NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Energy Sources and Systems Analysis

40 South Lincoln Redevelopment District

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Abbreviations and Acronyms

$K	thousands of dollars
Btu/h	British thermal unit per hour
CO_2	carbon dioxide
COP	coefficient of performance
CHP	combined heat and power
DHA	Denver Housing Authority
DHW	domestic hot water
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DSIRE	Database of State Incentives for Renewables & Efficiency
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
GSHP	ground-source heat pump
h	hour
HUD	U.S. Department of Housing and Urban Development
HVAC	heating, ventilating, and air conditioning
ITC	investment tax credit
kW_e	kilowatt-electric
kWh	kilowatt-hour
kW_t	kilowatt-thermal
kW	kilowatt
lb	pound
MBtu	thousand Btu
MMBtu	million Btu
MWh	megawatt-hour
NIST	National Institute of Standards and Technology
NPV	net present value
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PPA	power purchase agreement
PV	photovoltaics
RFP	request for proposal
SHW	solar hot water
SPP	simple payback period
W	watt
yr	year

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Introduction and Background

Homes and businesses are typically heated and cooled at the building level, meaning that one system is dedicated specifically to a single building. In many situations, though, it may be economically and environmentally beneficial to furnish these services at the community scale, where one large "district" system is designed to serve the entire community. These systems have a number of advantages—they are larger, they can capitalize on load diversity within the community, they are reliable and easier to maintain, they can potentially attain high efficiencies by combining electrical generation with heating or cooling or both, and they offer the community autonomy in terms of the system's fuel source and operation.

As part of the South Lincoln Redevelopment project in Denver, Colo., the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) worked with Group14 Engineering of Denver to analyze district energy systems for their potential use in the project.

The South Lincoln Project

Supported by a U.S. Department of Housing and Urban Development (HUD)/U.S. Department of Transportation (DOT)/U.S. Environmental Protection Agency (EPA) partnership, the Denver Housing Authority (DHA) is leading the redevelopment of the city's La Alma/Lincoln Park neighborhood (South Lincoln). The project, depicted in Figure 1, includes redeveloping 270 units of existing public housing, along with other sites nearby. When complete, the redevelopment project will encompass more than 900 mixed-income residential units, commercial and retail properties, and open space. Phase 1, the construction of 100 units of senior housing, began in fall 2010, with those units scheduled to open early in 2012. As part of the planning for the project, NREL was asked to perform an analysis of the potential for district energy systems.[1]

Figure 1. Artist's rendering of the planned South Lincoln redevelopment project

The analysis involved estimating the hourly heating, cooling, domestic hot water (DHW), and electric loads required by the community; investigating potential district system technologies to meet those needs; and researching available fuel sources to power such systems. To evaluate the economic and environmental viability of each system, the team used the following metrics: simple payback period (SPP), net present value (NPV), and greenhouse gas (GHG) reductions.

[1] South Lincoln Redevelopment, Denver, CO. *http://www.fta.dot.gov/documents/Reg8.pdf and DHA*. *http://www.denverhousing.org/development/SouthLincoln/Pages/default.aspx*. Accessed May 8, 2011.

Approach

Assessing Community Energy Requirements

When planning community energy projects, predicting the hourly heating, cooling, DHW, and electric energy load and requirements is a vital first step. For the purposes of this analysis the electric load includes all building-level uses except for those associated directly with heating and cooling. This includes lighting, plug loads, and HVAC fans. Load, which is a measure of heating, cooling, DHW, and/or electricity needed by a community at any one instant in time, is expressed in units of energy such as kilowatt-hours (kWh) or megawatt-hours (MWh). Estimating the community's load enables analysts to predict the amount of fuel expected to be used in a typical year.

Peak demand is the maximum hourly demand for the entire year. For instance, peak heating demand would be the amount of heating required to meet the community's needs on the coldest night of the year. Demand is expressed as a rate of energy production such as kilowatts (kW) or British thermal units per hour (Btu/h). Estimating maximum demand allows analysts to predict how large a district system must be to keep up with the community's needs during periods of peak demand.

First, then, the analysis team created building energy models to simulate the expected energy usage of each type of building in the community. These simulations predict hourly energy load and demand for each building type. Simulation results were scaled up to represent the entire community's usage.

All the building areas in the redevelopment project were represented with three models—one of the high-rise residential spaces, one of the low and mid-rise flats (both of these building types were represented with one model), and one of the townhouse units. Table 1 gives details of these models. The team used information on floor area by space use, number of residential units, and number of bedrooms taken from the DHA's Block-by-Block Analysis.[2]

[1] DHA. South Lincoln Redevelopment Master Plan. *http://www.denverhousing.org/development/SouthLincoln/MasterPlan/Pages/default.aspx*. Accessed May 8, 2011.

Table 1. Building Energy Model Details

Model	Space Use	Square Feet (ft^2)	Number of Residential Units	Number of Bedrooms per Unit					Model Description
				One	Two	Three	Four	Total	
A	High-Rise Flats (1099 Osage)	97,000	100	70	30	0	0	130	Eight-story senior housing building. Model was completed for Phase 1 of redevelopment (see Figure 2).
B	Townhouses (stand-alone and modular)	183,400	109	4	16	76	13	316	One model of a strip of 2-story townhouses with 8 units @ 1,683 ft^2 each with 23 total bedrooms (occupants). Eight is the average length of a strip of units. Using these parameters allowed the team to accurately model the ratio of end units to interior units.
C	Low- and Mid-Rise Flats	657,731 in residential units + 144,500 for circulation/ support	680	439	241	0	0	921	All of this type of building area was represented with one model, which consists of a mid-rise with 5 stories of flats above a ground level of retail, community, and lobby space. Each residential level contains 20 residential units (and 27 bedrooms) configured in an "L" shape around a central corridor.[a]
	Retail	24,700							
	Community	25,000							
	Lobby	10,850							
	Other	5,000							
	Totals	1,003,681	889	513	287	76	13	1,367	

[a] 19,350 ft^2 of residential + 4,250 ft^2 corridor/circulation (18% of floor plan assumed) = 23,600 ft^2 footprint. The ground level consists of 3,630 ft^2 of retail space, 3,680 ft^2 of community space, 1,600 ft^2 of lobby space, and 735 ft^2 of other space to make the multiplier consistent.

Figures 2, 3, and 4 show the energy models and floor plans for each type of space.

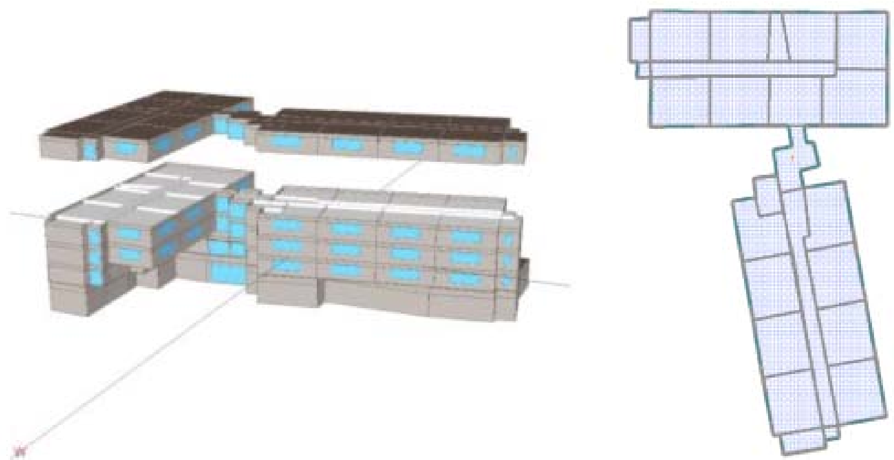


Figure 2. High-rise building energy model 3-D view and floor plan

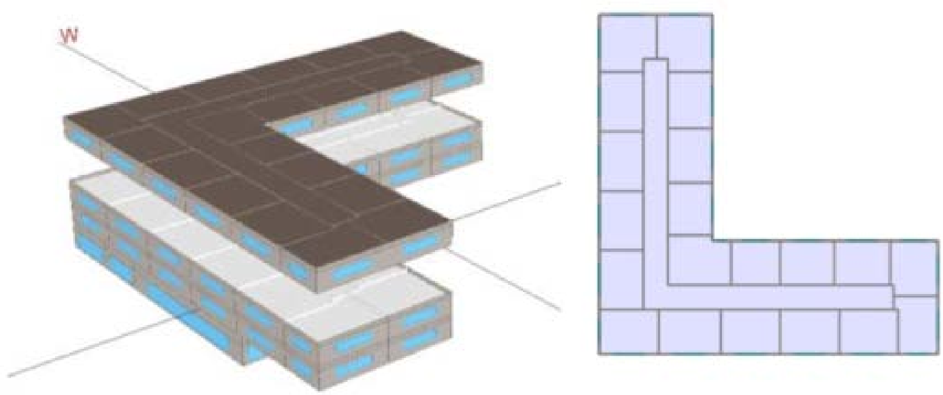


Figure 3. Mid-rise building energy model 3-D view and floor plan

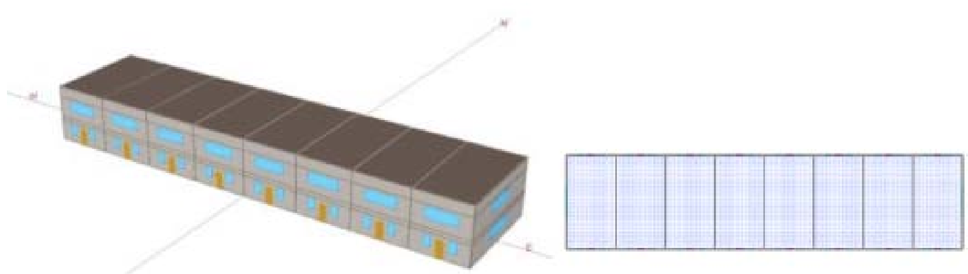


Figure 4. Townhouse building energy model 3-D view and floor plan

Modeling results indicate that electricity and space heating are the largest community loads, each requiring approximately 5,000 MWh/yr. Cooling and DHW require approximately 2,500 MWh/yr apiece. Figure 5 compares these annual loads.

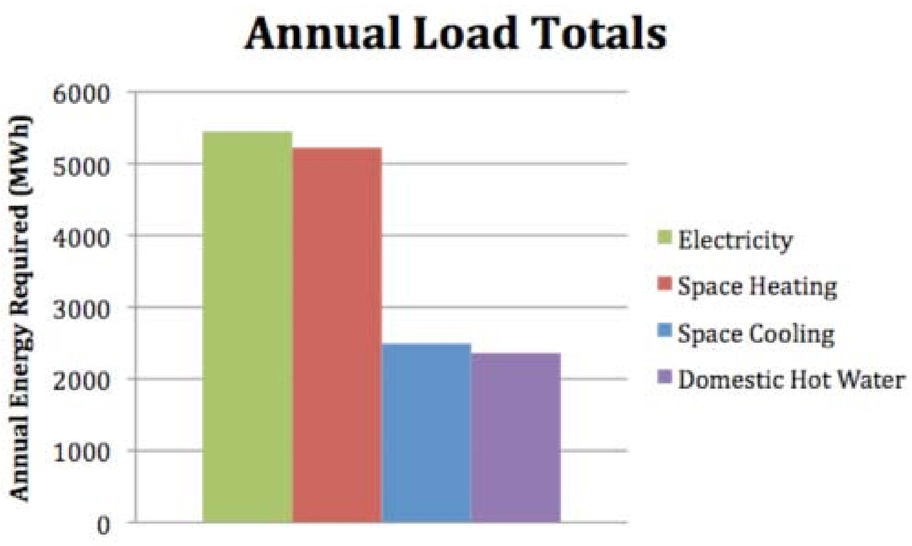


Figure 5. Predicted annual energy load requirements

Space heating and DHW are often lumped together as one thermal load when served by a cogeneration, trigeneration, or district heating system. A cogeneration system performs two functions simultaneously, and a trigeneration system performs three at the same time. Table 2 gives the site's annual energy requirements and shows that these two loads combined represent the dominant load. Table 3 gives the peak demand for electricity, heating, and space cooling. Again, heating and DHW are dominant. Figure 6 shows the load profiles over the course of a typical year.

Table 2. Predicted Annual Energy Load Requirements

Annual Energy Requirements (MWh)		
Electricity	Heating (including DHW)	Space Cooling
5,446	7,582	2,491

Table 3. Predicted Peak Energy Demand

Peak Demand (kW)		
Electricity	Heating (including DHW)	Space Cooling
994	4,636	1,839

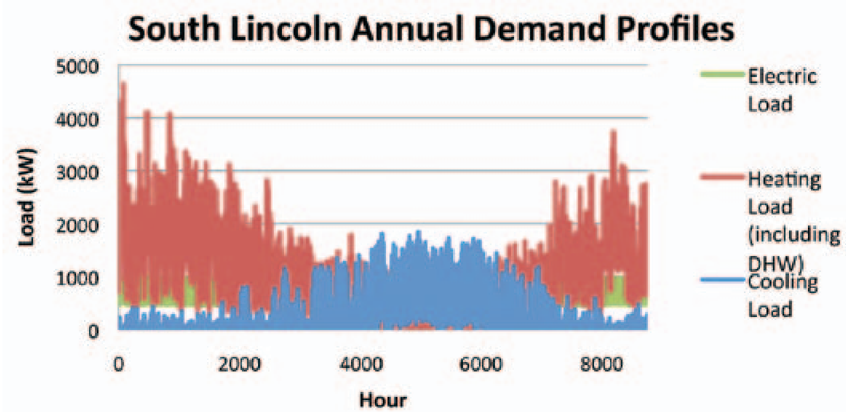


Figure 6. Predicted annual energy demand profiles

Economic Analysis

The team performed an economic analysis that follows the federal life-cycle costing requirements developed by the National Institute of Standards and Technology (NIST), using its federal guidelines for discount rate, electricity escalation rate, and fuel escalation rate. The discount rates for 2010 were valid from April 1, 2010, to March 31, 2011.

The appropriate escalation rates from a tool called the Energy Escalation Rate Calculator were applied to natural gas and electricity rates. The values given in this tool are based on Energy Information Administration (EIA) projections. The escalation rates were calculated assuming the project would come online in 2012 and have a lifetime of 25 years.

To calculate the electricity and natural gas rates for this analysis, the team used a sampling of energy bills for the existing South Lincoln community. The DHA typically uses a commercial utility rate structure for its larger buildings and a residential utility rate for its smaller units. Because the South Lincoln redevelopment is expected to have buildings of both types, average rates were calculated to apply to the entire site. Table 4 lists the parameters used for all energy use and economic analyses.

Table 4. Parameters Used in Energy Cost and Economic Analysis

Parameter	Value[a]
Project Lifetime	25 years
Real Discount Rate	3%
Electricity Escalation Rate	0.50%
Natural Gas Escalation Rate	0.40%
Blended Residential Electricity Rate	$0.104/kWh
Commercial Electricity Rate (energy only)	$0.033/kWh
Summer Commercial Electricity Demand Rate	$20.24/kW
Winter Commercial Electricity Demand Rate	$27.24/kW
Natural Gas Rate	$0.673/therm

[a] Rate data based on real escalation rates after inflation.

A federal investment tax credit (ITC) is available for photovoltaics (PV), solar hot water (SHW), biomass, cogeneration and trigeneration, and ground-source heat pump (GSHP) installations. Since DHA is a nonprofit organization, it is not able to directly take advantage of tax credits. However, DHA can still benefit by selling these tax credits on the market or if the systems are owned by a third party. For PV, SHW, and systems powered by fuel cells, the credit is worth 30% of the initial cost of the system. For GSHPs, biomass, and cogeneration or trigeneration systems not powered by fuel cells, the credit is worth 10% of the initial cost of the system. The analysis results presented in this report are for cases with and without these incentives.

Greenhouse Gas Emissions Analysis

The team took electricity emissions data directly from the EIA's publication of Colorado's electricity profile. Natural gas emissions data are from the EPA's Climate Leaders Program. Table 5 summarizes these data. Note that carbon dioxide (CO_2) is by far the dominant GHG emission for both electricity and natural gas. Note also that the emissions associated with utility-supplied electricity are nearly 5 times greater than those from natural gas. These facts play a major role in the final results of this analysis.

Table 5. Electricity and Natural Gas GHG Emissions

Energy Source	Emission Compound	Equivalent CO_2 Emissions (lb/MWh)
Electricity (generated in Colorado)	CO_2	1,883
	Methane	0.0228
	Nitrogen Oxide	0.02875
Natural Gas	CO_2	399
	Methane	0.0376
	Nitrogen Oxide	0.0008

Sources: Electricity: EIA. "Colorado Electricity Profile, 2009 Edition." DOE/EIA-0348(01)/2. *http://www.eia.doe.gov/cneaf/electricity/st_profiles/colorado.html*. Accessed May 8, 2011. Natural gas: EPA. August 2008, Version 1.3. *Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type: Commercial Boiler Efficiency (Space and Hot Water Heating)*. *http://www.epa.gov/climateleaders/documents/resources/comm_boiler_proto.pdf*. Accessed May 8, 2011.

Energy Sources

The source of energy used in buildings and district systems affects the economics, environmental impact, and feasibility of any proposed project. Several options are discussed here to address local availability, economic implications, environmental considerations, and any pros or cons specific to this project.

Utility-Supplied Electricity

The utility grid, ubiquitous as a consistent source of energy, will almost certainly play a part in the South Lincoln redevelopment. Although it is convenient, with relatively stable costs, electricity from the local utility carries with it significant environmental impacts.

The electricity costs incurred at the building level are highly dependent on the rate structure imposed by the local utility. Residential rates tend to have a fairly high electricity consumption charge (in dollars per kilowatt-hour), and typically no demand charge (in dollars per kilowatt).

Commercial rates in Colorado, on the other hand, typically have low electricity consumption charges and significant demand charges. The current rates for the South Lincoln community are discussed in more detail in the Economic Analysis section of this report.

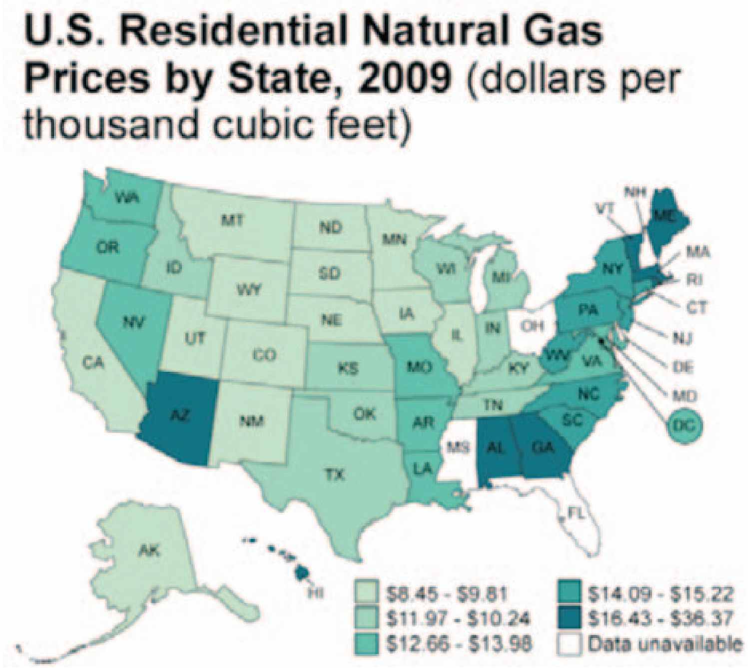
Because most of Colorado's electricity is generated by coal-fired power plants, the emissions associated with electricity are high. Of the typical fuel sources for generating electricity, coal has the most significant GHG emissions. Furthermore, the efficiency of a power plant and its distribution lines is typically around 35%. As a result, 1 kWh of electricity used in a building requires about 3 kWh of energy from coal. The CO_2 emissions from electricity must take this multiplying effect into account. More information on GHG emissions is given in the Emissions Analysis section of this report.

Natural Gas

Natural gas is the conventional fuel source for heating in the Denver area, but it can also be effectively used to generate electrical power. It is in ready supply and many of the systems that it can fuel are well-established, off-the-shelf technologies.

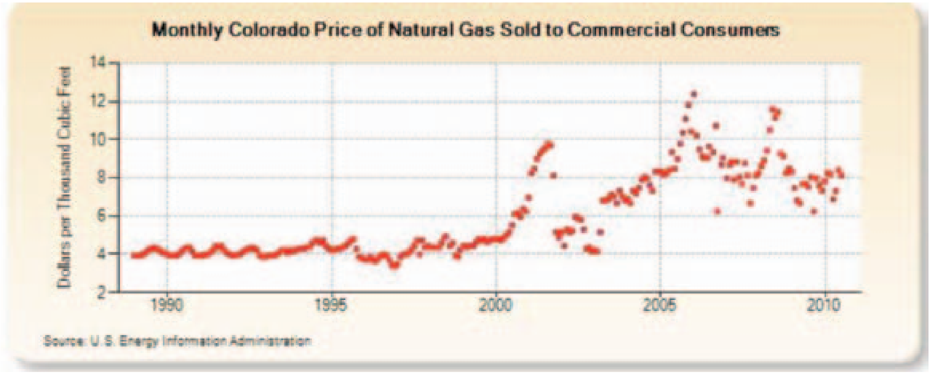
Current natural gas rates are relatively low by historical standards. In addition, Colorado has some of the lowest natural gas rates in the nation, as shown in Figure 7. The cost of natural gas for the South Lincoln community in the past year averaged to about $0.673/therm. Natural gas prices, however, are very volatile. Figure 8 shows prices tripling between 2000 and 2006. Using natural gas in this project would expose the neighborhood to potentially high fuel prices in the future.

Because burning natural gas releases significantly less CO_2 than burning coal, producing electricity using natural gas will generally result in sizable reductions of CO_2 emissions. Like coal, however, natural gas is a non-carbon-neutral ("carbon-neutral" means that the fuel has no net CO_2 emissions), nonrenewable resource.



Source: EIA. "Natural Gas Explained: Natural Gas Prices." *http://www.eia.doe.gov/energyexplained/index.cfm?page=natural_gas_prices.* Accessed May 8, 2011.

Figure 7. U.S. residential natural gas rates by state, 2009 (dollars per thousand cubic feet)



Source: EIA. "Natural Gas Navigator." *http://www.eia.doe.gov/dnav/ng/hist/n3020us3M.htm*. Accessed May 8, 2011.

Figure 8. Historical natural gas rates in Colorado

Biomass

Biomass fuel is produced from organic materials such as plants, agricultural residues, forestry by-products, and municipal or industrial wastes. In the Denver area, the most viable biomass options for the South Lincoln community are coarse-ground wood, wood chips, and wood pellets. The primary source for all three is beetle-killed pine, which is currently a plentiful biomass source and is projected to be a stable resource for decades. These fuels can also come from standard forest thinning, forest fire mitigation, and urban wood waste. Figure 9 shows the forest residue biomass resource in and around Denver. In addition, the Denver area has a handful of biomass suppliers that could be relied on for a consistent fuel supply.

Source: "Biomass Resources: Crop Residues." *http://rpm.nrel.gov/biopower/biopower/launch*. Accessed May 8, 2011.

Figure 9. Forest residue resource (shown in light green) in the Denver area

As shown in Table 6, wood pellets are currently the most expensive of these options, followed by wood chips and then coarse-ground wood. Because the primary driver for cost is the amount of processing required, the most consistent and easiest to use fuels are also the most expensive options. Coarse-ground wood is attractive from a cost standpoint, but any equipment chosen must be capable of processing the relatively larger and less consistent wood pieces.

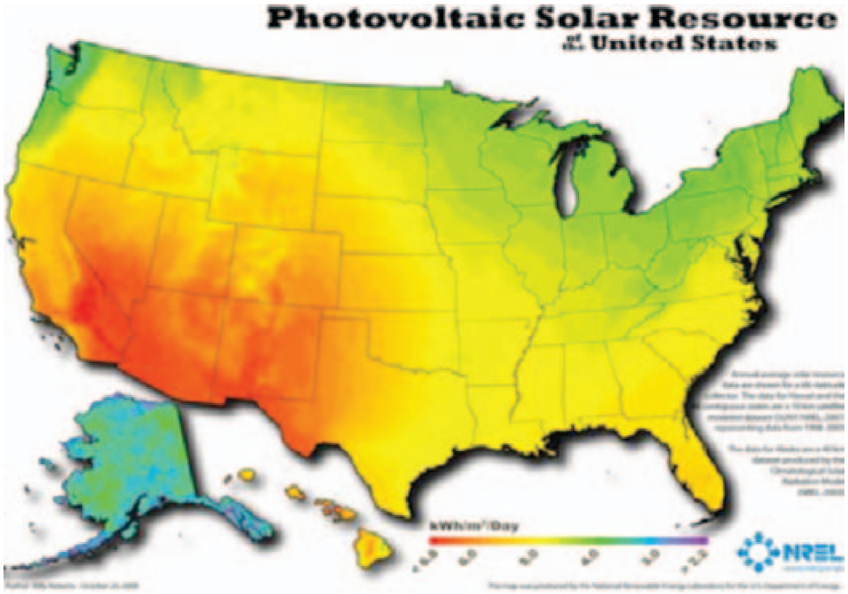
Table 6. Approximate Costs of Biomass Fuels

Biomass Fuel Type	Approximate Cost ($/MMBtu)
Pellets	12.2
Wood Chips	4.4
Ground Wood	2.3

In contrast to natural gas and other fossil fuels, biomass is a renewable, carbon-neutral fuel source. Its carbon neutrality stems from the fact that the organism from which the fuel is derived absorbs approximately the same amount of CO_2 while it is living as it will release during combustion or decomposition. Assuming that the resource is being replaced at the same rate as it is being consumed, the rates of CO_2 emission and absorption will be approximately equal, resulting in near net zero carbon emissions. The energy consumed by transporting the fuel from the source to the point of use results in minor carbon emissions that are not accounted for in this analysis.

Solar

Colorado has a particularly abundant solar resource, as shown in Figure 10. The state generally sees few overcast days, and its higher elevation reduces the amount of solar radiation lost while filtering through the atmosphere. No monetary or environmental costs are associated with using the sun for power throughout the life of a system.



Source: NREL. "Dynamic Maps, GIS Data, & Analysis Tools: Solar Maps." *http://www.nrel.gov/gis/solar.html*. Accessed May 8, 2011.

Figure 10. U.S. solar resource

District Systems Analysis

The Base Case

To generate a baseline energy usage profile for the South Lincoln redevelopment, the analysis team created a base case for the community. This baseline was used as the starting point for each energy, economic, and emissions analysis. Note that, in district systems analysis, the base case chosen has a significant impact on the results.

Base Case Assumptions

The base case used here assumes that heating would be supplied by natural gas boilers with an overall thermal efficiency of 85%. Cooling would be provided by chillers with an overall coefficient of performance (COP) of 3.1. Table 7 gives the assumed efficiencies and total costs.

The local utility would furnish electricity. The analysis team applied these efficiencies to the energy requirements predicted by the building energy models to determine the baseline energy usage of the community. The annual energy costs and GHG emissions were based on this baseline energy usage. Figure 11 shows the annual energy usage profile for the base case, and Figure 12 shows its annual GHG emissions profile. Note the disproportionate role that electrical energy usage, including that used for cooling, plays in the overall emissions profile.

Table 7. Assumed Boiler and Air Conditioning Efficiency and Cost

Parameter	Value
Overall Boiler Efficiency	85%
Total Boiler Costs	$491,129
Overall Air-Conditioning Efficiency	3.1 (COP)
Total Air-Conditioning Costs	$2,581,907

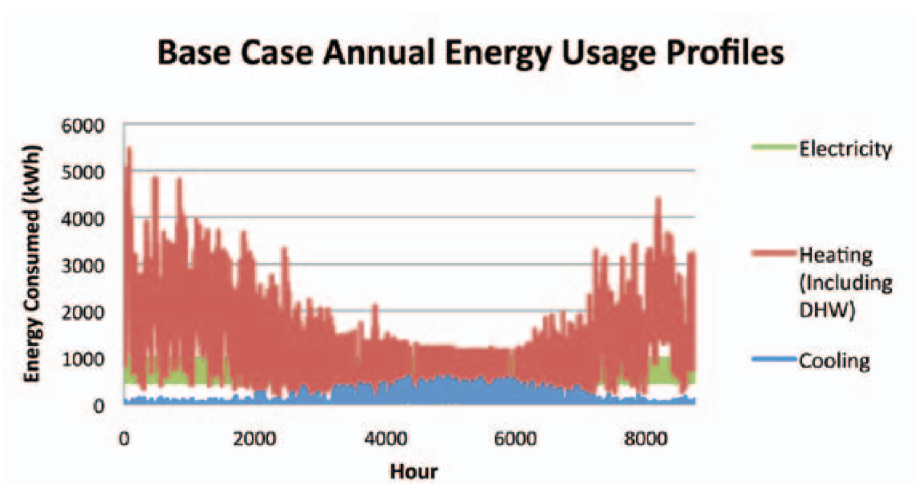


Figure 11. Predicted annual base case energy usage profiles

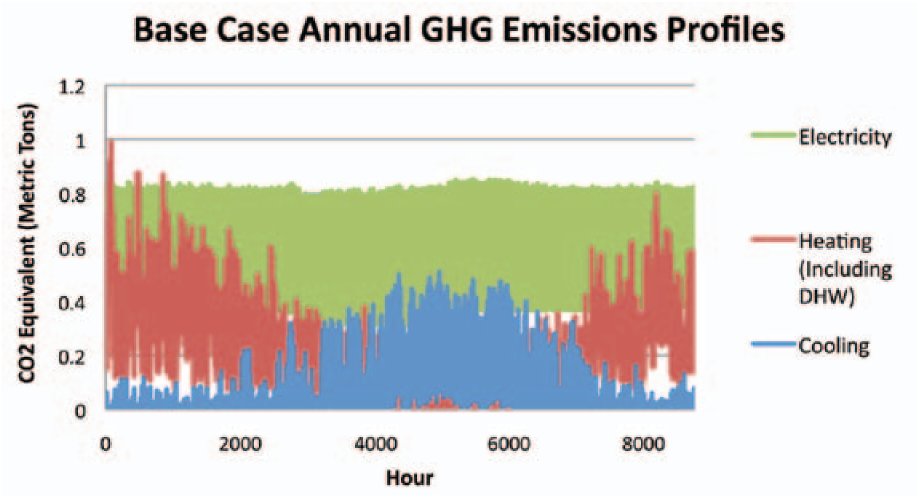


Figure 12. Predicted annual base case GHG emissions profiles

District Heating

A central biomass boiler can supply clean space heat and DHW for a district (see Figure 13 for an example). Such a plant requires infrastructure such as a building to house the boiler and the fuel, along with a road that allows easy access for fuel-delivery trucks. A natural-gas-fueled backup system should also be installed, which significantly increases the up-front cost as well as the SPP of the central boiler. Finally, a central biomass plant typically requires an operator much of the time, resulting in high operations and maintenance (O&M) costs and further lengthening the system's SPP.

Because a district biomass system requires large volumes of fuel to be delivered regularly, the site must be prepared for this increased traffic. For South Lincoln, the team performed an initial analysis to determine the approximate number of tractor-trailer loads of wood chips required per week to meet the proposed community's heating and DHW loads. During the peak heating season, the results indicated that about six tractor-trailer loads per week would be sufficient. During other times of the year, the number of loads needed would be less. Table 8 gives the results of this analysis.

Photo by Pat Corkery, NREL/PIX 15830

Figure 13. A central biomass plant like this one on the NREL campus could produce heat and DHW for a district

Table 8. Approximate Quantities of Wood Chip Fuel Required for Heating and DHW

Quantities	Minimum Heating Month	Average Heating Month	Peak Heating Month
MMBtu/month	938	3,423	6,971
Total Boiler Costs	137,940	503,372	1,025,118
Trailer Loads/Month	3	11	23
Trailer Loads/Week	1	3	6

The analysis team examined three biomass system sizes based on the heating demand of the community, using SPP to determine an optimal system size. For each analysis, wood chips were assumed to be the fuel of choice.

Note that, although the different system sizes produce energy ranging from 80% to 30% of the community's maximum demand, the percentages of annual heating energy needs met by each system vary only from about 100% to 80% because the community heating demand rarely reaches levels close to its peak demand. The majority of heating energy needed by the community occurs when the demand is at a small fraction of the peak, so smaller systems are capable of meeting these needs most of the time. Table 9 gives the results of this analysis.

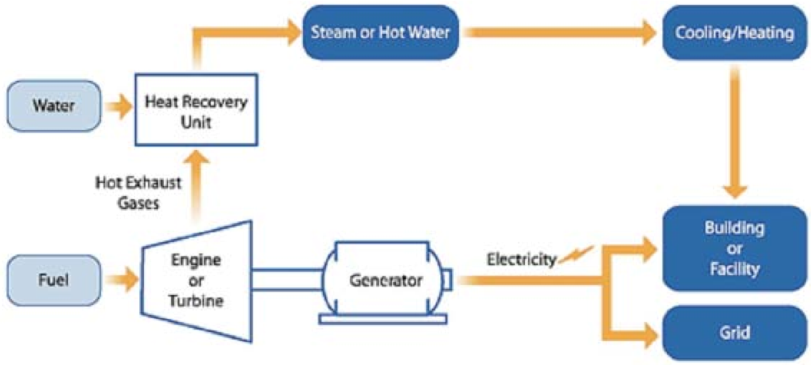
Table 9. Analysis Results for District Heating with Biomass (Wood Chip Boiler)

Heating and DHW Capacity (% of Maximum Demand)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV* ($K)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
80	3,399	17	200	−3,104	99.8	23	2,101
80 (with 10% ITC)	3,048	17	180	−2,753	99.8	23	1,884
40	1,832	16	112	−1,545	91.4	21	1,238
40 (with 10% ITC)	1,637	16	100	−1,351	91.4	21	1,106
30 (lowest SPP)	1,440	14	105	−1,200	81.8	19	1,085
30 (lowest SPP with 10% ITC)	1,284	14	94	−1,045	81.8	19	968

* NPV is based on all assumptions covered in the appendix.

Cogeneration

The main benefit of cogeneration (or trigeneration, discussed later) is that waste heat can be recovered and used, greatly increasing to the system's total efficiency. The most common type of cogeneration system is combined heat and power (CHP), in which the waste heat created during electricity generation is used to meet space heating, DHW, or industrial needs. Only CHP systems were analyzed in this study. Figure 14 is a diagram of a CHP system.



Source: Combined Heat and Power Partnership: Basic Information. *http://www.epa.gov/chp/basic/index.html*. Accessed May 8, 2011.

Figure 14. Schematic of a cogeneration or trigeneration plant

A cogeneration plant can be driven by gas turbines, internal combustion (IC) engines, or fuel cells. For the South Lincoln site, natural gas is the most appropriate fuel for all of these technologies because it has the lowest cost.

The size, or capacity, of a system can have a high impact on its economic viability. If a system is too large, it is likely to produce more thermal energy or electricity than the community can consume at a given time, wasting energy and money. Smaller systems, however, suffer from economies of scale because the up-front cost of the distribution system is virtually the same for large and small cogeneration plants. This cost becomes significant in relation to the smaller savings seen with smaller systems. For these reasons, each technology was analyzed based on three different capacities: (1) a larger size that is projected to meet most of the community's thermal loads; (2) a smaller size based on the lower size limits of most technologies; and (3) an optimal size based on the SPP analysis. Note that the optimal size may be smaller than is commonly available.

The monetary and environmental savings seen with cogeneration systems are mostly tied to electricity production. Electricity from the utility tends to be fairly expensive and is primarily generated using a high-emissions fuel such as coal. As a result, the efficiency with which a cogeneration system can produce electricity is very important. Overall efficiencies, which include the useful thermal energy produced, are generally of secondary importance. Table 10 summarizes the efficiencies and up-front costs used in this analysis.

Table 10. Efficiency and Cost Assumptions Used in this Analysis

Efficiency and Cost	Gas Turbine	IC Engine	Fuel Cell
Electrical Efficiency (%)	28	35	45
Thermal Efficiency (%)	47	35	20
Overall Efficiency (%)	75	70	65
Cogeneration Cost ($/kW$_e$)	2,500	1,500	5,000
Trigeneration Cost ($/kW$_e$)	3,550	2,020	5,320

Note: kW$_e$ = kilowatt-electric

Gas Turbine Cogeneration

A gas turbine combusts a gaseous fuel—such as natural gas—to produce energy that drives a high-pressure flow of air through a turbine, which then generates electricity.

The primary advantage of a gas turbine is its high overall efficiency. Of the three technologies considered, the gas turbine generally has the highest efficiency when both electricity and useful thermal energy are taken into account. Gas turbines have relatively low efficiencies, though, when considering only electric production at smaller capacities (less than 5 MW). This is a severe disadvantage. Gas turbines also have fairly high up-front costs at smaller capacities. Table 11 gives the analysis results for cogeneration using a natural gas turbine.

Table 11. Analysis Results for Gas Turbine Cogeneration

Capacity (kW_e/kW_t)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV* ($K)	Total Electricity Supplied (%)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
800/1310	2,264	–25	—	–2,636	74	66	20	1,617
800/1310 (with 10% ITC)	2,026	–25	—	–2,399	74	66	20	1,447
250/409	889	10	85	–673	23	29	8	1,528
250/409 (with 10% ITC)	789	10	75	–573	23	29	8	1,356
150/246 (lowest SPP)	639	9	72	–461	14	19	5	1,726
150/246 (lowest SPP with 10% ITC)	564	9	63	–386	14	19	5	1,523

Notes: kW_t = kilowatt-thermal; the cells that contain only dashes indicate no payback
* NPV is based on all assumptions covered in the appendix.

Internal Combustion Engine

Although IC technology also relies on the combustion of a gaseous fuel to power an engine or generator, an IC engine uses a different thermodynamic cycle than a gas turbine. Internal combustion is a common and well-established technology with well-understood maintenance and performance issues.

The two main advantages of the IC engine are its relatively low initial cost and high electrical efficiency. In addition, this technology tends to have the lowest O&M of the three technologies considered. Table 12 presents the analysis results for cogeneration using a natural gas IC engine.

Table 12. Analysis Results for IC Cogeneration

Capacity (kW_e/kW_t)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV* ($K)	Total Electricity Supplied (%)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
800/800	1,464	28	52	–848	89	51	28	758
800/800 (with 10% ITC)	1,306	28	46	–690	89	51	28	677
250/250	639	19	34	–262	28	21	10	934
250/250 (with 10% ITC)	564	19	30	–187	28	21	10	825
300/300 (lowest SPP)	714	22	33	–283	33	24	12	880
300/300 (lowest SPP with 10% ITC)	631	22	29	–200	33	24	12	778

* NPV is based on all assumptions covered in the appendix.

Fuel Cell Cogeneration

A fuel cell produces electricity through an electrochemical cycle. The mechanism used to produce power is similar to that of a typical battery, but a fuel cell uses an open cycle in which the fuel can be continuously supplied. Fuel cells can use hydrocarbon fuels such as natural gas, but the fuel is not burned as in an IC engine or gas turbine.

Fuel cells generally have the highest electrical efficiencies of the technologies considered, but they typically have the highest up-front costs as well. Overall efficiencies are on par with IC engines. Table 13 gives the analysis results for cogeneration using a natural gas fuel cell.

Table 13. Analysis Results for Fuel Cell Cogeneration

Capacity (kW_e/kW_t)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV ($K)*	Total Electricity Supplied (%)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
800/358	4,238	90	47	–2,521	84	26	37	1,629
800/358 (with 30% ITC)	3,064	90	34	–1,346	84	26	37	1,177
250/112	1,489	30	50	–920	26	9	12	1,799
250/112 (with 30% ITC)	1,139	30	38	–5,706	26	9	12	1,376
600/269 (lowest SPP)	3,239	70	47	–1,917	63	21	28	1,405
700/311 (lowest SPP with 30% ITC)	2,714	70	34	–1,191	63	21	33	1,177

* NPV is based on all assumptions covered in the appendix.

Trigeneration

A trigeneration plant supplies electricity, heating, and cooling. The cooling from a trigeneration plant is typically provided by an absorption chiller, which uses heat instead of electricity as its energy source. A trigeneration system is typically able to use more waste heat than a cogeneration system, but the up-front costs are higher.

Similar to cogeneration, a trigeneration plant can be driven by gas turbines, IC engines, or fuel cells. Again, natural gas is the most appropriate fuel for all these technologies because of its lower cost.

Like cogeneration, system size and efficiency of electricity production have a significant impact on the economics of a given installation. Trigeneration systems, though, have a greater ability to use the thermal energy produced by a system. In addition, when a trigeneration system is using thermal energy to deliver cooling, it is effectively replacing the electricity that would otherwise have been used for that purpose. As a result, larger system sizes become more feasible.

The same advantages and disadvantages listed previously for gas turbines, IC engines, and fuel cells apply when these technologies are used for trigeneration. Tables 14, 15, and 16 give the results of the analysis for each technology.

Table 14. Analysis Results for Gas Turbine Trigeneration

Capacity (kW_e/kW_t)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV* ($K)	Total Electricity Supplied (%)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
800/1310	3,104	–12	—	–3,046	83	66	27	1,638
800/1310 (with 10% ITC)	2,782	–12	—	–2,725	83	66	27	1,468
250/409	1,151	14	83	–873	24	29	9	1,761
250/409 (with 10% ITC)	1,025	14	74	–747	24	29	9	1,568
200/328 (optimal)	974	12	79	–729	19	24	8	1,858
200/328 (lowest SPP with 10% ITC)	865	12	70	–620	19	24	8	1,651

* NPV is based on all assumptions covered in the appendix.

Table 15. Analysis Results for IC Trigeneration

Capacity (kW_e/kW_t)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV* ($K)	Total Electricity Supplied (%)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
800/800	1,880	43	44	–993	95	51	32	838
800/800 (with 10% ITC)	1,680	43	39	–794	95	51	32	750
250/250	769	20	38	–366	28	21	10	1,077
250/250 (with 10% ITC)	681	20	33	–278	28	21	10	954
350/350 (lowest SPP)	971	27	36	–440	40	28	14	973
350/350 (lowest SPP with 10% ITC)	862	27	32	–332	40	28	14	865

* NPV is based on all assumptions covered in the appendix.

Table 16. Analysis Results for Fuel Cell Trigeneration

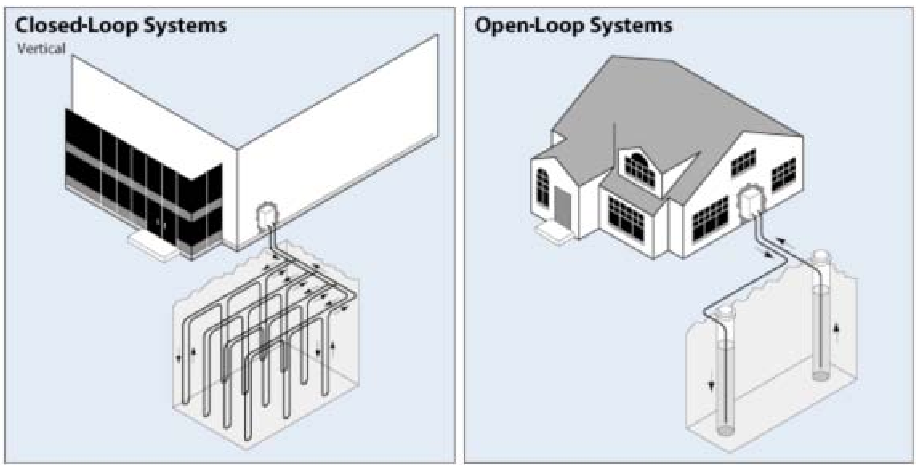
Capacity (kW_e/kW_t)	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV* ($K)	Total Electricity Supplied (%)	Total Heating and DHW Supplied (%)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
800/358	4,495	93	48	–2,723	86	26	38	1,687
800/358 (with 30% ITC)	3,243	93	35	–1,471	86	26	38	1,217
250/112	1,569	30	52	–995	26	9	12	1,884
250/112 (with 30% ITC)	1,195	30	40	–621	26	9	12	1,435
700/313 (lowest SPP)	3,963	82	48	–2,399	75	24	33	1,400
850/378 (lowest SPP with 30% ITC)	3,429	99	35	–1,555	75	24	41	1,211

* NPV is based on all assumptions covered in the appendix.

Ground-Source Heat Pump

A GSHP uses the stable temperatures of the ground or ground water to extract heating or cooling for space conditioning. It pulls heat out of the ground when in heating mode, and dumps heat into the ground when in cooling mode. GSHPs typically have high efficiencies for both heating and cooling, and use electricity as the only fuel source. Closed-loop GSHP systems circulate a fluid through tubes buried in the ground, typically in holes drilled 100 ft to 500 ft deep. Open-loop GSHP systems exchange heat directly with ground water by pumping it through the aboveground heat pump and then discharging the water back down to the water table from which it came. Figure 15 shows schematics of closed- and open-loop systems. GSHPs are sometimes referred to as geothermal heat pumps; the two terms are synonymous.

To accurately assess the thermal potential of the soil at a project site, test boreholes must be drilled, followed by thermal testing. Phase 1 of the South Lincoln redevelopment included borehole drilling and thermal testing, and the results may be used for the rest of the site because ground conditions are similar for the entire site. Boreholes were also drilled to determine the structural characteristics of the subsurface for the high-rise project at 1099 Osage, and it was found that groundwater can be reached at about 25 ft below grade. Although this relatively easily accessible groundwater may make an open-loop GSHP system a viable option for heating and cooling, local laws governing groundwater use could eliminate the possibility. If an open-loop GSHP could be used the economics would be significantly better.



Source: DOE. "Types of Geothermal Heat Pump Systems." *http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12650.* Accessed May 9, 2011.

Figure 15. Closed- and open-loop GSHP systems

GSHP systems are most effective when a community's heating and cooling needs are well balanced over the course of a year. This allows the ground to "recharge" and avoids a slow increase or decrease in soil temperature over time. The South Lincoln site presents a challenge in that the heating needs of the community are far greater than the cooling needs.

Although GSHP systems are highly efficient, their use of electricity as the fuel source for both heating and cooling can often result in marginal GHG reductions. Although CO_2 emissions are typically reduced when the heat pump is being used for cooling, the emissions can actually increase in heating mode. The reason for this is that, in the absence of a GSHP, natural gas is typically the fuel source for heating. Because the emissions associated with electricity in Colorado are so much higher than those for natural gas, heating with electricity, even at the high efficiencies seen from GSHPs, often results in increased CO_2 emissions. South Lincoln will require significantly more heating than cooling, making the net GHG savings from using a district GSHP marginal. Table 17 presents the results from the district GSHP analysis.

Table 17. Analysis Results for a District GSHP

Heating and Cooling Loads Met (%)	Initial Cost ($K)	Annual Savings ($K)	SPP (years)	NPV* ($K)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
100	5,905	71	83	–4,642	4	22,282
100 (with 10% ITC)	5,007	71	71	–3,744	4	18,894

* NPV is based on all assumptions covered in the appendix.

Photovoltaics

PV systems use only sunlight as a fuel source and produce only electricity. PV is a well-established and reliable source of electricity that tends to have fairly high up-front costs and low O&M costs. Installed costs for PV have dropped dramatically in the last decade, however, and that trend is continuing. Table 18 gives approximate values for current costs based on actual installations, and Figure 16 shows an existing residential community rooftop PV installation in Germany. To successfully implement PV at South Lincoln, thoughtful design of rooftops and parking areas would be necessary to maximize solar access.

Table 18. Approximate Current Costs of PV

System Type	Approximate Cost ($/W)
Standard Efficiency Panels	5
High Efficiency Panels	5.25
Carport System	6.50

Photo copyright: Rolf Disch Solar Architecture, Freiburg, Germany.

Figure 16. Rooftop solar PV installation at the Solar Siedlung in Freiburg, Germany

In addition to federal and state incentive programs, utility incentives for installing PV systems play an important role in a system's economic viability. The incentives available from Xcel Energy's Solar*Rewards Program depend on the size of the system. The program offers a rebate of $2/W with a maximum rebate of $200,000.

In addition, for systems between 10 kW and 500 kW, the system owner receives a production credit of 2.5 cents for every kilowatt-hour produced over a 20-year period. For systems above 500 kW, the incentives are the same except that the amount of the production credit is determined through an RFP process.

PV installations can be funded in a number of ways. For this analysis, the team assumed that DHA would purchase and own the system.[3] In this scenario, DHA could take advantage of Xcel Energy's Solar*Rewards incentives as well as the 30% ITC on the up-front cost of the system.

As an alternative to purchasing the PV system, the site could host the system under a third-party power purchase agreement (PPA) structure. In this structure, a third-party private entity (or entities) installs, operates, maintains, and owns the PV system on the site property. The site owners would sign a PPA and commit to purchasing electricity from this third party for a fixed amount of time, usually 10 to 25 years. The PPA could include a price escalator that would increase the cost of the electricity at a fixed rate each year over the life of the contract. This rate is usually between 0% and 4%. Since DHA is a nonprofit organization, it is not able to directly take advantage of tax credits. However, DHA can still benefit by selling these tax credits on the market or if the systems are owned by a third party.

The contract would be set up such that the DHA would sign a 20-year contract with the third party, and the third party, in turn, would sell the electricity to the site. DHA would have the option to "buy out" the PPA and become the system owner at any point after year 6. The third party would benefit from the 30% federal ITC as well as any state and utility incentives. These tax benefits and incentives reduce the installed cost of the PV system, which would translate into competitive electricity rates for DHA.

This PV analysis investigates two primary scenarios: one in which all suitable rooftop area is used for PV and carports are built for the purpose of mounting solar panels, and one in which only the suitable rooftop area is used. The team investigated each option for panels with efficiencies of 15% and 19%. Additional analyses examined the effect of installing PV as one large project versus multiple smaller projects. Dividing the installations into several smaller projects allows entry into a lower tier in the Xcel Solar*Rewards Program and takes greater advantage of the program's up-front rebates. Table 19 gives the results of these analyses.

[3] Xcel Energy Solar*Rewards Program (Colorado). *http://www.xcelenergy.com/Save_Money_&_Energy/For_Your_Home/Solar_Rewards/Solar*Rewards_-_CO.* Accessed May 9, 2011.

Table 19. Analysis Results for PV Systems

Project Description	Efficiency (%)	Electric Load Met	Initial Cost ($K)	Annual Cost Savings ($K)	SPP (years)	NPV*	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
Rooftop and Carport Systems (252,455 ft²)								
1 Large System	15	93	19,343	331	68	−14,838	62	4,466
1 Large System (w/ 30% ITC)	15	93	13,492	331	47	−8,987	62	3,115
8 Smaller Systems	15	93	18,343	331	64	−13,838	62	4,235
8 Smaller Systems (w/ 30% ITC)	15	93	12,092	331	42	−7,587	62	2,792
1 Large System	19	113	24,636	405	70	−19,120	76	4,647
1 Large System (w/ 30% ITC)	19	113	17,185	405	49	−11,669	76	3,241
8 Smaller Systems	19	113	23,236	405	66	−17,720	76	4,383
8 Smaller Systems (w/ 30% ITC)	19	113	15,801	405	45	−10,285	76	2,980
Rooftop Systems Only (188,848 ft²)								
1 Large System	15	69	13,387	248	63	−10,019	46	4,132
1 Large System (w/ 30% ITC)	15	69	9,319	248	44	−5,949	46	2,876
6 Smaller Systems	15	69	12,387	248	58	−9,019	46	3,823
6 Smaller Systems (w/ 30% ITC)	15	69	8,319	248	39	−4,949	46	2,568
1 Large System	19	85	17,327	303	66	−13,201	57	4,369
1 Large System (w/ 30% ITC)	19	85	12,069	303	46	−7,943	57	3,043
6 Smaller Systems	19	85	16,327	303	62	−12,201	57	4,117
6 Smaller Systems (w/ 30% ITC)	19	85	11,069	303	42	−6,943	57	2,791

* NPV is based on all assumptions covered in the appendix.

Solar Hot Water

SHW systems are designed to produce useful thermal energy using only the sun as the energy source. An auxiliary heat source is typically needed for a consistent supply of hot water for domestic use. Like a PV system, an SHW system requires rooftop space to mount the solar collectors. As a result, any area that is used for SHW cannot be used for PV, and vice versa. The team did an analysis to determine the optimal mix of SHW and PV under the assumption that all viable rooftop area with solar access would be used. Figure 17 shows the total energy production and GHG reduction of every combination of systems, from covering 100% of the roof with PV (on the left side of the graph) to using 100% of the roof for SHW (on the right side of the graph). The results showed that using 100% PV and 0% SHW gave the highest NPV and the greatest GHG savings. The economics of these technologies, though, are highly dependent on incentives and funding methods.

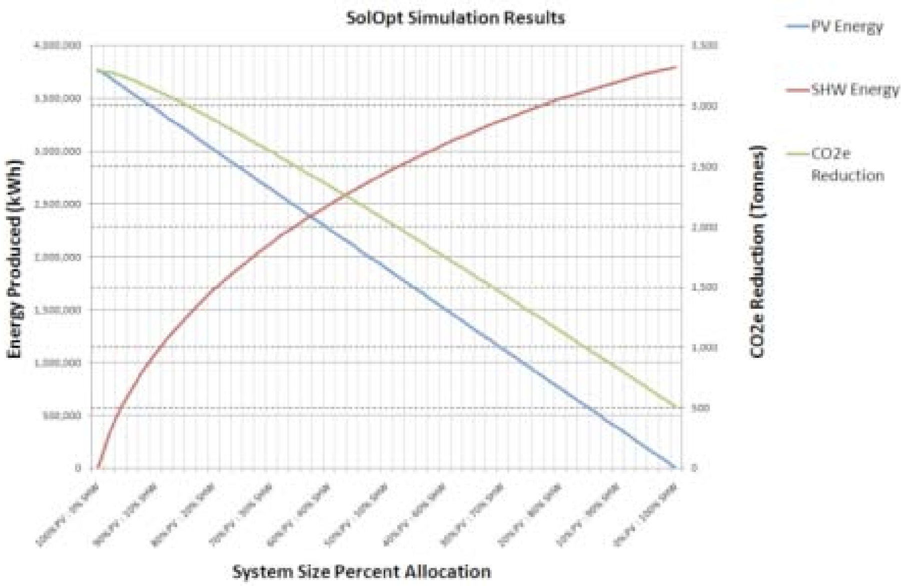


Figure 17. Rooftop PV/SHW optimization results based on GHG reduction

As an SHW system increases in size, its overall effectiveness generally diminishes because it begins producing more hot water than the building can use at certain times of the year. For this reason, SHW systems are typically sized to meet 70% to 80% of the building's total DHW load.

The team performed energy and economic analysis assuming an SHW system sized to meet 80% of the South Lincoln community's annual DHW load. This system would require about 90% of the total roof area deemed suitable for solar panels. Table 20 gives the results of this analysis.

Table 20. Analysis Results for an SHW System

DHW Load Met (%)	Initial Cost ($K)	Annual Cost Savings	SPP (years)	NPV* ($K)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
80	10,647	84	127	–12,265	6	26,354
80 (with 30% ITC)	7,453	84	89	–8,197	6	18,448

* NPV is based on all assumptions covered in the appendix.

Conclusions and Recommendations

Table 21 summarizes the results for selected systems from each of the technologies analyzed. The results shown here were selected based on SPP and feasibility of size. Although all results are not reported in this table, it gives a representative comparison of the various district systems.

Table 21. Summary of Analysis Results for Selected District Systems (all results shown include the ITC)

Technology	Size (kW_e/ kW_t)	SPP (years)	NPV* ($K)	Total CO_2 Equivalent Saved (%)	Initial Investment per Ton CO_2 Equivalent Saved ($/ton)
Cogeneration					
Natural Gas Turbine	250/409	75.4	–573	8	1,356
IC Engine	300/300	29.2	–200	12	778
Fuel Cell	700/311	33.9	–1,191	33	1,177
Trigeneration					
Natural Gas Turbine	250/409	73.9	–747	9	1,568
IC Engine	350/350	32.3	–332	14	865
Fuel Cell	850/378	34.8	–1,555	41	1,211
GSHP					
GSHP	100% of Load	70.6	–3,744	4	18,894
Biomass Heat					
Wood Chip Boiler	40% of Heating Demand	99.7	–1,351	21	1,106
PV					
Solar Panels (19% efficient; rooftops and carports)	252,455 ft^2 (as multiple smaller systems)	45.2	–10,285	76	2,980
Solar Panels (15% efficient; rooftops only)	188,848 ft^2 (as multiple smaller systems)	38.9	–4,949	46	2,568
SHW					
Flat Plate Panels	80% of DHW Load	88.8	–12,265	6	18,448

* NPV is based on all assumptions covered in the appendix.

Although none of the district systems investigated show favorable economics for South Lincoln Park, some options may make sense as integral parts of the final solution to meet a goal of reducing GHG emissions. The team strongly recommends, however, that building energy efficiency measures be maximized before any district system is implemented. Specifically, it is vital to reduce electrical, heating and DHW, and cooling loads in the community as much as possible. Electrical loads can be reduced by combining building system design elements (e.g., high-efficiency lighting, pumps, and fans; timers on bathroom vents; daylighting design); appliance efficiency standards; occupant education (e.g., to turn off the lights when not in use); and any number of occupant incentives such as rewards for using less energy. Heating loads can be reduced primarily through building design, including insulation levels and window specifications. DHW loads can be reduced by educating the occupants (e.g., to do laundry in cold water), using low-flow fixtures, and energy recovery.

Perhaps the greatest improvements in the baseline energy use can be found in the reduction of cooling energy use. The Denver climate is ideal for natural ventilation, direct cooling with outdoor air, nighttime precooling, and evaporative cooling. These technologies could conceivably virtually eliminate conventional cooling methods in the South Lincoln community and significantly reduce the electricity used for cooling.

For this community, the most drastic reductions in GHG emissions would be achieved using a combination of PV for electricity and biomass for heating and DHW. If cooling and other electrical loads could be reduced according to the recommendations just outlined, the community might be able to reach net zero GHG emissions by installing 19% efficient solar panels on rooftops and carports and installing a biomass heating system sized to 40% of peak heating and DHW demand. In this scenario, heating and DHW would require some natural gas input. With the reductions in cooling and other electrical energy, however, the PV system is projected to produce enough surplus electrical power to offset the GHG emissions from the site's natural gas usage. Although the economics of buying and owning a PV system might be prohibitive, entering into a PPA could make such a system viable.

An alternative to that scenario is to install PV to offset electricity use, concentrate on reducing heating/DHW loads, and use high-efficiency natural gas systems at the building level in lieu of a central biomass plant. Even though the community would not be expected to reach net zero GHG emissions in this scenario, emissions savings of about 80% or higher are achievable. In addition, up-front costs and O&M costs would be significantly lower. This approach would be much simpler and less costly to design and implement phase by phase, with a relatively small loss of environmental benefit. Considering both economics and environmental benefits, this may be the most reasonable option for South Lincoln.

A third possibility would be to use a cogeneration or trigeneration plant driven by an IC engine or a fuel cell to supply a portion of the community's heating and electricity needs. These systems show the most attractive economics of any of the systems analyzed. It would be possible to supplement a cogeneration plant with PV as a path to net zero emissions. Implementing a cogeneration or trigeneration strategy would require more planning and ongoing O&M work by DHA than a PV strategy, though. In addition, a PV system can be installed under a PPA, but a PPA for a cogeneration plant would require the utility's consent. Because the utility has little incentive to agree to this type of arrangement, approval of a cogeneration plant PPA is unlikely.

The team does not recommend SHW systems or a district GSHP system for this project. Both of these systems show poor economics and minimal savings in GHG emissions. Even though some trigeneration systems show comparatively good economics and GHG reductions, these systems are not recommended because reductions in cooling loads and cooling energy use, if realized, would make district cooling unnecessary. Finally, the same issues noted for cogeneration systems apply equally to trigeneration systems.

Appendix: Analysis Assumptions and Sources

Economic Parameters

Parameter	Value	Source
Project Lifetime	25 years	
Real Discount Rate	3%	NIST discount rate (valid from April 1, 2010 to March 31, 2011)
Electricity Escalation Rate (real)	0.50%	Energy Escalation Rate Calculator
Natural Gas Escalation Rate	0.40%	Energy Escalation Rate Calculator
Blended Residential Electricity Rate (energy)	$0.104/kWh	Sampling of South Lincoln Utility Bills (2010)
Residential Electric Demand Rate	$0.00/kW	Sampling of South Lincoln Utility Bills (2010)
Commercial Electricity Rate	$0.033/kWh	Xcel Energy
Commercial Summer Electric Demand Rate	$20.24/kW	Xcel Energy
Commercial Winter Electric Demand Rate	$17.24/kW	Xcel Energy
Natural Gas Rate	$0.673/therm	Sampling of South Lincoln Utility Bills (2010)

Greenhouse Gas Emissions

Energy Source	Emission Compound	Equivalent CO_2 Emissions	Source
Electricity (generated in Colorado)	CO_2	1,883 lb/MWh	EIA (1)
	Methane	0.0228 lb/MWh	EIA (1)
	Nitrogen Oxide	0.02875 lb/MWh	EIA (1)
Natural Gas	CO_2	53.06 kg/MMBtu	EPA (2)
	Methane	0.005 kg/MMBtu	EPA (2)
	Nitrogen Oxide	0.0001 kg/MMBtu	EPA (2)

Sources:
1. Electricity: EIA. Colorado Electricity Profile, 2009 Edition. *http://www.eia.doe.gov/cneaf/electricity/st_profiles/colorado.html*. Accessed May 9, 2011.
2. Natural Gas: EPA. August 2008, Version 1.3. Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type: Commercial Boiler Efficiency (Space and Hot Water Heating). *http://www.epa.gov/climateleaders/documents/resources/comm_boiler_proto.pdf*. Accessed May 9, 2011.

Base Case

Parameter	Value	Source
Overall Boiler Efficiency	85%	Based on ASHRAE Standard 90.1 (1)
Boiler Costs	$20.7/MBtu/h	RSMeans (2)
Overall Air-Conditioning Efficiency	3.1 COP	Based on ASHRAE Standard 90.1 (1)
Air-Conditioning Costs	$3,291/ton	RSMeans (2)

Sources:
1. ASHRAE. Energy Standard for Buildings Except Low-Rise Residential Buildings. *http://www.ashrae.org/*. Accessed May 31, 2011.
2. Reed Construction Data, Inc. *http://rsmeans.reedconstructiondata.com/*. Accessed May 31, 2011.

Distribution System[a]		
Parameter	**Value**	**Source**
Length of Piping Needed	5,000 ft	Estimated based on site map
Installed Piping Costs	$75/ft (based on 5-in. pipe)	Based on an Oregon Institute of Technology study (1)
Overall Air-Conditioning Efficiency	3.1 COP	Based on ASHRAE Standard 90.1 (1)
Air-Conditioning Costs	$3,291/ton	RSMeans (2)

[a]For all applicable district systems

Source:
Rafferty, K. June 1996. Selected Cost Considerations for Geothermal District Heating in Existing Single-Family Residential Areas. *http://geoheat.oit.edu/pdf/tp93.pdf*. Accessed May 9, 2011.

Cogeneration and Trigeneration Systems		
Parameter	**Value**	**Source**
Gas Turbine		
Overall Efficiency	75%	Product Data, RETScreen Database (1)
Electrical Efficiency	28.4%	Product Data, RETScreen Database (1)
Thermal Efficiency	46.6%	Product Data, RETScreen Database (1)
Altitude Derate	80% of rated capacity	EPA estimates (2)
Installed Cost (cogeneration)	$2,500/kW$_e$	EPA estimates, manufacturer quotes (3)
Installed Cost (trigeneration)	$3,550/kW$_e$	EPA estimates, manufacturer quotes (3)
O&M Cost	$0.008/kWh	Manufacturer recommendation
ITC	10% of Initial Cost	Database of State Incentives for Renewables & Efficiency (DSIRE) (4)
IC Engine		
Overall Efficiency	70%	Product Data, RETScreen Database (1)
Electrical Efficiency	35%	Product Data, RETScreen Database (1)
Thermal Efficiency	35%	Product Data, RETScreen Database (1)
Altitude Derate	80% of rated capacity	EPA estimates (2)
Installed Cost (cogeneration)	$1,500/kW$_e$	EPA estimates, manufacturer quotes (3)
Installed Cost (trigeneration)	$2,020/kW$_e$	EPA estimates, manufacturer quotes (3)
O&M Cost	$0.009/kWh	Manufacturer recommendation
ITC	10% of Initial Cost	DSIRE (4)
Fuel Cell		
Overall Efficiency	65%	Product Data, RETScreen Database (1)
Electrical Efficiency	45%	Product Data, RETScreen Database (1)
Thermal Efficiency	20%	Product Data, RETScreen Database (1)
Altitude Derate	80%	EPA estimates (2)
Installed Cost (cogeneration)	$5,000/kW$_e$	EPA estimates (3), manufacturer quotes
Installed Cost (trigeneration)	$5,320/kW$_e$	EPA estimates (3), manufacturer quotes
O&M Cost	$0.02/kWh	Manufacturer recommendation
ITC	30% of Initial Cost	DSIRE (4)

Sources:
1. Natural Resources Canada. RETScreen Clean Energy Project Analysis Software. *http://www.retscreen.net/ang/home.php*. Accessed May 31, 2011.
2. EPA. Combined Heat and Power Partnership: Catalog of CHP Technologies. *http://www.epa.gov/chp/basic/catalog.html*. Accessed May 9, 2011.
3. EPA. Combined Heat and Power Partnership. *http://www.epa.gov/chp/*. Accessed May 9, 2011.
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National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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