advanced Batteries (Cairns & McLarnon 1993)

	Ni-Cd	Zn-Br	Sodium-S	Li-Fe	Ni-H
Specific Energy [Wh/kg]	45	75	90	150	50
Specific Power [W/kg]		100	250	400	-
Life Cycle [hr]	2000	2000	2000 (600)	100	35,000
Efficiency [%]	80	75	-	-	60
Cost [$/Wh]	0.5-1.5	-	100	-	-

Under normal operating temperature, the estimated lifetime of these batteries are a minimum of 15 years. For cycle operation, life is expected to exceed at least 1500 cycles if a 75 % discharge of nominal capacity is achieved (Berndt 1993).

Table 1.5 Battery Comparisons (Berndt 1993)

	Lead Acid	Ni/Cd
Float voltage	2.23-2.37	1.40-1.45
Cycle Voltage	2.35-2.45	1.55-1.60

Lead acid cells have an average unit voltage that varies between 2.27 - 2.30 volts, and nickel-cadmium cells average between 1.45 - 1.55 volts (Berndt 1993). The literature refers to several types of batteries currently undergoing development and testing for later use in either vehicles or power plants in order to reduce consumption of fossil fuels, and thus the emission of green house gases, some are introduced in Table 1.3 and Table 1.4.

Wind-Diesel Systems

Several remote locations have reduced their energy costs by adding a wind power harnessing system to their diesel power production systems. Remote locations in Europe, primarily remote islands, have utilized wind/diesel combinations to desalinate water and to supply electricity to the utility grid with high rates of success (Twidell 1982). These systems were initially all diesel systems and the wind generation was added to reduce fuel costs, with good results. Today, on the other hand, research is looking into utilizing wind power as a primary energy source and the diesel generators as a back up to the variability and instability of wind coverage. These systems utilize one or more diesel generators to supply energy when the main systems are unable to meet demand.

The wind-diesel combination can be used for small remote sites or energy production for entire communities, generating several megawatts of power and energy. There are several benefits to a larger system. It will most likely have more than one diesel generator, improving the operation strategies of the generators. It is very inefficient and expensive to start and stop diesel generators frequently; optimizing the operation strategies will minimize fuel consumption and operating expenditures. Larger systems will have more stable loads than smaller systems, making operations smoother as well. A small wind-diesel system ranges from 10kW to 200kW of diesel generated power (Nacfaire 1989).

Wind-diesel systems may incur peak loads five times the average load. Many systems are designed to be able to meet twice the load of the peak load. Diesel systems consume about one third of their maximum fuel consumption when they are idling, and they are normally operating at a minimum of 30% of maximum work load at all times, with a proportional fuel consumption. The 30% is to save the machinery from unnecessary maintenance, due to shut down and startup, which would outweigh the cost of the extra fuel expenditures (Nacfaire 1989).

Remote communities in Europe have been using wind-diesel combinations for several years. Experiences vary with the size of the production system. Reports from Denmark show there to be a pronounced but acceptable variation in voltage quality using wind-diesel energy generation (Nacfaire

1989), research in Norway shows that wind-diesel combinations might have as much as fives times higher cost than only diesel generators (Skarstein 1989), and operation of a wind-diesel-battery system in Ireland has shown diesel fuel reductions with as much as 70% (Nacfaire 1989).

Heat Pumps

Heat pumps transport energy from a lower temperature to a higher temperature. Heat pumps are utilized for space heating and cooling in both residential and commercial sectors, and to generate process heating for the industry (Stene 1992, Stene 1993). Their capacity ranges from below 1KW to industrial heat pumps rated at 25 MW (IEA Heat Pump Centre 1993). Heat pumps are most effective when they provide energy to a reservoir with a temperature below 150 degree C. Heat pumps can reduce costs for low grade energy demands by as much as 60-80 % (Stene 1992) compared to the use of fossil fuel heating devices. Because heat pumps reduce the need for fossil fuels they also reduce CO_2 emissions. Norway's extensive use of heat pumps for space heating have reduced Norway's CO_2 emission by 8%[7] (Stene 1992).

Heat pumps have a high capital expense, but the reductions in energy costs usually offset those expenditures within 3-5 years depending on the application. Heat pumps are utilized in a large number of applications, such as district heating and cooling, drying of fruits and fish, regeneration of heat from waste and sewage refineries, heating of water(health care facilities), distillation of ethanol, and for production of foods in greenhouses (Stene 1992).

Heat pumps' main benefits come from space heating applications. In Norway, 28 % of the energy is used for space heating (Stene 1992). 8 percent of the energy utilized for space heating is electricity, which could be reduced if the consumer or supplier utilized heat pumps for that space heating instead. 40 % of all residential floor space heating in Norway is utilize district heating and cooling, 80 % of all commercial units utilize district heating and cooling (Stene 1992). Thus one can easily establish that there is tremendous potential for savings utilizing heat pumps for space heating and cooling.

District Heating and Cooling

District heating has been commercially utilized since the late 1800's (IDHA 1983). The first district heating system can be dated all the way back to ancient Rome where it was used for heating residential dwellings as well as water for baths. The use of district heating was not commonly utilized before World

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[7] Including energy consumption for transportation in Norway

War II because of the cheap prices on fossil fuels. Today both district heating and district cooling are commonplace in Europe, the United States, the former Soviet Union, and China (IDHA 1983, IEA Heat Pump Centre).

District heating and cooling systems are often combined with waste energy recovery or cogeneration, which is when thermal energy is a byproduct to the production of electric energy. District heating and cooling can also been combined with heat pumps as in the city of Aalesund in Norway (IEA Heat Pump Centre 1992). In the United States, district heating and cooling only supplies approximately 1% of the total demand for space heating and cooling. In comparison, in Finland 14% of residential sector is heated from district heating and cooling, 40% in Denmark, and in Rumania 50% of space heating demand is met by district heating and cooling (IDHA 1983).

District heating and cooling is useful where the annual load factor is high, and where the thermal load density is high in applications such as industrial complexes, densely populated urban areas, or high density building clusters with high thermal loads. District heating and cooling is best utilized in relatively cold climates (IDHA 1983).

There are several economic benefits to district heating and cooling: almost all expenses for mechanical rooms are eliminated, consumers will incur reduced insurance and increased usable space, to mention a few of the most attractive benefits. The energy supplier can reduce the use of fuels; in the United States alone, district heating and cooling could save as much as 2.5 million barrels of oil per day with the accompanying decrease in pollutions (IDHA 1983).

The expenditures experienced with district heating and cooling is mostly related to the distribution system. Approximately 50-75% of the costs stem from building distribution systems. There are three classifications of district heating and cooling systems (IDHA 1983):

- below 120^oC
- between $120^oC - 175^oC$
- above 175^oC

A system can either have direct connections or heat exchanger connections, where plate heat exchangers have shown the best results (IDHA 1983). There is usually a 5-10 percent energy loss in the distribution system, which is small compared to the 70% energy loss in combustion of fossil fuels.

Available and cheap oil, combined with little or no interest from the federal government has kept research on district heating and cooling at a relatively low level. But increased demand for optimal use of energy sources has again put the light on district heating and cooling systems.

One area of district heating and cooling that should be investigated more is the inclusion of heat pumps in the district heating and cooling system. This would reduce operation costs, air pollution, and optimize the use of high grade available energy.

District heating and cooling systems are usually one out of three types: steam, hot water, chilled water. The two first systems are good for space heating, but the last one has been difficult to use for space cooling due to physical limitations such as pipeline lengths and energy transfer to the cooling medium prior to end use (IDHA 1983).

Environmental Cost

The combustion of fossil fuels has traditionally provided energy consumers with the lowest costs for the energy they buy. The low energy costs might have been accomplished at the expense of the environment. Table 1.6 show the relative pollutions originating with each fuel or technology.

Each of these pollutants have been directly or indirectly related to environmental effects. Sulphur-oxides is a component related to acid rain and acid depositions, possibly causing deforestation and destruction of fish in lakes and oceans; carbon dioxide is directly related to the greenhouse effect and possible airway infections and diseases; and volatile organic compounds (VOC'S) have been related to lung cancer. Chapter 4 gives a brief but detailed look into the possible effects and estimated costs of pollution on our environment.

Table 1.6 Energy Emission Comparisons [g/KWh] (NREL 1992)

	Gas	Oil	Coal	Fuel-cell
SO_X	-	3.35	4.95	0.00
NO_X	0.89	1.25	2.89	0.00
VOC's	0.45	0.42	0.41	0.00

Organization of Topics

This thesis is divided into five chapters. Chapter one discussed the history and general characteristics of the features included in this simulation. It gave a brief introduction of wind power technology, fuel cells, batteries, heat pumps, and district heating and cooling.

Chapter two discusses the mathematical, physical, statistical, and theoretical part of the models used for simulating the different scenarios described in this thesis. There are five scenarios in three locations simulated in this thesis. A sensitivity study is done to evaluate variations of some of the most distinct features of the different scenarios for a standard population.

Chapter three discusses the results of the simulations, and chapter five makes conclusions and recommendations. Chapter four addresses the environmental effects of some of the current energy technologies used in this thesis and attempts to estimate an economic cost to the use of non-renewable energy sources.

The last of this thesis includes appendices and references (bibliography). Appendix A describes the data used to determine residential space conditioning energy demand. Appendix B tabulates the basic scenarios and their parameters. Appendix C tabulates the various pathway efficiencies and costs. Appendix D includes graphs of comparisons of energy cost for 2,700 simulations conducted in this study.

2 MODEL AND THEORY

There are three groups of models described in this chapter: energy supply, energy demand, and energy storage/distribution models. The energy supply is found from simulating the operation of wind-turbines, diesel generators, and utility power. Demand models are found from using physical principles, and various statistical data obtained from different sources. Storage/distribution models include lump models of electrolysis of water, fuel cell operation, lead acid batteries, district heat and cooling, and heat pumps.

This thesis has used weather data obtained from National Renewable Energy Laboratory in Colorado called Typical Meteorological Year 2 (TMY2). This thesis simulates only three regions of the United States, but the methodology is described so other locations can be simulated as well. Larger cities or locations with available weather data are used to model energy supply and demand. Table 2.1 shows the simulated locations, the average data from TMY2 data sets, and 30 year weather averages obtained from the National Weather Service (NWS). Comparing typical meteorological year data with minimum 30 year average from National Weather Services show that the data used in the simulations are close enough to give good predictions about the fraction of supplied energy and cost analysis using wind as an energy source on the locations.

Table 2.1 Average Weather Data, by Region (Marion 1995, Dept. of Commerce 1995).

Location	Temp [^oC]		Wind [m/s]	
	TMY2	NWS	TMY2	NWS
Des Moines, Iowa	9.8	9.9	4.70	4.83
Honolulu, Hawaii	24.6	25.1	4.95	5.05
Kodiak Island, Alaska	4.65	4.78 (Juneau)	4.78	3.71 (Juneau)

Supply and demand for each location is a function of weather and climate, population, fraction of employment in commercial versus industrial sector, and residential structures.

The results are presented normalized per 1,000 people, so different scenarios and locations can be compared both in regards to fraction of supplied energy and economical assessments.

Modeling Energy Demand

These models emphasize the fact that high grade energy should not be utilized for meeting low grade energy demand and thus evaluate demand for low grade and high grade energy separately. Low grade energy, for space heating, space cooling and water heating is modeled separately from electricity demand for the different end users. End-users are in the residential, commercial, and industrial sectors. The residential sector is divided into space heating, space cooling, water heating, and demand for electricity. Space heating and cooling demands in residential units depend strongly on the ambient outside temperature. Both the industrial and commercial demand is divided into two end user groups, electricity and heating[1]. Commercial heating demand is dependent on the ambient outside temperature and anticipated load profiles. Commercial units have their time divided into on and off hours, with different load characteristics for week-days and week-ends. Industrial loads are predicted based on daily continuous operation.

The residential sector is modeled based on consumption per dwelling unit, while end use in both commercial and industrial sector is modeled on the average consumption per employee.

Energy Demand for Residential Space Heating and Cooling

The demand for energy for heating and cooling in residential units is a function of several factors. The model is energy balance from the equation (ASHRAE 1993) :

$$Q = U * A_s * (T_{bal} - T_a)$$

where:

Q - is transferred energy , positive for heating and negative for cooling

U - is the overall heat transfer coefficient

A_s - is the area over which the heat transfer takes place

T_{bal} - is the inside balance temperature

T_a - is the ambient outside temperature

Infiltration, ventilation, people, lighting, power, and appliances are taken into consideration through the balance temperature.

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[1] All other form of energy except electricity

Overall Heat Transfer Coefficient

This model uses the thermal resistance approach to the U-value. These calculations are all taken from 1993 ASHRAE Handbook, SI version, Chapters 20 through 22. There are five different types of building materials and structures used in this model.

1. Walls made from wood with average insulation
2. Walls made from concrete blocks
3. Walls made from clay bricks
4. Roof structures
5. Floor structures

For wood-walls the thickness of insulation is an average 90 mm. The average portion of the wall that have studs is 0.25, which gives 0.75 of the wall with an insulated cavity. The thermal resistance for the outside air varies with seasons, and the thermal resistance for the inside air varies with the direction of the heat flow. Standard walls all have outside boards 19 mm thick, and inside insulation of a 13 mm gypsum boards. The inside interior decorations are neglected in this model.

Appendix C gives the values for thermal resistances used in this model. The first subscript describes walls or studs, while the second subscript describes winter or summer. Calculations for average concrete blocks are found in the 1993 ASHRAE Handbook as well. Section 22.5 of the Handbook returns an average U-value for concrete blocks of 1.64 W/m^2K. Table 2.2 shows the different U-values used.

The regions simulated have different fractions of residential units made from wood, brick, and concrete. The various fractions used for each region are described in Appendix B.

Surface Area (A_s)

The average heated floor space in residential units in United States is 145.8 m^2 (EIA-RECS 1993). For this study these floors are assumed to be square shaped. Thus each wall is 12.1 meters long. The average home is assumed to be approximately 3 meters tall. Each residential unit has a perimeter wall surface of 12.1 m * 3 m * 4 walls = 145.2 m^2. Windows and door are accounted for through the balance temperature. The roof of each residential unit has a 145.8 m^2 large surface. The floors of each unit is assumed to be adiabatic, this is justified for single family units as well as for multiple family units. Single family units is assumed to have little or no heat loss from the basement, and for multiple family units the roof will be the only surface which will experience heat losses.

Balance Temperature

The inside temperature of a residential unit is set at a comfortable level, but not to exceed the most common values. The balance temperature also accounts for heat losses and heat gains from electric appliances and residents in the units. Commercial inside temperatures are set a little bit higher than for residential units (Watson 1983). The balance temperature is set at approximately 5^oC below the thermostat temperature for both residential and commercial units. For residential units the balance temperature is set at 16^oC and for commercial units the balance temperature is set at 19^oC. The inside temperature of a residential units should at least be 21^oC (Watson 1983), whereas the inside temperature of a commercial unit should at least be 24^oC (Watson 1983). Off hour balance temperature for commercial units are set at 14^oC.

For the purpose of this thesis, balance temperatures for cooling are set to be the same as for heating.

Table 2.2 Residential Heat Transfer Surfaces and Characteristics

Surface	Area	U-value
	m^2	$\frac{W}{m^2K}$
Wall, wood	145.2	0.363
Wall, concrete	145.2	1.640
Wall, brick	145.2	2.330
Roof, wood	145.8	0.479
Floor, slabs	145.8	0.000

Outside Temperature and Wind Speed

Outside temperatures are retrieved from the National Renewable Energy Laboratory's Typical Meteorological Years data (TMY2). The TMY2 data were derived from the 1961-1990 National Solar Radiation Data Base. TMY2 is hourly values of solar and meteorological data for a one year period. The data are selected months from a period of 30 years, collected to form one typical year.

The purpose of TMY is to provide means to simulate energy conversion systems, not for one particular year, but rather over decades. Users of TMY2 data are warned that the sets should not be used for simulating wind conversion system because of the weighting of the different parameters in the sets (Marion 1995). Comparing TMY2 data to 30-50 year average weather data obtained from the National Weather Service (Dept. of Commerce 1995) indicates that the yearly average wind and temperature data calculated from TMY2 is very similar to the statistical average. TMY2 is therefore used for these studies with the understanding that the primary predictions from these simulations should be used to determine whether or not to buy more detailed information.

Because TMY2 does not include extreme weather conditions, the TMY2 data sets should not be used for design, but rather studying potential and to compare various systems (paths) (Marion 1995).

TMY data are recorded at 239 weather stations in the United States or on properties under US governance. The TMY2 Manual produced by National Renewable Energy Laboratory describes in detail procedures for making and collecting the TMY2 data sets (Marion 1995).

Energy Demand for Residential Water Heating

Several studies have been conducted to survey the use and consumption of hot/warm water in residential units. These surveys have been compiled into one huge data-base (Becker & Stogsdill 1990). The numbers from this data base have been used to simulate the hourly consumption of residential and commercial units in this model.This consumption has been converted to SI units, and linearly regressed to model a whole year of hot water consumption. Data used are shown in Appendix C. Temperature of water at consumption is set at a minimum 55^oC (ASHRAE 1992), while the temperature of water from city supply lines assumed at 10^oC (ASHRAE 1992). For the purpose of these simulations water heater efficiencies are introduced during pathway analysis. It is the purpose at this stage to model the energy demand at the location of the user. The hourly energy demand for heating the water is an found from the energy balance :

$$Q = \frac{q*(T_{w,i}-T_{w,o})*\rho*C_{P_{water}}}{\eta}$$

where,

Q - is energy demand for water heating

q - flow rate $\frac{m^3}{hr}$ (Becker & Stogsdill 1990)

η - electric water heater energy efficiency factor

$T_{w,i}$ - wanted temperature of consumer's water supply

$T_{w,o}$ - temperature of city water supply to consumer

ρ - water density is 998.2 $\frac{kg}{m^3}$ (Moran & Shapiro 1992)

$C_{P_{water}}$ - specific heat capacity of water, 4.18 $\frac{kJ}{m^2K}$

The units of the data used in the data bases are flow rate per resident in a rented residential unit. Statistics show that people renting their dwelling units tend to use more water than the average resident. Statistical data obtained from the County and City Data Book (Dept. of Commerce 1991), suggest that there were on the average 2.70 people living in each occupied residence in the United States in 1990. Assuming that the 2.70 people on the average represent a family, and that most of the consumption in a residential unit is related to household duties, is it assumed that the hourly load found from equation 2.2 represents the hourly load of the entire household, and thus represent the hourly demand of energy for hot water heating per residential unit.

Energy Demand for Residential Electricity

Electric demand in the residential sector can be modeled several different ways. The literature shows many approaches that could be utilized (Reddy 1995, Zhen 1993, Zhen 1994, Macal 1987), but they all require a large amount of statistical data or energy audits conducted on the location. Some models survey the number of different electrical appliances in the home such as TV's, radios, light bulbs and so forth (Reddy 1995). This a very tedious and accurate method, but it is specific to the particular location and can therefore not be used generally. Models using price elasticities to predict future consumption has been deemed to inaccurate because they do not take into account hidden politics and legislative initiatives (Reddy 1995).

Several load profiles of residential electricity use (excluding energy for heating/cooling purposes) have been discussed in by Nielsen 1993, Kuo & Hsu 1993, Capasso et al. 1994, Sargent et al. 1994, Therien & Coupal (undated), and Mitchell 1978. The sources agree that load profiles have relative peaks in the morning, and that the daily peaks occur in early evening. To find the hourly electric demand, several data-sets have been obtained from Statistical Abstracts of the United States (Dept. of Commerce 1995). The total number of residents in the United States is divided by the number of residential units, giving the average number of residents per residential unit in the United States. The average monthly electrical residential electricity consumption is found by multiplying th e total annual electricity consumption with the fraction that represents the months fraction of yearly energy demand found from historical trends (EIA 1989). The individual monthly demand is then divided by the total number of residential units in the Unites States, giving the monthly electric demand per residential unit. It is assumed that the electric energy demand profile is the same each day for weekdays and weekends, but that weekdays and weekends have a slightly different load profile. Dividing each monthly load by number of days in each month[2], and multiplying with hourly load profile fractions result in an hourly average electricity demand per residential unit in the United States.

From the hourly demand, a fraction of the heating/cooling load must be subtracted to avoid modeling

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[2] Arbitrarily year that starts on a Monday, and has 365 days

a too high demand. 27% of all residential units in the United States use electricity as the primary energy source for heating, while 67.3% of all residential units use electricity for cooling the residence (EIA-RECS 1993). If the space conditioning load is used for cooling, 67.3% of the hourly space heating energy demand is subtracted from the hourly electricity demand, while 27 space conditioning load used for space heating is subtracted from the hourly electricity demand. The result is the hourly electric demand per residential unit in the United States.

Energy Demand for Commercial Space Heating and Cooling

Modeling Commercial Load Profile

Statistical data from the tri-annual energy survey conducted by the United States Energy Information Administration are used determine an accurate profile of floor space usage for commercial units (EIA-MECS 1991). The EIA surveys the use of floor space based on end use activities. The end use activities range from office space, education space, parking space and health care space. The data utilized to determine the floor space usage profile is described in Appendix E.

Each activity's floor space usage was found and converted into metric units. Each activities use by the hour was found based on total hours of usage per week, divided into 5 intervals for both week-days and week-end days. These intervals and the usage (and no usage) of floors pace results in a fraction of the floor space used (on-hours) and a fraction of floor space not used per hour (off-hours).

For the purpose of this thesis, on-hours are assumed to have a balance temperature of 19^oC, and off-hours have a balance temperature set at 14^oC. The outside ambient temperature is then subtracted from the balance temperature, and the difference is multiplied with the respective fractions of on and off hours resulting in a number of degrees of energy demand for heating for the hour, respectively DED and DEDH. The total number of degrees is added together for each weekday and weekend over each month of the year. Each month, a percentage of the total yearly energy consumption is allocated, found from trends over years (EIA 1989). The total monthly energy demand for heating[3] per commercial employee is then divided by the total number of degrees in that particular month giving the energy demand per DEDH. Monthly variations are found multiplying the yearly consumption with monthly trends (EIA 1989). Multiplying DEDH with the energy demand per DEDH, results in the hourly demand for heating energy per commercial employee.

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[3] All forms of energy except electric energy

Energy Demand for Commercial Electricity

The same procedure as used in commercial heating demand is used to find fractions of on-use and off-use to determine commercial electricity demand. For off hours, 80.9% of each activity's floor space have a reduction of electricity consumption (EIA-MECS 1991). For the purpose of this model it is assumed that floor space not in use have electricity consumption reduced by 81%. This results in a fraction of use for off-hours reduced by 81 %, and 100% use for on hours. For each day, the fraction of use is added together per the hour for one week day and one week end. The total number of fractions of energy demand is then multiplied with the number of days and week-ends and week-days per month, and added together resulting in degree hours (DH) of use per month based on commercial floor space.

The total consumption of electricity for the commercial sector is found from Statistical Abstract of the United States (Dept. of Commerce 1995), and divided into 12 months based on monthly average trends (EIA 1989), divided by the total number of employees in the commercial sector (EIA-MECS 1991). The total energy per month is then divided per degree hour per month resulting in the amount of energy that is required to meet the anticipated use of floor space at current levels of floor space activities. By multiplying the electrical energy demand per degree hour by floor space usage, load profiles for week-ends and week-days can be found.

For the same reasons as described in residential electric demand, the hourly demand has to be adjusted not to double model heating demand. The fractional reduction for cooling loads are 0.805 and 0.228 for heating loads.

Energy Demand for Industrial Sector

The fraction of space heating in industrial units is small compared to the energy demand for processes, thus this energy demand is included in demand for heating. The total demand for energy consumed in the industry was obtained from Statistical Abstract of the United States (Dept. of Commerce 1995), as was the total net consumption of energy. It is assumed that the total amount of energy (except electricity) accounts for the total energy demand for all heating or cooling processes in any or all of the industries in the United States. This total end use is then adjusted for monthly trends found in the EIA's Historical Monthly Energy Audit (EIA 1989) , and divided by the total number of workers (EIA-MECS 1991) resulting in monthly use of energy for electricity and heating per industrial employee. It is assumed that the daily load profiles remain constant every day of the year including weekends. The hourly consumption per industrial employee is thus found based on the hourly load profile. The load profile describes both the demand for heating and electricity. The literature shows that different industries have slightly different load profiles (Mitchell 1978), but the majority of the different total industrial load profiles reflect the trend this model is using (Mitchell 1978, Kuo & Hsu 1993).

Model of Supply, Storage, and Distribution

The objective of the supply model is to predict how much energy one wind turbine can generate. More than one wind generator can be used, assuming that the siting of the turbines are such that wake effects are avoided.

The demand model has predicted the actual demand of the end user. The supply model returns the available energy at the production site. The storage and distribution model utilize a methodology introduced by National Renewable Energy Laboratory, Pathway Analysis (Dept. of Energy 1992). Pathway analysis uses storage efficiencies to predict the energy required to meet demand at all levels in the energy delivery network. The pathway methodology is addressed later in this section.

Wind Generated Energy Production

When moving wind hits a surface, it creates a pressure gradient or a force, which causes the wind generator's rotors to turn. The most common way to assess the available wind power is to apply physical laws. Theoretical available wind power (P_a) is found from the equation (Gipe 1993, Hunt 1981, Johnson 1985):

$$P_a = \frac{1}{2} * \rho_{air} * A * (v^3)$$

where,

ρ_{air} is the density of the air

A is the swept area

- $A = \pi * (\frac{D}{2})^2$ for conventional rotors

- $A = 0.85 * D * H$ for Darrieus rotors[4] [5] (Gipe 1993)

v is the wind speed measured at some height

The generated energy is not equal to the theoretical available energy and this number must be multiplied with a turbine conversion efficiency (Gipe 1993, Johnson 1985, Hunt 1981) .

The height of the wind data measuring equipment (i.e. anemometer) might be different from the height of the turbine tower. The wind speed is adjusted by using this equation :

$$\frac{S}{S_0} = (\frac{H}{H_0})^{\alpha} \quad \text{(Gipe 1993, Hunt 1981)}$$

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[4] Diameter of the blades (Area swept by the blades)

[5] Height of the tower

Where,

S is the wind speed at the new height H

S_0 is the original wind speed at height H_0

α is the surface roughness exponent (SRE)

Anemometers are usually placed 10 meters above the surface (Gipe 1993). As a rule of thumb, for plain grass fields the SRE is set to be 1/7 (Gipe 1993). The SRE may vary for other surfaces. For row crops of corn (e.g. Iowa), the SRE rises to 0.15-0.20. In areas with many trees and rough surfaces the SRE might be as high as 0.25, and for winds over water, the SRE equals 0.10 (Gipe 1993)

Wind turbine manufactures test their turbines and the above mentioned theory is compared to records of the generated power over time. This record becomes a power curve. These power curves have shown to be good to predict potential power generation comparing wind and a specific wind turbine's characteristics. This model utilizes the power curve method to predict energy supply from the wind.

Power Curve Method

The purpose of this model is the predict how much energy one wind turbine will make available at the site of production, not including distribution and storage efficiencies. Wind energy generation is based on the cube of the wind speed, it is therefore important to model and simulate wind energy production at the smallest time intervals possible. The time intervals used for simulating the locations for this thesis are every hour for a year.

There is a problem related to using hourly data. The power curve method is essentially used to predict the average wind production for a year (Gipe 1993). The hourly wind speeds may not be accurate for the next year, but one goal of this model is to simulate the need for auxiliary energy and energy storage, and for that purpose it is necessary to model supply and demand per the hour. The total yearly production found from adding all the hourly productions was compared to the production predicted by a recognized wind simulator, WA^SP (Mortensen et al. 1993). The power curve model produced approximately 5% less energy than the WA^SP predictions for the same regions. For every hour, the supply picture may not be correct, but over the year the trends will average out and the yearly picture will give good indications of both wind potential and energy economy of the location.

The power curve method utilizes power curves published by wind turbine manufacturing companies. The power curve is the produced power at a specific location as a function of the wind speed at the top of the tower. This model uses linear interpolation between data points on the power curve to find the appropriate power production for a given turbine location at a given wind speed.

Wind speeds measured at 10 meter above ground level are adjusted for surface roughness over the year and tower height. The seasonal changes in roughness are particularly important in Iowa. During the late summer months, the roughness will be different from winter months because of snow and simple dusty fields compared to rows of corn.

The difference in air temperature from the standard temperature assumed to be used for the manufactures power curves (Mortensen et al. 1993, Hau et al. 1993), is then adjusted for using the $p = \rho_{air}RT$ equation. The wind speed is assumed to be the average wind speed of the hour, and this wind speed results in a constant hourly power production. This results in a conservative estimate of the wind energy produced each hour. For locations in the United States, wind generated energy production is simulated for 8760 hours, equaling a typical meteorological year.

Wind turbines used in these simulations are VESTAS and WEGA. Vestas has a turbine rated at 600 kW, at approximately $1,100 per installed kW (White 1996), while WEGA's 2 MW turbine cost approximately $5,800 per installed kW (Hau et al. 1993).

Electrolysis of Water and Hydrogen Distribution

For the purpose of this thesis it is assumed that electrolysis of water is an instant reaction and that the efficiency is relatively high, 92 %. There is a 8% heat transfer loss during electrolysis of water producing hydrogen and oxygen gas. Both gases are then stored and could be transported in intervals of 800 km, with distribution losses of 5% per each interval. Research and testing in Belgium, France, Germany and the United States has shown that there is no or insignificant increased risk transporting hydrogen in modified existing pipelines used for transportation of natural gas. Hydrogen gas can therefore either be consumed on site, stored or transported using already existing pipelines (Pottier 1995).

The cost of hydrogen is assumed to range from $6-18 per GJ, while the capital cost of distribution of hydrogen is assumed to be $ 50 per delivered kW (Dept. of Energy 1992). This cost is an extra cost needed to modify the pipes in pipelines to transport hydrogen gas instead of natural gas, and thus there are no costs affiliated with the use of transporting natural gas (See later in this section). The modification of existing steel pipelines is to avoid cracking from hydrogen embrittlement (diffusion). The capital cost of electrolysis equipment is set at $1,000/kW (Dept. of Energy 1992).

Fuel Cells

Fuel cells are highly efficient to convert chemical energy into electricity. Using co-generation, fuel cells can obtain efficiencies up to 80 %, and cost a little bit more per installed kW than most energy conversion systems currently available. Fuel cells have very short reaction times, and it is assumed that there is no lag time for production of energy using fuel cells and hydrogen. It is also assumed that the current and voltage generated is sufficient to support the demand using multiple stacks to achieve the desired levels of current and voltage. Fuel cell efficiencies vary a great deal depending on the amount of money one is willing to pay. Fuel cells using cogeneration has achieved 80% efficiency, but efficiencies average 40-80%. The base scenarios use a fuel cell efficiency of 50% (Dept. of Energy 1992). The cost of fuel cells is set at $3,200 per installed kW. In a sensitivity study future costs of fuel cell at $ 500 per installed kW will be simulated.

Batteries

Batteries in this model are assumed to be stacks of lead-acid batteries and very responsive to load changes. The batteries are modeled as black boxes, requiring at least 90% discharge before recharging, and there is no limitations on the number of cells that can be used simultaneously. Batteries are modeled to have a 80% efficiency and a capital cost of $100 per KW.

Diesel Generators

In this model diesel generators are used for auxiliary back up of the wind turbine only, with the exception of always running at 30% of maximum load to reduce maintenance costs. If the wind generated energy and the stored energy is not sufficient to meet demand, auxiliary power must be utilized. There are two auxiliary systems investigated in these simulations, the use of diesel generators or buying electricity from the utility company.

It is very expensive and impractical to start and stop diesel generators frequently. Most wind diesel systems therefore try to minimize stopping the generator. The diesel generator is assumed to be well regulated and reacts instantaneously to changes in demand in the range 30-100 % of rated power generation. More than one diesel generator can be used, and one or more can be running at minimum generation, while one or more is adjusting for increases in demand. The power generation from diesel generators are related to consumption of diesel fuel and the appropriate costs of diesel fuels. The fuel consumption is assumed to be proportional to the power output. An average cost of diesel fuel is assumed at $0.34 per liter, and each produced kWh requires 0.27 liter diesel including system losses, which result in a cost of $ 0.01 per delivered kWh (EIA 1994). It is assumed that the diesel generators are operating on location of the wind turbine. It is further assumed that energy and costs for transportation of diesel to the location of consumption are not included in this model. The cost of installed power from an diesel generator is set at $750 kW (Sinha 1993).

Utility Grid

If demand is not met by supply and it becomes necessary to buy energy from the utility company it is assumed the efficiency of these services are 92% per every 800 km and that the cost of electricity is 8 cents per delivered kWh. The relative high price is what the energy consumer would have to purchase the electricity from the utility company for. The 8 cents represent an average electricity price for Iowa in 1994 (EIA 1994).

Heat Pumps

A heat pump is a machine that transports energy (heat) from an environment with low temperature to an environment with a high temperature (Stene 1992). There are four major components in a heat pump system. Energy is removed from the original environment into a refrigerant using an evaporator. The refrigerant is then pressurized with a compressor, and the energy is removed from the refrigerant using a condenser. The refrigerant passes through an expansion valve before restarting the cycle. A heat pump's efficiency is measured by the coefficient of performance (COP), which is the fraction of low grade energy removed from the original environment over the amount of high grade energy added to the compressor (Stene 1992).

For the purpose of this model, it is assumed that the heat pumps operating in this system can be regulated to different levels of supply, and thus be used to meet various load profiles. It is further assumed that the heat pumps instantaneously meet change in demand, and that their operation can vary between 0-100% of full capacity. One or more heat pumps can be used to meet demand.

The heat pumps will be used with district heating and cooling, and used at the remote power plant supplying the district heating and cooling network with energy. It is assumed that the district and heating network is as efficient for both space heating and cooling, and water heating. Use of heat pumps utilizing wind generated energy will attempt to reduce demand for electricity for space conditioning applications.

A good heat pump will have a COP equal 2 or higher, which means that if the compressor uses 1 kW of electricity, it will transport 2 kW in low grade energy that can be used for heating purposes.

The heat pumps used in the base simulation is set to have a COP of 3.0. District heating and cooling network efficiencies vary from 85 % to 100%, the base simulation efficiency is set at 90 % which reflects an average distribution loss of 10% (IDHA 1983).

The cost of heat pumps is estimated at $350 per delivered kWh (IEA Heat Pump Centre), while the cost of a district heating and cooling system is assumed to be approximately $1,050 per delivered kWh which is approximately 75% of the total cost (IDHA 1983).

Pathway Analysis

Pathway analysis is a simple methodology introduced by NREL to determine energy demand for the supplier based on the efficiencies of storage and distribution systems. The previous supply and demand models have only looked at actual energy supply and demand. Now it is time to look at the entire picture to determine whether or not it is feasible using any or all of the above described technologies to supply adequately a certain niche in the energy market.

Pathway analysis uses two major concepts. The first is that one starts the analysis at the demand side and uses system efficiencies to calculate energy flow back to the original source to find what supply is required to meet predicted demand. Second, each stage of the pathway from supplier to end user is used to estimate the cost of the pathway per delivered kWh of energy.

This study evaluates several pathway scenarios:

* Wind generated energy using hydrogen and fuel cells as means of storage
* Wind generated energy using batteries as means of storage
* Wind generated energy using diesel generators without batteries
* Wind generated energy using diesel generators with batteries
* Wind generated energy supported by the utility grid

Example of Pathway Analysis

Let us assume that the pathway described in Table 2.3 is to be analyzed. If one looks at the pathway described in Table 2.3 the demand at the location of the consumer is 1 kW. On an average hour this results in an average energy consumption of 1 kWh. The last step in the pathway before the consumer, is the electric distribution. The efficiency of the electric distribution system is 92 %. This means that the system must deliver 1.00/0.92 = 1.09 kWh to the electric distribution system. The cost of the electric distribution system is $50 per kW, which result in a cost of this step in the pathway to be (1.00kWh * $50/kW =) $ 50.

The next step in the pathway going backwards from the energy consumer is the fuel cells. These fuel cells have an efficiency of 50 % and cost 3,200 per kW. The system must therefor deliver 1.09/0.50 = 2.17 kW to the fuel cells. The cost of using the fuel cells is thus 1.09*3,200 = $ 3,488. These calculations is done for each step in the pathway until the energy requirement form the supplier is found. The cost of the pathway is found from adding the cost of each up. For the pathway described in Table 2.3 the cost of each consumed or delivered kW to the consumer is $9,037 and for each consumed kW the energy supplier, in this case a wind turbine, must provide 2.70 kW. This cost will most likely be reduced when larger energy demands are endured because larger demand for equipment may force unit costs down. This number gives a good basis for comparing costs between different scenarios. For the purpose of determining the fraction of energy supplied for a system, the supplied energy is divided by the energy demand for a whole year.

Pathway analysis is used to find the fraction of supplied energy (FSE) and capital cost for the different storage and distribution combination system. Appendix C shows the different efficiencies and costs used in the pathway analysis. Appendix B shows the pathway scenarios and the parameters used in each of the various pathway simulations.

Table 2.3 Example of Pathway Analysis

	Eff. (%)	Energy (kWh)	Cost/kW	Total Cost
Demand	-	1.00		9,037
Electric Distribution (on site)	92	1.09 kWh	50	50
Hydrogen Fuel Cell	50	2.17 kWH	3,200	3,488
Hydrogen Pipeline (800km)	95	2.29 kWh	50	114
Hydrogen Production	92	2.49 kWh	1,000	2,290
Electric Distribution	92	2.70 kWh	50	125
Wind Turbine	40	-	1,100	2,970

Economic Modeling

Three costs are used to determine the the economy of each system. The capital cost described in this section is multiplied with the maximum demand for an hour to find the capital cost of the system in order to meet demand. Second, any fuel cost, or cost of energy purchased from the utility is multiplied with the total energy demand for that particular fuel to find total fuel costs. Third, a constant 5 percent of the total capital investment for all systems is assumed to cover operation and maintenance cost for year. Using a present worth factor, PWF(N=10, i=5, d=7)=8.579 (Duffie & Beckman 1991), multiplied with the sum of fuel costs and operation and maintenance cost, added to the capital investment gives the present worth of the energy system. The present worth of the system is divided by the the estimated accumulated energy demand of which the system is sized for ten years[6] to find the cost of each delivered kWh to the consumer.

Description of Simulations

Several simulations have been conducted based on the model described previous in this chapter. Five pathways with three variations for three climatic regions have been simulated for FSE and cost. Fraction of supplied energy (FSE) is defined as the fraction of supplied energy divided by energy demand. Energy demand is simulated for 1,000 persons in various scenarios. Further for this thesis, cost is the unit price of delivered kWh of energy to the end user for each pathway where the total demand is met. This indicates that utility purchases are included in the total cost of energy for the specific pathway. The cost includes fuel costs, capital expenditures, and operation and maintenance costs.

Simulated Pathways

Five pathways were chosen for the simulations done in this study. There are other pathways that could be analyzed as well. Other systems could be gas turbine pathways and various steam turbine pathways to mention a limited few. The five simulated pathways were:

Wind - Utility
Wind - Batteries
Wind - Hydrogen/Fuel Cells
Wind - Diesel Generators
Wind - Diesel Generators with Batteries

Wind-Utility Pathway

This pathway is assumed to have no storage capability, and any surplus energy from the wind turbine is not utilized. The pathway simply simulates FSE of the wind turbine alone. The system itself is not sized, but the cost is found from multiplying the highest hourly demand for the year with the cost of that particular installed pathway (Appendix B). This number will represent fractions of wind turbines as well as fraction of the storage systems, but the resulting cost is used for relative comparisons between the systems.

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[6] Life of system may vary

Wind-Batteries Pathway

This pathway utilizes lead acid batteries to store any surplus energy from the wind turbine. The batteries discharge stored energy when wind generated supply is less than demand. If energy from batteries and wind turbines is insufficient to meet demand, energy is purchased at market price from the utility grid. The system is sized to meet maximum energy demand, which is the highest hourly demand over a year. The highest demand is multiplied with the installed cost of the pathway (Appendix B) to determine capital investments required to meet demand. This number will represent fractions of wind turbines as well as fraction of the storage systems, but the resulting cost is used for relative comparisons between the systems.

Wind-Hydrogen Pathway

This pathway uses hydrogen to store any surplus energy from the wind turbine, and fuel cells to use the stored energy when needed. If the energy supply from the storage and wind generator is insufficient to meet demand, energy will be purchased from the utility grid. The system is sized multiplying the highest hourly demand for a year with the installed cost of the pathway (Appendix B) to determine the capital investments needed for energy supply to 1,000 people. This number will represent fractions of wind turbines as well as fraction of the storage systems, but the resulting cost is used for relative comparisons between the systems.

Wind-Diesel Pathway

This pathway uses a combination of a series of diesel generators to meet demand. Each diesel generator runs at at least 30 % of maximum at all times. The systems is sized so that there are enough generators to meet demand if the wind turbine is down. For the diesel generators this results in a slight over sizing. The diesel generators used in these simulations are assumed to have maximum output of 500kW, and the supply is in steps of 500 kW. Purchasing energy from the utility grid is not included in this model since this option is assumed to be feasible at all times. There is no storage capability in this pathway. The capital cost is found from multiplying the possible supply with the cost of the pathway (Appendix B).

Wind-Diesel with Batteries Pathway

This pathway has a series of diesel generators at minimum 30% of maximum load at all times. Any excess energy is stored in lead acid batteries and the highest total demand can be met by the series of diesel generators. The batteries discharge stored energy when demand exceeds the combined supply from the wind turbine and 30% output of the diesel generators. The maximum supply from this pathway is the wind-generated energy and the energy supplied from the diesel generators. There is no need to purchase energy from the utility grid as the pathway is assumed to be feasible for all regions and variations. As in the previous pathway, the diesel generator system will be slightly oversized, as supply is in fractions of 500 kW. The minimum number of diesel generators need to meet the highest hourly demand is the sizing factor of this system.

Simulated Heating Options

Three heating options have been studied in this thesis, which are listed below. There is a multitude of other options available, i.e. heat pumps on the location of the user excluding the district heating and cooling option, wood burners, and any combinations of the heating options mentioned to mention e few. These simulations have been done using three different heating devices at the site of the end user:

1. Electric furnace
2. Gas Furnace
3. District Heating and Cooling with Heat Pumps

Electric Furnace

This variation simulates an all-electric consuming population. Both low grade and high grade energy demand is met with supply of electric energy either directly from the wind turbine or the different storage paths. It is assumed for all three options that the heating devices are already on the location and that the pathway describes the energy path from the wind turbine to the doorstep of the end user.

Gas Furnace

It is the assumption of this system that there is an already existing network of pipes distributing natural gas to end users. The cost of this pathway only includes the cost of natural gas per delivered kWh. There are no capital, maintenance, or operating costs for the gas furnace option. This is the same assumption as made for the utility network since it is already existing and the cost is per volume unit accounts for operation costs etc. Energy supplied from the wind system is entirely used to meet high grade energy demand. Low grade energy demand is at all times met by the gas furnace on the location of the end-user.

This system is not sized, as it assumed that the heating devices are already existing on-site of location of end-user. The only cost incurred with this option is the cost of natural gas required to meet low grade energy demand.

District Heating and Cooling with Heat Pumps

In this variation the low grade energy demand is supplied by a series of heat pumps using a district heating and cooling network for energy distribution. Electricity generated from the wind generator and energy from storage is used to meet high grade energy demand and to operate the heat pumps.

This option is sized as previous. The system is designed to meet the highest hourly demand at any given hour of the year.

Simulated Climatic Regions

- Iowa using Des Moines weather data
- Hawaii using Honolulu weather data
- Alaska using Kodiak Island weather data

Simulated Wind Turbines

Energy supply is simulated from the use of two wind turbines. Two power curves were obtained from VESTAS (White 1996) and WEGA (Hau et al. 1992).

Simulated Populations

Variations in populations have been done in fractions of residential demand and fractions of commercial versus industrial employment per 1,000 people in the region. Each 1,000 people live in 370 residential units based on a national average of 2.70 people per occupied dwelling unit. Of the entire population of the United States 47.4% are employed. This result in 474 people employed in all scenarios simulated in this thesis. For each pathway and region, fraction of energy supplied is found for 100 % employment in steps of 25% of the two employment groups. For each variation of employment, supply to residential units vary from 0 to 100% in steps of 20%. This gives a total of 30 variations for each pathway and heating device option. A total of 2,700 simulations were conducted for all regions, pathways, and variations. Details for the case study of Ames will detailed a section in next chapter.

3 RESULTS AND DISCUSSION OF SIMULATIONS

This chapter discusses the results obtained from simulating the models as detailed in chapter 2. There are 2,700 different scenarios with varying regions, pathways, heating options, wind turbine types, and populations. The different scenarios are:

Climatic Regions:

Iowa
Hawaii
Alaska

Pathways:

Wind - Utility Pathway
Wind - Battery Pathway
Wind - Diesel/Batteries Pathway
Wind - Hydrogen Pathway
Wind - Diesel Pathway

Heating Options:

Electric Furnaces Option
Gas Furnaces Option
District Heating and Cooling with Heat Pumps Option

Wind Turbine Types:

Four (4) Vestas (600 kW) wind turbines
One (1) Wega (2 MW) wind turbine

Populations, per 1,000 persons:

Commercial Employment (0-100%, steps of 25%)
Industrial Employment (100-0%, steps of 25%)
Residential Energy Demand Coverage (0-100%, in steps of 20%)

The results of the simulations carried out are fraction of supplied energy (FSE) and cost per delivered unit of energy (energy cost).

Fraction of Supplied Energy (FSE) is the fraction of the total amount of energy supplied by the wind-storage network divided by the total demand for the particular scenario.

Energy Cost is the present worth of each delivered kWh of energy delivered by the system to cover demand 100%.

Lowest energy demand scenario (LES) is the scenario with 0% industrial employment, 100% commercial employment and 0% residential energy demand coverage.

Highest energy demand scenario (HES) is the scenario with 100% industrial employment, 0% commercial employment and 100% residential energy demand coverage.

Results of Demand Simulations

Energy demand in Iowa

Table 3.1 shows the simulated energy demand per 1,000 persons in each demand sector for the Iowa region. The simulated energy demand of Iowa shows that demand for low grade energy accounts for approximately two thirds of total residential energy demand (Table 3.1). This is consistent with residential energy surveys on a national level (EIA-RECS 1993).

Table 3.1 Simulated Demand in Iowa (GWh per year per 1,000 persons)

	Low	High	Total	% Low	Surveys (%)
Residential	4.04	2.35	6.39	63.2	67
Commercial	6.22	3.52	9.75	63.8	50
Industrial	49.88	6.61	56.49	88.3	90

Predicted energy demand in the commercial sector shows a slight difference from a national survey which concludes that the low grade energy demand is approximately 50% of the total demand. The difference might be accounted for through how the commercial demand is modeled, since commercial consumer data is used to model the same demand. The consumer surveys indicate that space cooling is usually accomplished by consuming electricity for air conditioning. This model has included cooling as low grade energy which should explain the difference in simulated versus surveyed commercial low grade energy demand.

Industrial energy demand is consistent with national figures. The low grade energy demand is much larger than the demand for high grade energy due to process heat demand in industrial manufacturing.

Energy demand in Hawaii

Table 3.2 shows the simulated energy demand in each sector per 1,000 person in the Hawaii region. The simulated energy demand of Hawaii shows that demand for low grade energy account for approximately two thirds of total residential energy demand (Table 3.2). The Hawaii region is consistent with residential energy surveys on a national level (EIA-RECS 1993).

Table 3.2 Simulated Demand in Hawaii (GWh per year per 1,000 persons)

	Low	High	Total	% Low	Surveys (%)
Residential	3.57	1.93	5.50	64.9	67
Commercial	6.22	2.39	8.61	72.3	50
Industrial	49.88	6.61	56.49	88.3	90

Energy demand in the commercial sector in Hawaii shows a slight difference from the national survey data, which concludes that the low grade energy demand is approximately 50% of the total demand for all regions in the United States. The difference might be accounted for through how the commercial consumption is modeled, but also by the climate. In comparison to Iowa where the average temperature is much lower, the fraction of low grade energy used is higher in Iowa. Since less energy for space heating than space cooling is supplied through electricity, the electric demand should be higher in a region with higher demand for space cooling, rather than for space heating. This is consistent among the three simulated regions in regards to commercial sector's simulated energy demand.

Industrial energy demand is consistent with national figures. The low grade energy demand is much larger than the demand for high grade energy due to process heat demand in industrial manufacturing (Table 3.2).

Energy demand in Alaska

The simulated energy demand of Alaska shows that demand for low grade energy account for three fifths of total residential energy demand (Table 3.3). One could expect that since the average temperature in Alaska is so much lower than Hawaii that a larger fraction of the energy demand would be low grade energy demand. This is not the case, but the total energy demand per 1,000 persons is larger in the Alaska region than in the Hawaii region. The Alaska region does not require as much energy for space cooling as the other regions and thus the high grade energy demand is not adjusted as much as for the other regions. Thus the variation can be explained, and the number is comparable to national residential energy surveys (EIA-RECS 1993).

Energy demand in the commercial sector shows a slight difference from the national survey which concludes that the low grade energy demand is approximately 50% of the total demand. The difference in simulated and surveyed demand can possibly be explained from how commercial energy demand is modeled. The energy demand is modeled based on national consumer records and estimated load profiles, which do not distinguish between demand for electric space conditioning devices or demand for any other electrical appliances, thus making it difficult to estimate how much of commercial low grade energy demand is met by electric energy. For this reason, the numbers are slightly off, but they will serve well as a basis for comparison of the different regions and scenarios.

Industrial energy demand is consistent with national figures. The low grade energy demand is much larger than the demand for high grade energy due to process heat demand in industrial manufacturing (Table 3.3).

Table 3.3 Simulated Demand in Alaska (GWh per year per 1,000 persons)

	Low	High	Total	% Low	Surveys (%)
Residential	4.09	2.54	6.64	61.7	67
Commercial	6.22	4.07	10.30	60.5	50
Industrial	49.88	6.61	56.49	88.3	90

Test of Demand Model - The Iowa Scenario

In 1990, 2,776,755 persons were occupying 1,065,325 residential units in the state of Iowa. 1,340,242 of those persons were employed, 17.4% were employed in the industrial sector[1]. This indicates 48.3% employment of the total population and an average 2.61 persons per residential unit. Using these numbers the simulated demand for the State of Iowa becomes 6,807 GWh in the residential sector; 10,794 GWh in the commercial sector; and 13,174 GWh in the industrial sector totaling 30,775 GWh yearly end demand.

Using the national averages described in chapter 2, the energy demand becomes 6,571 GWh in the residential sector; 10,561 GWh in the commercial sector; and 13,162 GWh in the industrial sector totaling 30,294 GWh per year. These numbers vary with less than 2%, which supports using average national data as well as local data for modeling energy demand.

Gathering data from the Energy Information Administration (EIA 1994), the 1990 Iowa total energy consumption was approximately 263,500 GWh. The same source estimates that 26.5% of the total energy consumption was used in the transportation sector, resulting in an energy consumption of

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[1] Industrial sector includes employment and energy demand for agricultural use

193,640 GWh for the residential, commercial, and industrial sector. The same source further estimates distribution losses to account for 23.6% of the total energy consumption, which would result in a total consumption for the three simulated sectors in Iowa to be 147,950 GWh per year. Comparing this number to the average simulated energy demand of Iowa equal to 30,500 GWh per year there is an obvious discrepancy in these numbers. The simulated demand represents 20.6% of the actual consumption. This is probably a result of the fact that industrial energy demand does not account for the agricultural sector, which is a major energy consumer in Iowa. There is room for improvements to the models which will be detailed in chapter 5.

Energy consumption is difficult to simulate and this has been established with these results as well. The fraction of low grade energy demand versus the fraction of high grade energy demand is similar to the fraction resulting from national surveys.

Test of Demand Model - The Ames Scenario

The demand model was used to model energy consumption in Ames, Iowa based on census data from 1990 (Table 3.4). If one uses the census data uncritically, the simulated demand for Ames becomes much larger than the measured consumption in 1985. When adjusting the census data by excluding the university community the results become more like the actual consumption. Excluding 25,000 students from the work-market, and using the national average of 2.70 person per occupied residential unit, the simulated demand is 408 million kWh in a typical year. Comparing this result to consumption data provided by the City of Ames, the actual consumption in 1985[2] was roughly 290 million kWh. Assuming that the average yearly inflation rate is 5%, and that the increase in energy consumption is proportional to inflation rates and thus the economy, the anticipated consumption in 1990 would be 370 million kWh.

Table 3.4 Simulated Demand in Ames (GWh per year)

	Low	High	Total	% Low	Surveys (%)
Residential	88.82	51.79	140.61	63.2	34.5
Commercial	129.96	73.59	203.55	63.8	49.9
Industrial	55.97	7.42	63.38	88.3	15.6
Total	274.74	132.81	407.55	67.4	100.0

Comparing this number to the simulated 1990 demand, the difference is 9.3%. The simulated demand is thus higher than the anticipated demand, which helps to underline the conservative approach with

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[2] Except energy for transportation sector

this methodology and study.

The wind generated supply for Ames is equivalent to the wind generated energy for the Iowa region (Table 3.5).

Results of Supply Simulations

Each of the regions was simulated using two different wind turbines, Vestas (600kW) and Wega (2MW) turbines. Tables 3.5 through 3.7 show the predicted energy production in each of the regions using one turbine of each of the two types and TMY2 data. As expected, the Wega turbine generates more energy per year than the Vestas turbine. Comparing energy production using the WA^sP computer simulations (Mortensen et al. 1993) the energy production in each region is approximately 1 GWh using the Vestas turbine. The model described in chapter 2 predicts energy production in Iowa to be 90 % of what WA^sP estimates. WA^sP simulates power production at a constant air density at approximately 15°C. Chapter 2 on the other hand indicated that a change in air density can make a large difference in wind generator energy production, and thus the production must be adjusted for air density, which explains differences in this simulation energy productions to those of WA^sP.

Table 3.5 Wind Generated Energy in the Iowa Region

	Energy	Wind Speed
	MWh/year	m/s
Vestas	903	4.70
Wega	3,687	4.70

Table 3.6 Wind Generated Energy in the Hawaii Region

	Energy	Wind Speed
	MWh/year	m/s
Vestas	877	4.95
Wega	3,562	4.95

Table 3.7 Wind Generated Energy in the Alaska Region

	Energy	Wind Speed
	MWh/year	m/s
Vestas	999	4.65
Wega	3,847	4.65

Comparing the average wind speed in Alaska to the two other regions it is smaller, but the energy production is larger (Table 3.7). This is most likely due to the fact that the average temperature in Alaska is lower than in the two other regions, resulting in higher density of the air and thus more energy production. The average wind speed in Hawaii (Table 3.6) is larger than in both Iowa and Alaska, but here the average temperature is much larger than the two other regions resulting is lower air density and thus smaller energy production.

Results of Fraction of Energy Supplied (FSE) Analysis

The highest FSE appears in the scenario with the lowest energy demand (LES) using the gas furnace option while the lowest FSE appears in the scenario with the highest energy demand (HES). These two trends are appearing in all scenarios without exception, not including any of the six different diesel or diesel/batteries pathways.

Iowa Region

Wind-Utilities Pathway

Table 3.8 shows the fraction of supplied energy varying from 0.053 to 0.514 with different heating options and various energy demand scenarios.

Wind-Batteries Pathway

Table 3.9 shows the fraction of supplied energy varying from 0.053 to 0.873 with different heating options and various energy demand scenarios.

Wind-Diesel/Batteries Pathway

Table 3.10 shows the fraction of supplied energy varying from 0.602 to 8.377 with different heating options and various energy demand scenarios. This system has a fraction of supplied energy higher than one due to the way the systems is sized. The number of diesel generators energy production highest energy production is matched to the peak load of any hour of the year for the highest energy demand scenario which is the electric furnace option. The fraction of energy supplied is found from comparing the wind generated energy added, the minimum energy generation operating diesel generators at 30% of maximum load, and the energy demand. This fraction is higher than one for approximately half of all the scenarios, then the level of energy production from the diesel generators must be increased.

Table 3.8 FSE for Wind-Utilities Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.053	0.286	0.054	0.305
Gas Furnace	0.064	0.467	0.065	0.514
DHC	0.058	0.375	0.059	0.407

Table 3.9 FSE for Wind-Batteries Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.053	0.330	0.054	0.339
Gas Furnace	0.064	0.848	0.065	0.873
DCH	0.058	0.412	0.059	0.407

Using the wind-diesel/batteries pathway, the FSE is increased above one, the same goes for the gas furnace option which is less energy demanding option. These findings are consistent for all regions in this chapter.

Wind-Hydrogen Pathway

Table 3.11 shows the fraction of supplied energy varying from 0.053 to 0.703 with different heating options and various energy demand scenarios.

Wind-Diesel Pathway

Table 3.12 shows the fraction of supplied energy varying from 0.570 to 3.031 with different heating options and various energy demand scenarios.

Table 3.10 FSE for Wind-Diesel/Batteries Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.602	3.349	0.603	3.355
Gas Furnace	0.675	8.362	0.676	8.377
DCH	0.637	3.118	0.638	3.123

Table 3.11 FSE for Wind-Hydrogen Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.053	0.309	0.504	0.323
Gas Furnace	0.064	0.668	0.065	0.703
DCH	0.058	0.437	0.059	0.459

Table 3.12 FSE for Wind-Diesel Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.570	1.000	0.571	1.000
Gas Furnace	0.664	3.031	0.664	3.031
DCH	0.611	1.000	0.612	1.000

Hawaii Region

Wind-Utilities Pathway

Table 3.13 shows the fraction of supplied energy varying from 0.052 to 0.598 with different heating options and various energy demand scenarios.

Wind-Batteries Pathway

Table 3.14 shows the fraction of supplied energy varying from 0.052 to 1.217 with different heating options and various energy demand scenarios.

Wind-Diesel/Batteries Pathway

Table 3.15 shows the fraction of supplied energy varying from 0.609 to 12.233 with different heating options and various energy demand scenarios.

Table 3.13 FSE for Wind-Utilities Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.052	0.343	0.053	0.359
Gas Furnace	0.062	0.553	0.063	0.598
DCH	0.057	0.455	0.058	0.490

Table 3.14 FSE for Wind-Batteries Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.052	0.368	0.053	0.376
Gas Furnace	0.062	1.192	0.063	1.217
DCH	0.057	0.472	0.058	0.478

Table 3.15 FSE for Wind-Diesel/Batteries Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.609	3.756	0.610	3.761
Gas Furnace	0.679	12.216	0.680	12.233
DCH	0.643	3.661	0.644	3.665

Wind-Hydrogen Pathway

Table 3.16 shows the fraction of supplied energy varying from 0.052 to 0.925 with different heating options and various energy demand scenarios.

Wind-Diesel Pathway

Table 3.17 shows the fraction of supplied energy varying from 0.576 to 3.998 with different heating options and various energy demand scenarios.

Alaska Region

Wind-Utilities Pathway

Table 3.18 shows the fraction of supplied energy varying from 0.056 to 0.385 with different heating options and various energy demand scenarios.

Table 3.16 FSE for Wind-Hydrogen Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.052	0.356	0.053	0.368
Gas Furnace	0.062	0.891	0.063	0.925
DCH	0.057	0.522	0.058	0.546

Table 3.17 FSE for Wind-Diesel Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.576	1.000	0.576	1.000
Gas Furnace	0.664	3.998	0.664	3.998
DCH	0.618	1.000	0.618	1.000

Table 3.18 FSE for Wind-Utilities Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.058	0.289	0.056	0.298
Gas Furnace	0.070	0.356	0.068	0.385
DCH	0.064	0.335	0.062	0.353

Wind-Batteries Pathway

Table 3.19 shows the fraction of supplied energy varying from 0.056 to 0.794 with different heating options and various energy demand scenarios.

Wind-Diesel/Batteries Pathway

Table 3.20 shows the fraction of supplied energy varying from 0.603 to 7.337 with different heating options and various energy demand scenarios.

Wind-Hydrogen Pathway

Table 3.21 shows the fraction of supplied energy varying from 0.056 to 0.590 with different heating options and various energy demand scenarios.

Table 3.19 FSE for Wind-Batteries Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.058	0.343	0.056	0.335
Gas Furnace	0.070	0.794	0.068	0.773
DCH	0.064	0.416	0.062	0.396

Table 3.20 FSE for Wind-Diesel/Batteries Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.605	3.210	0.603	3.199
Gas Furnace	0.677	7.337	0.675	7.311
DCH	0.637	2.940	0.635	2.932

Table 3.21 FSE for Wind-Hydrogen Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.058	0.318	0.056	0.318
Gas Furnace	0.070	0.587	0.068	0.590
DCH	0.064	0.417	0.062	0.420

Wind-Diesel Pathway

Table 3.22 shows the fraction of supplied energy varying from 0.568 to 2.759 with different heating options and various energy demand scenarios.

Comparisons of Wind Turbines

Fraction of supplied energy (FSE) is smaller for the four Vestas (4X 600kW) turbines than for the one Wega (1X 2 MW) in the Iowa and Hawaii region, but not in the Alaska region where fraction of energy supplied is larger using four Vestas turbines compared to using one Wega turbine in all energy demand scenarios. Comparing only the lowest simulated energy demand scenarios[3], the lowest FSE for four Vestas turbines appear in the wind-utilities pathway, using the electric furnace option in the Iowa region and equals 0.286 (Table 3.8). The highest FSE using four Vestas turbines appears in the wind-batteries pathway with the gas furnace option in the Hawaii region where FSE equals 1.192 (Table

Table 3.22 FSE for Wind-Diesel Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	0.569	1.000	0.568	1.000
Gas Furnace	0.665	2.759	0.663	2.759
DCH	0.608	1.000	0.607	1.000

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[3] For all comparisons in this thesis unless otherwise noted

3.14). Both the highest and lowest FSE for the Wega turbine appear in the same scenarios as for the four Vestas turbines (Table 3.8 and Table 3.14).

Comparisons of Pathways

The FSE follow the same trends for all regions comparing pathways. The highest FSE appears with the wind-batteries pathway, while the lowest FSE appears with the wind-utilities pathway. Comparing the two wind-diesel pathways, the wind batteries pathway has a larger fraction of supplied energy than the wind diesel only pathway. These results are consistent with what was expected based on the models. The wind-batteries pathway has a higher pathway efficiency for stored energy and thus a higher fraction of supplied energy when stored energy is utilized. The highest FSE equal 1.192 (Hawaii) and appears with the wind-batteries pathway (Table 3.14), while the lowest FSE appears with the wind-utilities pathway and is equal to 0.286 (Iowa) (Table 3.8). The highest fraction of energy supplied achieved comparing the two diesel pathways is equal to 12.233 (Hawaii) and appears with the wind-diesel/batteries pathway using the gas furnace option (Table 3.15). The lowest FSE comparing the two diesel pathways, appears in the Iowa region and is equal to 0.570 using the electric furnace option for the wind-diesel only pathway, which is consistent with lower energy availability that follows without any energy storage system.

Comparisons of Heating Device Options

The highest fraction of energy supplied is consistently using the gas furnace option. This is as expected based on the basis for the simulations, where electric energy demand is lowest using the gas furnace option and thus increasing the possibility of success for the wind turbines. The lowest FSE is consistently appearing with the electric furnace option for all regions and wind turbines. The highest FSE appears using the gas furnace option in the Hawaii region with a Wega turbine and the wind-batteries pathway equal to 1.217, while the lowest FSE appear in the Alaska region with the wind-utilities pathway and the electric furnace equal to 0.356.

Comparisons of Population Variations

The fraction of energy supplied is decreasing with increased demand in energy. Increased energy demand is a result of a shift in fractions of commercial employment from purely commercial towards a mixture of industrial and commercial employment. The highest FSE appears in the lowest energy demand scenarios, while the lowest FSE appears in the highest energy demand scenarios consistently throughout this section. The FSE varies from 1.217 using the Wega turbine with the wind-batteries pathway, gas furnace option in the Hawaii region to 0.052 in the same region and pathway using the electric furnace pathway.

Comparisons of Regions

The highest fraction of supplied energy is consistently appearing in the Hawaii region, while the Iowa region has the lowest FSE for all pathways and heating options. This is most likely due to lower demand in the Hawaii region compared to the cold weather in Iowa demanding more energy for space conditioning during the winter.

Comparisons of Regions with Various Supply Scenarios

The previous results describe a series of different scenarios, this section will evaluate the the hourly matching of high grade energy using one or more wind turbines in the Iowa region using the gas furnace option. Demand has been simulated for a fraction of industrial employment of 17.7% and a 82.3% commercial employment per 1,000 people, living in 370 residential units from average national census data. For the purpose of this thesis, the previously described population scenario will be called a standard population or a standard population scenario. Supplied energy is produced with one, two, and five wind turbines, both Vestas and Wega turbines. The systems are analyzed for hourly matching of high grade energy demand only. This results in six different scenarios/simulations.

Figures 3.1 through 3.6 show how well supply matches demand for different levels of energy supply for the option of gas furnace in Iowa using national employment rates.

Using one Vestas turbine has 308 surplus energy hours (Figure 3.1) when supply is greater than or equal to demand. 45% of the operation time produce up to 600 kWh less than demand. The highest shortage of energy is approximately 1870 kW per hour, which occurs when there is no wind generated energy.

Increasing supply by using two Vestas turbines increases the number of hours with surplus energy to 936 (Figure 3.2). 45% of the operating time is producing up to 600 kW less than demand.

Using five Vestas turbines for energy generation provides 2406 surplus energy hours (Figure 3.3). 226 operating hours have surplus energy exceeding 1800 kW. 39% or 3441 operating hours produce up to 600 kW less then demand.

Using one Wega turbine compared to one Vestas turbine provided surplus energy production during 2097 hours (Figure 3.4). 42% of the operation time produce up to 600 kW less than demand.

Using two Wega turbines provides surplus energy for 3570 operating hours (Figure 3.5). 754 operating hours provide surplus energy exceeding 1800 kW. The fraction of operating time producing up to 600 kW less than demand is down to 34%.

Changing from five Vestas to five Wega turbines provides 5070 operating hours with surplus energy production (Figure 3.6). 2748 operating hours have surplus energy production exceeding 1800 kW. The fraction of operating time producing up to 600 kW less then demand is reduced to 26%.

The Wega turbines are producing more energy than the Vestas turbines, and are thus better one on one versus the Vestas turbine in regards to energy supply. The results presented here would indicate that 5 Wega turbines could match most of the demand of a standard population scenario.

Figures 3.1 through 3.6 show the energy surplus using different numbers of the different wind turbines. Negative surplus indicates that demand is higher than supply and thus stored or auxiliary energy is required. Positive surplus energy indicates that the system can either sell or store the extra energy. The last bar in all six figures shows energy production exceeding 1800 kWh. As the number of wind turbines increase the number of hours with surplus energy higher then 1800 kWh increase as well, in particular using five Wega turbines, where the number of yearly hours with excess energy above 1800 kWh is as high as the number of hours with less.

Results of Cost Analysis

The cost of each system consists of three expenditures: capital expenditures, operation and maintenance expenditures, and fuel and utility expenditures. The wind utility pathway is assumed not to sell of any excess energy/power, so that the only flow of funds are the three costs included. Capital expenditures are expenditures endured to build or modify already existing energy supply systems and are one-time investments. Operation and maintenance expenditures equal a fraction of the capital investment endured yearly for the anticipated life time of the energy pathway. Fuel expenditures are either purchases of natural gas to meet low grade energy demand, or purchases of diesel fuel to operate the diesel generators. These expenditures are assumed to be constant for each year, throughout the years of the anticipated lifetime of the pathway. It is assumed that for the next ten years that the increase in energy demand will be offset with increasing energy efficiencies. This is not entirely correct but it eases the economic calculations.

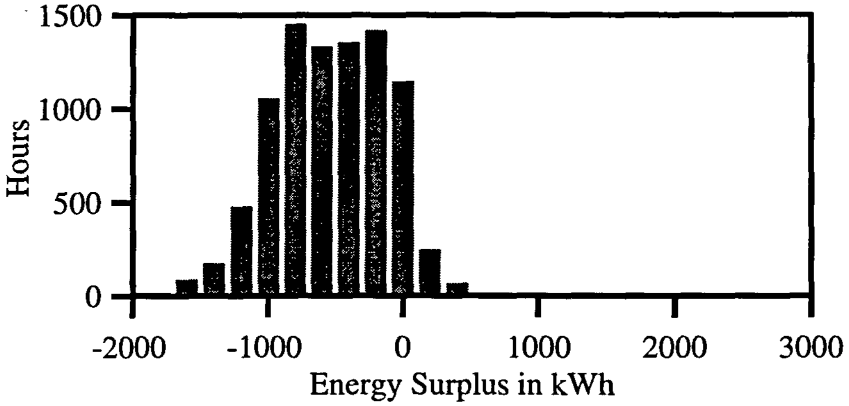

Figure 3.1 Energy Surplus with One Vestas Turbine

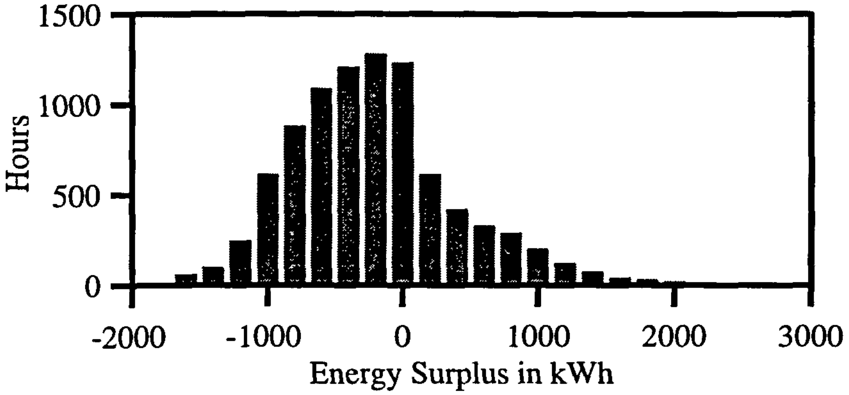

Figure 3.2 Energy Surplus with One Wega Turbine

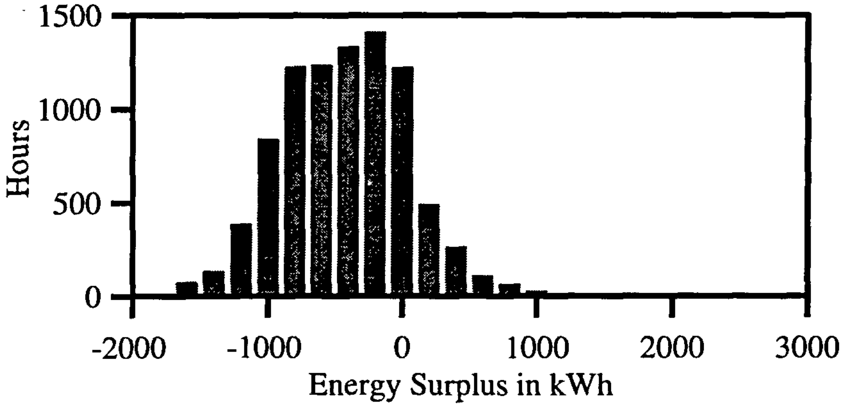

Figure 3.3 Energy Surplus with Two Vestas Turbines

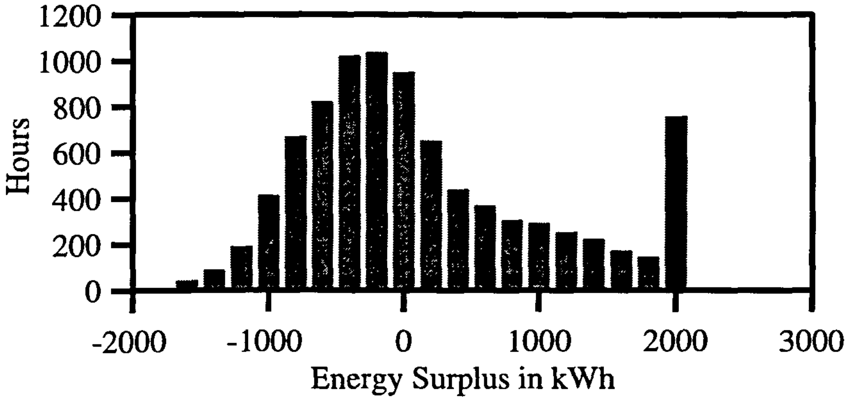

Figure 3.4 Energy Surplus with Two Wega Turbines

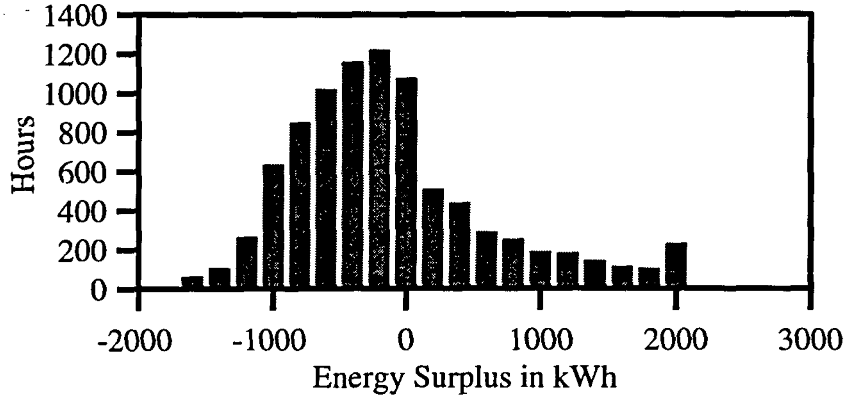

Figure 3.5 Energy Surplus with Five Vestas Turbines

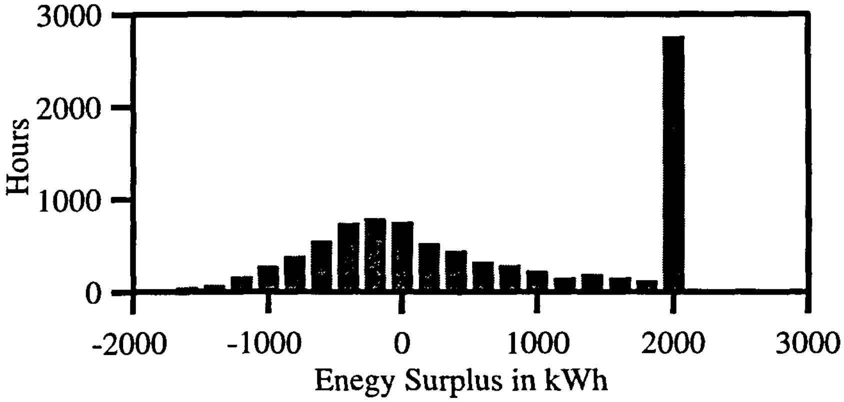

Figure 3.6 Energy Surplus with Five Wega Turbines

Utility expenditures are expenditures endured when energy demand exceeds the supplied energy from the wind turbine and storage system. Utility expenditures are assumed to remain at the same level for the anticipated lifetime of the energy pathway.

Using the present worth factor method, the sum of all expenditures is divided by the total energy demand over the total anticipated life time of the pathway, to find a cost per energy unit of demand. This cost is used to compare the 2,700 scenarios simulated in this thesis. Appendix D shows the costs of all simulated scenarios.

Iowa Region

Wind-utility Pathway

The cost of energy in the Iowa region using the wind-utilities pathway vary between $0.04 to $0.35 per delivered kWh as Table 3.23 shows. There is an increase in cost with increase in energy demand for all heating options.

Table 3.23 Energy Cost for Wind-Utilities Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.10	$0.11	$0.26	$0.35
Gas Furnace	$0.04	$0.09	$0.11	$0.23
DHC	$0.13	$0.14	$0.20	$0.21

Wind-Batteries Pathway

Looking at the wind-batteries pathway for the Iowa region, energy costs range from $0.04 to $0.42 per delivered kWh to the end user (Table 3.24). The cost of energy increase with an increase in energy demand.

Wind-Diesel/Batteries Pathway

Using the electric furnace option, the energy cost with the Vestas turbine ranges from $0.16 to $0.41 per kWh with decrease in cost with increase in energy demand. The Wega turbine shows the same trend with an energy cost ranging from $0.35 to $0.71 per kWh (Table 3.25).

Using the gas furnace option, energy costs increase from a minimum $0.13 per kWh to $0.28 per kWh with increased energy demand for the Vestas turbine and from $0.27 to $0.38 for the Wega

Table 3.24 Energy Cost for Wind-Batteries Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	\$0.11	\$0.12	\$0.31	\$0.42
Gas Furnace	\$0.04	\$0.10	\$0.13	\$0.28
DHC	\$0.13	\$0.15	\$0.22	\$0.24

Table 3.25 Energy Cost for Wind-Diesel/Batteries Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	\$0.16	\$0.41	\$0.35	\$0.71
Gas Furnace	\$0.13	\$0.28	\$0.27	\$0.38
DHC	\$0.15	\$0.51	\$0.24	\$0.62

turbine. The lowest energy cost for the Wega turbine is with a 25% industrial employment, while the energy costs for the Vestas turbine decreases with increased energy demand.

The cost of energy ranges from \$0.15 to \$0.51 for the Vestas turbine, and between \$0.24 and \$0.62 for the Wega turbine, with decreasing energy cost with increasing energy demand.

Wind-Hydrogen Pathway

The cost of energy using the electric furnace option with the hydrogen pathway is expensive. The energy cost with the Vestas turbine ranges from \$0.32 to \$0.43 per kWh with decrease in cost with increase in energy demand. The Wega turbine has the same trend with an energy cost ranging from \$0.68 to \$0.99 per kWh (Table 3.26).

Using the gas furnace option, energy cost increases from a minimum \$0.13 per kWh to \$0.27 per kWh with increased energy demand for the Vestas turbine and from \$0.29 to \$0.60 for the Wega turbine.

Using the district heating and cooling option, energy costs are lowest with industrial employment of 25% for both turbines. The cost of energy ranges from \$0.23 to \$0.24 for the Vestas turbine, and between \$0.39 and \$0.43 for the Wega turbine.

Wind-Diesel Pathway

Table 3.27 shows the cost of energy using the wind-diesel only pathway in the Iowa region. Using the electric furnace option the cost of wind and diesel generated energy becomes high. The cost vary between \$0.16 and \$0.41 per kWh for the Vestas turbine with a rapid decrease in cost with increase in energy demand. The same trends appear for cost of energy with the Wega turbine ranging from $0.30 to $0.71 with the highest energy demand scenario.

Using the gas furnace option the cost of energy vary between $0.13 and $0.27 for the Vestas turbine and between $0.30 and $0.62 for the Wega turbine (Table 3.27). The lowest energy cost occurs when the fraction of industrial employment is 50% for the Vestas turbine and 25% for the Wega turbine.

The district heating and cooling option has an energy cost that ranges from $0.16 to $0.52 per kWh for the Vestas turbine and $0.23 to $0.62 for the Wega turbine, with decreasing cost of energy with increasing energy demand scenarios.

Table 3.26 Energy Cost for Wind-Hydrogen Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.32	$0.43	$0.68	$0.99
Gas Furnace	$0.13	$0.27	$0.29	$0.60
DHC	$0.23	$0.24	$0.39	$0.43

Table 3.27 Energy Cost for Wind-Diesel Pathway, Iowa

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.14	$0.38	$0.30	$0.62
Gas Furnace	$0.13	$0.27	$0.23	$0.35
DHC	$0.16	$0.53	$0.23	$0.61

Hawaii Region

Wind-Utility Pathway

Using the electric furnace option, energy costs range between $0.08 and $0.11 per kWh for the Vestas turbine, and $.20 to $0.27 per kWh for the Wega turbine(Table 3.28). Energy cost increase with increased energy demand for both wind turbines.

Using the gas furnace option, energy cost varies between $0.03 and $0.09 per kWh for the Vestas turbine, and $0.11 to $0.23 per kWh for the Wega turbine. Increase in industrial employment increases the cost of energy, but the cost of energy decreases with an increase in residential coverage.

Using the district heating and cooling option, energy costs range between $0.13 to $0.14 per kWh for the Vestas turbine and $0.17 to $0.21 per kWh for the Wega turbine. The cost increases with increased fraction of industrial employment.

Wind-Batteries Pathway

Using the electric furnace option, energy costs increase with increased energy demand scenarios for both turbines. The energy costs vary from $0.10 to $0.12 per kWh for the Vestas turbine and from $0.25 to $0.32 per kWh for the Wega turbine (Table 3.29).

Using the gas furnace option, energy costs increase with increased energy demand scenarios and vary between $0.04 and $0.10 per kWh for the Vestas turbine and $0.13 and $0.28 per kWh for the Wega turbine.

Table 3.28 Energy Cost for Wind-Utilities Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.08	$0.10	$0.20	$0.27
Gas Furnace	$0.03	$0.09	$0.11	$0.23
DHC	$0.11	$0.14	$0.17	$0.21

Table 3.29 Energy Cost for Wind-Batteries Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.08	$0.12	$0.24	$0.32
Gas Furnace	$0.03	$0.10	$0.13	$0.28
DHC	$0.10	$0.14	$0.18	$0.24

Using the district heating and cooling option, the cost of energy varies from $0.13 to $0.15 per kWh for the Vestas turbine, and from $0.18 to $0.24 per kWh for the Wega turbine. Energy costs increase with increase in energy demand.

Wind-Diesel/Batteries Pathway

The energy cost with the Vestas turbine ranges from $0.14 to $0.37 per kWh with decrease in cost with increase in energy demand. The Wega turbine has the same trend with an energy cost ranging from $0.30 to $0.59 per kWh (Table 3.30).

Using the gas furnace option, energy cost increases from a minimum $0.13 per kWh to $0.30 per kWh with increased energy demand for the Vestas turbine and from $0.24 to $0.38 for the Wega turbine. The lowest energy cost for both turbines are with a 50% industrial employment.

The cost of energy ranges from $0.17 to $0.59 for the Vestas turbine, and between $0.24 and $0.66 for the Wega turbine, both turbines with decreasing energy costs with increasing energy demand.

Table 3.30 Energy Cost for Wind-Diesel/Batteries Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.15	$0.34	$0.34	$0.56
Gas Furnace	$0.13	$0.31	$0.27	$0.41
DHC	$0.16	$0.59	$0.24	$0.67

Wind-Hydrogen Pathway

The energy cost with the Vestas turbine ranges from $0.27 to $0.33 per kWh with decrease in cost following increase in energy demand. The Wega turbine has the same trend with an energy cost ranging from $0.54 to $0.69 per kWh (Table 3.31).

Using the gas furnace option, energy cost increases from a minimum $0.14 per kWh to $0.29 per kWh with increased energy demand for the Vestas turbine and from $0.30 to $0.60 for the Wega turbine. With increase in industrial employment, energy costs increase, but with increase in residential coverage energy costs decrease.

Using the district heating and cooling option energy cost increase with increase in energy demand. The cost of energy ranges from $0.22 to $0.24 for the Vestas turbine, and between $0.34 and $0.41 for the Wega turbine.

Wind-Diesel Pathway

Using the electric furnace option the cost vary between $0.16 and $0.19 per kWh for the Vestas turbine with a rapid decrease in cost with increase in energy demand. The same trends appear with the Wega turbine, the cost ranging from $0.35 to $0.56 (Table 3.32).

Using the gas furnace option the cost of energy vary between $0.13 and $0.31 for the Vestas turbine and between $0.27 and $0.41 for the Wega turbine. The lowest energy cost occurs when the fraction of industrial employment is 25% for the Wega turbine. An increase in energy demand results in a decrease in energy cost for the Vestas turbine.

The district heating and cooling option has an energy cost that ranges from $0.16 to $0.59 per kWh

Table 3.31 Energy Cost for Wind-Hydrogen Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.25	$0.32	$0.53	$0.69
Gas Furnace	$0.13	$0.28	$0.31	$0.60
DHC	$0.19	$0.24	$0.34	$0.41

Table 3.32 Energy Cost for Wind-Diesel Pathway, Hawaii

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.14	$0.37	$0.29	$0.51
Gas Furnace	$0.13	$0.30	$0.24	$0.38
DHC	$0.16	$0.60	$0.24	$0.66

for the Vestas turbine and $0.24 to $0.67 for the Wega turbine, with decreasing cost of energy with increasing energy demand scenarios.

Alaska Region

Wind-Utility Pathway

Using the electric furnace option, energy cost range between $0.10 and $0.11 per kWh for the Vestas turbine, and $0.26 and $0.29 per kWh for the Wega turbine (Table 3.33). Energy cost decrease with increased energy demand for this option for both wind turbines.

Using the gas furnace option, energy cost vary between $0.04 and $0.09 per kWh for the Vestas turbine, and $0.11 and $0.23 per kWh for the Wega turbine. Each increase in industrial employment increases the cost of energy from the previous industrial employment level, but then decreases with the increase in residential coverage.

Using the district heating and cooling option, energy costs range between $0.13 to $0.14 per kWh for the Vestas turbine and $0.19 and $0.21 per kWh for the Wega turbine. The cost increases with increased fractions of industrial employment.

Wind-Batteries Pathway

Using the electric furnace option, energy cost decreases with increased energy demand scenarios for both turbine. The energy cost vary from $0.10 to $0.12 per kWh for the Vestas turbine and from $0.31

Table 3.33 Energy Cost for Wind-Utilities Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.10	$0.10	$0.26	$0.28
Gas Furnace	$0.04	$0.09	$0.11	$0.23
DHC	$0.12	$0.14	$0.19	$0.21

to $0.34 per kWh for the Wega turbine (Table 3.34).

Using the gas furnace option, energy costs increase with increased energy demand scenarios and vary between $0.04 and $0.10 per kWh for the Vestas turbine and $0.12 and $0.28 per kWh for the Wega turbine.

Using the district heating and cooling option, the cost of energy very from $0.14 to $0.15 per kWh for the Vestas turbine, and from $0.20 to $0.24 per kWh for the Wega turbine. Energy costs increase with increase in energy demand.

Table 3.34 Energy Cost for Wind-Batteries Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.10	$0.12	$0.31	$0.34
Gas Furnace	$0.04	$0.10	$0.12	$0.28
DHC	$0.11	$0.14	$0.20	$0.24

Wind-Diesel/Batteries Pathway

The energy cost with the Vestas turbine ranges from $0.14 to $0.34 per kWh with a decrease in cost with increase in energy demand. The Wega turbine has the same trend with an energy cost ranging from $0.30 to $0.53 per kWh (Table 3.35).

Using the gas furnace option, energy cost increases from a minimum $0.13 per kWh to $0.26 per kWh with increased energy demand for the Vestas turbine and from $0.23 to $0.33 for the Wega turbine. The lowest energy cost for the Wega turbine is with a 25% industrial employment, while the energy cost with the Vestas turbine reduces with increased energy demand.

The cost of energy using the district heating and cooling option ranges from $0.16 to $0.48 for the Vestas turbine, and between $0.23 and $0.55 for the Wega turbine, both turbines with decreasing energy cost with increasing energy demand.

Table 3.35 Energy Cost for Wind-Diesel/Batteries Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.16	$0.37	$0.35	$0.61
Gas Furnace	$0.12	$0.27	$0.26	$0.36
DHC	$0.15	$0.47	$0.24	$0.56

Wind-Hydrogen Pathway

The energy cost with the Vestas turbine ranges from $0.32 to $0.37 per kWh with decrease in cost following an increase in energy demand. The Wega turbine has the same trend with an energy cost ranging from $0.67 to $0.79 per kWh (Table 3.36).

Using the gas furnace option, energy cost increases from a minimum $0.14 per kWh to $0.27 per kWh with increased energy demand for the Vestas turbine and from $0.29 to $0.60 for the Wega turbine. With each increase in industrial employment, energy cost increase, but decrease with increase in residential coverage.

Using the district heating and cooling option, energy cost increase with increase in energy demand. The cost of energy ranges from $0.23 to $0.24 for the Vestas turbine, and between $0.37 and $0.41 for the Wega turbine.

Table 3.36 Energy Cost for Wind-Hydrogen Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.32	$0.35	$0.67	$0.79
Gas Furnace	$0.13	$0.28	$0.29	$0.60
DHC	$0.21	$0.24	$0.37	$0.41

Wind-Diesel Pathway

Using the electric furnace option the cost vary between $0.16 and $0.37 per kWh for the Vestas turbine with a rapid decrease in cost with increase in energy demand. The same trends appear with the Wega turbine, with energy costs ranging from $0.35 to $0.61 (Table 3.37).

Using the gas furnace option, the cost of energy vary between $0.12 and $0.27 for the Vestas turbine and between $0.26 and $0.36 for the Wega turbine. The lowest energy cost occurs when the fraction of industrial employment is 50% for the Vestas turbine and 25% for the Wega turbine. An increase in energy demand results in a decrease in energy cost for the Vestas turbine.

The district heating and cooling option has an energy cost that ranges from $0.16 to $0.47 per kWh for the Vestas turbine and $0.24 to $0.56 for the Wega turbine, with decreasing cost of energy with increasing energy demand scenarios for both turbine.

Table 3.37 Energy Cost for Wind-Diesel Pathway, Alaska

Heating	Vestas		Wega	
Option	Lowest	Highest	Lowest	Highest
El. Furnace	$0.14	$0.34	$0.30	$0.53
Gas Furnace	$0.13	$0.26	$0.23	$0.33
DHC	$0.16	$0.48	$0.23	$0.55

Cost Comparisons of Wind Turbines

All simulated scenarios show a higher energy cost using Wega turbines versus using Vestas turbines. The cost of energy varies for a Vestas turbine from $0.03 to $0.60 per kWh. The lowest cost appears in using the gas furnace option and wind-utility pathway. The highest energy cost appears using the diesel pathway and the district heating and cooling option. For the Wega turbines, the occurrence of the highest energy cost appears when using the hydrogen pathway and electric furnace option and is $0.99 per kWh in the Iowa region. The lowest cost for the Wega turbine appears with the utility pathway and gas furnace option and is $0.11 per kWh.

Cost Comparisons of Pathways

Table 3.38 shows the highest and lowest cost of energy for each of the pathways. When comparing cost of energy among pathways, there is one highest cost and one lowest cost per pathway. One region can have both the highest and lowest energy cost for that particular pathway. Both the highest and the lowest cost of energy for the wind-utility pathway appear in Iowa, but both Hawaii and Alaska have the same lowest energy cost for the wind-utility pathway using either turbine with the gas furnace option.

The lowest energy cost for the wind-batteries pathway using the Vestas turbine appears in Alaska and Hawaii, while the highest energy cost ($0.14/kWh) for the same pathway appears in all three regions. The lowest energy cost using a Wega turbine appears in the Alaska region, while the highest energy cost appears in Iowa.

Looking at the wind-diesel pathway the lowest energy cost using the Vestas turbine appears in

Table 3.38 Lowest and Highest Cost of Energy ($/kWh), By Pathway

Pathway	Low. Vestas	High.Vestas	Low. Wega	High. Wega
Wind-Utilities	$0.04	$0.15	$0.11	$0.35
Wind-Batteries	$0.03	$0.14	$0.13	$0.42
Wind-Diesel	$0.12	$0.60	$0.24	$0.71
Wind-Hydrogen	$0.13	$0.46	$0.29	$0.99
Wind-Diesel/Batteries	$0.13	$0.60	$0.22	$0.67

Alaska, while the highest energy cost appears in the Hawaii region. Using the Wega turbine for the same pathway, both Alaska and Iowa have the lowest energy cost per kWh, while the highest energy cost is in Iowa. Comparing energy costs for the hydrogen pathway shows that the lowest energy cost for the use of both wind turbines appears in Alaska, while the highest energy costs appear in Iowa using both wind turbine types. Comparing the wind-diesel pathway result in the observation that the lowest energy costs appear in the Alaska region for the use of both wind turbines, while the highest energy costs for the same turbines appear in the Hawaii region.

Comparing the costs of the pathways shows that when using the Vestas turbine, energy cost is lowest using the wind-batteries pathway and the gas furnace option, with increasing energy costs with the following pathways: wind-utility pathway, hydrogen pathway, diesel-batteries pathway, and the highest energy cost using the Vestas turbine is with the wind-diesel pathway. Using the Wega turbine for harvesting energy, the order of the most costly versus less costly pathway is the same as for the use of the Vestas turbine with one exception. The wind-utility pathway is the cheapest pathway and the wind-batteries pathway the second cheapest pathway, while the reminding order of costly pathways is the same for both types of wind turbines.

Cost Comparisons of Heating Device Options

Using the Vestas turbine, with the electric furnace option, the cost of energy varies from $0.09 to $0.46 per kWh and from $0.20 to $0.99 using the Wega turbine (Table 3.38). The lowest cost using both turbines appears in Hawaii, while the highest cost appears in Iowa using both turbines.

Using the gas furnace option,.all three regions have the lowest cost of $0.04 for the Vestas turbine and $0.11 for the Wega turbine. The highest cost using both turbines appears in Iowa. Using the Vestas turbine the highest cost is $0.31 per kWh, while for the Wega turbine the cost is $0.60 per kWh.

Using the district heating and cooling option, the cost of energy varies between $0.13 and $0.60 with the Vestas turbine and from $0.16 to $0.67 with the Wega turbine. Both the highest and lowest costs for both turbines appear in the Hawaii region.

It is appearant that the heating device option with the lowest cost is the gas furnace, with the electric furnace option following, and finally the district heating and cooling option. Comparing the two turbine types, energy provided with the Vestas turbines is less expensive than the energy produced with the Wega turbine, with one exception (Table 3.38). The option of the gas furnace and the Wega turbine is cheaper than the cost of energy using the Vestas turbine and the district heating and cooling option. The use of gas furnaces for the purpose of providing low grade energy is the least costly method used in this comparison.

Cost Comparisons of Population Variations

In all the simulated scenarios, cost of energy either decreases with increased energy demand, or remain the same with increased energy demand. This is primarily because the the capital investment is the same for a lot of the scenarios and it therefore becomes more cost efficient to have larger systems. Higher energy production and energy demand is therefor decreasing the cost of energy.

Cost Comparisons of Regions

The cost of energy in Iowa ranges from $0.04 to $0.52 per kWh for the Vestas turbine, and from $0.11 to $0.72 per kWh for the Wega turbine. Both the lowest costs appear with the gas furnace option and utility pathway. The highest energy cost appears for the diesel-batteries pathway for both turbines. The option costing the most with the Wega turbine, is the electric furnace option, while the district heating and cooling option is the most expensive one for the Vestas turbine.

The cost of energy in the Alaska regions vary from $0.04 to $0.48 per kWh using the Vestas turbine, and $0.11 - $0.79 per kWh using the Wega turbine. The lowest energy cost appears for both turbines using the gas turbine option and utility pathway. The highest cost for the Vestas turbine appears in the diesel-batteries pathway using the district heating and cooling option. For the Wega turbine the highest energy cost appears in the hydrogen pathway with the electric furnace option.

The cost of energy in Hawaii ranges between $0.04 and $0.59 for the Vestas turbine, and from $0.11 to $0.60 for the Wega turbine. The lowest energy cost for both turbines appears with the utility pathway and gas furnace option, while the highest energy cost appears in the Alaska region to be for the Vestas turbine with the diesel pathway and district heating and cooling option, and for the Wega turbine the hydrogen pathway with the electric furnace option.

The lowest energy cost drawn from the options available in this study comes from using a Vestas turbine, in a wind-batteries pathway, and using a gas furnace option.

Sensitivity Study of Different Standard Scenarios

This sensitivity study has been conducted on the pathways and options that have shown the best results discussed earlier in this chapter. Parameters were changed to see how future improvements in efficiencies and anticipated cost reductions would impact both the FSE and energy cost. The number of wind turbines was previously varied to determine the effect on surplus energy per the hour for a year. The sensitivity study has been conducted in the Iowa region using the standard population scenario.

Control Simulations

Two scenarios are simulated with standard population scenarios compared to the previous simulations in order to serve as control simulations for the sensitivity studies. Coverage of residential energy demand is set at 100%.

The six scenarios used for control simulations are:

Iowa, Wind-Batteries, Gas furnace option, Vestas
Iowa, Wind-Batteries, Gas furnace option, Wega
Iowa, Wind-Batteries, District heating and cooling option, Vestas
Iowa, Wind-Batteries, District heating and cooling option, Wega
Iowa, Wind-Hydrogen, Gas furnace option, Vestas
Iowa, Wind-Hydrogen, Gas furnace option, Wega

The control simulations show that for the Vestas turbines and the district heating and cooling option in the wind-batteries pathway the FSE is equal to 0.176 and energy cost is $0.12 per kWh. The same numbers for the Wega turbine result in a FSE equal to 0.179 and an energy cost of $0.14 per kWh.

Controlling the wind batteries pathway with the gas turbine heating device option, show a FSE 0.232 and an energy cost that vary between $0.06 and $0.07 per kWh using the Vestas turbines. The Wega turbine control simulation for the same scenario shows a FSE equal to 0.238 and an energy cost equal to $0.17 per kWh.

Making a control simulation of the wind-hydrogen pathway with the gas furnace option has a FSE equal to 0.226 and energy cost of $0.18 per kWh when using the Vestas turbines, while the FSE for the Wega turbine is 0.233 with a cost of $0.39 per kWh.

Increased COP for Heat Pumps

This simulation is done with the Iowa region, district heating and cooling option, wind-batteries pathway, and both wind turbines. The scenario has been simulated for a possible heat pump COP equal to ten, assuming that the COP is constant for all outside ambient temperatures.

When improving heat pump COP from three to ten, the energy demand becomes less and thus cost per installed kWh is also reduced. The new efficiency for low grade energy demand pathway is 0.19, while the cost of the pathway is reduced from $2567 per kW to $2031 per kW for the Vestas turbine. The cost of the Wega turbine system is reduced from $5528 per kW to $2808 per kW. Simulating the above improvement in COP for a heat pump results in a FSE improvement to 0.207 and an energy cost of $0.11 per kWh using the Vestas turbines. Using the Wega turbine the cost remain the same $0.14 and the FSE increases to 0.212. This is an approximate 18% improvement in FSE using both turbine types. Changes in cost of energy is negligible for both turbines.

Reduced Cost of Hydrogen Pathway

This simulation has been done similar to the previous one. Changes made in this scenario is the assumption that there will be drastic reductions in the cost of fuel cell and hydrogen technology. The future cost is assumed to be reduced from $3,200 to $500 per installed kW for a fuel cell and that the future cost of equipment for electrolysis of water is reduced from $1,000 to $500 per installed kW. A simulation using the gas furnace option for both turbines in the Iowa region has been conducted to see how these changes in cost will effect the energy cost of the system.

Energy cost is reduced to $0.08 per kWh using the Vestas turbines with a FSE equal to 0.226. Energy cost using the Wega turbine is reduced to $0.12 per kWh with a FSE equal to 0.233. The cost reduction is approximately 55 % for the Vestas turbines and approximately 70% for the Wega turbine.

Increased Efficiency of Fuel Cells

This sensitivity study will assume that fuel cell efficiency are improved drastically in the future. Fuel cell efficiency for this simulation is set at 90% compared to the rest of the simulations where the efficiency was set at 50%.

Fraction of energy supplied using the Vestas turbines improves to 0.232 (+3%) and to 0.237 (+2%) using the Wega turbine. The cost of energy remained the same for both wind turbine types.

Improving Hydrogen Pathway Efficiencies and Costs

Applying both of the two previous improvements of reduced cost and improved efficiencies in the same sensitivity study result in energy cost of $0.08 for the Vestas turbines with a FSE of 0.232. For the Wega turbine the cost is reduced to $0.12 with a FSE equal to 0.237.

Reduced Cost of Large Wind Turbines

This sensitivity simulation studies the effect of reducing the cost of the Wega turbine by 50% from an estimated $5,800 per installed kW to approximately $2,900 per installed kW. The study has been done with the Wega turbine, gas furnace option, and wind-batteries pathway.

The effect of reduced cost of large wind turbine on the cost of delivered kWh is large. The cost is reduced from $0.17 per kWh to $0.10 per kWh. This is reduction of 41%. The fraction of supplied energy remains the same. This result would indicate that there is a lot to gain by conducting extensive research in the field of large wind turbines.

Discussion of Sensitivity Study

The sensitivity simulations discussed previous in this chapter show that there are possible improvements and savings to be made in the near future. Table 3.39 compares the percentage sensitivity of the different model parameters that were addressed for the Vestas turbines, while Table 3.40 compares the effects on energy cost and FSE for the Wega turbine.

Table 3.39 Sensitive Improvements in Energy Cost and FSE, Vestas Turbine

Scenario	Control	Improved	Control	Improved
	$/kWh	$/kWh	FSE	FSE
Heat Pumps COP	0.12	0.11	0.176	0.207
Hydrogen Pathway cost	0.18	0.08	0.226	0.226
Hydrogen Pathway efficiency	0.18	0.18	0.226	0.232
Both Hydrogen improvements	0.18	0.08	0.226	0.232

All of the scenarios simulated in this sensitivity study show reductions in cost, some greater than others. It is appearant that even with some of the current renewable energy technology being expensive, in the near future, improvements might make the technologies more cost efficient.

Table 3.40 Sensitive Improvements in Energy Cost and FSE, Wega Turbine

Scenario	Control	Improved	Control	Improved
	\$/kWh	\$/kWh	FSE	FSE
Heat Pumps COP	0.14	0.14	0.179	0.212
Hydrogen Pathway cost	0.39	0.12	0.233	0.233
Hydrogen Pathway efficiency	0.39	0.39	0.233	0.237
Both Hydrogen improvements	0.39	0.12	0.233	0.237
Reduced Costs, LWECS	0.17	0.12	0.238	0.238

Variations of Residential Demand Only

This simulation has been made using the gas furnace option, wind-batteries pathway in the Iowa region. Both industrial and commercial employment are zero, while residential energy demand for 1,000 persons residing in 370 residential units is covered completely (100%).

Compared to the control simulations, the four Vestas turbines have a FSE equal to 1.225 for 100% residential energy demand coverage when employment of any kind is excluded, while the cost of energy for complete coverage is \$0.03 per delivered kWh. The FSE of Wega turbine is 1.261 for 100% residential coverage, while the cost is \$0.14 per delivered kWh. We see from these results that wind energy is useful for scenarios with lower energy demand than scenarios including commercial or industrial employment or floor space. The difference between the use of one Wega versus four Vestas turbines is not large, and considering the high capital cost of Wega turbines, they are currently not cost efficient. With reduced cost on installed energy from the large wind turbines, they will be more cost efficient in the future.

4 AN ESTIMATE OF THE COST OF AIR POLLUTION

Due to global concern about greenhouse effects; depletion of stratospheric ozone, and depletion of current stocks of non-renewable energy, renewable energy technologies are likely to become more attractive in the next two decades both for energy consumers as well as politicians. One problem related to renewable energy sources is that they are usually neither adaptable nor flexible, but with practically no emissions, their future in the global economy must be considered seriously. Today's energy market is filled with competitive non-renewable energy sources that are on the surface more cost-effective than the renewable energy systems currently available, both in regards to capital investments and, most of the time, operation and maintenance costs.

This chapter argues that these 'cheap' costs may not be as accurate as believed when accounting for long term and sometimes hidden effects of air pollution on the environment. In the United States alone, the estimated emissions of CO_2, NO_X, volatile organic compounds ($VOC's$), and SO_2 from generating energy were in 1992 respectively 1348 million, 20 million, 8 million (Dept. of Commerce 1995), and 143.8 million metric tons (NREL 1992), respectively.

Pollution affects both the local and global environment. The greenhouse effect and ozone depletion have been widely discussed, but less known are various kinds of cancer, airway and lung diseases, asthma, and chronic bronchitis just to mention a few of the effects introduced later in this chapter. Illnesses may not only cause the individual pain and discomfort, but may decrease productivity in the workplace, resulting in lowered income, and possible increased hospital and medical expenditures. Pollution is not only a large potential global environmental problem, but could also be a local/national economic problem, and may in the future become more dominant as energy consumption continues to increase and long term effects of pollution may start to show.

Tropospheric ozone has, for instance, been related in some studies to an increase in airway diseases in places like Los Angeles - Long Beach, where smog has been a problem for several years (Dept. of Commerce 1995, Appleby & Foulkes 1989). A research group, on the behalf of the United States Congress, estimated the benefits of reduced ozone levels ranged between $200 million to $ 9.5 billion

(U.S. Congress 1989). Pollution abatement and control expenditures in the United States in 1992 exceeded $ 101 billion (Dept. of Commerce 1995), while expenditures related to energy use in the United States in 1992 were $ 472.8 billion (Dept. of Commerce 1995) [1]. The cost of air pollution to energy consumers and residents affected by pollution is perhaps too significant to ignore when renewable energy sources like wind and solar energy are available with no significant emissions to the environment.

Much research has been conducted on the relationship between human skin cancer and the depletion of stratospheric ozone. The cost of decrease in stratospheric ozone is easier to estimate than some of the other costs introduced in this paper. This is largely due to the fact that the relationship between skin cancer and depletion of stratospheric ozone are gaining more and more support in the main stream of scientists, while other more controversial effects discussed in this chapter are primarily intended to be used as an indication that there are more to energy prices than only the cost of i.e. fuel. The cost of decreasing the ozone layer is included in this paper so economic impacts of air-pollution can be related to money and to try to show why the hidden costs and effects should be included in the total picture when trying to assess a economic cost of a 'scientific improvement'.

This chapter first looks at the individual human effects and their estimated economic impact on a national scale, before trying to estimate national and global costs of the greenhouse effect. Some of the estimates can only be done very conservatively, and as in the case for a rise in sea levels the estimates become very complex. For this reason, some of the most complex effects are briefly introduced and discussed, while other effects are given an estimated cost.

Environmental changes and effects currently suspected of relation to energy consumption:

- Greenhouse effects
    - Increase in the average global temperature
    - Increase in the average yearly precipitation
    - Rise in sea level due to melting of glaciers
    - Increase in average ocean temperature
    - Change in social pattern
    - Change in usage of land areas
    - Change in habitats for animals, plants, and humans

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[1] These expenditures include pollution abatement and control

- Acid deposition
  - Deforestation
  - Causing death of fish and algae in oceans and lakes
  - Both reduced or increased agricultural yields in different regions
- Stratospheric ozone depletion
  - Increased rates of incidents and deaths from skin cancer
  - Decreased agricultural yield
- Air-pollution
  - Increased rates of acute and chronic respiratory diseases
  - Wear on automobile tires due from tropospheric ozone
  - Increased aggression and change in social behavior and attitudes
  - Erosion of historical buildings (Acropolis, Athens)
  - Possible mutagenic effects on biological life
  - Extra pulmonary effects on human health

National Costs from Artificial Environmental Change

Several studies in various scientific societies, are being conducted world wide to assess the impact of air pollution. Air pollution may be the cause of human illnesses and diseases. Not only do diseases affect the individual person, but also the person's family, workplace, and personal, local, and national economy.

Individual Greenhouse Effect - Tropospheric Ozone

A potential increased threat of skin cancer caused by depletion of stratospheric ozone due to chlorofluorocarbons (CFC's) in the upper atmosphere and stratosphere have been widely discussed. Fewer might have heard about tropospheric ozone, a secondary product of reactions between NO_x and volatile organic compounds (VOC's) in the presence of high energy solar radiation (Burkhardt 1990). NO_x and VOC's are largely a result of internal combustion engines (ICE) or simple combustion of fossil fuels (Burkhardt 1990). Ozone is a major component of photochemical smog which occurs predominantly in areas with high traffic density and/or large industry (Donnell 1995). National ambient air quality standard (NAAQS) for ozone was set in 1979 to 0.12 parts per million, not to be exceeded for more than one hour on one occasion per year (McKee 1990). Several big cities and industrial locations in the United States are above that level on a regular basis (U.S. Congress 1989, Dept. of Commerce 1995); residents in the Los Angeles - Long Beach area are on the average experiencing levels of 0.18 ppm ozone or above every 4th day (Dept. of Commerce 1995).

The long term effects of tropospheric ozone pollution are receiving more attention in research. High levels or prolonged exposure to tropospheric ozone is suspected of being responsible for chronic airway diseases such as lung cancer, asthma, bronchitis, and emphysema (U.S. Congress 1989, Canada 1990,Sham 1990, Dockery 1990). There are several indicators to support this. Whereas no studies are conclusive at this time relating atmospheric ozone to respiratory diseases, the possible ramifications of atmospheric ozone pollution is not worth ignoring.

- Studies from Britain indicate there are higher frequencies of lung cancer and respiratory diseases in urban regions than in rural regions (Robin 1988). Surveys have attempted to relate the difference in rates of lung cancer between rural and urban areas to smoking patterns with little luck. The British literature stated the that '... of all possible explanations, geographical variation in smoking habits are clearly of most interest since smoking is the prime cause of lung cancer.' The attempt to relate other socio-economic variables to the differences was unsuccessful (Robin 1988).

- New studies have shown that ozone has many severe short term impacts on the respiratory system as well as other vital parts of the human anatomy; up to 40 % incomplete dis-association of oxygen from hemoglobin have been observed in clinical studies of humans exposed to high levels of ozone (Canada 1990), humans have experienced abnormal drowsiness, severe headaches, impaired visual ability after short exposure to ozone levels above NAAQS (Canada 1990). Tropospheric ozone have been correlated to rapid, shallow breathing, coughing, pain upon deep inhalation, dizziness, head aches, initiating asthma attacks, accelerated aging of lung tissues, and lung retardation in children (U.S. Congress 1989, Donnell 1990, Canada 1990, Dockery 1990).

The long term effects have yet to be correlated and established and may never be, since lung cancer and other chronic diseases can be latent for decades, and the impacts of ozone have only been aggressively investigated since the early 1980's (U.S. Congress 1989).

- The effects of ozone on animals have varied from mice becoming more susceptible to sedative drugs (Donnell 1990), increasing respiratory frequencies (Barry 1990), to ozone acting as a mutagen in hamsters (Donnell 1990). Dogs exposed to 50 ppm of ozone for 1-4 minutes experienced temporary halt in breathing followed by abnormal low blood pressure and slow hearth action (Donnell 1995).

- An effect that has been discovered in rats is a change in the hormone production and balance. High levels of ozone has been shown to increase the endocrine production in the pituitary and thyroid glands (Canada 1990). Hormone production in the pituitary gland control hormone production in the other glands, and an imbalance of the thyroid have severe consequences for both rats and humans that show the same symptoms and disorders. An increase in thyroid production increases the rate of metabolism (Sham 1990), which can result in constant hunger, hyper-activity, and instability in psychological behavior. A decrease in thyroid production will result in slower metabolism, weight gain, sleeping disorders, and imbalance in the body's fluid balance. In regards to humans, both effects have psychological and physiological effect on a person experiencing any of the symptoms.

- In a study in Utah Valley in 1987 where a steel mill endured a one year's stop in operation, the incidence of asthma, emphysema and bronchitis decreased with by more than 75 %. Since most residents in Utah are members of the Mormon church (90%), which bans smoking, only 5.5 % of the state's population are known to smoke. Ozone levels in Utah were not measured in this study, levels of carbon-oxides and VOC's were, and there were strong correlations between hospital admission rates from respiratory symptoms and air pollution from the steel-mill (Arden 1989).

- The total consumption of tobacco products has declined in the last 30 years (Dept. of Commerce 1995), this should indicate that if smoking were the sole cause for lung cancer (Robin 1988), the rates of lung cancer should decline proportionally. Statistics show that incidents of lung cancer have not declined (Dept. of Commerce 1995). But air-pollution has increased and in 1984, 79.2 million people in the United States lived in counties which violated the NAAQS for ozone (Dept. of Commerce 1995). That is almost one fourth of the entire population of the United States. The current average level of ozone is 0.11 ppm (Dept. of Commerce 1995) compared to the NAAQS which is 0.12 ppm (Dept. of Commerce 1995). Considering the new discoveries of the effects of tropospheric ozone on human anatomy, it would indicate that lower atmospheric ozone might a be much larger problem than earlier believed.

Tropospheric Ozone - Short Term Airway Illnesses

Ozone is, because of its physical structure, reactive with almost everything (Donnell 1990). It has been shown to react very easily with the protective lining cells in the cavities in the lungs that contain air (Donnell 1990), exposing unprotected tissue to potential danger from repeated ozone exposure (U.S Congress 1989).

Too high exposures to ozone are known to create acute respiratory diseases. Some symptoms may not be diagnosed before 2-3 days after the exposure, others might be experienced instantly. Some symptoms have been observed up to 12 days after the initial exposure (Canada 1990). Air-pollution and ozone have been known to cause rapid, shallow breathing, cough, pain upon deep inhalation, dizziness, and head aches to susceptible people (U.S. Congress 1989, Donnell 1990, Canada 1990, Dockery 1990). Research trying to find differences between susceptibility between genders and age have shown that there are no or insignificant differences (Donnell 1990).

Most of the short term effects are resolved shortly after discovery in most cases, causing halts in activity and lowered productivity for a shorter period of time. The critical question is; if these symptoms are a result of a underlying process endangering the human tissues and systems or just temporary discomfort caused by protective mechanisms of the human body (Donnell 1990). Repeated and prolonged exposure may result in chronic diseases, no studies are as of yet conclusive to a correlation.

Tropospheric Ozone - Long Term Airway Illnesses

For the purpose of estimating a cost of long term airway diseases in this thesis it is assumed that the difference between rural and urban lung cancer frequency is caused by air pollution, or that the effect is increased by a combination of smoking, air-pollution, traffic, and crowdedness, all factors related to metropolitan areas. In 1992, 203 million people (Dept. of Commerce 1995) of the total population of 255 million (Dept. of Commerce 1995) lived in metropolitan areas of the United States. Of these 119 million lived in areas with a population exceeding 1,000,000 people (Dept. of Commerce 1995).

Early studies suggested that smoking alone was responsible for 80-90 % of the deaths from lung cancer (Robin 1988), but smoking was at that time the 'only reasonable' cause for lung cancer (Robin 1988). With the knowledge we have today, research should be directed towards each possible cause and their possible correlation. These possible causes could be stress, smoking, air pollution, car use, traffic density, and many others.

2,175,613 people died in the United States in 1992 (Dept. of Commerce 1995). Of these deaths approximately 24 % were caused by respiratory diseases and incidents of airway cancer (Dept. of Commerce 1995). Consider that the number of current smokers [2] have been reduced by 20 % since 1975 (Dept. of Commerce 1995) and the total consumption of tobacco products in the United States has been reduced by 50 % since 1977 (Dept. of Commerce 1995). If the assumption that smoking alone is causing 80-90 % of respiratory diseases and lung cancer is correct, then the death rates from

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[2] Person who has smoked more than 100 cigarettes.

respiratory diseases should decrease based on the consumption of tobacco products. This does not seem to be the case. The average percentage of death rates from respiratory diseases is still increasing (Dept. of Commerce 1995). The death rates from lung cancer among 35-65 year old people is declining (Dept. of Commerce 1995), but not comparable to decreases in total use of tobacco products (Dept. of Commerce 1995). Thus there might be other potential causes either directly or indirectly responsible for the increased incidents of lung cancer and deaths from respiratory diseases. One factor that has increased is the number of vehicles on the road (Dept. of Commerce 1995), the average mileage on the road has stayed almost the same for the last 15 years (Dept. of Commerce 1995). Vehicle owners are using their vehicles for more urban travel (Dept. of Commerce 1995), which is a more inefficient use of engines and fuel, and causes more incomplete combustion and higher emissions of air-pollutants. At the same time the consumption of fossil fuels has increased and air-pollution has increased.

Due to high traffic density in cities, people in cites are more likely to be exposed to higher levels of air-pollution, tropospheric ozone, carbon-oxides, and VOC's. If one assume that the increase in traffic and air pollution balances out the decreased rates of smoking, one can further assume that todays air pollution accounts for 50 % of the total diseases and deaths from respiratory diseases, a total 261,100 people.

There is no accurate way of assessing the cost of each of these death and the loss of work and productivity. There is no statistical cost for the death of a person, but one statistic that can be used for comparison is the average cost per community patient per hospital stay, assuming that each death was a result from at least one hospital admission in the year which the death occurred. In 1992 the average cost per hospital admission was $5,794 (Dept. of Commerce 1995)[3]. A conservative estimated annual cost of air-pollution induced deaths in the United States is assumed to be at least $1,513 million.

Again this picture is not entirely correct, since the lag time for some of the diseases are decades, and thus the energy consumption from 1992 may or may not be directly causing deaths. But the underlying assumption is that there is a hidden cost to the use of non-renewable energy sources and that the cost is potentially much larger than what the utility bill shows.

Of the estimated 172,000 new cases of lung cancer in 1994 (Dept. of Commerce 1995), 50 % of the new incidents could be assumed to be induced by air-pollution and result in at least one hospital admission per year. If one assumes the average cost of $5,794 per hospital stay (Dept. of Commerce 1995), the total estimated cost of newly developed incidents of air-pollution induced lung cancer becomes $498.3 million.

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[3] For this paper this cost is assumed to include expenditures endured premature to a naturally caused death

Lost productivity is also a major factor in the overall cost of tropospheric ozone. The attempt to estimate this cost is very conservative, but would indicate possible magnitudes of such a related cost.

In 1992, the United States population was 255.407 million people (Dept. of Commerce 1995). Of those, 121.099 million were employed, accounting for 47.4% of the total population. If one assumes that 48.7% of the air-pollution induced deaths lost a minimum of 10 years productivity, producing a minimum of 8 h/day for $4.25 per hour for 261 producing days per year (excluding week-ends), it results in lost productivity conservatively estimated to $ 11 billion for the deaths endured in 1992.

If one further assumes that the newly discovered lung cancer patients were treated and that the same fraction workers, spending an average 6.5 days in the hospital (Dept. of Commerce 1995) per admission, losing 8 hours of work per day for $4.25 per hour, this becomes an estimated loss of production of $ 9 million.

Further assumptions are that of all incidents classified as chronic respiratory conditions in the United States in 1993, 50% were related to air pollution, and that each incident result in at least 0.5 %[4] lower productivity due to the condition, and at least one day in hospital per year.

Estimating the cost of lost productivity for chronic respiratory conditions per year: 0.5% lost time of 8 hours per day at$ 4.25 per hour for working days 261 per year for 47.4 % of the people of the 50% of the 88 million people with chronic respiratory condition (Dept. of Commerce 1995) totals $ 926 million per year. The average cost per day in a community hospital in 1992 was $820 (Dept. of Commerce 1995)[5], increased medical expenditures with $36.1 billion. The total estimated cost of increased air pollution on the publics' health in the United States is estimated at $ 49 billion per year.

Effects of Stratospheric Ozone Depletion

Stratospheric ozone is depleted rapidly. Stratospheric ozone is responsible for absorbing ultra-violet (UV) radiation emitted from the sun. UV light contains high levels of energy, and the human skin in not equipped to deal with the high energy light efficiently, with the result that human skin exposed to UV light becomes more susceptible to cancer. Every year skin cancer causes pain and discomfort to thousands of people around the world, and the worst cases are fatal for several thousands. In just the United States, more than 1,000,000 people were anticipated to develop skin cancer in 1995 (Dept. of Commerce 1995), and more than 7,000 people were expected to die from the same disease (AAD 1996). The United States Environmental Protection Agency estimates that there will be 12 million new cases of skin cancer in the United States in the next 50 years, resulting in more than 210,000 skin cancer

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[4] Approximately one working day per year

[5] For the purpose of this paper this cost is assumed to include medication etc. for the condition

deaths (AAD 1996). Worst scenarios anticipate more than 3.2 million skin cancer deaths by 2075 (AAD 1996). This is an effect from the lag time of developing cancer, it can take as long as 20 years to develop any form of cancer (AAD 1996).

Assuming that all new incidents of skin cancer are detected and that each incident requires treatment and at least one admission to a community hospital, and that the average cost an admission is \$ 5,794 (Dept. of Commerce 1995), it would result in a potential total cost of \$ 5.8 billion for the possible increase in stratospheric ozone depletion induced skin cancer incidents.

If one further assumes that each death from skin cancer costs approximately \$ 5,794 (Dept. of Commerce 1995)[6], and that each death occurs in a hospital, or that each death occur after being admitted to a hospital[7], the estimated cost of the deaths would be \$4.6 million.

Possible lost productivity caused by hospital admissions for treatment of skin cancer could result in:

- 47.4% of 1,000,000 people
- average 6.5 days in the hospital (Dept. of Commerce 1995),
- losing 8 hours of production per day
- at minimum wage \$4.25 per
- cost of \$104.8 million

If one assumes that the 7,000 deaths loses at least 10 years of productivity with the same basis as above with 261 producing days per year, it would result in an estimated lost productivity of \$294.4 million. The total estimated cost of depletion of stratospheric ozone totals conservatively \$ 6.2 billion per year. Whereas this cost is not related to combustion of fossil fuels directly, these numbers are included to show one of the areas which have received a lot of attention and it would therefore be easier the verify the validity of these economical estimations that others introduced in this paper.

Global Costs from Artificial Environmental Change

Greenhouse Effect - Climate Change

With the current consumption of energy, CO_2 levels in the atmosphere will most likely continue to rise (Therien Undated), and the estimated global warming from this increase is predicted to raise the average global surface temperature between $1.5^oC - 4^oC$ (IUCC 1996). A 50 % increase in precipitation is also expected to take place (IUCC 1996) from the effect. These two changes may not have any direct costs themselves, but they may lead to several other effects introduced in the next section.

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[6] The total cost is assumed to include medical and other expenditures endured premature to a natural caused death

[7] This is not to suggest that hospital admissions cause deaths

Greenhouse Effect - Agricultural Yield

The increase in temperature and precipitation might have a detrimental effect on agricultural yield, not only economically for the regions where climate may change but the for the global food supply as well. Several regions of the world are efficiently producing food. Areas like the mid-western United States produce large amounts of corn and grain for both human food and animal feed-stock. This high yield is primarily due to the nearly perfect average temperature and precipitation in the region. If the average temperature in Iowa increases by a few degrees, this will decrease the yield because the average temperature will most likely be too high for the corn. This same effect would occur in the rice fields in Asia, and the plains of grain production in the Ukraine and Russia. Food production might decrease globally. Contradictory to popular belief in the western world, which is that there has been enough food to feed the entire world; 1998 is the year in which the earth's food demand becomes higher than the potential supply. If the current rate of increase in world population continues, there will most likely not be enough food to feed the world's population in 1998. If there is an increase in the average global temperature, it might decrease the world's food production as well. As grain consumption continues to grow (Brown et al. 1995) it is evident that an reduction in food production might have detrimental effects to future world residents. A cost of such an effect is impossible to estimate, but to give an approximation of the magnitude, think of a potentially 10 % decrease in food supply, and the result of 600 - 700 million people fighting for food. Riots, revolutions, and wars for food stock might become reality. Costs for any of these possibilities are rather complex and almost impossible to predict, if they at all will occur.

Taken into account that the suspected primary source of global warming is carbon-dioxide from the combustion of fossil fuel (IUCC 1996, Therien et al. undated), and that the United States alone, is responsible for using approximately one fourth of the world's total energy consumption (Dept. of Commerce 1995), a large responsibility of human made environmental changes belong to energy consumers in the Unites States. In the future, the world's population might point the finger at the United States, requesting compensation for the environmental changes that could possibly be related to the relatively large energy consumption by and in the United States.

Theories of changes caused by the greenhouse effect are gathering support in the United States as scientists are confirming predictions made several years ago; species of invertebrates observed along the California coast line have moved their habitat northward, along with a measured increased average temperature in the same region (Rachel's 1995); plants growing on mountain tops in the Austrian Alps have slowly been moving towards the top of the mountains and are expected to become extinct if the increase in the average temperature continues at the current rates (Rachel's 1995).

Effects of ozone on plants have been observed to reduce rates of photo-synthesis, reduce leaf growth, and lower absorption of nutrients (U.S. Congress 1989, Manning 1990, Adams et al. 1990).

Greenhouse Effect - Rise of Sea Level

With an anticipated increase in the average global temperature of $2^oC - 4^oC$ over the next 100 years (IUCC 1996), there is an anticipated minimum 1-2 mm increase in sea level per year following the increase in temperature (IUCC 1996). With such an increases in sea level millions of people and vast areas of land amy 'sink' into the water. A other option is the possibility of more accumulation of snow in Antarctica, which could help reduce the sea level (IUCC 1996).

But if the rise in sea-level occurs, it will have effects impossible to predict, even less possible to estimate a cost. More wet-lands will induce higher rates of mosquitoes, resulting in perhaps as many as 190 million new cases of malaria per year, compared to the current 110 million new cases (Rachel's 1995). Not only could the change in sea-level change surface above water, but the change could also effect the the major sea currents. For instance if the gulf Stream providing Norway with warm water was to turn cold, it might affect the biological as well as the economical infra-structure of Norway. The main reason for Norwegian ports being open to ship traffic in the winter is due to these warm waters from the Gulf Stream. A reduction in the average sea temperature could increase the number of closed ports and affect the Norwegian economy and standard of living adversely.

Loss of commercial, as well as agricultural land, and reduction in available recreational location, will most likely have economic as well as psychological effects to humans. An increase in sea-level could dramatically affect Egypt where large areas of agricultural production are close to or at sea-level (i.e. the Nile delta) (IUCC 1996).The cost of protecting threatened land could be enormous, and it is too complex of a calculation to attempt for this paper. The hidden costs of combustion of fossil fuels are again larger than what the electricity bill would indicate.

Greenhouse Effect - Crime Rates

Studies of criminal and seasonal variation in violent crime are conclusive that there is a strong correlation between warm, hot days and an increase in violent crimes (Anderson 1989, Anderson 1987, Field 1992, Defronzo 1984, Anderson et al. 1984). During the summer months the number of violent crimes such as rapes and aggravated assaults increase drastically. Some studies show an large increase of reported violent incidents during 'hot' hot summer months (Anderson et al. 1984). The literature does not conclude if increases in apparent temperatures is a direct or indirect cause to increased violence. An indirect cause could be that more people are more likely to be socializing during warmer weather, and thus are more likely to be victimized. There is no compelling evidence to support either view, except that almost all literature supports that increases in temperature increase the rate of violent crimes. Defronzo reports that climate association to crime rates are weak relative to non-climate variables between surveyed regions (Defronzo 1984), while other studies report seasonal variation in violent crime rates within surveyed cities (Anderson et al 1984). Some studies have indicated that even after adjusting for socio-economic effects, temperature still has a strong correlation to violent crime rates (Anderson 1987).

One explanation for the increase in violent crime rates during higher temperatures has been offered; increased socializing due to warmer weather may result more psychological stress and higher risk of aggression (Anderson 1989). This would indicate that the highest crime rates would appear every time the winter season is over; the contrary has been observed (Anderson 1989, Field 1992). In most big cities in the United States surveyed by the FBI, the peak of violent crimes occur in July or August (Defronzo 1984), which average the highest temperature of the year in most of the United States (Dept. of Commerce 1995). Literature also support hotter summers to have higher violent crime rates than during more soothing summers (Fields 1992). Studies done to attempt to independently relate violent crimes to temperature have failed (Defronzo 1984). Dependant relationship between violence, crowdedness, air-pollution, and other socio-economic variables should be conducted on a large scale to estimate the future effects of global warming on humans and their social behavior and attitudes.

With an anticipated increase in the average temperature and precipitation caused by the greenhouse effect (IUCC 1996), the apparent average temperature observed by humans and other animals could possibly increase. There could be more warmer/hotter days than there currently are. More than 200 million people in the United States live in metropolitan areas (Dept. of Commerce 1995). People living is cities are more likely to be more susceptible to psychological effects of increased temperatures along with the psychological effects of crowdedness, high dense populations - the result will most likely be an increase in violent crimes, in particular assaults and forced or attempted rapes.

948,000 people were in 1992 serving prison terms (Dept. of Commerce 1995), 60 % were related to some form of violent crime (Dept. of Commerce 1995). This does not reflect all unreported domestic violence that are more dominant during summer months, which there are no reliable sources for, simply because the incident are not reported. One study has reported a possible correlation between increased domestic violence and high levels of tropospheric ozone (Anderson 1987). The judicial and correctional system handling criminals and prisoners, cost the United States a minimum of $79.5 billion dollars (Dept. of Commerce 1995) per year. Adding medical expenditures and lost productivity of the victims, this cost suddenly becomes very large. If increased temperature could possibly be related to as little as a 0.5 percent increase in crime-rates per year with an proportional increase in judicial and correctional costs on society, the cost of this greenhouse effect becomes a minimum of $ 0.8 billion, plus any costs that the any victims may endure.

Tropospheric Ozone - Social Behavior

Investigation of possible relationships between ozone levels and violent crime rates should also be conducted beyond what has been done until now. As suggested earlier in this paper, a change in the hormone balance may induce hyper-activity or sleeping disorders, both which have psychological effects on human behavioral patterns and could possible be related to high levels of tropospheric ozone levels.

Tropospheric Ozone - Agricultural Yield

Comparing today's levels of low atmospheric ozone to preindustrial levels of 0.03 ppm (U.S. Congress 1989), the agricultural yield in the United States could increase with 1 to 20 % for important crops (U.S. Congress 1989). This equates that a reduction in the current low atmospheric ozone with 25 % would increase the economic yield with as much as $ 500 - 1,000 million (Brown et al 1995).

Ozone is also correlated as the primary cause for the decline of certain trees in the United States, such as white pine, ponderosa and Jeffrey pine (U.S. Congress 1995, Manning 1990). This will increase deforestation, and thus have an impact on the climate as well as the economy. The picture is very complicated, and thus this complication is what makes it difficult to determine if the alleged effects are caused by human or just seasonal effects in the earth's several million year life.

Tropospheric Ozone - Corrosion of Tires

This is included to show the complexity and quantity of tropospheric ozone pollution. Before atmospheric ozone was investigated in the 1950's, the average mileage of a tire was 3,500 miles. Since that time, tires have been gradually developed to contain materials that protects against ozone corrosion, and today tires run for more than 50,000 miles (Kuczkowski 1990). This improvement has saved the average vehicle owner more than 93 % of tire expenditures endured in the life of motor vehicle.

Air pollution - Acid Deposition

Acid deposition is often caused by air pollutants reacting with water or vapor in the atmosphere creating acid rain or deposits. Acid deposition threatens most life forms breathing in water. Fish and algae have been completely terminated in many southern Norwegian lakes, due to air pollution originating from continental Europe. In the United States, acid rain has affected aquatic life in 10 % of the eastern water-ways (Leslie 1991). Acid rain also results in corrosion of building materials, and have been known to create reduced visibility in western parts of the United States. Sulphates, usually the largest contributor to acid deposition, is in addition to producing acid rain, making contribution to global warming as a greenhouse effect gas (IUCC 1996, Leslie 1991). The cost of acid deposition is again too large to estimate for this paper, but the possible effects on agricultural yield and deforestation should be evaluated thoroughly.

Possible Hidden Cost From Using Renewable Energy Technologies

As suggested earlier in this chapter there is more to the consumption of energy than merely the equipment and fuel prices. In the total picture of energy consumption, there are potential effects beyond what the consumer see on a daily basis. From early 70's until today most energy consumers have had the benefit of not having to think beyond their own expenditures when choosing an energy system, this chapter should lead to serious consideration of renewable energy technologies. Renewable energy technologies are not completely safe to the environment, but as of yet renewable energy technologies have proven to be less harmful to the environment than the non-renewable options. The few effects that might cause some problems, are mostly local disturbances compared to effects caused by combustion of fossil fuel. This section gives a short introduction to the negative effects currently known originating from renewable technologies.

Fuel Cells - Hydrogen

Fuel cells are mostly non-polluting, but under certain operating conditions (Appleby & Foulkes 1989) they emit NO_X. Compared to combustion of fossil fuels these emissions are very very small, and in practicality the use fuel cells almost eliminates emissions of NO_X.

A problem that has raised some concern, is the flammability of hydrogen gas. Gasoline, methane[8], and hydrogen gas are all very flammable, but under different conditions. They have different charac-

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[8] Major component in natural gas

teristics which makes them dangerous under different conditions (Pottier 1995), but everything taken into consideration, neither one of them can be said to be any worse or better than the other. They all require special care and handling. We have gotten used to handle both gasoline and methane responsibly, hydrogen will require our same attention to safety, but no more or less than the others.

Fuel cells are in general safe, operates with no moving parts, are quiet, and reduces pollution by approximately 100%. Any hidden costs to the national or global environment are not established at the time.

Batteries

Batteries are not a renewable technology, but they are an important part for storing the generated energy and thus their hidden costs must be discussed. The largest problem related to rechargeable batteries is disposal after use. Lead acid as well as Nickel-Cadmium contain environmentally toxic elements which should not be disposed of at the consumers own choosing. Yearly the world consumption of cadmium and lead is 7,000 and 2,200,000 metric tons respectively (Berndt 1993). Recycling of lead acid batteries is relatively high (+95%), but recycling of cadmium batteries are relatively low, less than 60%. The cost of any environmentally danger related to rechargeable batteries is not determined. As with many of the suggested hidden effects described in this thesis, only time will show the cost of the effects if any at all.

Heat Pumps

Heat pumps themselves do not pose any danger to the environment. But there are some current drawbacks to the technology. In the past, the refrigerants used in heat pumps were the same as used in cooling equipment (CFC's), responsible for depletion of stratospheric ozone. In the past decades, research has been made on alternative refrigerants with some luck and is expected to eliminate the problem of ozone depleting refrigerants in the near future.

Heat pumps is by utilizing geo thermal energy an option to reduce the consumption of natural gas and other fossil fuels for heating purposes.The use of heat pumps can therefore help reduce carbon dioxide emissions to the environment and could therefore play a major role in future energy energy networks.

Diesel Generators

Diesel generators serve in the same groups as batteries. They do not belong to the group of renewable energy technologies, but they are currently necessary for optimal use of some renewable energy sources, because of the limitations placed on renewable energy sources. Diesel generators burn fossil fuels and are therefore part of the complex picture that was drawn up earlier in this chapter. Like most consumers of fossil fuels, the fuel must be transported to the generator. The transportation increases the chance of oil spill, both at sea and on land. An oil-spill usually does not have large effects on the global environment but can be fatal to local communities, killing much if not all of the biological life in the area.

Diesel generators also produce air pollution and sometimes noise pollution. The air pollution is accounted for earlier. The noise pollution is more a question of convenience, and for remote locations where diesel generators may be the only viable option, noise is one of the consumers' least concerns.y

Wind Turbines

Some problems have been related to wind turbines as well. People opposing wind generated energy have been blaming wind turbines for killing birds, being in the bird's migration path. Scientist having analyzed the impact of Altamont Pass in California estimate that it would take 7,000 wind turbines 1,000 years to kill as many birds as the Exxon Valdez oil spill in the Prince William Sound (Gipe 1993). The wind turbines in Altamont Pass on the average kill a bird every 20 years. Records like this do not justify the claim that wind turbines are a significant problem to wild-life, unless the wind turbines are sited close to habitats of endangered species.

Safety of new technologies is always a concern. Wind turbines have been around for a while and their rate of failure is very low (Gipe 1993), and with the proper maintenance and operation, wind turbines can operate far beyond the 20 years economic calculations are based on (Gipe 1993). In most residential areas, 11 meters is the maximum height of any built object reducing risks even more. It is safe to say that wind turbines are safe to the environment under design conditions.

Another problem related to wind turbines is the subjectivity of people living near to the site. This result in problems with esthetics and noise. Esthetics are usually taken care of by laws or ordinances, but the noise problem is a little more complex. Sound or noise is measured in decibels (dB). The threshold of hearing is 0 dB, while the threshold of pain is 140 dB. Table 4.1 shows some typical noise levels for different activities at a given distance of the origin of the noise.

As table 4.1 shows the noise problem of wind turbines is relatively small, and currently does not threaten the global environment, but is more a subjective problem related to neighbors and the looks

Table 4.1 Typical Noise Levels from Wind Turbines (Gipe 1993)

Source	Distance (m)	dB
Threshold of pain	-	140
Ship Siren	30	130
Jet Engine	61	120
Jack Hammer	-	100
Inside Sports Car	-	80
Freight Train	30	70
Vacuum Cleaner	3	70
Freeway	30	70
Small WECS(10kW)	37	57
Large transformer	61	55
Small WECS(10kW)	100	55
Wind in Trees	12	55
Light traffic	30	55
Average Home	-	50
300 kW WECS	200	45
30-300kW WECS	500	45
Soft Whisper	2	30
Sound Studio	-	20
Threshold of sound	-	0

of the wind turbine. With the current knowledge of wind turbines and renewable technologies, there are no significant environmental problems related to the operation of wind turbines.

One cannot assume that there are no other hidden costs related to renewable energy sources. One example is the use of freon as refrigerants. They did not exist naturally before 1940. Looking at the consequences CFC's have had on the environment, it should not be taken for granted that there are no hidden impacts related to renewable energy sources. But at the current time their global impact is far less noticeable and costly then the ones of non-renewable energy sources.

Estimated Economic Impacts of Artificial Environmental Change

This chapter has conservatively attempted to estimate expenditures related to the public health caused by artificially induced environmental changes from energy consumption in the United States. The hidden estimated expenditures average at least \$ 55 billion a year. Of those \$ 49 billion is estimated to be caused by air pollution and \$ 6 billion to be caused by depletion of stratospheric ozone. This is in addition to more than \$ 101 billion in pollution abatement and control included in the \$ 473 billion in expenditures related to energy consumption and production in the United States. United States, which has reduced its fraction of the world's energy consumption over the past 20 years, is currently consuming one fourth of the world's total energy. The minimum estimated cost of \$ 49 billion from air pollution could add approximately 12% to the expenditures related to energy consumption including abatement costs and 15.3% to energy expenditures excluding abatement costs.

Trying to estimate all possible costs is beyond the scope of this chapter or thesis, due to the complexity and size of the artificial environmental changes. It has become very clear that not only is there an unsustainable use of energy in the United States and the Western World, but also that the cost of this use might be larger than believed and has effects beyond the borders of the continental United States. Whereas the use of renewable energy sources does have some undesirable consequences, the known effects are currently small, perhaps even minute compared to the effects caused by non-renewable energy sources.

Reduced food production and increased incidents of acute and chronic pulmonary and extra-pulmonary diseases may affect large parts of the world's population in the near future. One option of nature controlling itself is that an increase in death rates might cause a negative feedback to the food supply, balancing out for possible reductions in agricultural yields.

With all this in mind non-renewable energy sources and their effects should receive more attention as this author sees them detrimental to the global economy as well as the environment, both in the short and long term.

5 CONCLUSIONS

The objective of this thesis is two fold. The first objective is to develop a methodology for wind energy network analysis. The methodology evaluates high grade and low grade energy demand separately. Low grade energy demand is used for space conditioning such as space heating and cooling, water heating, and process heat for the industrial sector. High grade energy is primarily used for electrical appliances and lighting. Electric appliances in the residential sector can for instance be steak ovens, computers, laundry machines, radios, refrigerators, etc.

The second objective of this thesis is to use the pathway methodology to determine the fraction of supplied energy and energy cost of each modeled and simulated energy networks.

Evaluation of Methodology

Demand Models

Comparing simulated demand to consumer energy data in the simulated regions, the simulated energy demand is comparable to the energy survey data in terms of fraction of high and low grade energy demand. This applies both on a state level (Iowa) and for smaller areas (Ames). The demand model models high grade and low grade energy demand separately. This feature is useful for total energy management when optimization or comparisons of energy systems is a goal. The results from the demand simulations show that the numerical energy demand may not be completely accurate themselves. The inaccuracy can be improved with future studies (detailed later in this chapter). The difference in energy demand based on variations in model parameters show that the models are reliable for comparisons of different regions and scenarios. The results obtained from simulating the models show an expected correlation with the variation in model parameters such as temperature, wind speed, pathway costs, and pathway efficiencies. These simulations used a constant COP of heat pumps, while the COP actually varies with outside temperature, future simulations should take this into effect.

The demand model used in this thesis can be used to model energy demand for diverse populations.

Average data obtained from national statistical agencies as well as local population surveys can be used to determine populations and their energy demand.

Supply Model

The supply model used in this thesis is an efficient tool to predict the energy generated by a wind turbine. The knowledge required is the wind speed, the power curve of the simulated turbine, and local surface roughness data. The power curve method is designed for instantaneous power production, but if the time intervals becomes small enough, the instantaneous power becomes the average energy generation for that time interval. The time interval used in these simulations is every hour for a whole year. The wind turbine model used in this thesis takes into account changes in air density and change in tower height.

The results obtained from the simulations of wind generated energy, show reasonable variation and correlation to change in wind speed, temperature and air density, and surface roughnesses for different regions, scenarios, and wind turbines.

This model is not a substitute for common sense when siting a wind turbine, and thus may be used as tool to predict energy supply, and not to determine where to site a turbine. Only an extensive on-site audit will enable optimal harnessing of the available wind resources.

Pathway Analysis

This thesis introduces a concept from the National Renewable Energy Laboratory: pathway analysis (Dept. of Energy 1992). Pathway analysis is a helpful tool to determine both energy network efficiencies and costs for different pathways and scenarios. Pathway analysis takes into account each individual process or application in the energy pathway and calculates the path efficiency and cost. These efficiencies and costs can be used to determine energy network fraction of supplied energy and cost per delivered unit of energy. The FSE's and energy costs resulting from simulating the energy pathways show variations and correlation to changes in model parameters such as capital investments and application efficiencies expected for those variations.

Summary

Demand, supply, and pathway analysis show good results with variations of model parameters. The results show trends that are expected from various scenarios. The quantitative results can be improved by more detailed modeling such as dividing commercial demand into more sub-categories. These sub-categories should be end-use activities of floor space and/or employees. There are different levels of energy consumption for different commercial activities. The models used in this thesis do not account for those differences, and this explains why Ames cannot be modeled including Iowa State University.

Residential demand should also be divided into sub-categories. The consumption of hot water for senior citizens is different from the consumption of hot water for persons renting their residential units. Hot water consumption also varies with region, climate, size of dwelling, etc. None of these effects have been accounted for, which would improve the quantitative quality of the demand models. Demand for residential space conditioning can also be improved. The models used in this thesis have only accounted for percentage of wooden, brick, and concrete walls with their overall heat transfer coefficients. This does not take into account different levels of insulation and the impact of increased insulation costs and decreased heat transfer. Residential high grade energy demand is difficult to model accurately because there can be so many variations among individual households. One way to circumvent this problem is to determine average electricity consumption for different standards of living, using detailed energy audits of residential units.

Industrial demand models can also be improved by differentiating among industrial activities, such as high and low energy intense industries. All these improvements can be made, but would require energy audits on a large scale. The benefits of doing this would be that a detailed model can also be used to predict future energy demand scenarios, and thus be utilized by energy utilities as well as legislatures.

Evaluating the comparative qualities of the energy demand models, the methodology developed is reliable. But, there are many improvements that can be achieved by further detailed developments of the quantitative qualities of the demand models introduced in this thesis.

Conclusion of Energy Supply Analysis

It s very clear from the results that different turbines have different fractions of supplied energy for different applications. When used for industrial energy demand, each of the two turbines simulated in this thesis showed a reduction in the ability to provide high fractions of supplied energy. Vestas turbines which have lower fractions of supplied energy for all simulated scenarios even using four turbines compared to the one Wega turbine. Wega turbines with a higher potential energy production per hour is able to obtain a higher fraction of supplied energy for higher levels of energy demand than the Vestas turbine. This would indicate that research should be directed towards reduction in cost of large wind turbines along with improved reliability and efficiencies.

Simulating commercial or residential demand only, the fraction of supplied energy for both turbines types rises above one for the Iowa region. It is apparent that with the current energy production and costs related to wind turbines, they are unsuited as primary energy sources for industrial energy consumers. The wind turbines used in this thesis are best suited for less energy intense scenarios such as for instance residential high grade energy demand only.

Looking at the fraction of supplied energy in the three regions used in these simulations and estimated mean wind power density (Johnson 1985), the simulated results are consistent with the available wind power (Johnson 1985). Alaska has the highest power density per swept turbine area of 500 $\frac{W}{m^2}$, while Iowa has the lowest power density out of the three regions ($250\frac{W}{m^2}$), but not much lower than the Hawaii region ($300\frac{W}{m^2}$). This research has shown that the highest energy productions occur in the Alaska region, and that the lowest energy production occur in the Hawaii region, almost similar to the energy production in the Iowa region. This research has shown that the highest FSE is obtained in the Hawaii region and the lowest FSE is obtained in the Alaska region. The differences between mean average power density estimates and simulated supply can be explained from variations in air temperature and it's effect on air density and thus energy production. Comparing these scenarios also support of the comparative validity of the models introduced in this thesis.

Conclusions from Energy Cost Study

This research has shown that the current renewable energy technologies are not competitive with non-renewable technologies if only the cost of fuel and capital are taken into consideration. If one conservatively assert a 15% environmental tax to the consumption of energy generated from consumption of fossil fuels, the cost of non-renewable energy is still cheaper than energy from renewable technologies. Considering that stock of coal is anticipated to last for 300 to 400 years, it is not a good outlook for the environment. Chapter 4 briefly introduced causes and effects from the use of non-renewable energy technologies. The possible effects and the possible levels of their cost on society is frightening even without substantial research to back up the findings. If the worst case scenarios should be verified in the future, an energy tax of perhaps four to eight hundred percent would be appropriate. This is still a very difficult concept to convey to energy consumers anywhere in the world.

It is clear from this research that even with today's limited knowledge of the cost of hidden effects of fossil fuel combustion, there should be a minimum 20% pollution tax added to every kWh consumed originating from non-renewable energy sources.

Conclusions from Comparing FSE to Energy Cost

Comparing results of the FSE studies to the energy cost studies, the trends show that with increased FSE there is an increase in cost of delivered energy. It is clear that it is difficult to achieve high fractions of supplied energy using only one wind turbine, but that using more than one turbine and batteries or hydrogen and fuel cells for energy storage improve FSE to an acceptable level. With the current high cost of the hydrogen pathway, this option is not very attractive. Today's battery technology is showing limitations because of negative effects on the environment and size limitations. At the current time the FSE that can be achieved with the wind turbines alone make wind technology unattractive to most energy consumers and suppliers. With future improvements in both application efficiency and reduced cost of energy storage applications, wind turbines will become more attractive for low energy intensity demand scenarios such as commercial or residential high grade energy demand with natural gas or high COP heat pumps with district heating and cooling options. Reduced cost of large wind turbines would also be beneficial to the the energy consumer, since one large turbine would be able to provide several times more energy than many small turbines. But there is still much research and development necessary before this can be achieved.

Recommended Future Studies

The method and models introduced in this thesis are acceptable, but there is much room for improvement. One improvement would be with the weather data used to model demand and supply. The data obtained from National Renewable Energy Laboratory is being used, in contradiction to the advice of NREL. The simulations conducted in this thesis should be made using statistically manipulated weather data from the National Weather Service. This would result in a more statistically reliable model. For the purpose of improving the results obtained from the demand models, both commercial and industrial energy consumers should be audited in detail.

One significant area that will require attention in the future are the expenditures associated with renewable energy sources and technologies. Their impact on the environment in negligible compared to the consumption of non-renewable energy, but their costs still make them unattractive. It is therefore very important that costs of these technologies are reduced so the concept of renewable energy technologies can more easily be sold to consumers and politicians making the decisions.

It has also become appearant that current research into the effects and costs of artificially made environmental changes is only scratching the surface of these problems. Tropospheric ozone for instance has only become an apparent threat in the last few years, and the more we learn about ozone the more we should be concerned about the impacts in may have on our lives. It would further be appropriate to try to assess the cost of the emission of carbon-dioxide and environmentally toxic fumes more accurately both nationally and globally to determine an appropriate environmental tax that should be added to purchases of fossil fuels.

Theoretically the use of large wind turbines shows high fractions of supplied energy with noticeably higher expenditures than for smaller wind turbines. Research should be conducted to reduce the cost of large wind turbines. The cost of large wind turbines related to the large tower heights etc. should be minimized. A problem often related to large wind turbines is their lack of ability to stay operational for longer periods of time. If a large wind turbine could achieve as high a level of dependability as smaller turbines, and if their cost could be reduced it would save a lot of money for future energy consumers. If reduced cost could be achieved, the high fraction of supplied energy could offset the extra cost endured with the larger wind turbine.

Energy analysis is complicated to conduct. But this study has introduced a methodology to perform energy analysis of any energy system. The two parameters evaluated in this particular study were the fraction of supplied energy and the cost of the supplied energy. This method is a tool that can be modified and used for all areas of the energy forecasting and preliminary design of energy systems.

APPENDIX A BUILDING PARAMETERS

Table A.1 Thermal Resistances, Wooden Wall

Element	Rw,w	Rw,s	Rs,w	Rs,s
Outside air	0.030	0.044	0.030	0.044
Plywood panels	0.160	0.160	0.160	0.160
Outside insulation	0.700	0.700	0.700	0.700
Mineral fiber	2.300	2.300	0.000	0.000
Studs	0.000	0.000	0.630	0.630
Inside Insulation	0.100	0.100	0.100	0.100
Inside air	0.120	0.120	0.120	0.120
R_total	3.410	3.424	1.740	1.754

Wooden Wall Calculcations

$R_{wall} = \frac{Rw,w+Rw,s}{2} = \frac{3.410+3.424}{2} = \underline{3.417}$

$R_{studs} = \frac{Rs,w+Rs,s}{2} = \frac{1.740+1.754}{2} = \underline{1.747}$

$U_{wood,wall} = \frac{0.75}{3.417} + \frac{0.25}{1.747} = \underline{\underline{0.363 \frac{W}{m^2K}}}$

Walls made from concrete blocks

Ashrae Handbook, section 22.5 returns an average U-value for concrete blocks of 1.64 W/m^2K.

Walls made from bricks

Ashrae Handbook, chapter 22 returns an average U value equal to 2.33 W/m^2K.

Floor slabs

Section 25.12 ASHRAE Handbook returns R=0.95 which result in a U-value of 1.05 W/m^2K.

Roof/Ceilings

Ceiling Calculations

Table A.2 Thermal Resistances, Roof/Ceilings

Element	Rw,w	Rw,s	Rs,w	Rs,s
Outside air	0.030	0.044	0.030	0.044
Asphalt shingles	0.077	0.077	0.077	0.077
Mineral fiber	2.300	2.300	0.000	0.000
Studs	0.000	0.000	0.630	0.630
Inside Gypsum	0.079	0.079	0.079	0.079
Inside air	0.110	0.160	0.110	0.160
R_total	2.497	2.516	0.827	0.846

$$R_{wall} = \frac{Rw,w+Rw,s}{2} = \frac{2.497+2.516}{2} = \underline{2.507}$$

$$R_{studs} = \frac{Rs,w+Rs,s}{2} = \frac{0.827+0.846}{2} = \underline{0.837}$$

$$U_{wood,wall} = \frac{0.75}{2.507} + \frac{0.25}{0.837} = \underline{\underline{0.479\frac{W}{m^2K}}}$$

APPENDIX B SIMULATION PARAMETERS

Table B.1 Wind - Utility, Energy Pathway (Efficiency)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Demand (kW)	1.0	1.0	1.0	1.0
Heater Eff.	100%	80%	80%	-
DHC Distribution Eff.	-	-	90%	-
Heat Pump Eff.	-	-	300%	-
El. Distribution Eff.	92%	-	92%	92%
Supply (kW)	1.09	1.25	0.50	1.09

Table B.2 Wind - Utility, Energy Pathway (Cost-$/kW)

	El.Furnace	Gas Furnace	DHC/HP	Utility
Heater	-	-	-	-
DHC Distribution	-	-	$1,050	-
Heat Pump	-	-	$350	-
El.Distribution	$50	-	$50	$50
Wind Turbine (Vestas)	$1,100	-	$1,100	-
Wind Turbine (Wega)	$5,800	-	$5,800	-
Capital (Vestas)	$1,249	-	$2,372	-
Capital (Wega)	$6,372	-	$4,722	-
Fuel ($/kWh)	-	$0.01	-	$0.08

Table B.3 Wind - Battery, Energy Pathway (Efficiency)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Demand (kW)	1.0	1.0	1.0	1.0
Heater Eff.	100%	80%	80%	-
DHC Distribution Eff.	-	-	90%	-
Heat Pump Eff.	-	-	300%	-
Lead Acid Battery Eff.	80%	-	-	80%
El. Distribution Eff.	92%	-	92%	-
Supply (kW)	1.09	1.25	0.50	1.25

Table B.4 Wind - Battery, Energy Pathway (Cost-$/kW)

	El.Furnace	Gas Furnace	DHC/HP	El.Supply
Heater	-	-	-	-
DHC Distribution	-	-	$1050	-
Heat Pump	-	-	$350	-
Lead Acid Battery	$100	-	$100	$100
El.Distribution	$50	-	$50	$50
Wind Turbine (Vestas)	$1,100	-	$1,100	$1100
Wind Turbine (Wega)	$5,800	-	$5,800	$5,800
Capital (Vestas)	$ 1,659	-	$2,567	-
Capital (Wega)	$8,051	-	$5,528	-
Fuel ($/kWh)	-	$0.01	-	$0.08

Table B.5 Wind - Diesel, Energy Pathway (Efficiency)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Demand (kW)	1.0	1.0	1.0	1.0
Heater Eff.	100%	80%	80%	-
DHC Distribution Eff.	-	-	90%	-
Heat Pump Eff.	-	-	300%	-
El. Distribution Eff.	92%	-	92%	-
Diesel Demand	0.27 l/kWh	-	-	-
Supply (kW)	1.09	1.25	0.50	-

Table B.6 Wind - Diesel, Energy Pathway (Cost-$/kW)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Heater	-	-	-	-
DHC Distribution	-	-	$1,050	-
Heat Pump	-	-	$350	-
El.Distribution	$50	-	$50	-
Diesel Generator	$750	-	$750	-
Wind Turbine (Vestas)	$1,100	-	$1,100	-
Wind Turbine (Wega)	$5,800	-	$5,800	-
Capital (Vestas)	$2,067	-	$2,747	-
Capital (Wega)	$7,190	-	$5,097	-
Fuel ($/kWh)	$0.01	$0.01	$0.01	$0.08

Table B.7 Wind - Diesel, Energy Pathway (Efficiency)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Demand (kW)	1.0	1.0	1.0	1.0
Heater Eff.	100%	80%	80%	-
DHC Distribution Eff.	-	-	90%	-
Heat Pump Eff.	-	-	300%	-
Lead Acid Battery Eff.	-		-	80%
El. Distribution Eff.	92%	-	92%	-
Diesel Demand	0.27 l/kWh	-	-	-
Supply (kW)	1.09	1.25	0.50	1.25

Table B.8 Wind - Diesel, Energy Pathway (Cost-$/kW)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Heater	-	-	-	-
DHC Distribution	-	-	$1,050	-
Heat Pump	-	-	$350	-
El.Distribution	$50	-	$50	-
Diesel Generator	$750	-	$750	-
Wind Turbine (Vestas)	$1,100	-	$1,100	-
Wind Turbine (Wega)	$5,800	-	$5,800	-
Capital (Vestas)	$2,691	-	$2,518	-
Capital (Wega)	$9,083	-	$5,244	
Fuel ($/kWh)	$0.01	$0.01	$0.01	$0.08

Table B.9 Wind - Hydrogen, Energy Pathway (Efficiency)

	El.Furnace	Gas Furnace	DHC/HP	El. Supply
Demand (kW)	1.0	1.0	1.0	1.0
Heater Eff.	100%	90%	80%	-
DHC Distribution Eff.	-	-	90%	-
Heat Pump Eff.	-	-	300%	-
Fuel Cell Eff.	-	-	-	50%
Hydrogen Pipeline Eff.	-	-	-	95%
Electrolysis Eff.	-	-	-	92%
El.Distribution Eff.	92%	-	92%	92%
Supply (kW)	1.09	1.25	0.50	2.49

Table B.10 Wind - Hydrogen, Pathway (Cost-$/kW)

	El.Heating	Gas Furnace	DHC/HP	El. Supply
Heater	-	-	-	-
DHC Distribution	-	-	$1,050	-
Heat Pump	-	-	$350	-
Fuel Cell	$3,200		$3,200	-
Hydrogen Pipeline	$50		$50	-
Electrolysis	$1,000		$1,000	-
El.Distribution	$50	-	$50	-
Wind Turbine (Vestas)	$1,100	-	$1,100	-
Wind Turbine (Wega)	$5,800	-	$5,800	-
Capital (Vestas)	$8,264	-	$5,606	-
Capital (Wega)	$20,000	-	$11,011	-
Fuel ($/kWh)	-	$0.01	-	$0.08

Table B.11 Census Information for Ames (City and County Book, 1990)

Population	47,198
Housing Units	15,058
Civilian Employment	25,307
Industrial Employment	5.1 %

Note! The census population includes approx. 25,000 college students

Table B.12 Fractions of Building Structures for Space Conditioning Modeling, By Region

Structure	Iowa	Hawaii	Alaska
Wood	0.45	0.90	0.98
Brick	0.45	0.05	0.01
Concrete	0.10	0.05	0.01

APPENDIX C PATHWAY PARAMETERS

Table C.1 Pathway Efficiencies and Costs

Technology	Efficiency (%)	Cost ($/kW)
WindTurbine	-	-
VESTAS	-	1,100
WEGA	-	5,800
Fuel Cell	50	3,200
Lead Acid Battery		100
Water Electrolysis	50	1,000
Hydrogen Pipeline	95	50
Electric Distribution	92	50
Heat Pumps	300	350
DHC Distribution	90	1,050
Electric Furnace	100	-
Gas Furnace	80	-
Diesel Generator		750

APPENDIX D ECONOMIC RESULTS

The graphs included in this appendix are comparisons of cost of the 2,700 different scenarios simulated on the basis of the models described in Chapter 2.

The heading of each figure describes region, storage/distribution systems, heating device, and wind turbine type.

- *Regions:* Iowa, Hawaii, and Alaska
- *Storage and Distribution:* Batteries, Hydrogen/fuel cells, and District heating and cooling
- *Wind Turbine Type:* Vestas and Wega
- *Heating Devices:* Electric Furnace, Gas Furnace, Heat pumps

How the different equipment in the systems were sized are detailed in Chapter 2.

The tables in this appendix describes the variation in cost per delivered kWh to end consumer, the cost is found using the method discussed in Chapter 2 and reiterated in Chapter 3.

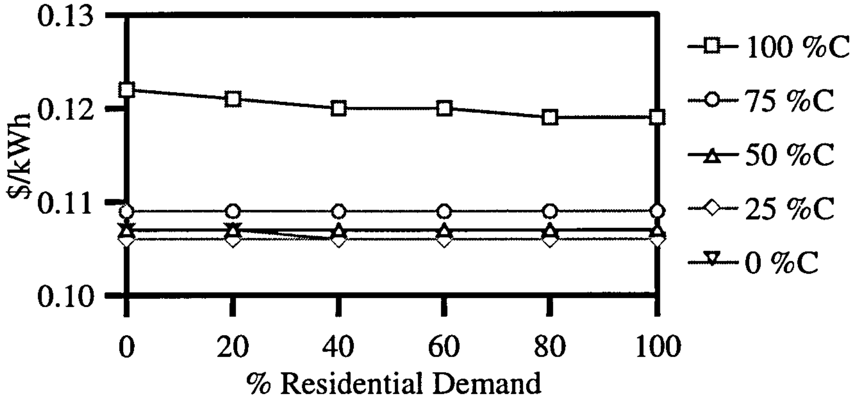


Figure D.1 Energy Cost: Iowa, Wind-Utility, El.Furnace, Vestas

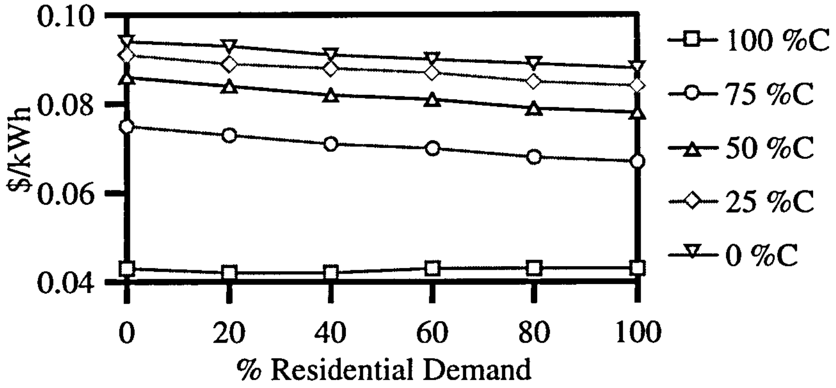


Figure D.2 Energy Cost: Iowa, Wind-Utility, Gas Furnace, Vestas

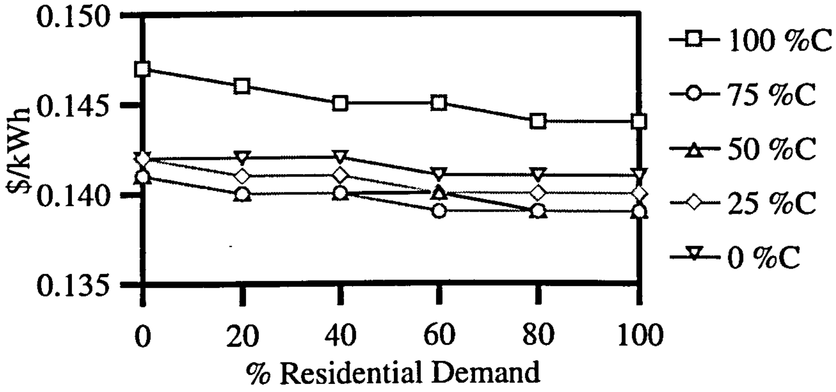


Figure D.3 Energy Cost: Iowa, Wind-Utility, DHC, Vestas

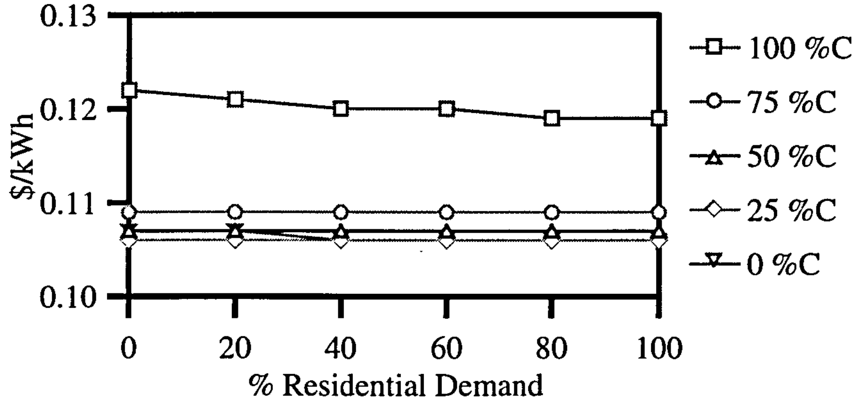


Figure D.4 Energy Cost: Iowa, Wind-Utility, El. Furnace, Wega

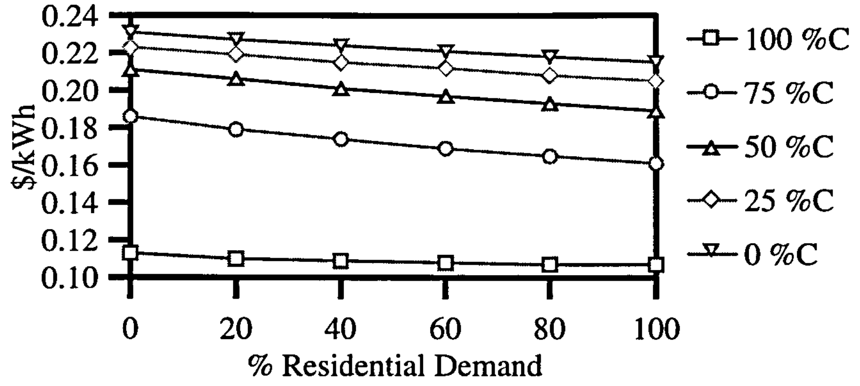


Figure D.5 Energy Cost: Iowa, Wind-Utility, Gas Furnace, Wega

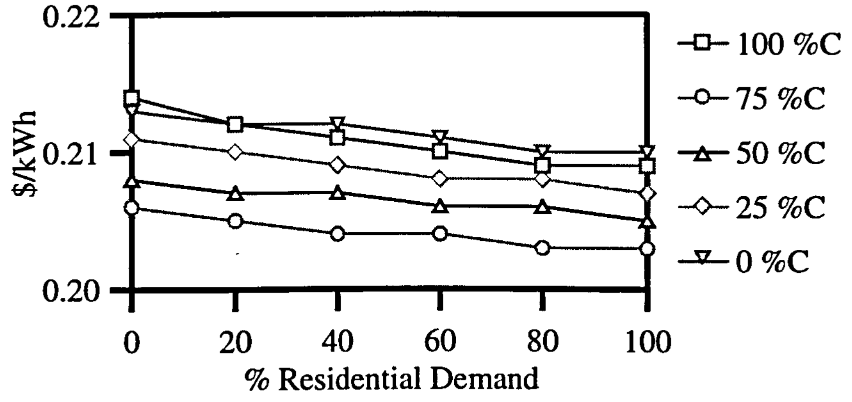


Figure D.6 Energy Cost: Iowa, Wind-Utility, DHC, Wega

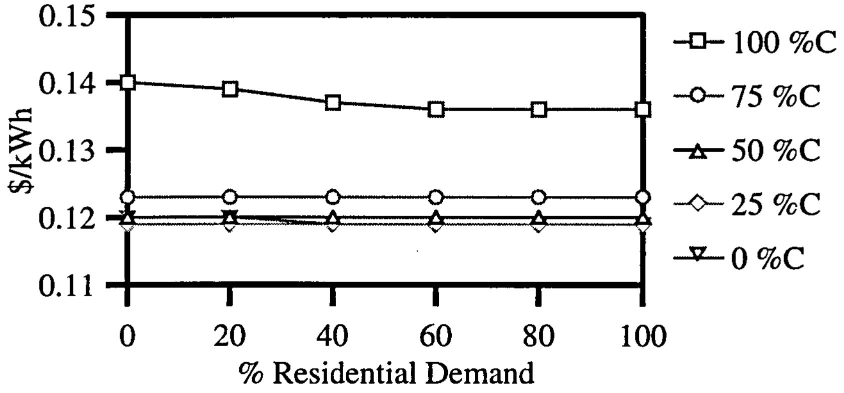


Figure D.7 Energy Cost: Iowa, Wind-Batteries, El.Furnace, Vestas

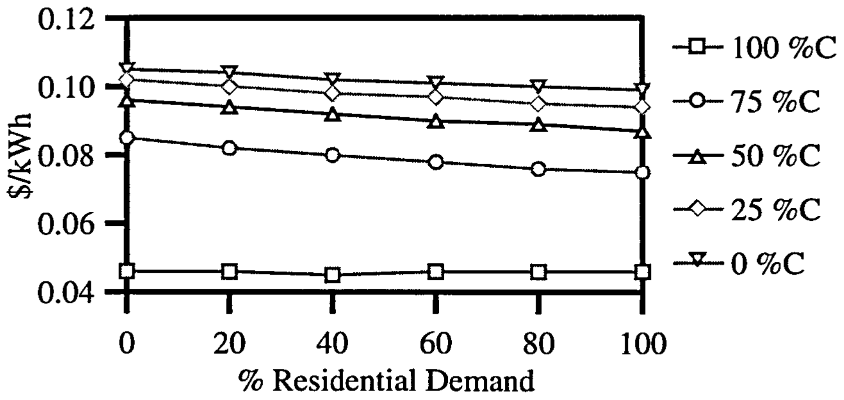


Figure D.8 Energy Cost: Iowa, Wind-Batteries, Gas Furnace, Vestas

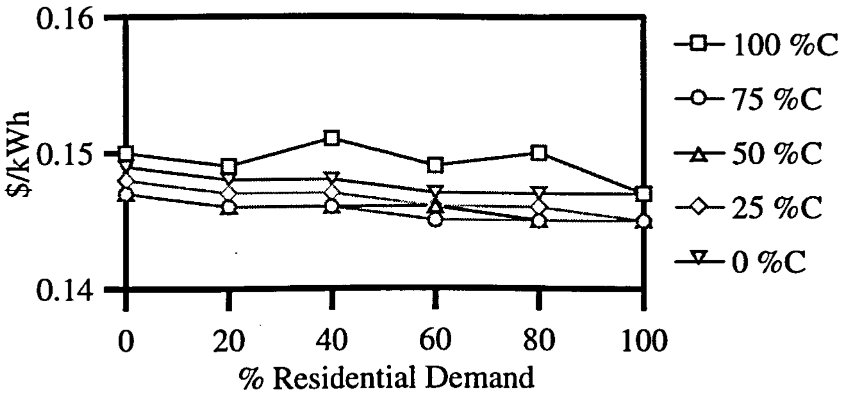


Figure D.9 Energy Cost: Iowa, Wind-Batteries, DHC, Vestas

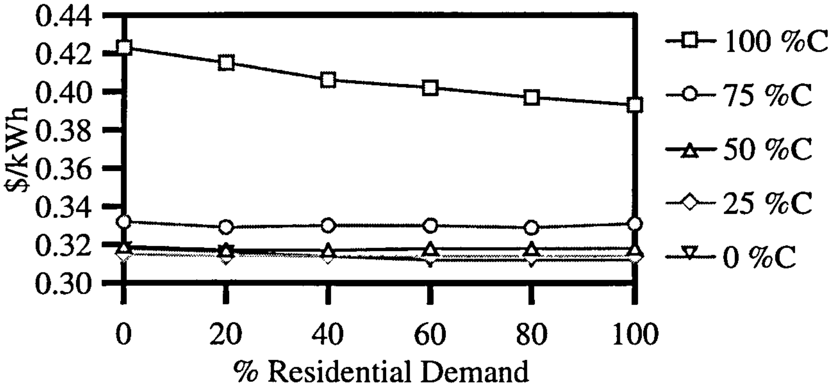


Figure D.10 Energy Cost: Iowa, Wind-Batteries, El.Furnace, Wega

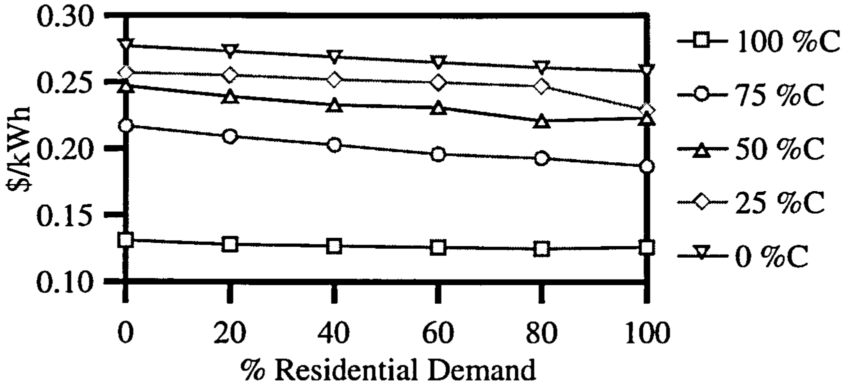


Figure D.11 Energy Cost: Iowa, Wind-Batteries, Gas Furnace, Wega

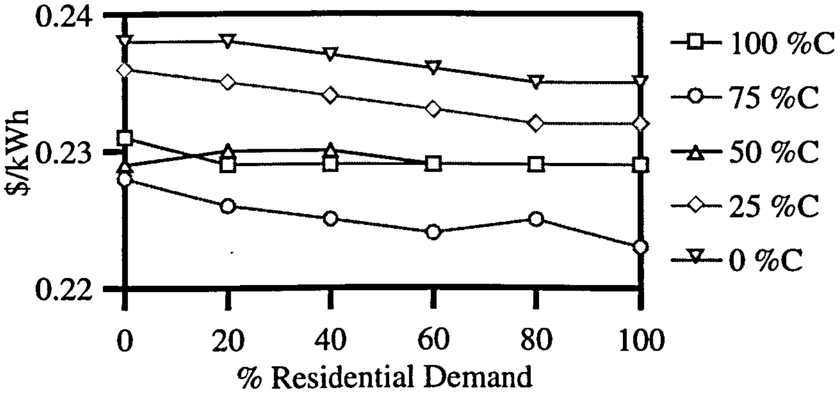


Figure D.12 Energy Cost: Iowa, Wind-Batteries, DHC, Wega

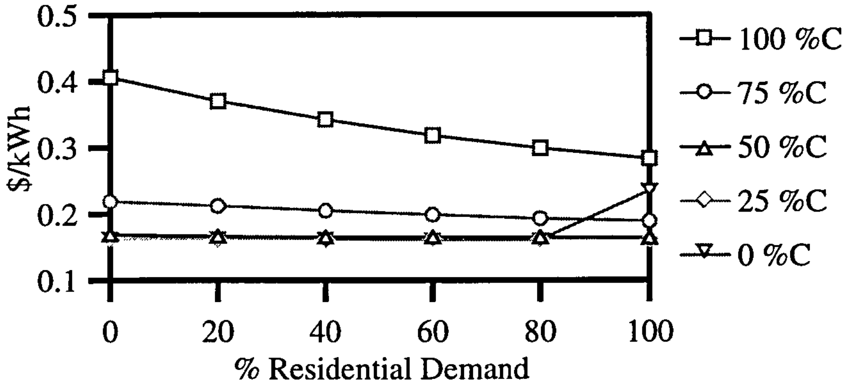


Figure D.13 Energy Cost: Iowa, Wind-Diesel, El.Furnace, Vestas

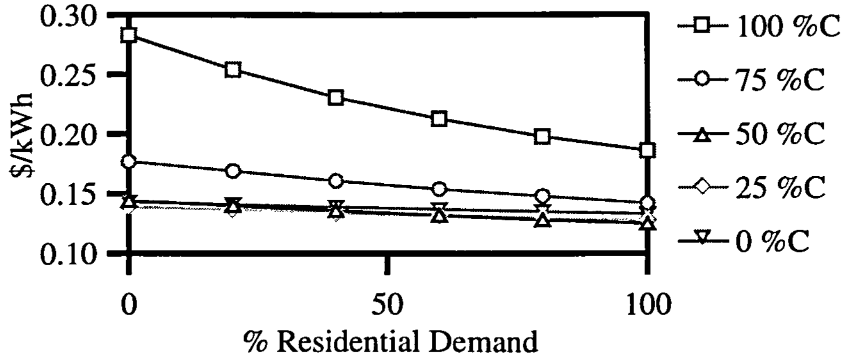


Figure D.14 Energy Cost: Iowa, Wind-Diesel, Gas Furnace, Vestas

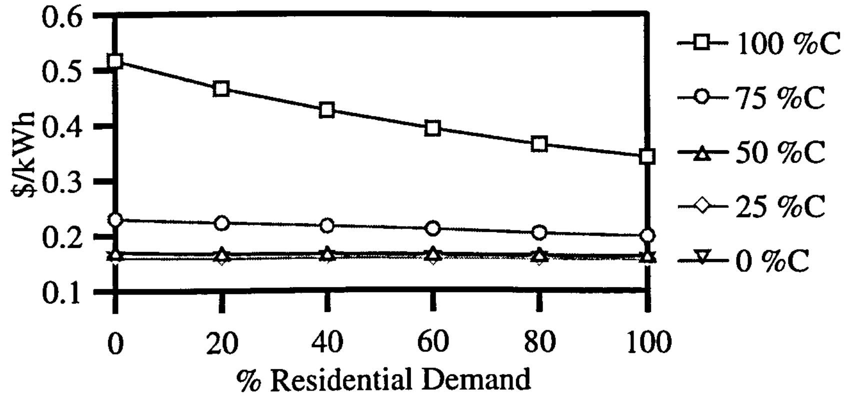


Figure D.15 Energy Cost: Iowa, Wind-Diesel, DHC, Vestas

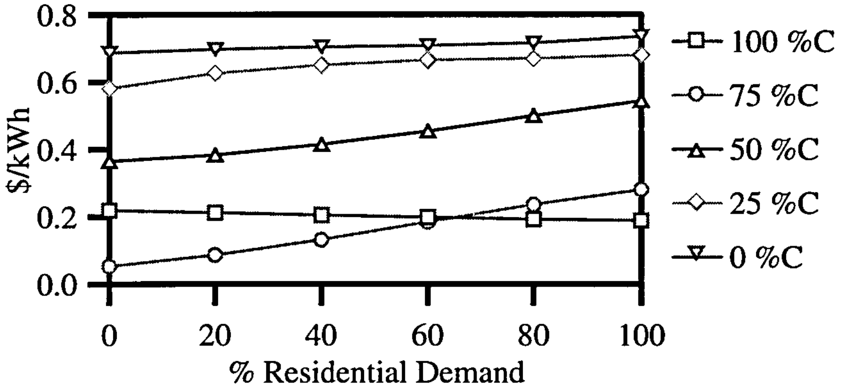


Figure D.16 Energy Cost: Iowa, Wind-Diesel, El.Furnace, Wega

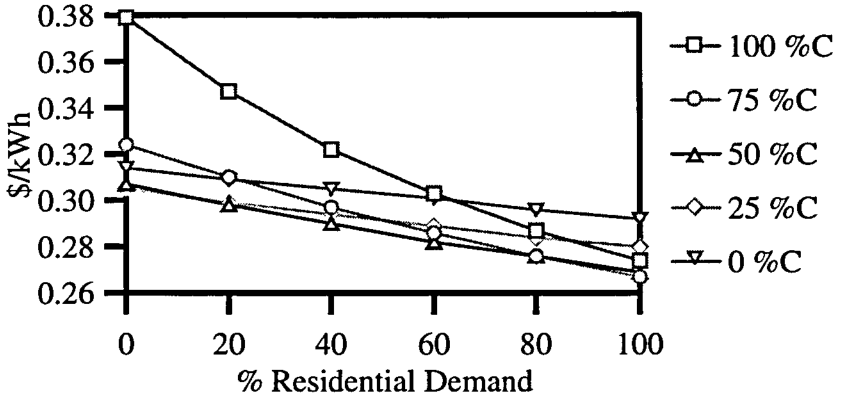


Figure D.17 Energy Cost: Iowa, Wind-Diesel, Gas Furnace, Wega

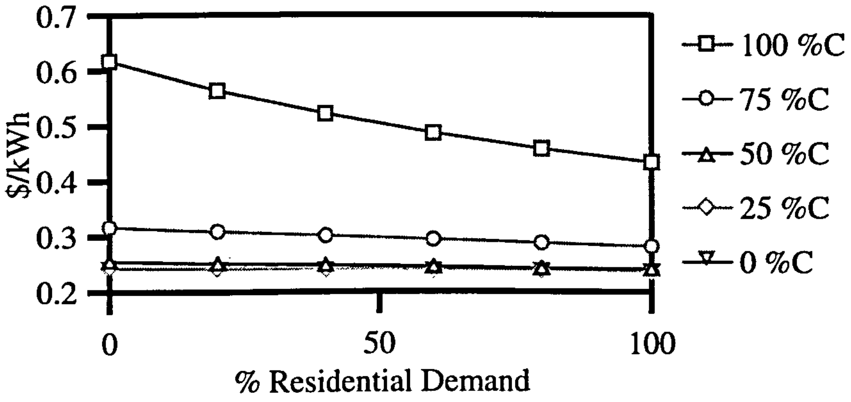


Figure D.18 Energy Cost: Iowa, Wind-Diesel, DHC, Wega

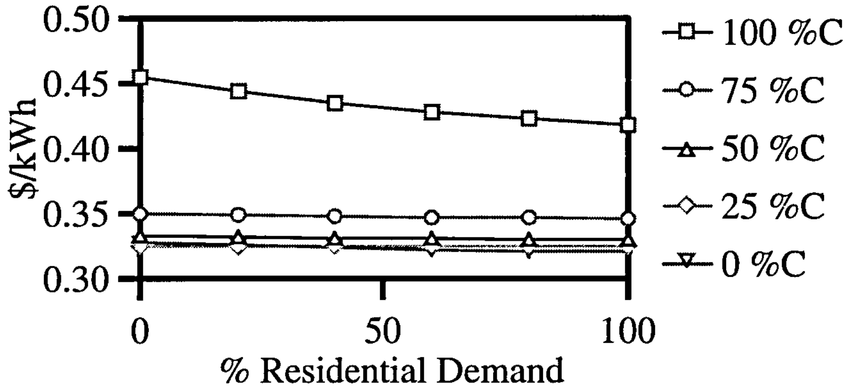


Figure D.19 Energy Cost: Iowa, Wind-Hydrogen, El. Furnace, Vestas

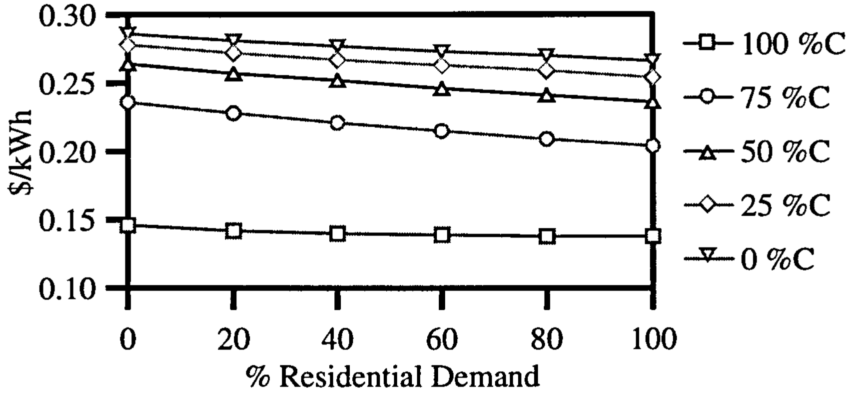


Figure D.20 Energy Cost: Iowa, Wind-Hydrogen, Gas Furnace, Vestas

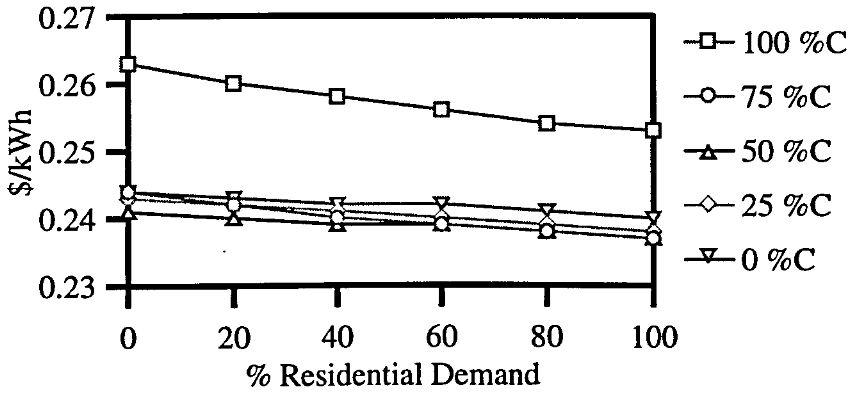


Figure D.21 Energy Cost: Iowa, Wind-Hydrogen, DHC, Vestas

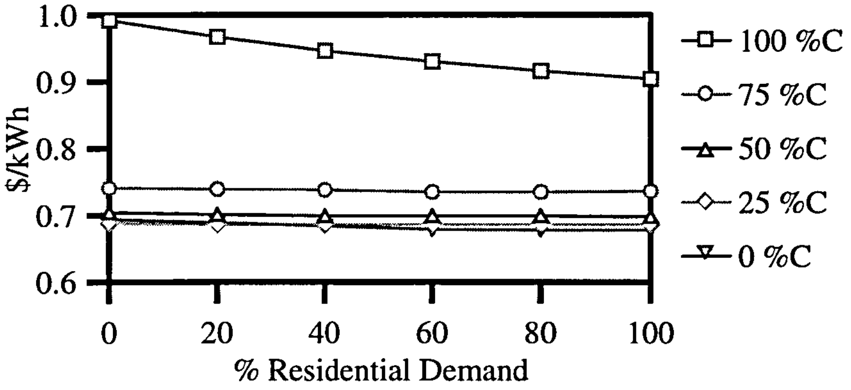


Figure D.22 Energy Cost: Iowa, Wind-Hydrogen, El. Furnace, Wega

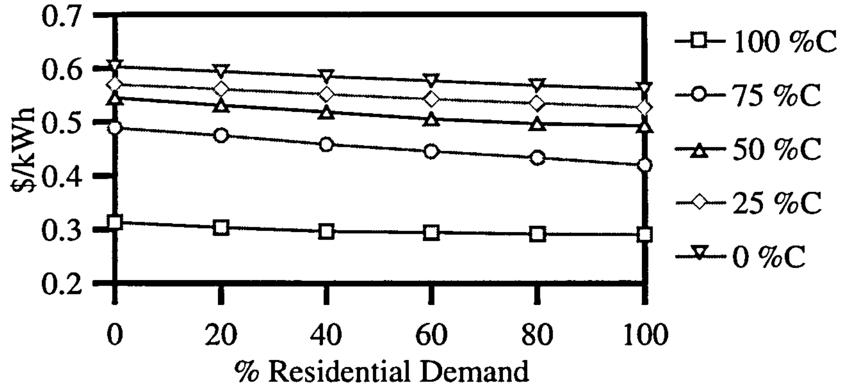


Figure D.23 Energy Cost: Iowa, Wind-Hydrogen, Gas Furnace, Wega

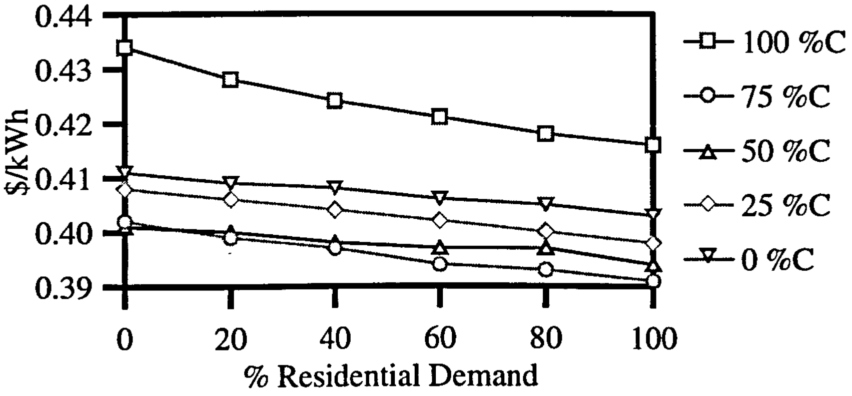


Figure D.24 Energy Cost: Iowa, Wind-Hydrogen, DHC, Wega

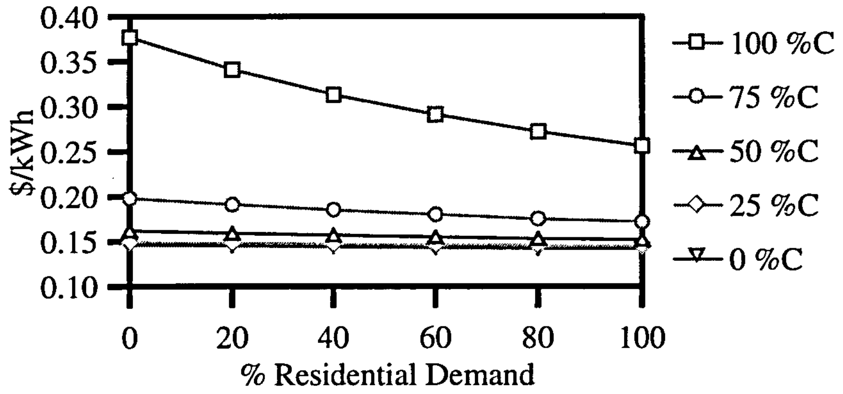


Figure D.25 Energy Cost: Iowa, Wind-Diesel/Batteries, El. Furnace, Vestas

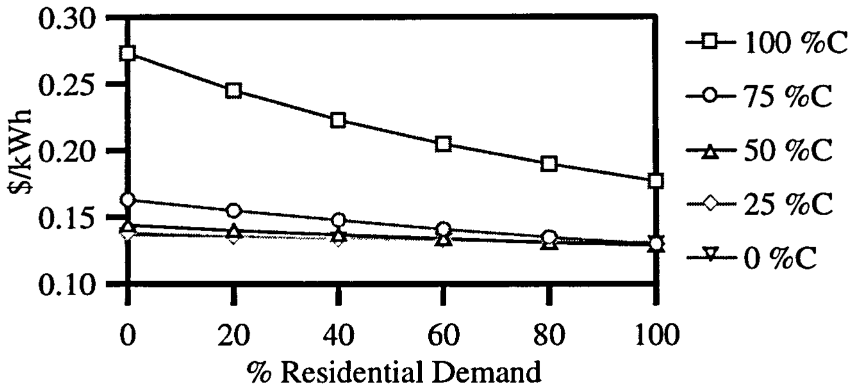


Figure D.26 Energy Cost: Iowa, Wind-Diesel/Batteries, Gas Furnace, Vestas

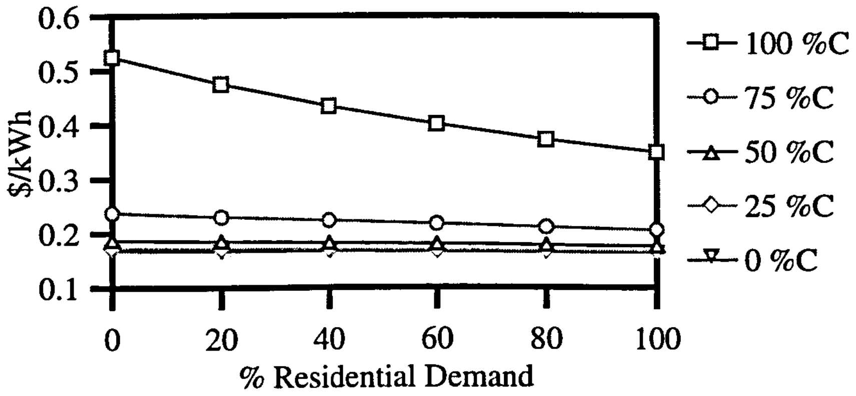


Figure D.27 Energy Cost: Iowa, Wind-Diesel/Batteries, DHC, Vestas

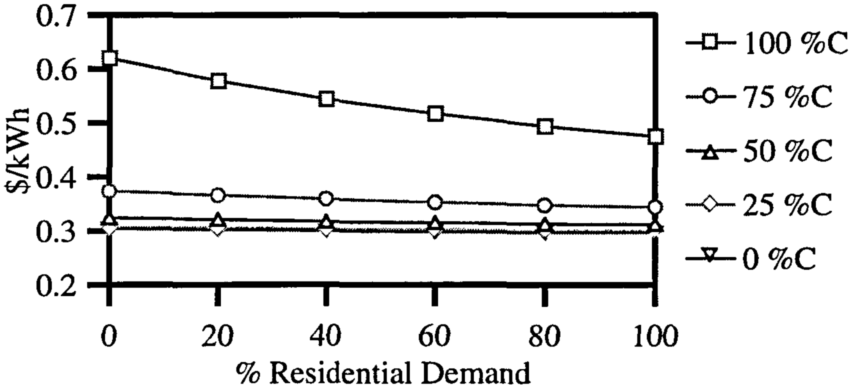


Figure D.28 Energy Cost: Iowa, Wind-Diesel/Batteries, El. Furnace, Wega

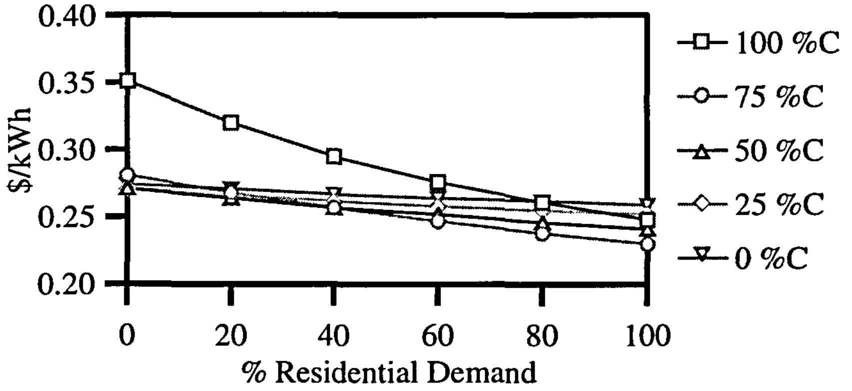


Figure D.29 Energy Cost: Iowa, Wind-Diesel/Batteries, Gas Furnace, Wega

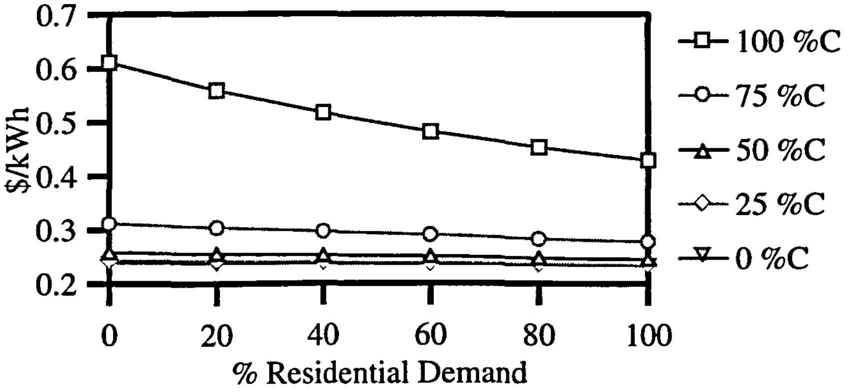


Figure D.30 Energy Cost: Iowa, Wind-Diesel/Batteries, DHC, Wega

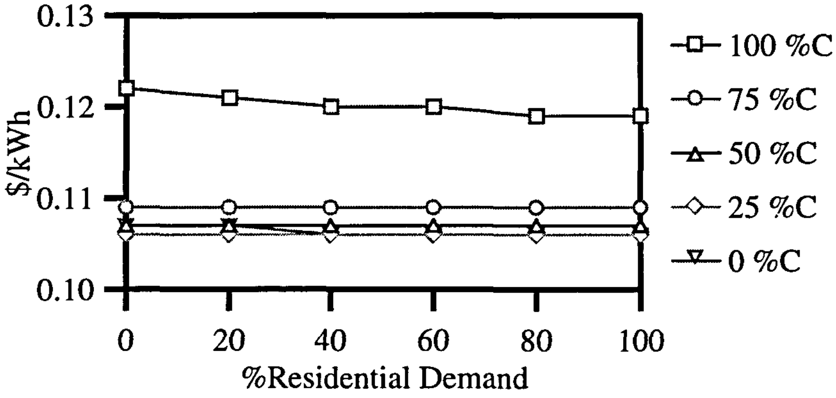


Figure D.31 Energy Cost: Alaska, Wind-Utility, El. Furnace, Vestas

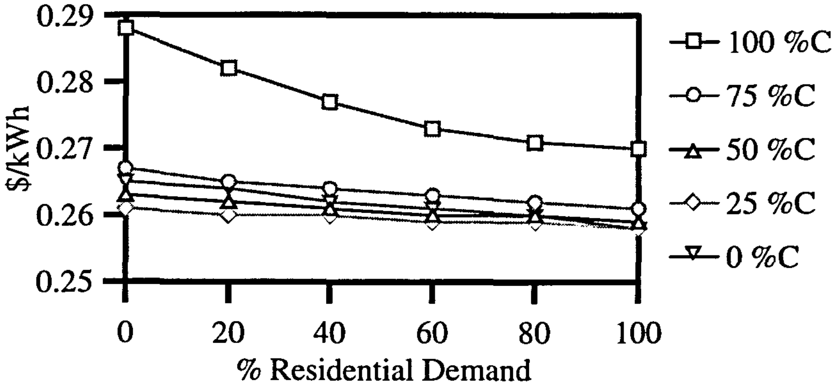


Figure D.32 Energy Cost: Alaska, Wind-Utility, Gas Furnace, Vestas

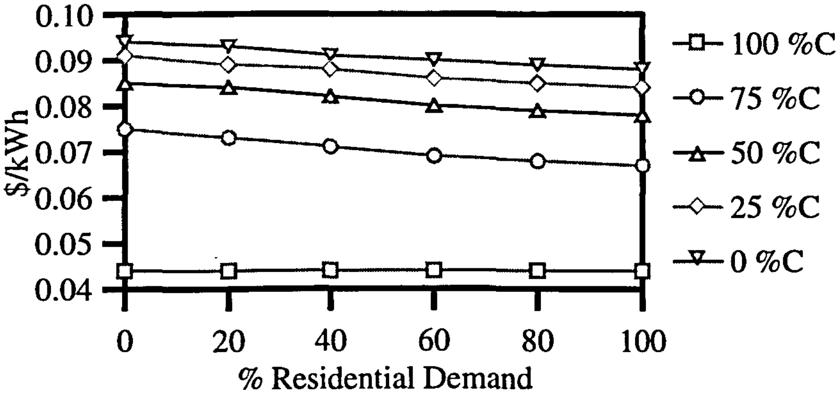


Figure D.33 Energy Cost: Alaska, Wind-Utility, DHC, Vestas

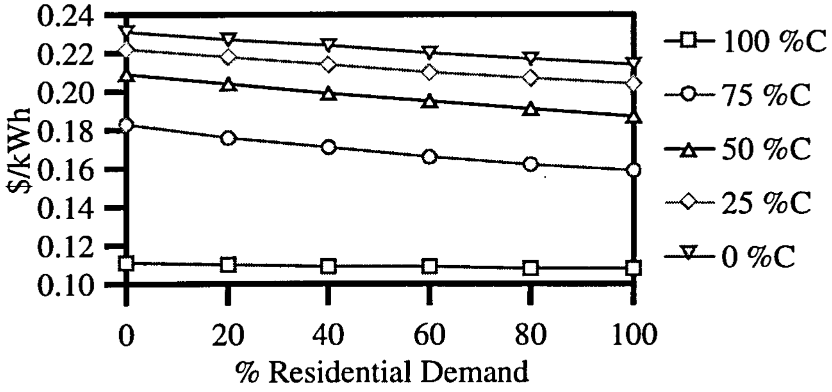


Figure D.34 Energy Cost: Alaska, Wind-Utility, El. Furnace, Wega

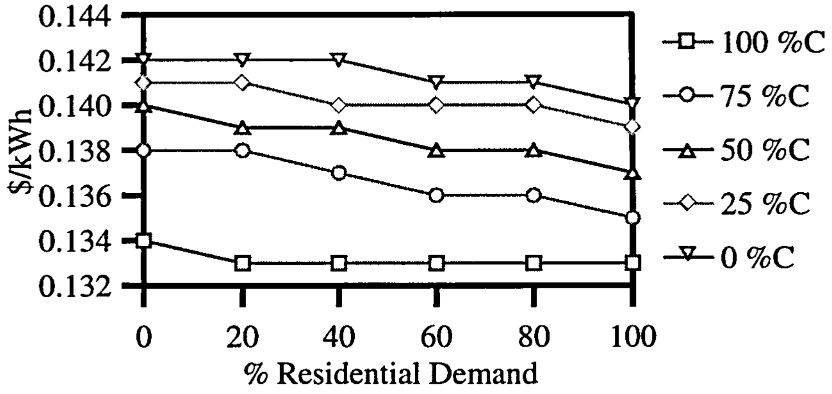
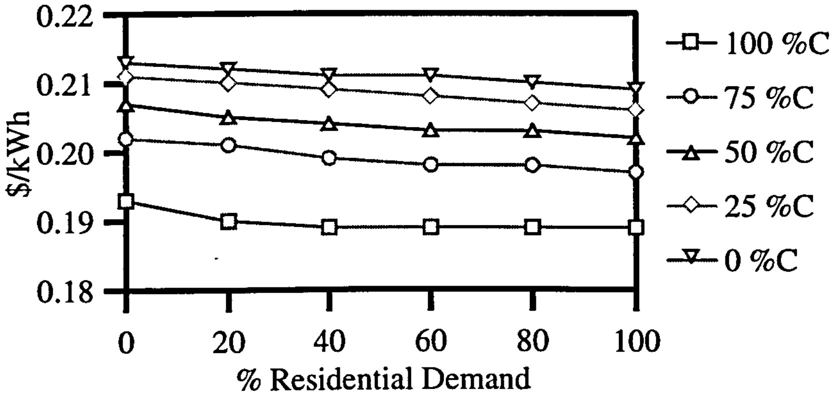


Figure D.35 Energy Cost: Alaska, Wind-Utility, Gas Furnace, Wega



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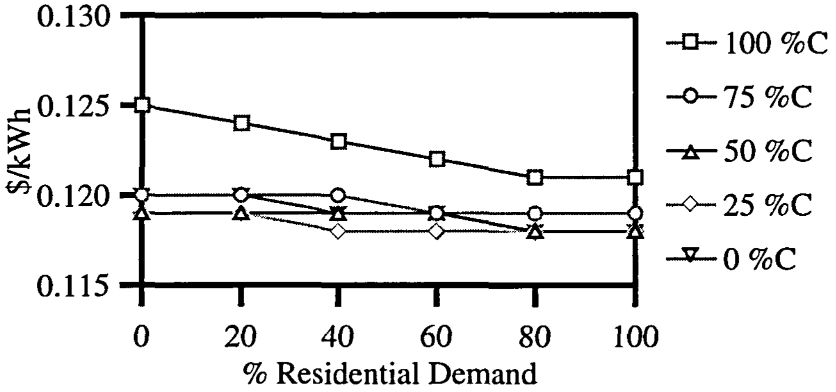


Figure D.37 Energy Cost: Alaska, Wind-Batteries, El. Furnace, Vestas

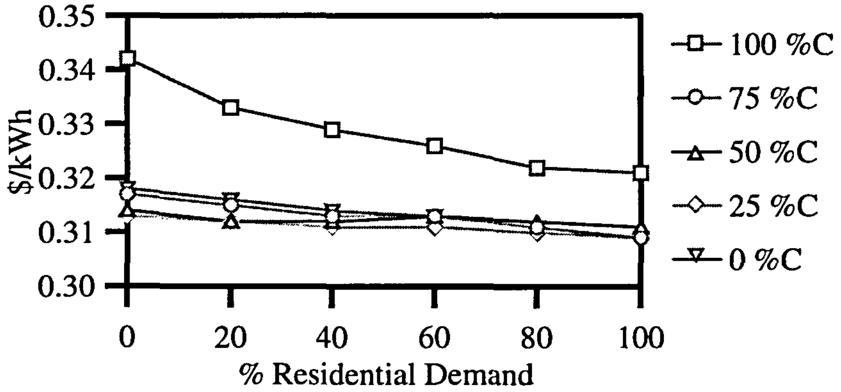
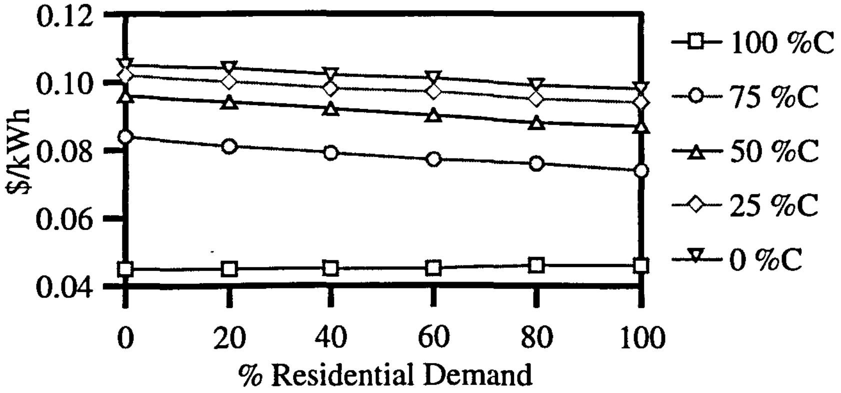


Figure D.38 Energy Cost: Alaska, Wind-Batteries, Gad Furnace, Vestas



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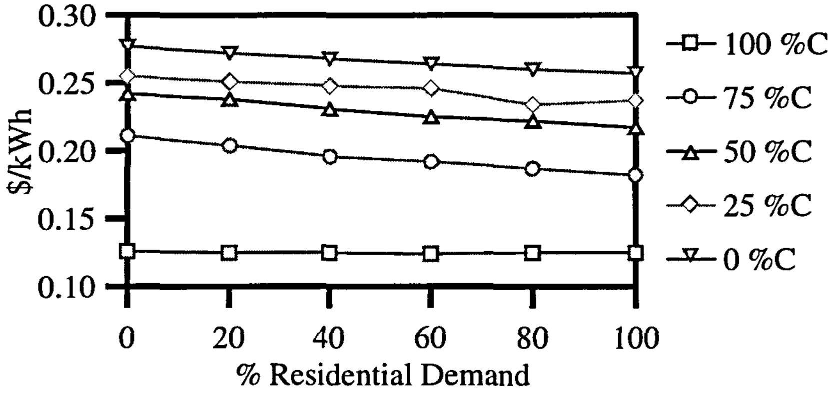

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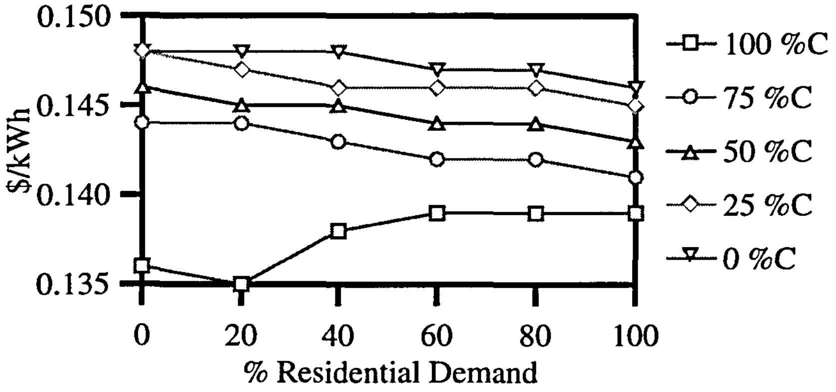
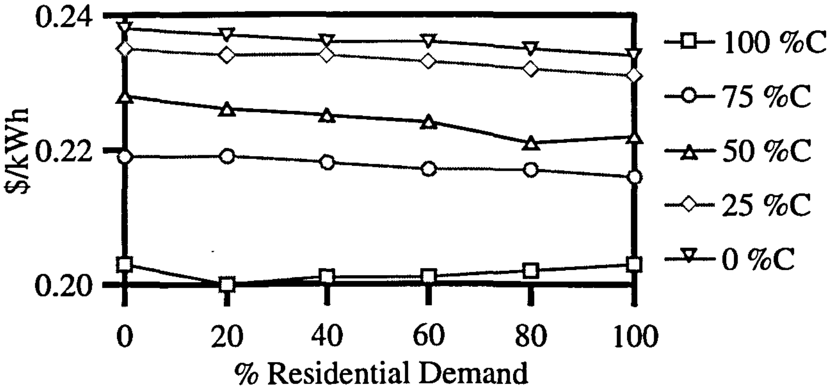


Figure D.41 Energy Cost: Alaska, Wind-Batteries, Gas Furnace, Wega



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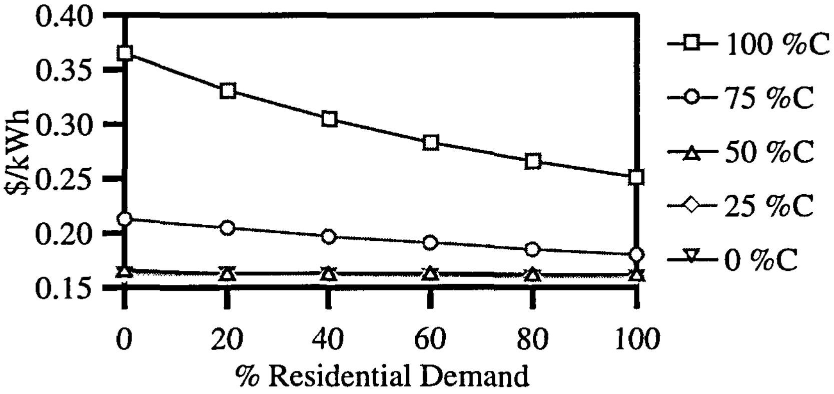
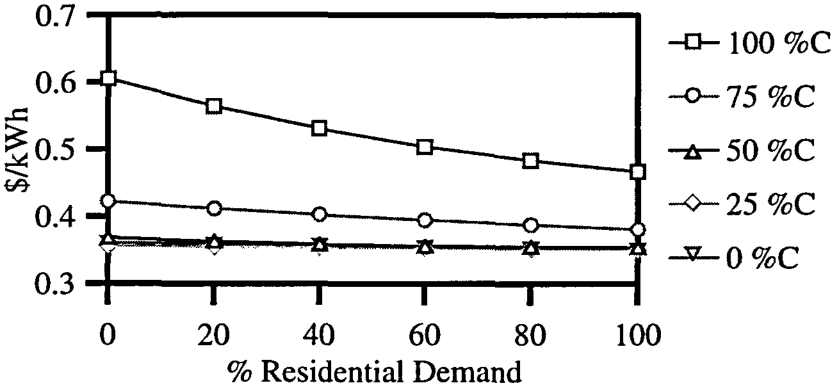


Figure D.43 Energy Cost: Alaska, Wind-Diesel, El. Furnace, Vestas



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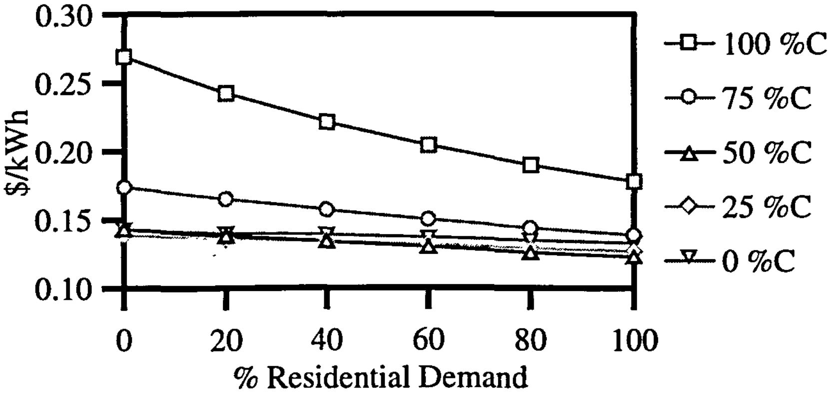

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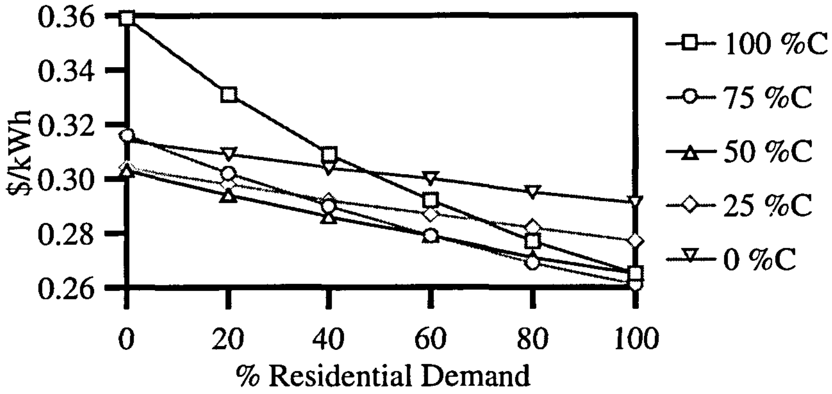
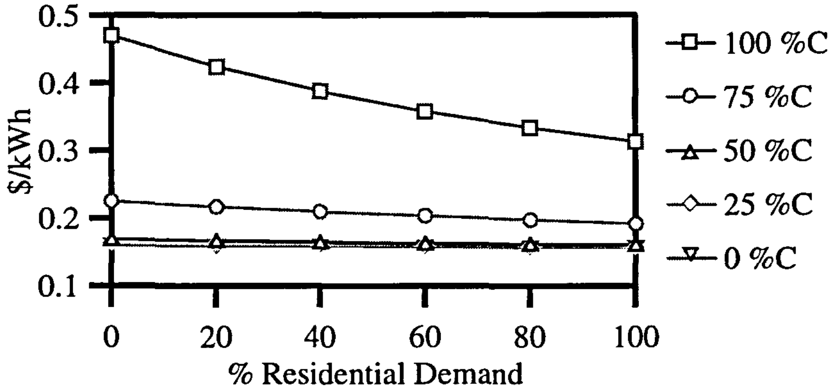


Figure D.46 Energy Cost: Alaska, Wind-Diesel, El. Furnace, Wega



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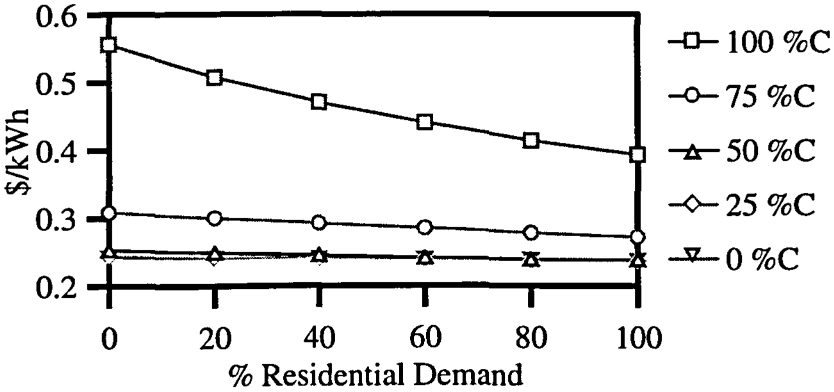

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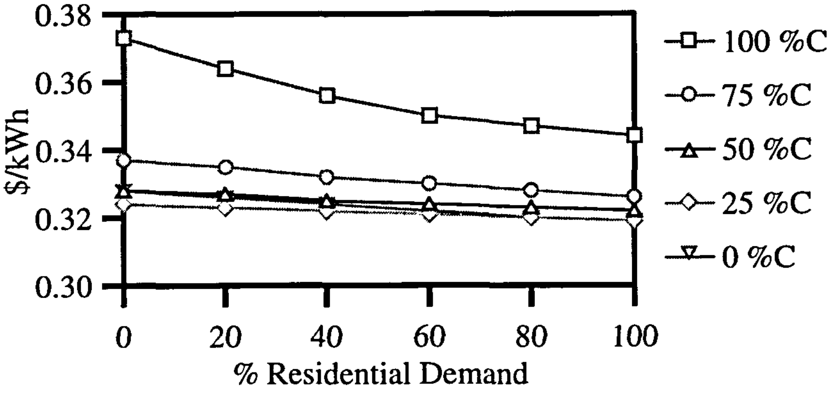

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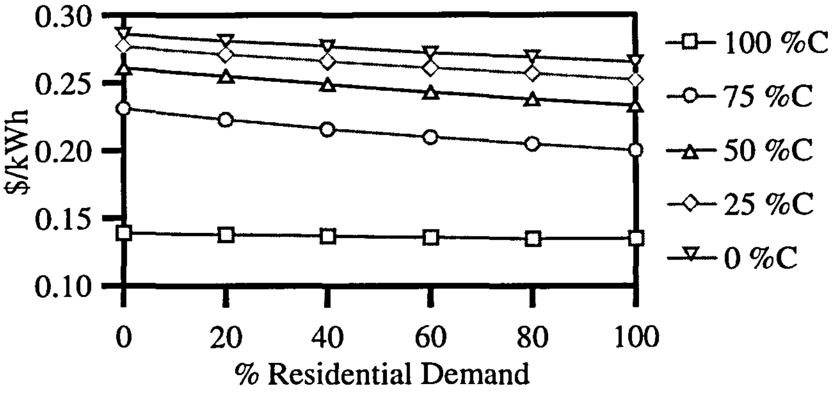
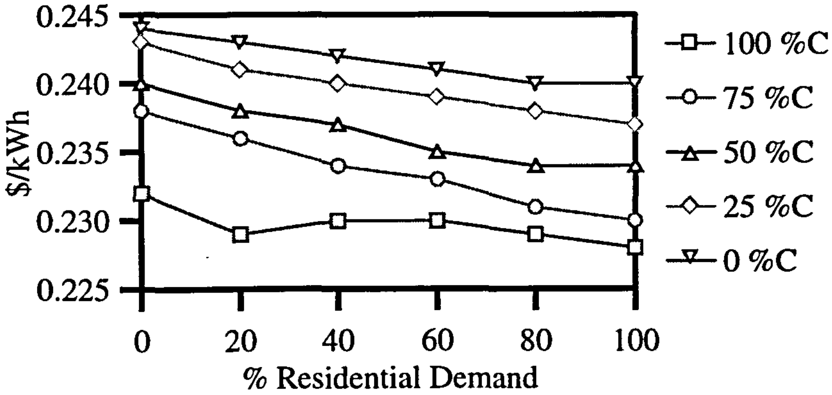


Figure D.50 Energy Cost: Alaska, Wind-Hydrogen, Gas Furnace, Vestas



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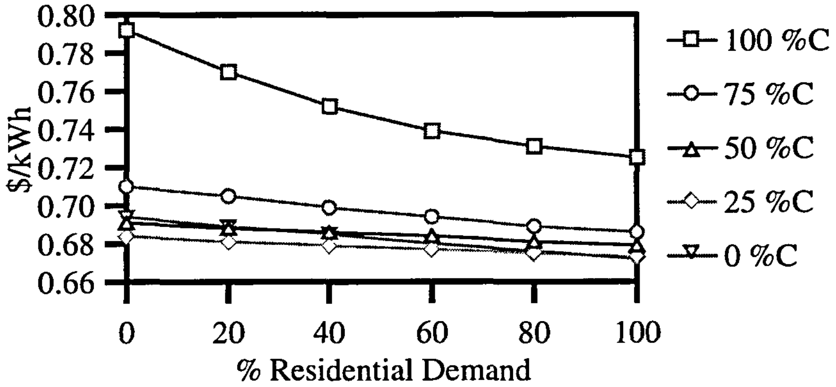

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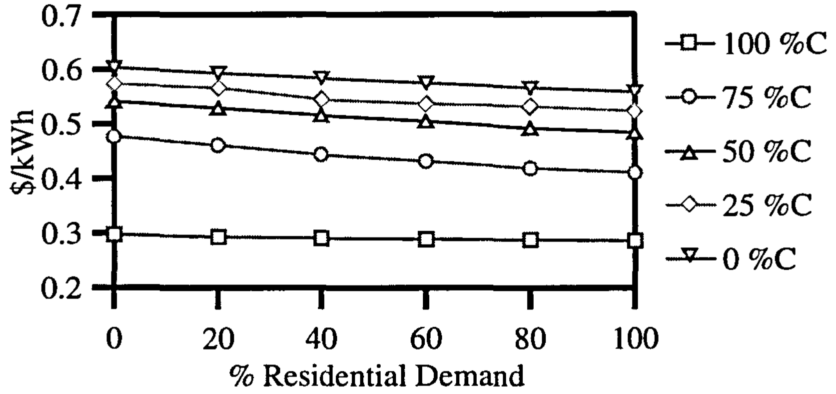
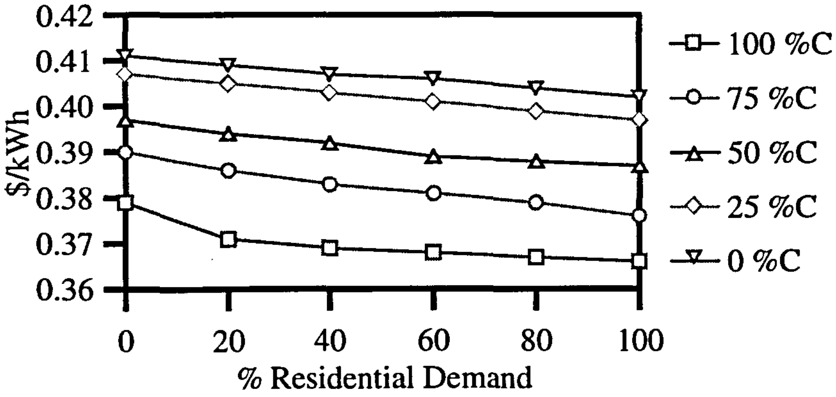


Figure D.53 Energy Cost: Alaska, Wind-Hydrogen, Gas Furnace, Wega



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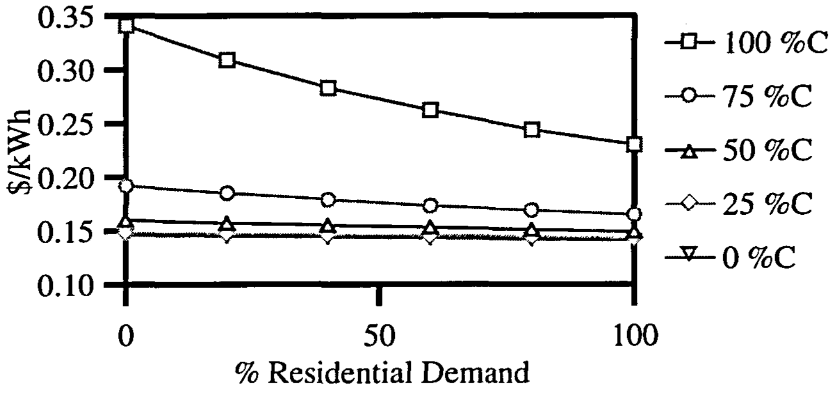

Figure D.55 Energy Cost: Alaska, Wind-Diesel/Batteries, El. Furnace, Vestas

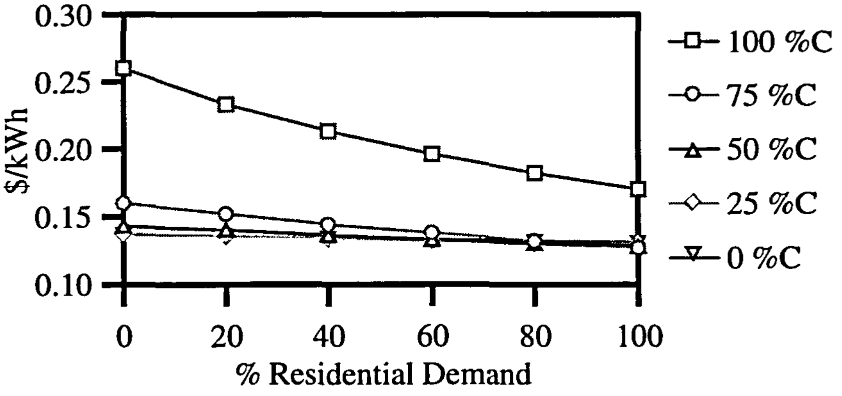

Figure D.56 Energy Cost: Alaska, Wind-Diesel/Batteries, Gas Furnace, Vestas

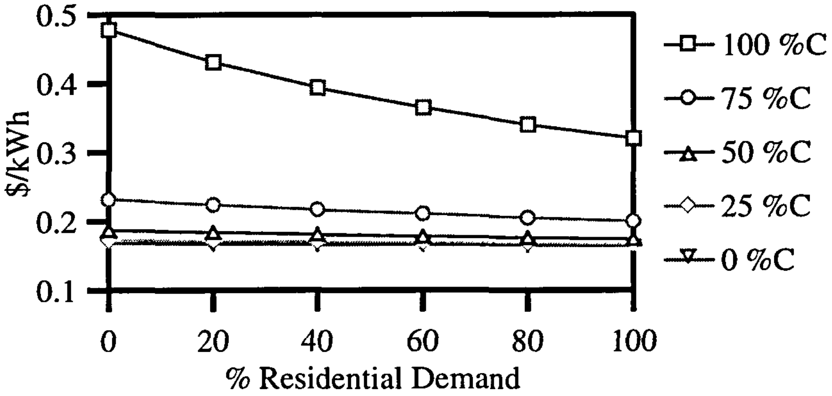

Figure D.57 Energy Cost: Alaska, Wind-Diesel/Batteries, DHC, Vestas

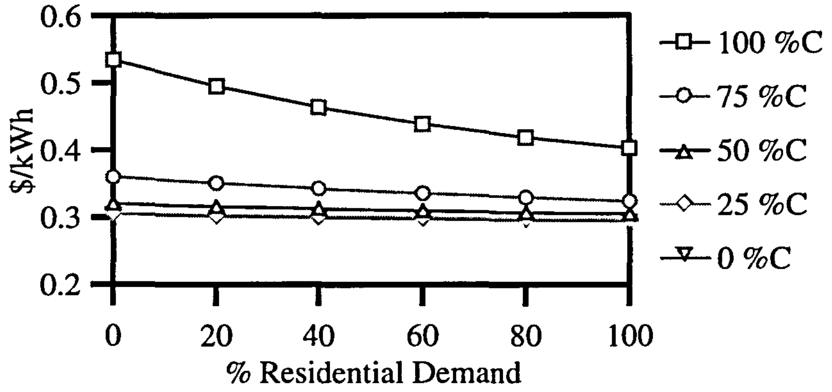

Figure D.58 Energy Cost: Alaska, Wind-Diesel/Batteries, El. Furnace, Wega

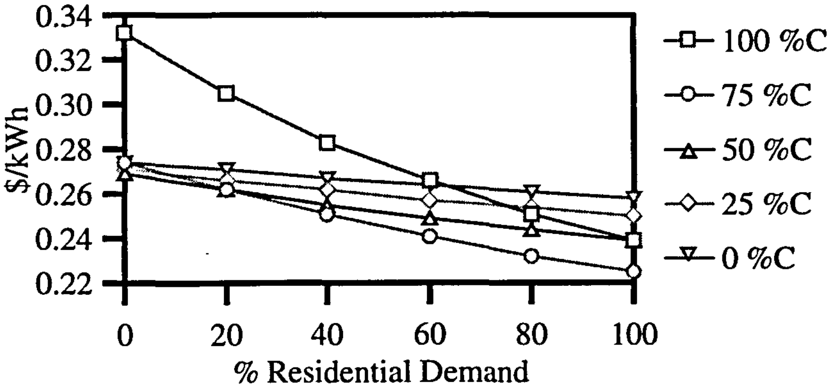

Figure D.59 Energy Cost: Alaska, Wind-Diesel/Batteries, Gas Furnace, Wega

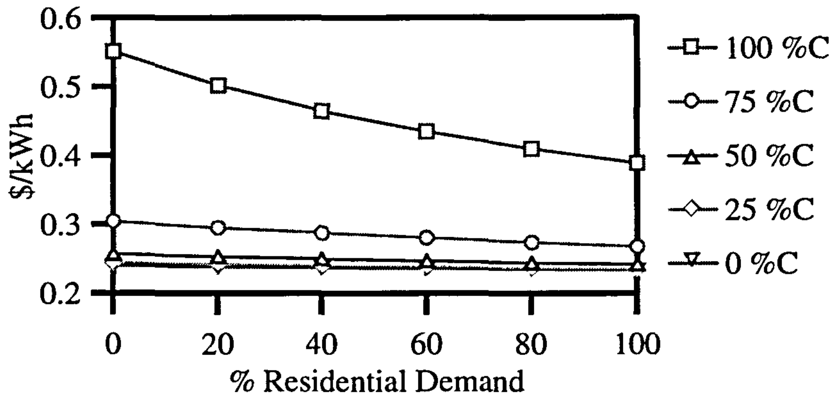

Figure D.60 Energy Cost: Alaska, Wind-Diesel/Batteries, DHC, Wega

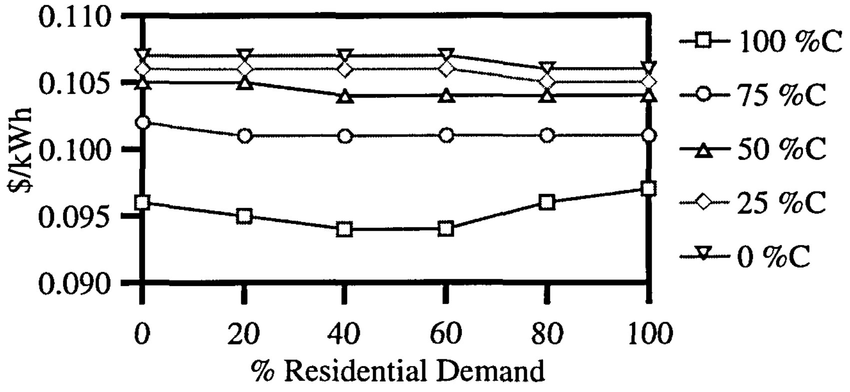

Figure D.61 Energy Cost: Hawaii, Wind-Utility, El.Furnace, Vestas

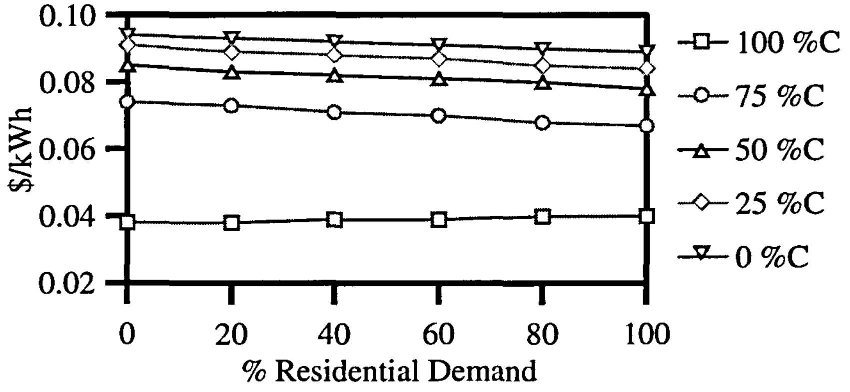

Figure D.62 Energy Cost: Hawaii, Wind-Utility, Gas Furnace, Vestas

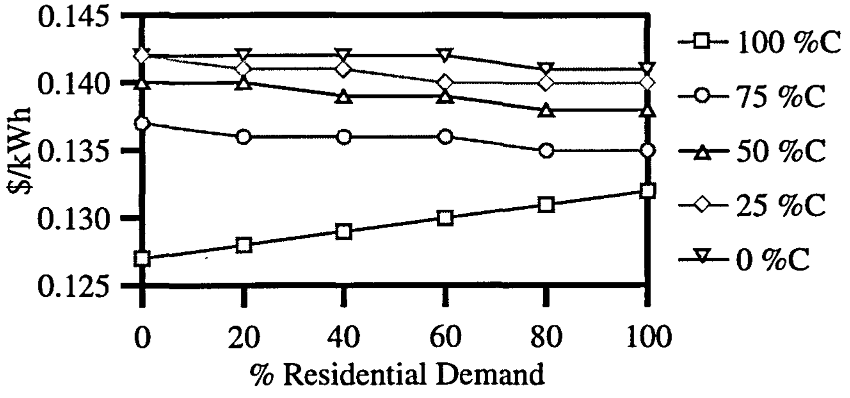

Figure D.63 Energy Cost: Hawaii, Wind-Utility, DHC, Vestas

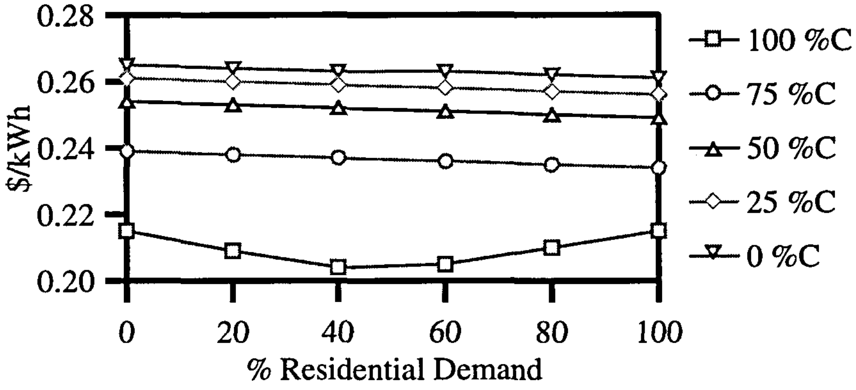

Figure D.64 Energy Cost: Hawaii, Wind-Utility, El.Furnace, Wega

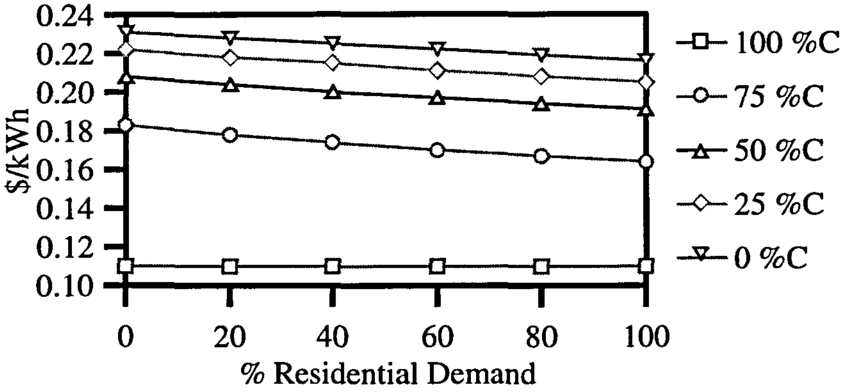

Figure D.65 Energy Cost: Hawaii, Wind-Utility, Gas Furnace, Wega

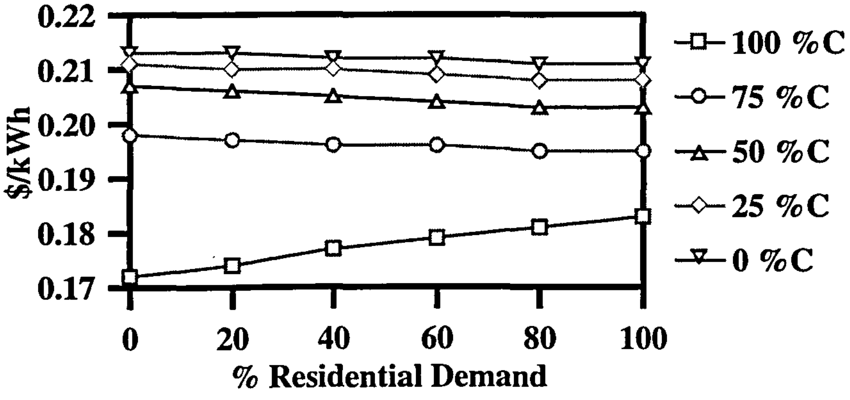

Figure D.66 Energy Cost: Hawaii, Wind-Utility, DHC, Wega

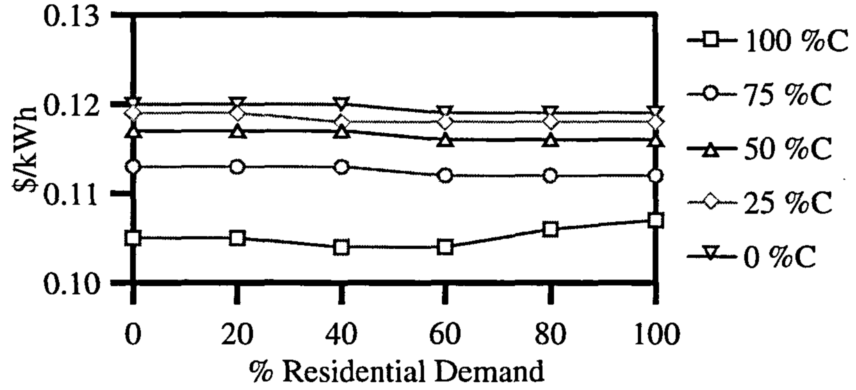

Figure D.67 Energy Cost: Hawaii, Wind-Batteries, El.Furnace, Vestas

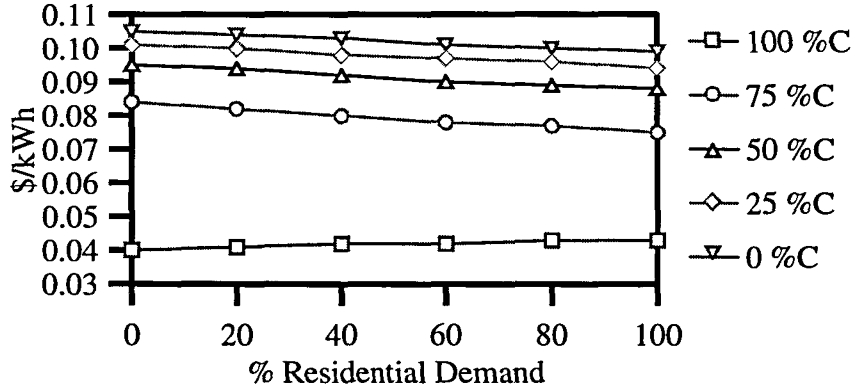

Figure D.68 Energy Cost: Hawaii, Wind-Batteries, Gas Furnace, Vestas

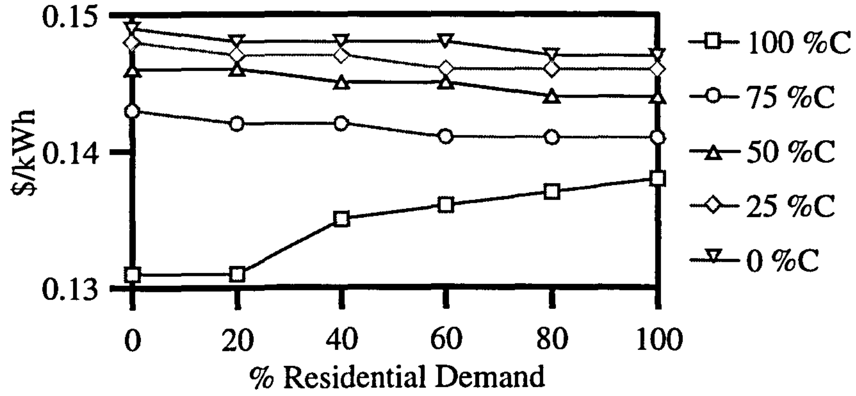

Figure D.69 Energy Cost: Hawaii, Wind-Batteries, DHC, Vestas

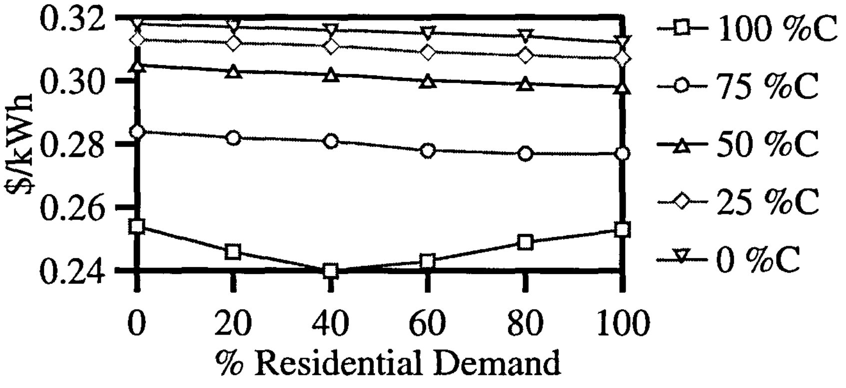

Figure D.70 Energy Cost: Hawaii, Wind-Batteries, El.Furnace, Wega

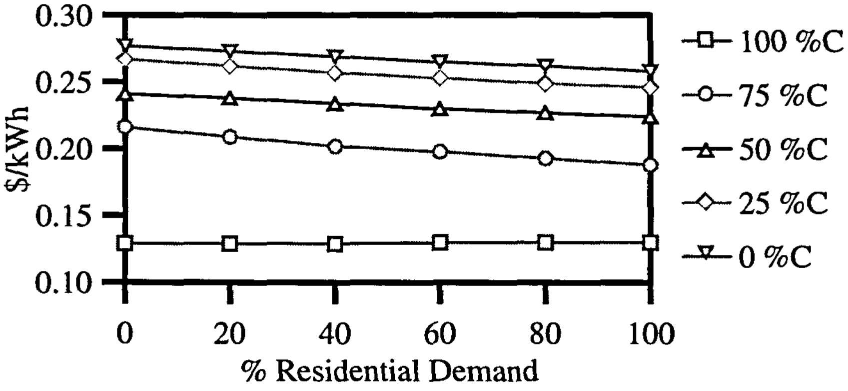

Figure D.71 Energy Cost: Hawaii, Wind-Batteries, Gas Furnace, Wega

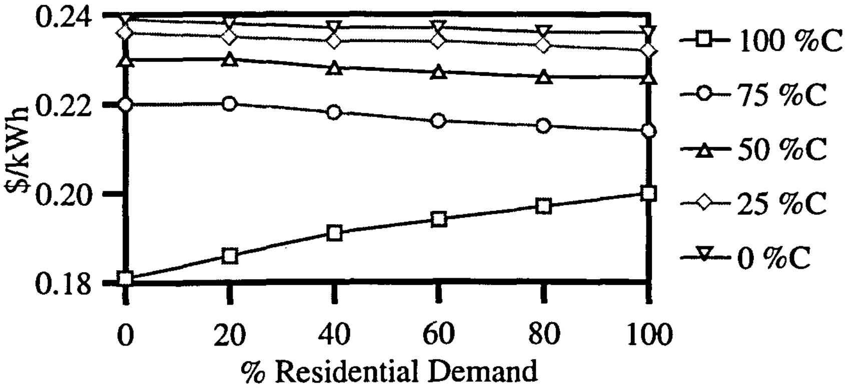

Figure D.72 Energy Cost: Hawaii, Wind-Batteries, DHC, Wega

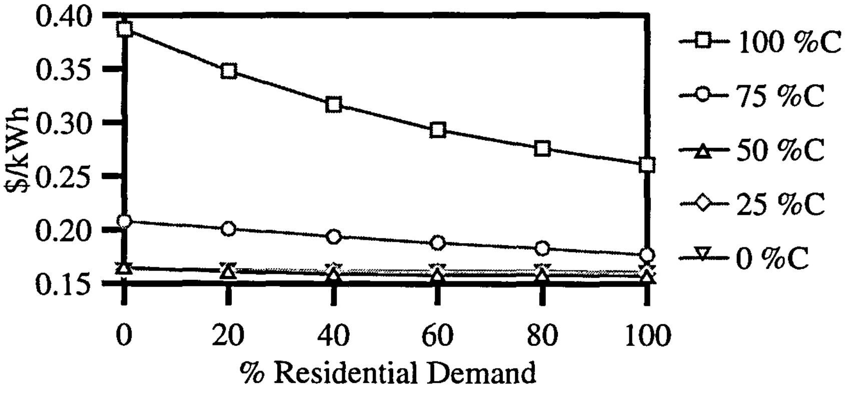

Figure D.73 Energy Cost: Hawaii, Wind-Diesel, El.Furnace, Vestas

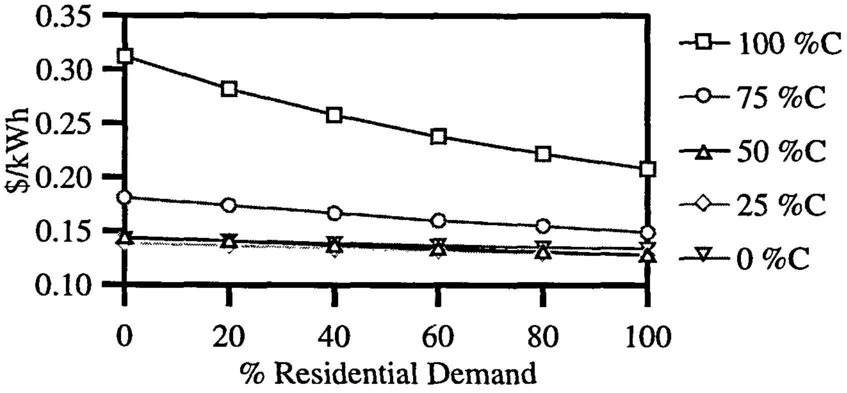

Figure D.74 Energy Cost: Hawaii, Wind-Diesel, Gas Furnace, Vestas

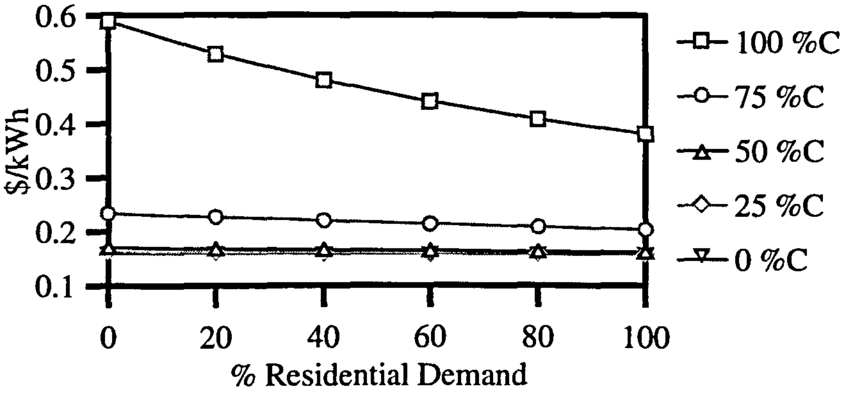

Figure D.75 Energy Cost: Hawaii, Wind-Diesel, DHC, Vestas

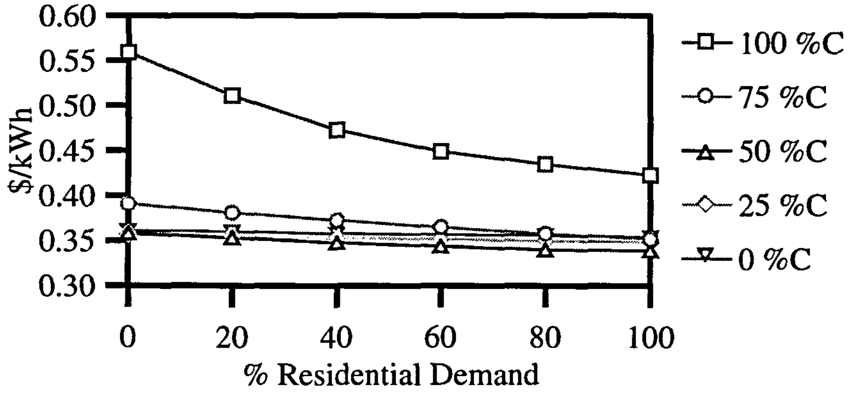

Figure D.76 Energy Cost: Hawaii, Wind-Diesel, El.Furnace, Wega

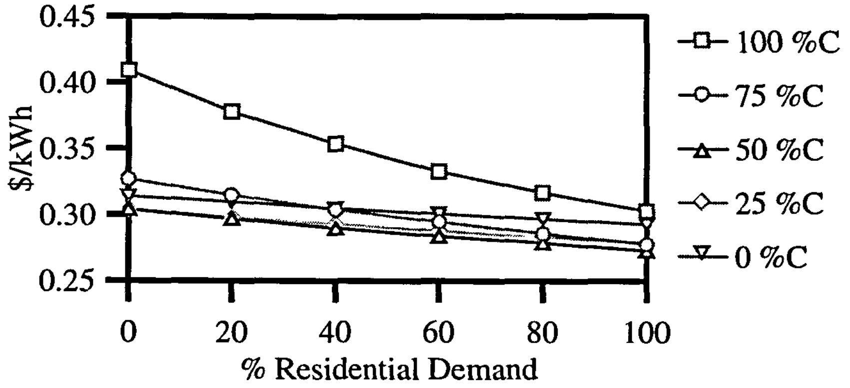

Figure D.77 Energy Cost: Hawaii, Wind-Diesel, Gas Furnace, Wega

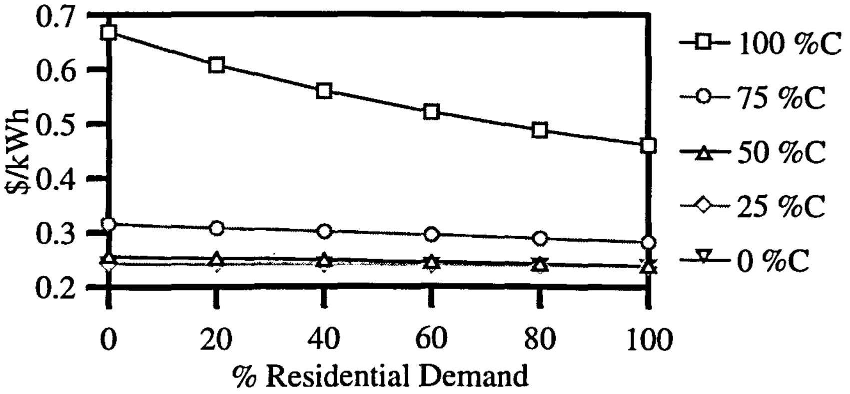

Figure D.78 Energy Cost: Hawaii, Wind-Diesel, DHC, Wega

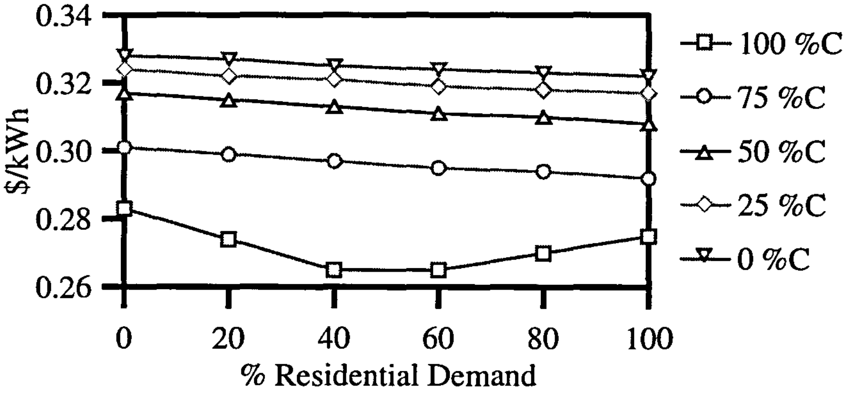

Figure D.79 Energy Cost: Hawaii, Wind-Hydrogen, El.Furnace, Vestas

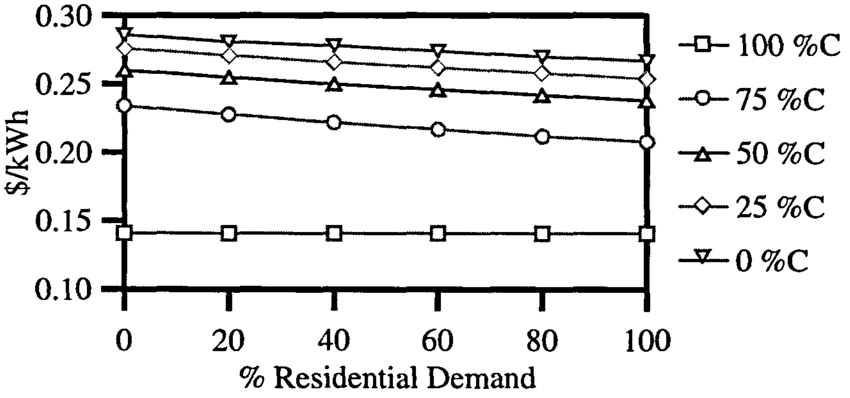

Figure D.80 Energy Cost: Hawaii, Wind-Hydrogen, Gas Furnace, Vestas

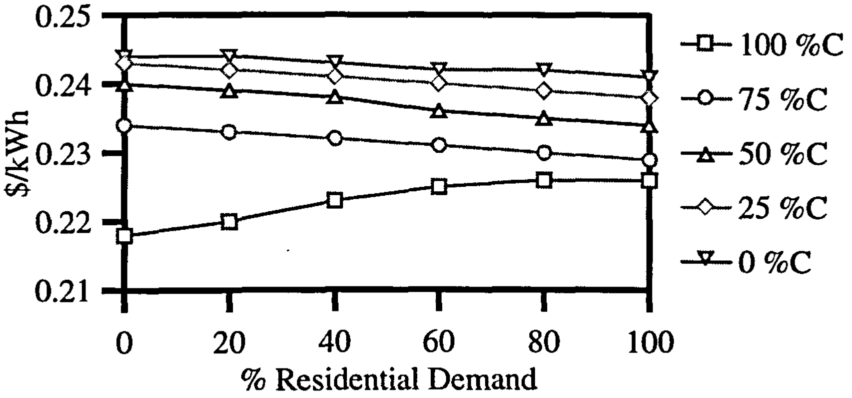

Figure D.81 Energy Cost: Hawaii, Wind-Hydrogen, DHC, Vestas

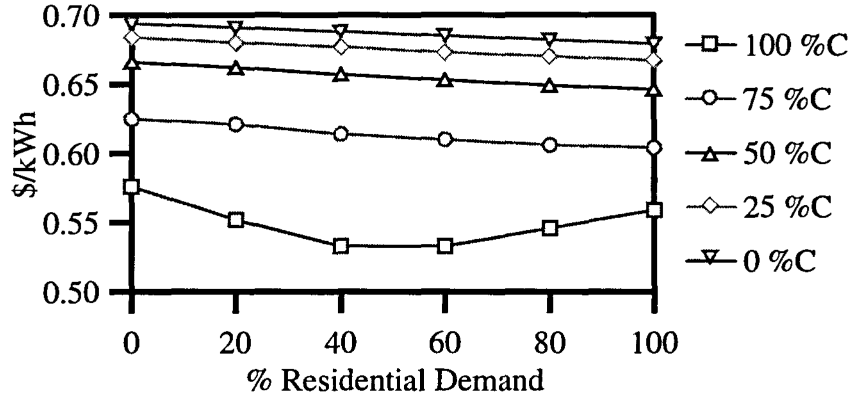

Figure D.82 Energy Cost: Hawaii, Wind-Hydrogen, El.Furnace, Wega

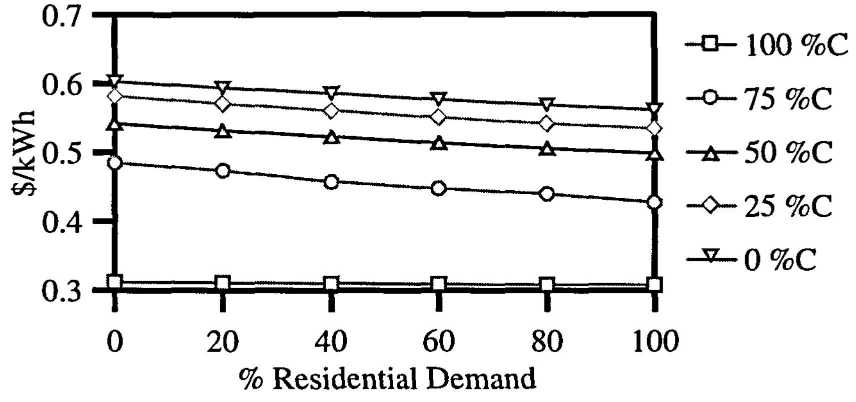

Figure D.83 Energy Cost: Hawaii, Wind-Hydrogen, Gas Furnace, Wega

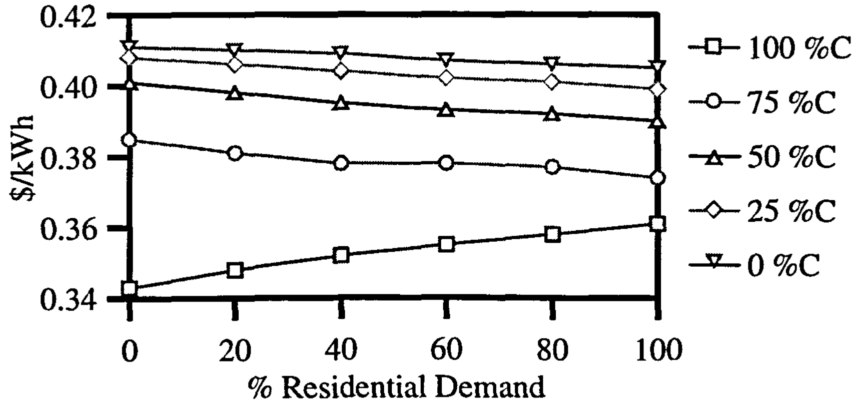

Figure D.84 Energy Cost: Hawaii, Wind-Hydrogen, DHC, Wega

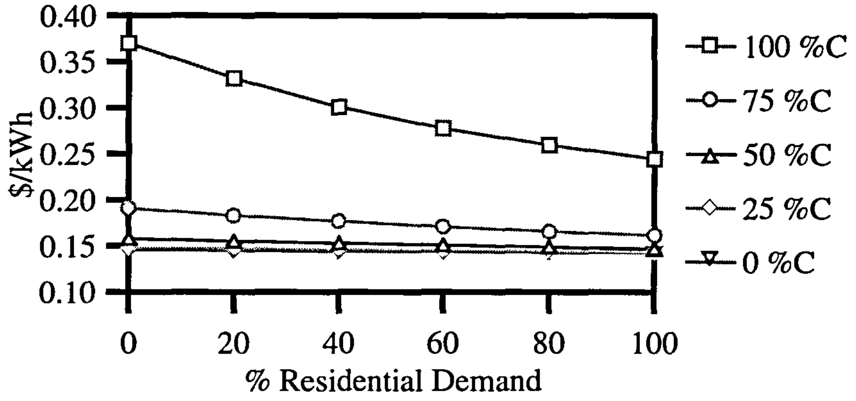

Figure D.85 Energy Cost: Hawaii,Wind-Diesel/Batteries, El.Furnace, Vestas

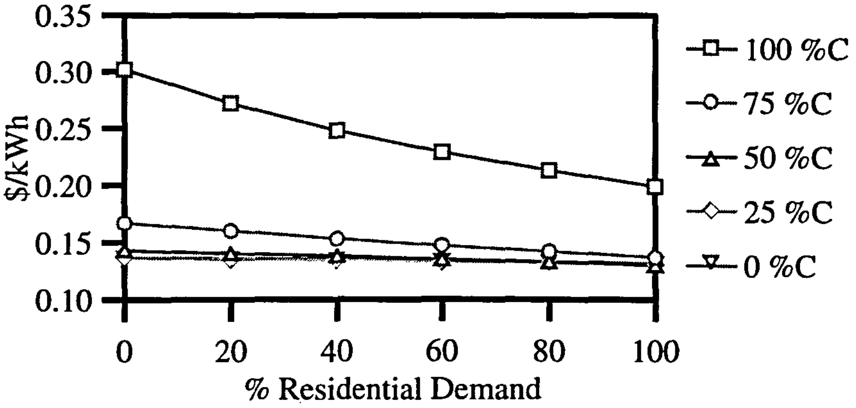

Figure D.86 Energy Cost:Hawaii,Wind-Diesel/Batteries, Gas Furnace, Vestas

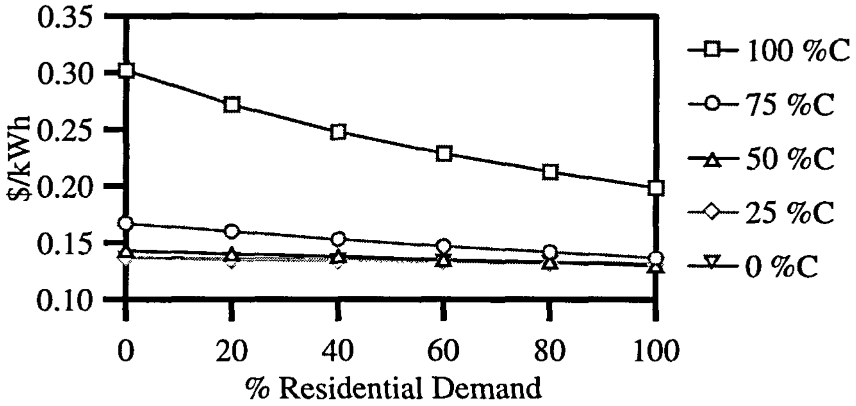

Figure D.87 Energy Cost:Hawaii,Wind-Diesel/Batteries, DHC, Vestas

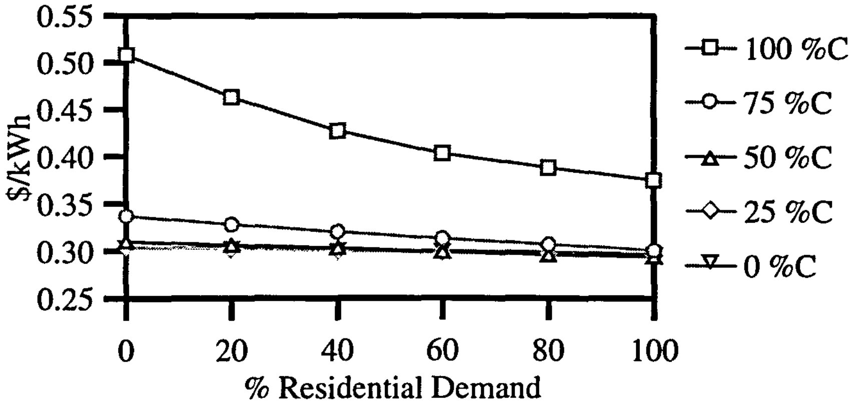

Figure D.88 Energy Cost:Hawaii,Wind-Diesel/Batteries, El.Furnace, Wega

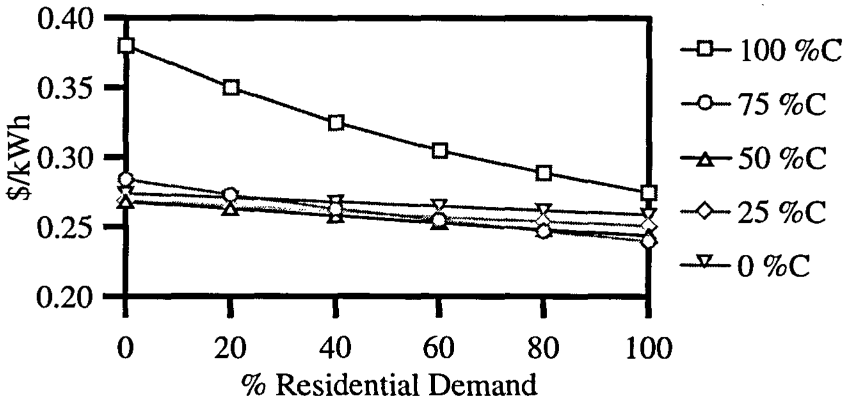

Figure D.89 Energy Cost:Hawaii,Wind-Diesel/Batteries, Gas Furnace, Wega

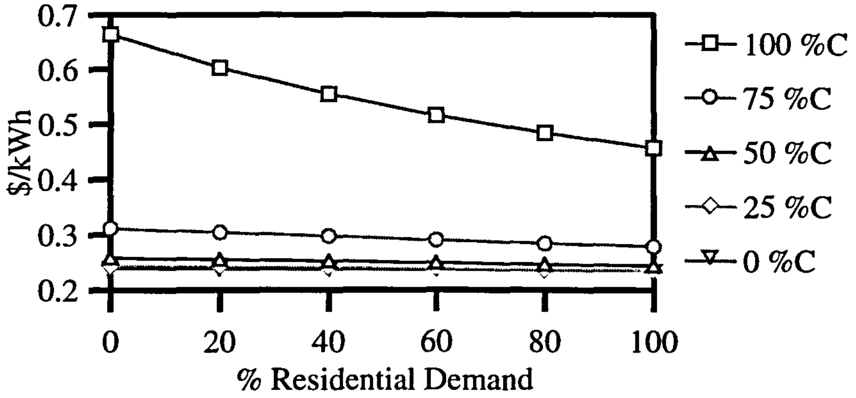

Figure D.90 Energy Cost:Hawaii,Wind-Diesel/Batteries, DHC, Wega

APPENDIX E LOAD PROFILE PARAMETERS

Table E.1 Hourly Commercial Floor Space (ft^2) Use (On-hours), By End-Use Activity (MECS 1991)

Hour	Education	Food Sale	Food Service	Healt Care
1	0	200	0	1284
2	0	200	0	1284
3	0	200	0	1284
4	0	200	0	1284
5	0	200	0	1284
6	0	200	0	1284
7	0	200	0	1284
8	8369	721	1277	1586
9	8369	721	1277	1586
10	8369	721	1277	1586
11	8369	721	1277	1586
12	8369	721	1277	1586
13	8369	721	1277	1586
14	8369	721	1277	1586
15	8369	721	1277	1586
16	7148	721	1277	1586
17	7148	721	1277	1586
18	4387	721	1196	1435
19	4387	721	1196	1435
20	1333	572	862	1284
21	1333	572	862	1284
22	1333	572	862	1284
23	0	200	0	1284
24	0	200	0	1284

Table E.2 Hourly Commercial Floor Space (ft^2) Use (On-hours), By End-Use Activity (MECS 1991)

Hour	Lodging	Mercantile	Office Space	Parking Space
1	2730	392	626	1268
2	2730	392	626	1268
3	2730	392	626	1268
4	2730	392	626	1268
5	2730	392	626	1268
6	2730	392	626	1268
7	2730	392	626	1268
8	2730	12401	12318	1268
9	2730	12401	12318	1268
10	2730	12401	12318	1268
11	2730	12401	12318	1268
12	2730	12401	12318	1268
13	2730	12401	12318	1268
14	2730	12401	12318	1268
15	2730	12401	12318	1268
16	2730	12053	12098	1268
17	2730	12053	12098	1268
18	2730	10396	7643	1268
19	2730	10396	7463	1268
20	2730	2430	1378	1268
21	2730	2430	1378	1268
22	2730	2430	1378	1268
23	2730	392	626	1268
24	2730	392	626	1268

Table E.3 Hourly Commercial Floor Space (ft^2) Use (On-hours), By End-Use Activity (MECS 1991)

Hour	Public Assembly	Public Order	Worship	Warehouses
1	0	619	0	967
2	0	619	0	967
3	0	619	0	967
4	0	619	0	967
5	0	619	0	967
6	0	619	0	967
7	0	619	0	967
8	3382	619	0	11485
9	3382	619	0	11485
10	3382	619	0	11485
11	3382	619	0	11485
12	3382	619	0	11485
13	3382	619	0	11485
14	3382	619	0	11485
15	3382	619	0	11485
16	2565	619	0	6643
17	2565	619	0	6643
18	2212	619	0	3370
19	2212	619	0	3370
20	978	619	0	2065
21	978	619	0	2065
22	978	619	0	2065
23	0	619	9	967
24	0	619	9	967

Table E.4 Hourly Commercial Floor Space (ft^2) Use (On-hours), By End-Use Activity (MECS 1991)

Hour	Other	Vacant	Total
1	261	0	8347
2	261	0	8347
3	261	0	8347
4	261	0	8347
5	261	0	8347
6	261	0	8347
7	261	0	8347
8	261	3996	60982
9	261	3996	60982
10	261	3996	60982
11	261	3996	60982
12	261	3996	60982
13	261	3996	60982
14	261	3996	60982
15	261	3996	60982
16	261	1240	50778
17	261	1240	50778
18	261	639	36987
19	261	639	36987
20	261	0	15780
21	261	0	15780
22	261	0	15780
23	261	0	8347
24	261	0	8347

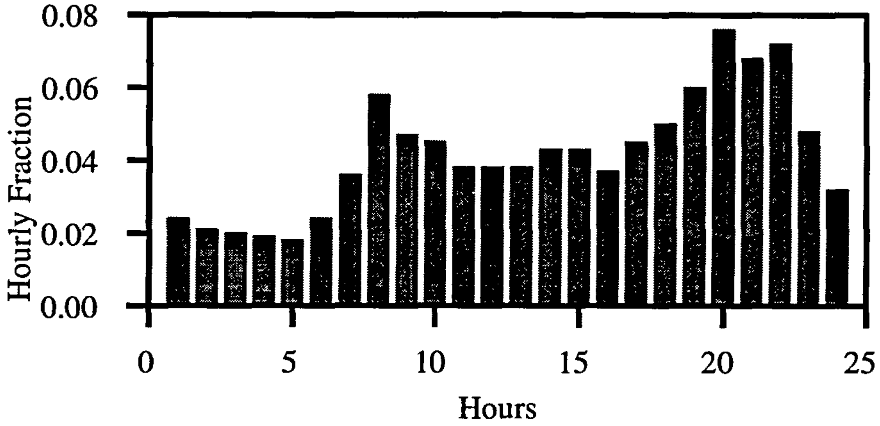

Figure E.1 Residential Week-Day Electricity Load Profile

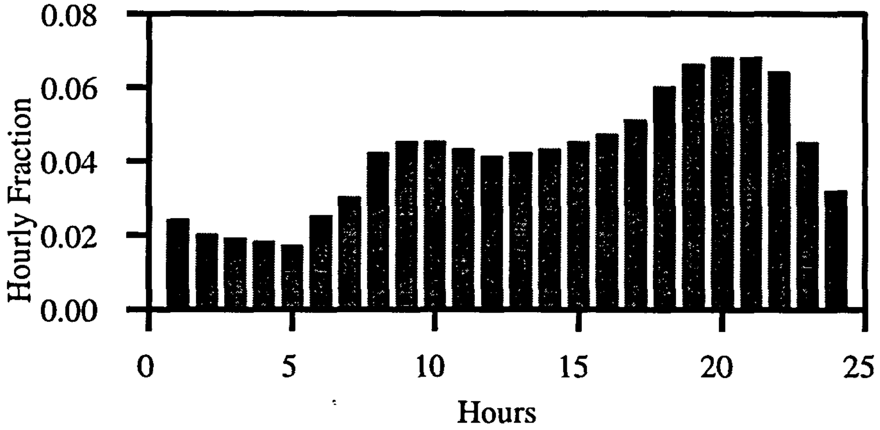

Figure E.2 Residential Week-End Electricity Load Profile

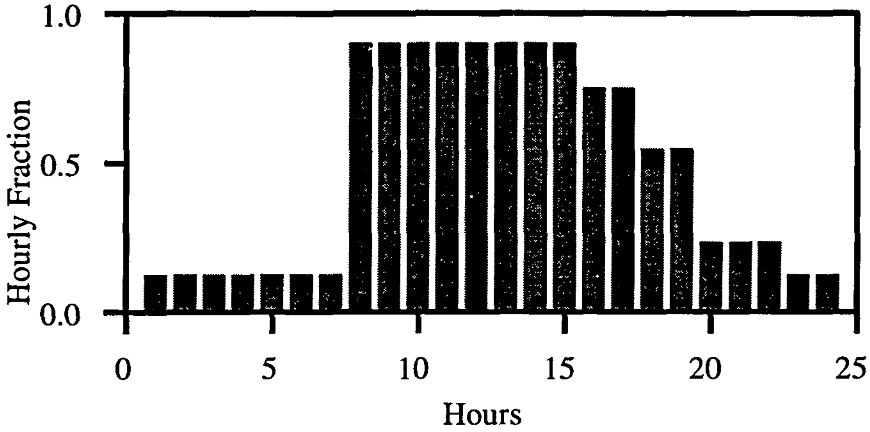

Figure E.3 Commercial Week-Day Energy Load Profile

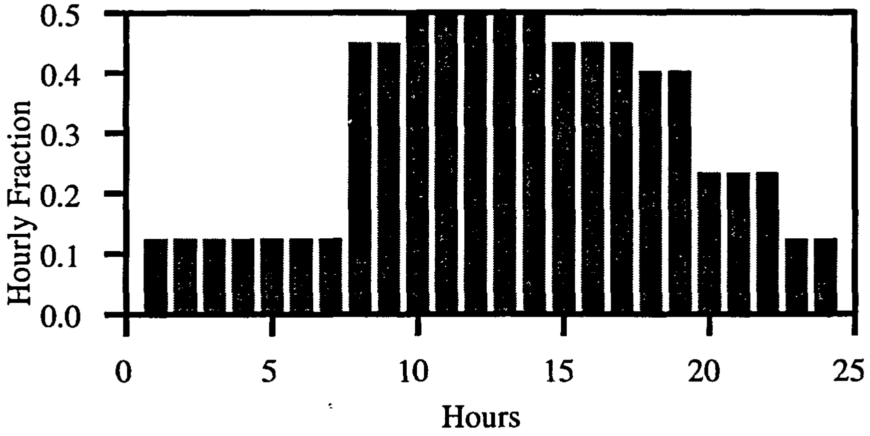

Figure E.4 Commercial Week-End Energy Load Profile

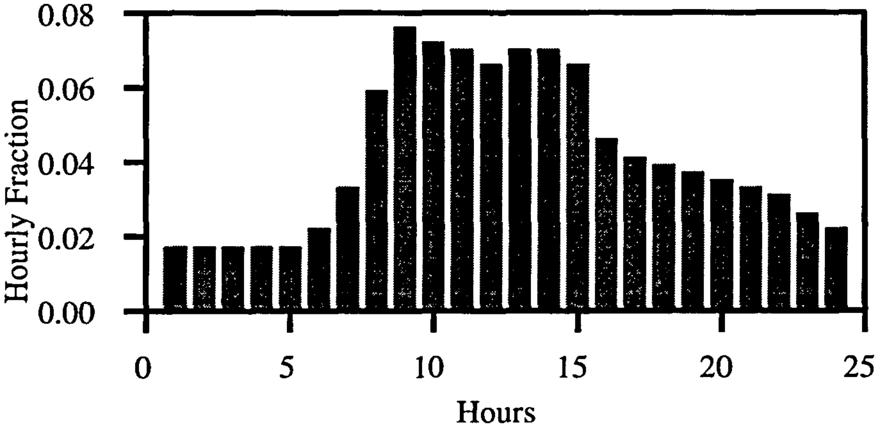

Figure E.5 Industrial Daily Energy Load Profile

APPENDIX F WIND TURBINE POWER CURVES

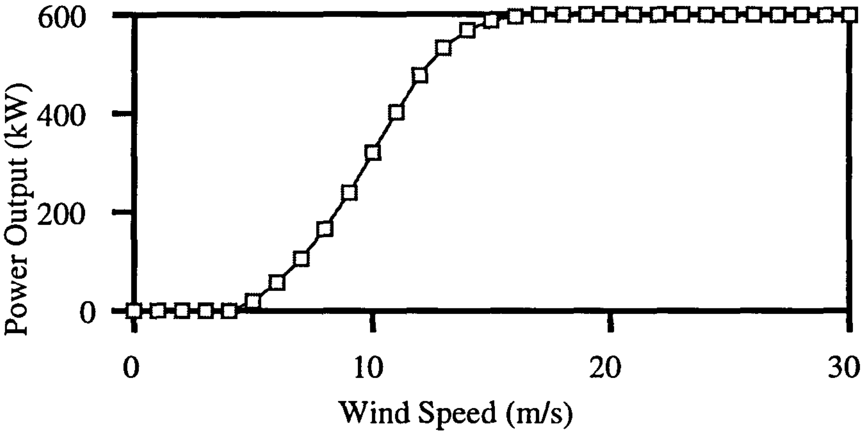

Figure F.1 Power Curve for Vestas Wind Turbine (White 1996)

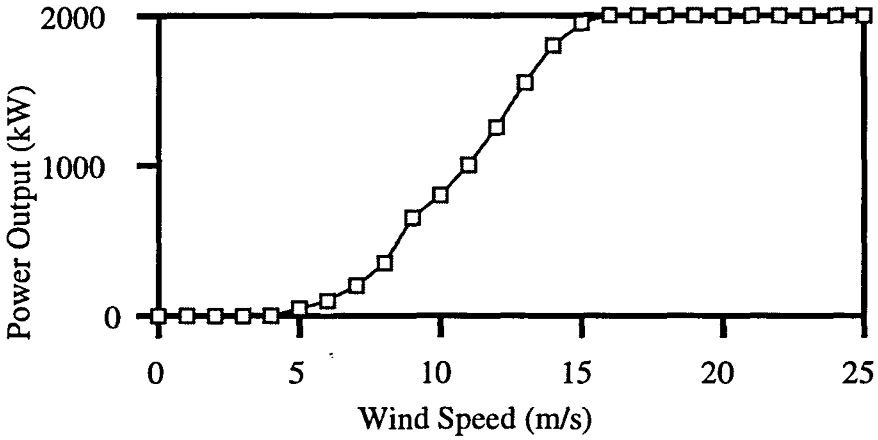

Figure F.2 Power Curve for Wega Wind Turbine (Hau et al. 1993)

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