Design and Evaluation of a Net Zero Energy Low-Income Residential Housing Development in

Lafayette, Colorado

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Affordable housing development authorities throughout the United States continually struggle to find the most cost-effective pathway to provide quality, durable, and sustainable housing. The challenge for all such authorities is to achieve their mission of delivering affordable housing at the lowest cost per square foot in environments that may be rural, urban, suburban, or within a designated redevelopment district. With the challenges the United States faces regarding energy, the environmental impacts of consumer use of fossil fuels and the increased focus on reducing greenhouse gas emissions, housing authorities are pursuing the goal of constructing affordable, energy efficient and sustainable housing at the lowest life-cycle cost of ownership.

This report outlines the lessons learned and sub-metered energy performance of the Paradigm Pilot Project, an ultra-low-energy single-family ranch home and duplex unit, and presents the final design recommendations for a 153-unit net zero energy residential development called the Josephine Commons Project. In addition to describing the results of the performance monitoring from the pilot project, this report describes the recommended design process of

1. Setting performance goals for energy efficiency and renewable energy on a life-cycle cost basis
2. Using an integrated, whole building design approach
3. Incorporating systems-built housing, a green jobs training program, and renewable energy technologies into a replicable high-performance, low-income housing project development model.

Energy Vision and Goals

In 2007, Boulder County Housing Authority (BCHA) created a strategic vision for a 14-acre parcel of land in Lafayette, Colorado that the agency had available, but undeveloped, for the past decade. The property would become known as Josephine Commons and is designed to house 153 residential housing units. A computer rendering of the development is provided in Figure 1.

Figure 1. Josephine Commons Residential Community. *Illustration from HB&A Architects*

The Josephine Commons development will consist of the following housing units:

- 70 senior units, 1- and 2-bedroom apartments
- 54 1- and 2-story townhouse units
- 22 1- and 2-story duplex units
- 7 single-family lots.

In 2008, BCHA approached the City of Denver with the idea of collaborating under a grant application to the Department of Energy (DOE) Solar America Cities Initiative. The Solar America Cities Initiative is a partnership between DOE and a select group of cities across the country. Solar America Cities form teams with municipal, county, and state agencies, nonprofit organizations, universities, utilities, developers, and solar companies to accelerate the adoption of solar energy. The Paradigm Pilot Project was awarded funding through the larger Solar America Cities grant with the City of Denver and named because of its potential to bring about a paradigm shift in reducing the cost of affordable housing and substantially changing the way large-infill affordable housing could be assembled.

The BCHA used the pilot project as a baseline to revise design strategies and assess design recommendations for the Josephine Commons Project. The process for designing, constructing, and testing the Paradigm Pilot Project and Josephine Commons Project consisted of three main steps:

1. Partnering with All American Group (Manufacturing Sector), H&BA Architects, Farnsworth Group engineers, and NREL, BCHA designed and constructed a single-family ranch house and a two- story duplex using modular, systems-built construction in Lafayette, CO. The duplex unit was designed with the assistance of an optimization tool to maximize energy savings with the combined mortgage plus energy bill cost at parity with a code built home. The single-family house was designed to incorporate different energy systems than the duplex units to test the performance of the building energy systems over a one-year period.
2. The single-story house and duplex integrated a number of innovative building systems, such as ground source heat pumps (GSHP) with de-super-heaters (DSH) for domestic hot water, condensing gas furnaces, energy recovery ventilators, automated natural ventilation, evacuated tube solar hot water systems, and building integrated photovoltaics (PV) with micro-inverters. NREL evaluated all of these technologies against one another over a one-year period and compared the modeled energy performance of the two homes to short-term and long-term test data.
3. NREL used the sub-metered performance data and lessons learned from the pilot project to develop the design requirements for the residential units on the Josephine Commons site. In this process, NREL:

    a. Ran an isolated analysis of the HVAC systems performance based on measured performance data
    b. Created a revised EnergyPlus energy model and calibrated it with measured energy usage data
    c. Created a final set of prescriptive design specifications to achieve a net zero energy development at the Josephine Commons site.

Another goal of the Paradigm Pilot Project was to test and develop an affordable net zero energy residential building model that could be replicated at the main Josephine Commons site at a total construction cost between \$90 to \$125/ft^2. BCHA set a target to ensure that the units met a local affordability threshold and incorporated four separate goals:

1. Minimize energy use on a life-cycle cost basis with the ultimate goal of developing a template for a net zero energy residence at the Josephine Commons site.
2. Incorporate manufactured or systems-built assembly methods to reduce the total installed costs of the development.
3. Create a local green jobs training program to assist with the construction of the homes and installation of the renewable energy systems.
4. Incorporate onsite renewable energy systems to achieve an ultra low energy / net zero energy development.

Manufactured Housing

BCHA chose to use manufactured or systems-built assembly methods to reduce the installed costs of the Paradigm Pilot Project duplex and ranch home. Systems-built homes are constructed off site in a controlled environment and delivered to the site for final assembly and the field application of certain internal and external finishes. The systems-built approach to building affordable housing can be accomplished through economies of scale. Large production manufacturing companies in the United States have access to high volume supply of residential building components and can purchase high performance paned windows, wall insulation materials, and other sustainable building materials in bulk. Leveraging the high production advantages of a systems-built manufacturer and using a high production affordable housing developer offers mutual economies of scale, bringing economic benefits to both parties.

The execution of large-scale residential construction using the systems-built process is inherently risky and often takes developers through unknown processes and levels of risk. This risk in the manufacturing sector for housing developers is real because of the vulnerabilities associated with the less known assembly of modular-built homes. One error in design can have a ripple effect on the cost of an architectural or engineering oversight, thereby forcing a heavy front end investment on constructability due diligence and even fatal flaw analysis. The BCHA addressed this perceived risk through the execution of a proof of concept, the Paradigm Pilot Project.

Green Jobs Training Program

The BCHA worked with Workforce Boulder County to train seven local residents on a number of residential construction trades. The trainees assisted with:

- Ground source heat pump (GSHP) installation tasks, including assistance with the ground loop installation and heat pump installation
- Insulated concrete form foundation tasks, including assistance laying the foundation.
- Solar hot water and photovoltaic installation tasks, including installing the mounting rack, running hot water piping, wiring the PV system, and general installation support.

Paradigm Pilot Project

The Paradigm Pilot Project is comprised of a single-family home and residential duplex that showcase a mix of super-insulated building envelope construction elements, passive solar design strategies, natural daylighting, compact fluorescent lighting, high performance windows, ENERGY STAR® appliances, sustainable building materials, high performance heating, ventilating and air conditioning systems, balanced energy recovery ventilators, automated natural ventilation, and building integrated renewable energy systems.

The single-family house was designed and built as an all-electric home with a GSHP, a de-super heater (DSH) for domestic hot water (DHW) and a roof-mounted PV system. The duplex units were designed and built with condensing gas furnaces, natural ventilation, solar hot water (SWH), and roof-mounted PV systems. All of the other components of the homes were built with the same specifications so the HVAC and renewable energy systems could be directly compared. A construction table comparing the design features of the Paradigm Pilot Project homes and final Josephine Commons design is provided in Table 1. A visual rending of the paradigm pilot project site plan with a rendering of the duplex and single-family residence is provided in Figure 1.

Figure 1. Paradigm Project site plan. *Illustration from HB&A Architects*

The NREL team worked with the housing authority, architects, and engineers to develop a baseline model of the main duplex unit based on the existing designs and specifications. The baseline design was analyzed in BEopt and compared to the 2008 baseline Building America Benchmark. The Benchmark at the time is consistent with mid-1990s standard practice, as reflected in the Home Energy Rating System (HERS).[1]

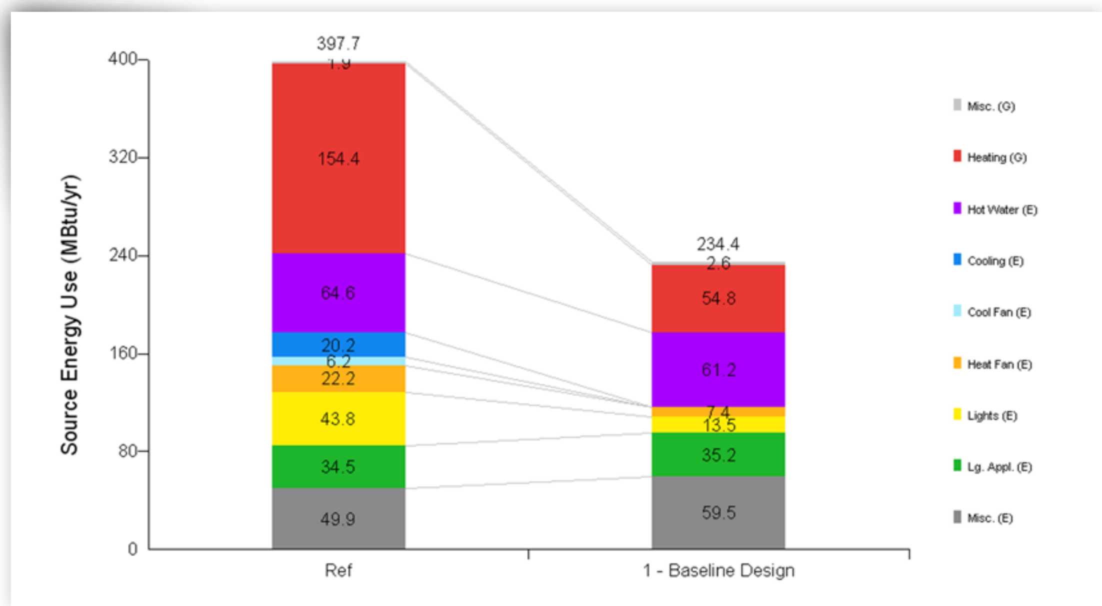

Figure 2. Building America benchmark versus baseline design source energy use.

The reference BCHA building produced a source energy savings of 42% when compared to the Building America Benchmark. Source energy savings is represented as the amount of energy used at this site, as well as energy losses through the generation and distribution system. Thus, it captures the amount of energy required to get the total energy to the site and accounts for source electricity use and source natural gas use. The design resulted in an incremental mortgage and utility cost of $2,481/yr, versus the baseline design which had an annual utility bill of $4,202/yr. Thus, before any type of building optimizations were performed the homes were already projected to perform significantly better than a standard mid 1990's home and projected to save $1,721 per year. This annual cost of $2,481 represents the cost per duplex, thus the total incremental mortgage and utility costs for one residence would be $1,240.5/year.

Design Optimization

Once the design team agreed on the baseline model, NREL optimized the overall design with a selection of 41 optimization variables. Each optimization variable has an energy implication and an associated incremental cost. Installed costs for each measure were provided by All American homes and local contractors. Without the use of a software program like BEopt, a total of 1,681 individual energy models would have to be created and compared to develop an optimal solution. From an economic perspective, this is an unrealistic number of simulations and would not be feasible without the use of a tool like BEopt.

1 Hendron R., Engebrecht, C. (2010) Building America Benchmark Definition, Updated December 2009, NREL/TP-550-47246, http://www.nrel.gov/docs/fy10osti/47246.pdf. Accessed July 2011.

In the following graph, each grey dot represents a different combination of optimization variables and the results of an annual simulation. On the y-axis is a listing of the increased incremental cost amortized over the mortgage period plus the annual utility bill. The final design that NREL selected for BCHA provides the greatest energy savings on a life-cycle cost basis while maintaining a total cost of ownership that is lower than the baseline design.

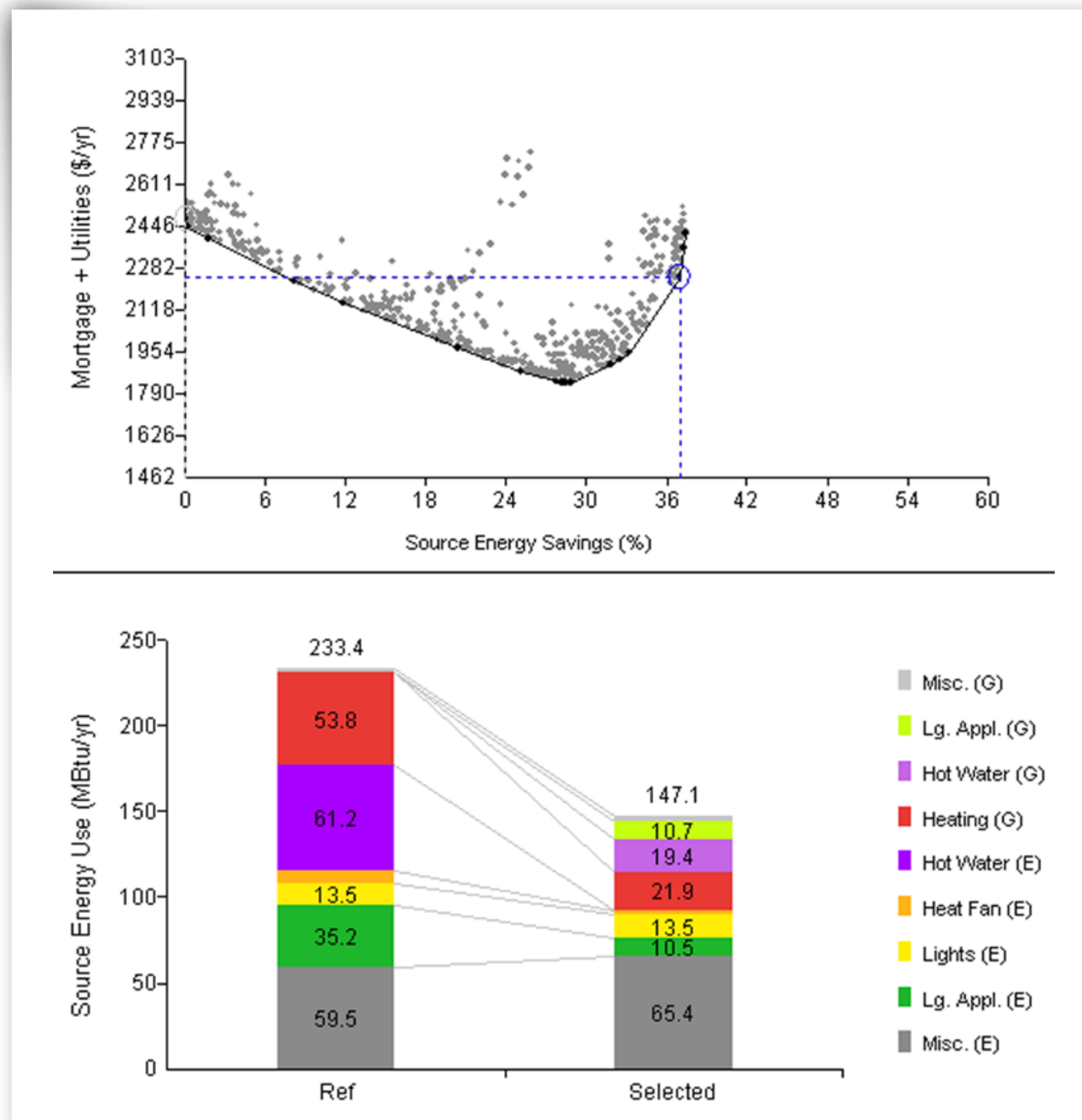

Figure 3. Source energy savings and incremental costs of optimized design.

The proposed design results in a source energy savings of 37% over the proposed BCHA baseline design, while reducing the incremental mortgage and utility costs by approximately $166 per year. The total incremental installed cost to implement the energy efficiency upgrades was approximately $9,085, per residence. In addition to the energy efficiency measures, a solar hot water system was installed on each duplex unit with a total collector area of 56.11 ft2 and a 120 gallon storage tank. A roof-mounted PV array was also installed. The system was sized based on the available roof area to 2.2 kW per unit. The additional cost for each SHW system was approximately $9,000 per unit and $4,400 for each 2.2 kW PV system. A construction table illustrating the design features of the Paradigm pilot project homes is provided in Table 1.

Performance Testing

NREL and Mountain Energy Partnership conducted short-term and long-term performance tests on all three housing units over a one-year period in order to evaluate the performance of individual energy systems and their interactive effects. The modeled and measured annual utility bills are provided in the following graph. It should be noted that the duplex was the only residence that was modeled in BEopt. The ranch house is provided for consistency, but was not compared to a separate energy model.

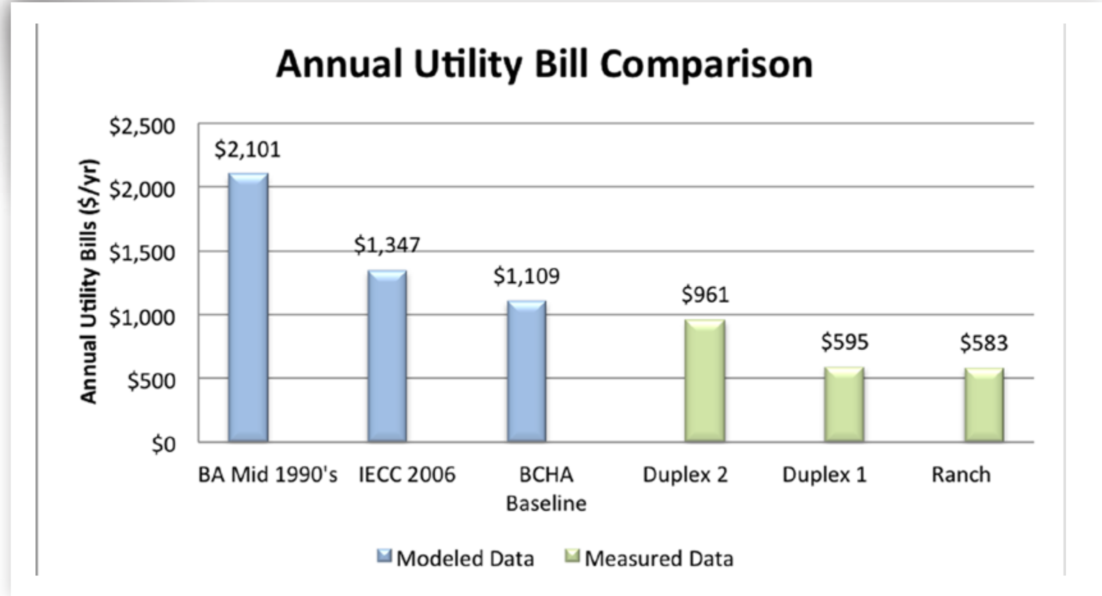

Figure 4. Annual utility bill comparison.

The measured utility data shows significant savings over all three baselines. Duplex #1 provided an energy cost savings of $757/year over a code compliant IECC 2006 home. The increased annual utility bill of duplex 2 was driven by increased occupant energy use. The residents in duplex #2 used 2.5 times the lighting and miscellaneous plug load energy use as duplex #1, stressing the importance of occupant education and training programs.

The site energy use intensity of each residence and the predicted energy intensity of each duplex is provided in the following graph. The baseline modeled EUIs are provided for each duplex and do not include any onsite renewable energy systems. The measured data for the duplex units and ranch house include the reduction in energy use associated with the production from the renewable energy systems.

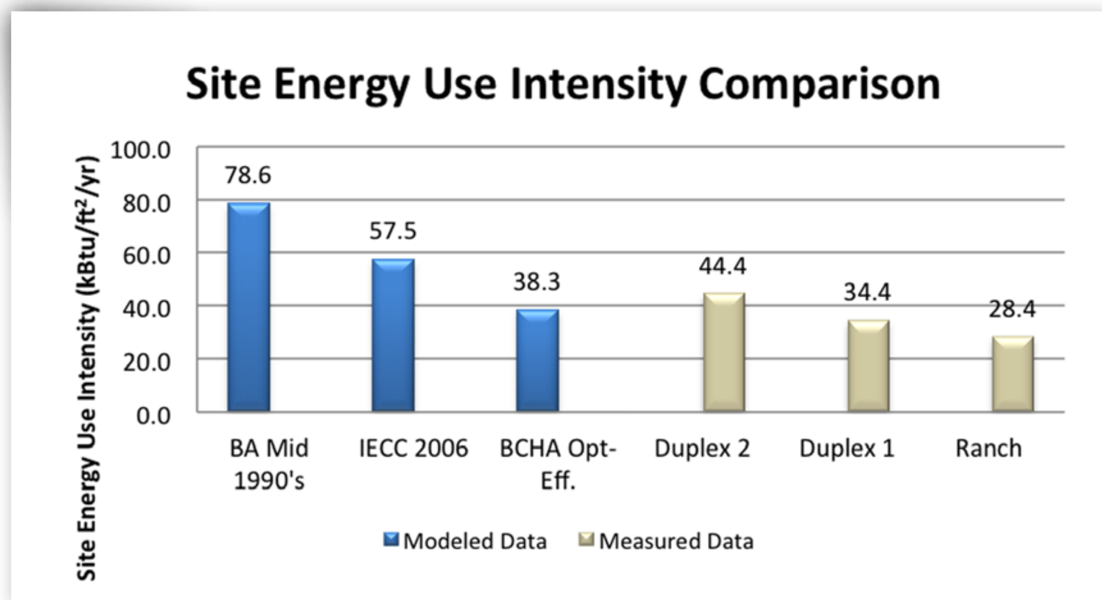

Figure 5. Site energy use intensity comparison.

The data showed that Duplex #1 provided a 40% savings over an IECC 2006 home and the ranch house provided a 50% savings over an IECC 2006 home. In addition to the measured energy savings, the single-family ranch house was awarded a HERS rating of 37 and the duplex received a HERS rating of 45. Both these ratings are in line with the measured reduction in energy use over an IECC 2006 home.

The energy end-use break out for the single family ranch house and Duplex #1 are provided in the following figure.

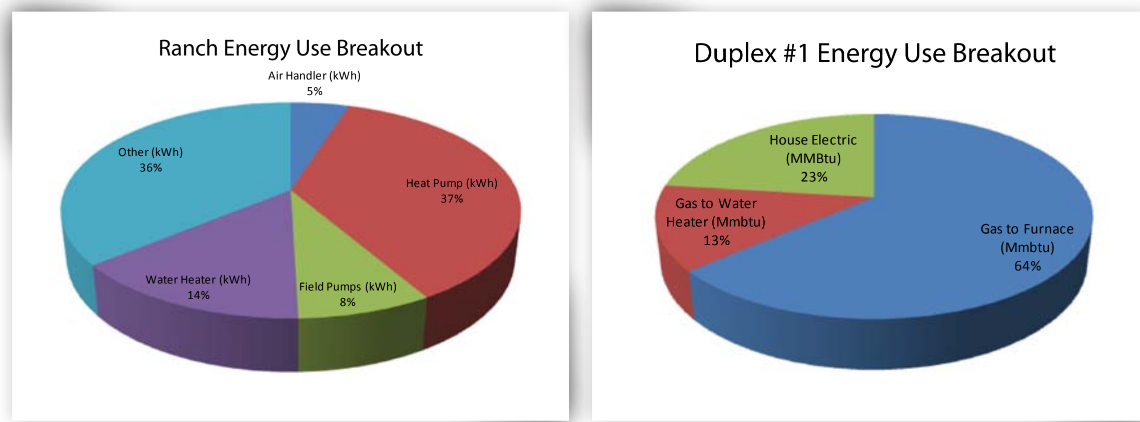

Figure 6. Ranch and duplex #1 energy use breakout.

The majority of the energy use of the duplex is associated with the condensing gas furnace. The domestic hot water also represents a significant end use load. Based on the fact that only 23% of the energy use is associated with onsite electricity use in the duplex it is apparent that it is difficult to achieve a true net zero energy development with this type of design. To achieve net zero energy, the heating and domestic hot water loads must be transferred to an electrical load through a technology such as a ground source heat pump or met by a local renewable energy source such as a biomass heating system.

Based on the detailed sub-metering and installed cost analysis, the all-electric home with a GSHP, DSH, super insulated building envelope construction elements, and roof-mounted PV systems was found to be the most cost-effective option to achieve a net zero energy development.

Josephine Commons Development

NREL used the lessons learned and sub-metered energy performance of the Paradigm Pilot Project to inform the final design recommendations for a 153-unit residential development called the Josephine Commons Project. The Josephine Commons development is located on a 14-acre parcel of land in Lafayette Colorado and will consist of the following housing units:

- 70 unit senior 1 and 2 bedroom apartments
- 54 1- and 2-story townhouse units
- 22 1- and 2-story duplex units
- 7 single-family lots.

As a part of the strategic vision for the project, the BCHA set performance goals for energy efficiency and renewable energy on a life-cycle cost basis for the residential units with assistance from NREL. The site is located just northwest of the intersection of Highway 7 (Baseline Road) and 119th Street in Lafayette, Colorado and a graphical representation of the site is provided in the following graphic.

Figure 7. Josephine Commons net zero energy community. *Illustration from HB&A Architects*

NREL created a new BEopt energy model of the duplex units on the Paradigm pilot project site using the sub-metered performance data and the lessons learned from the Paradigm pilot project. A visual rending of the modeled residence is provided below.

Figure 8. Visual rendering of duplex unit in BEopt (south side: left; north side: right). *Illustration from HB&A Architects*

The sub-metering presented above showed that 50% to 75% of the energy use of all three residences was associated with HVAC and DHW energy use. In addition, the IECC 2009 and 2012 code requirements are projected to significantly increase the thermal performance requirements of the roof, windows, and walls in Boulder CO.

The City of Lafayette will be adopting the 2009 International Building Code the spring of 2011. Thus, the final energy modeling analysis focused on a series of parametric runs to determine the cost effectiveness of increasing the performance of the building envelope characteristics and using a programmable thermostat. The resulting recommendations are as follows:

- Programmable thermostats Programmable thermostats resulted in an additional 5% EUI savings. The successful execution of this measure will require the housing authority develop a tenant education program.
- Roof insulation requirement was raised to an R 60. The housing authority can achieve this by adding two inches of foam board to the exterior roof or changing the type of spray foam insulation (polyurethane foam with an insulation value R 6.8/inch). This measure resulted in a 1.4% reduction in energy use intensity.
- Window type performance was increased to an R-5 window, with a higher SHGC. The modeled U value was 0.20 with a SHGC of 0.45. This measure produced an EUI savings of 6.6% and was found to be cost effective if the increased cost for the glazing was approximately $5/ft2.
- Wall insulation R vale was increased to ~ R 29.4 by increasing the external foam board thickness from 0.5 inches to two inches or changing the type of spray foam insulation. This resulted in a 3.8% EUI savings at a cost premium of $2,580.
- The final design recommendations for the Josephine commons development are provided in the following graphic.

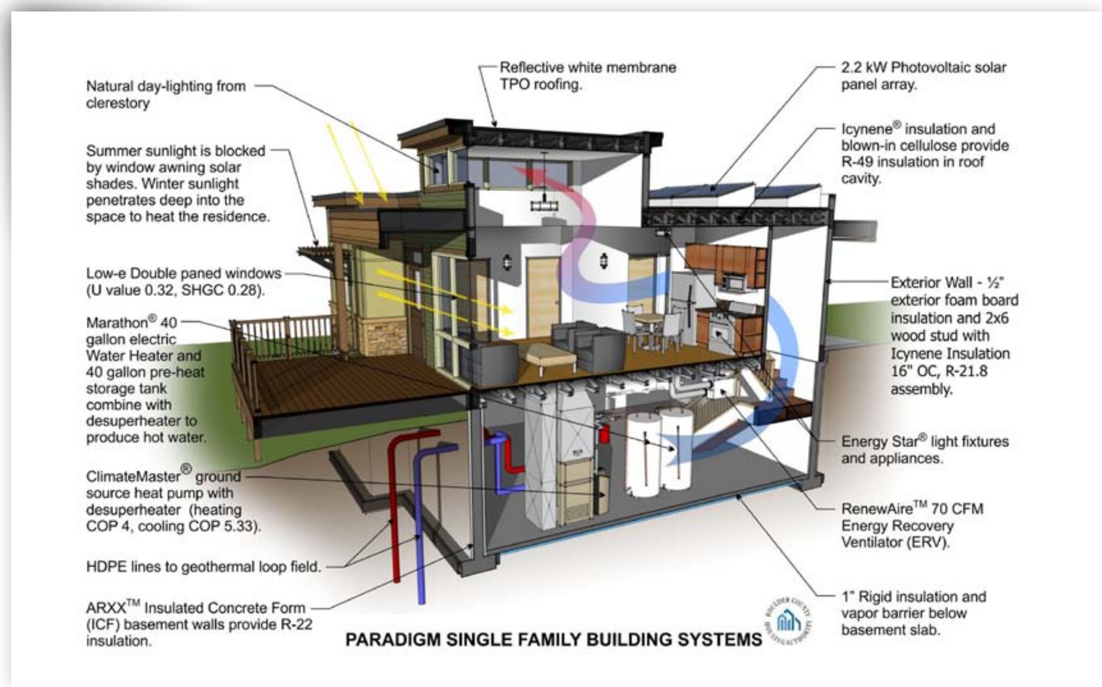

Figure 9. Josephine Commons final net zero energy building. *Illustration from HB&A Architects*

NREL determined that the site would need to install a 6 kW PV system on each building to reach a true net zero energy development. Given the design characteristics for the Josephine Commons development, the total installed costs are \$120 to \$129/ft^2 for phase 1 of the development (including the senior housing building and two duplex units). Phase II of the project will include all of the remaining residential units and is projected to come in at a lower cost per square foot, based on the economies of scale of the second phase. The 6 kW of PV on each building would add an additional \$9.21/ft^2 to \$14/ft^2 of capital cost to the development if the housing authority were to purchase the PV systems outright.

The specific design criteria for all of the baseline buildings, the Paradigm Pilot Project, and the Josephine commons project are provided in Table 1.

Conclusion and Recommendation

NREL found the all-electric home with a GSHP, DSH, super insulated building envelope construction elements, and roof-mounted photovoltaic systems to be the most cost-effective option and, if executed correctly, would result in a net zero energy development. The final design that was optimized for energy efficiency produced a 52% source energy savings over an IECC 2006 baseline and the 6 kW PV system would result in a net zero energy development for the low-use tenants. The proposed building systems are commercially available, highly efficient, and simple solutions that provide a cost-effective means of achieving a net zero energy development with minimum capital costs and operation and maintenance costs.

Table 1: Design Criteria for Baseline Buildings, the Paradigm Pilot Project, and the Josephine Commons Project

	Paradigm Pilot Duplex	Paradigm Pilot Ranch House	Josephine Commons
Finished floor area	1732 ft^2	1014 ft^2	1954 ft^2
Bedrooms/bathrooms	3 bed / 2 bath	2 bed / 1 bath	3 bed / 2 bath
Orientation (S = 0o)	Facing southwest (150o)	Facing southwest (150o)	Front facing north (180o)
Neighbors	at 20 ft	at 20 ft	at 20 ft
Heating/cooling set point	71° F to 73 F constant	71° F to 73° F constant	71° F w/setback 65° F (wkdy) / 76° F w/ setup to 85° F
Misc. hot water loads	Low-flow showers and sinks	Low-flow showers and sinks	Low-flow showers and sinks
Walls	R-22 spray foam, 2x6 16" oc + 0.5" foam (R-21.8 effective)	R-22 spray foam, 2x6 16" oc + 0.5" foam (R-21.8 effective)	R-30 spray foam, 2x6 16" oc + 0.5" foam (R-30 effective)
Ceiling	Spray foam and batt insulation (R-50 effective)	Spray foam and batt insulation (R-50 effective)	Spray foam and batt insulation (R-60 effective)
Roof material	White TPO (absorptivity 0.3)	White TPO (absorptivity 0.3)	White TPO (absorptivity 0.3)
Radiant barrier	None	None	None
Unfinished basement	ICF Foundation (R-22 effective)	ICF Foundation (R-22 effective)	ICF Foundation (R-22 effective)
Window area		(north 125 ft^2, south 173 ft^2, east 42.3 ft^2, west 81.3 ft^2)	(north 108 ft^2, south 145 ft^2, east 54 ft^2, west 54 ft^2)
Window type	2-Pane (U-Value 0.32, SHGC 0.28)	2-Pane (U-Value 0.32, SHGC 0.28)	3-Pane (U-Value 0.28, SHGC 0.5)
Overhang (east, west, south façade)	None	None	2ft @ 6 in above window
Infiltration (avg. annual ACH)	0.1	0.1	0.1

	Paradigm Pilot Duplex	Paradigm Pilot Ranch House	Josephine Commons
Mechanical ventilation	ERV, 100% of ASHRAE 62.2	ERV, 100% of ASHRAE 62.2	ERV, 100% of ASHRAE 62.2
Furnace	96% eff. Condensing	None	None
Air conditioner	None	None	None
Ground source heat pump	None	4.0 COP heating, 18.2 EER cooling, forced air system	4.0 COP heating, 18.2 EER cooling, forced air system
Water heater	On-demand natural gas	Conventional electric tank, 0.94EF, 40 gallons with de-super heater	Conventional electric tank, 0.94EF, 40 gallons with de-super heater
Refrigerator	ENERGY STAR	ENERGY STAR	ENERGY STAR
Cooking range	Electric	Electric	Electric induction
Dishwasher	ENERGY STAR Electric	ENERGY STAR Electric	ENERGY STAR Electric
Clothes washer	ENERGY STAR Electric	ENERGY STAR Electric	ENERGY STAR Electric
Clothes dryer	Electric	Electric	Electric
Hardwired lighting	100% CFL	100% CFL	100% CFL
Plug-in lighting	100% CFL	100% CFL	100% CFL
Renewable energy	2.2 kW PV system, 30 evacuated tube solar hot water	2.2 kW PV system	6.0 kW PV system

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