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CO-DESIGN OF ENERGY-EFFICIENT HOUSING WITH THE PINOLEVILLE-POMO NATION

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ABSTRACT

The Pinoleville-Pomo Nation of northern California is seeking to implement sustainable technologies and best practices that will increase their self sufficiency and meet their housing, energy, and water conservation needs. Since 2008, the Tribe has worked with UC Berkeley on sustainable community projects, including the design of a prototype "roundhouse" design, to be constructed in 2010 in Ukiah, California. Using an energy-efficient architecture and an analysis tool for selection of the engineered systems (the Native American Energy Analysis Tool, or NAEPA), the new homes are predicted to emit less than 50% of the carbon emissions over their lifetime, and have lower lifetime energy expenditures. The design methodology, energy analyses and life cycle assessment used by NAEPA will be discussed. Extensions to community-based housing energy plans and an optimization will also be discussed.

INTRODUCTION

The Pinoleville Pomo Nation (PPN) of northern California, and the University of California, Berkeley, have worked together on a wide range of projects since the beginning of 2008. Collaborative projects have included; assessment of retrofit potentials for existing Tribal homes, co-design of plans for new Tribal homes, and conceptual design of a renewable energy system to be implemented on Tribal lands.

The PPN initially contacted Dr. Alice Agogino from UC Berkeley to aid in the development of a new house design; this led to a collaborative co-design process, where Tribal members met with her and engineering students in Spring 2008. The preliminary roundhouse design that emerged from this class was refined by a student team (led by Tobias Schultz and Yael Perez, both graduate students at UC Berkeley) with the PPN into a final prototype roundhouse design, which will be constructed in 2010 (see Figure 1).

Existing building and community energy models haves focused on municipalities, regions, and countries [1,2]. Work in assessment and modeling of low and zero-energy homes has often focused on single homes, as well, and typically do not look at the multiple objectives of financing, construction emissions, and use-phase energy consumption [3,4].

In particular, there has been little or no work in the development of community-scale housing energy and emission models for Native American Tribes. The data collected in this work was used to build a software tool to analyze the energy systems incorporated into the prototype roundhouse. This paper details the methodology and results of the Native American Energy Plan Analysis (NAEPA) Tool. NAEPA was developed to aid in the development of a sustainable infrastructure for the Pinoleville Pomo Nation of northern California using an infrastructure that includes; (1) improvements to existing homes, (2) design of new homes, and (3) the implementation of a renewable energy system. These were the three primary degrees of freedom identified to be suitable for investments by the PPN. The development of the roundhouse is a special case of the sustainable infrastructure development, involving a single new home.

The NAEPA tool seeks to find the most cost-effective means of minimizing recurring initial investment costs, energy expenditures, and lifetime carbon emissions. It was developed in conjunction with the PPN, but is meant to have application for Native American Tribes around the country.

The tool as presented in this paper is designed for analysis; in the future, it will be incorporated into an optimization tool – Native American Energy Plan Optimization (NAEPO) – as discussed in the Future Work section.

MOTIVATION

Today, there is a strong interest in creating sustainable buildings that are energy efficient, both to reduce energy consumption and reduce carbon dioxide emissions. Carbon control legislation is pending on a federal level; government departments, some of which have been conservative in the past about investments in "green" building design, are looking to construct buildings which consume less energy, and emit less carbon [5].

Native American tribes have a critical need for housing. According to members of the Senate Indian Affairs Committee, roughly 90,000 American Indian families are homeless or under-housed; more than 30 percent of reservation households are crowded; 18 percent are severely crowded; one in five American Indian houses lacks complete plumbing facilities; and fewer than 50 percent of homes on reservations are connected to a public sewer system. Regional variations exist; according to an EPA report, Native American tribes in Arizona have a rate of substandard housing of over 60% [6].

Native American communities, however, are severely constrained in available funding for building construction; 90% of all funding for housing is provided by the federal government. In the past, these home designs have focused on minimizing the initial investment cost, and are typically constructed with poor insulation, "commodity" house layout plans, and energy-inefficient equipment and appliances.

The PPN are no exception to these trends. Assessment of the annual household energy expenditures of PPN Tribal members in Lakeport, California, found that their energy consumption was in excess of four times the nationwide average, and nearly six times the California average, mostly due to poor insulation in their low-cost homes [7]. Questionnaires given to PPN residents indicated that these homes were overcrowded, with five or six residents inhabiting two and three-bedroom homes.

Due to the crisis in supply for Native American housing, tribes across the country are seeking to build more sustainable, and affordable, housing stock. Since the passage of the Native American Housing Assistance and Self-Determination Act (NAHASDA) in 1996, Tribes have been given much more autonomy in the design and deployment of their housing stock, and have shown a strong interest in the design of sustainable, culturally-appropriate housing.

Figure 1: FINAL ROUNDHOUSE PROTOTYPE DESIGN.

In addition to housing shortages, many Tribes across the country are energy impoverished; studies exist which show that electrification rates on some Tribal lands are on par with developing regions. At the same time, renewable energy potential has been shown to often be disproportionately high on Tribal lands [8]. For Tribes like the PPN, the harnessing of clean, "natural" resources like the sun and wind are very appealing culturally, as well, leading to a coincidence of factors encouraging the development of renewable energy technologies on Tribal lands. The PPN is subject to the same concerns as other Tribes across the country, and are seeking to minimize energy expenditures for their Tribal members, as well as reduce their environmental impact.

GOALS OF THE PINOLEVILLE-POMO NATION

The PPN is interested in deployment of a Tribal Energy and Land Use Sustainability (TELUS) Plan, which incorporates the design of sustainable housing and renewable energy generation technologies; the PPN has obtained federal funding to implement these systems. Their motivation for the TELUS Plan is to capture energy savings for their Tribal members, and at the same time to minimize water consumption and lifetime carbon emissions. These minimization goals are constrained by finite levels of funding obtained from the Department of Energy, Housing and Urban Development, and other federal and local funding sources.

PPN residents and stakeholders have a strong interest in the preservation of the environment, both in principle, as well as for practical matters. In general, Tribal cultural values show a strong interest in environmental stewardship and Tribal governments are also encouraged at a federal level to measure and limit carbon emissions. Thus a proactive stance in emission reductions is especially beneficial to Tribes [10].

The TELUS plan can be summarized as a set of four qualitative objectives.

1. Financial security, for the Tribe and Tribal citizens.
2. Environmental stewardship and harmony.
3. Promotion of health and safety of Tribal citizens.
4. Tribal sovereignty.

The PPN has identified three sustainability strategies in the TELUS plan:

1. Improvements to existing housing stock (retrofits).
2. Construction of new homes.
3. Implementation of a renewable energy generation system on Tribal lands.

The long-term goal of the Native American Energy Plan Analysis (NAEPA) tool is to offer design recommendations consistent with the TELUS strategies and objectives. The work presented in this paper focuses on improvements to existing housing stock and the design of new housing, with outputs of initial costs, recurring energy expenditures, and lifetime carbon emissions. Inclusion of renewable energy systems and water consumption is set to be developed later in 2010 (see Future Work). The results presented here, with a focus on housing, can be seen as a special case of the general NAEPA analysis methodology.

SYSTEM MODEL

To fulfill the qualitative objectives, NAEPA focuses on three quantitative outputs; total initial costs, annual energy expenditures, and lifetime carbon dioxide emissions. NAEPA takes a portfolio view, by incorporating degrees of freedom for multiple houses. It is designed to provide an equipment list for an entire housing plan, not just a single home. Figure 2 presents the primary inputs, and outputs, of the NAEPA tool.

The satisfaction of the four objectives described for the TELUS plan is accomplished by analysis of three quantitative metrics, which comprise the multiple objectives of the NAEPA tool; initial costs, annual recurring energy expenditures, and lifetime carbon emissions. The three cardinal outputs of NAEPA were chosen for two reasons: (1) they represented metrics of high importance to the Tribe, and (2) could be assessed by data that was feasible to collect under the time constraints of the project. Water consumption was another metric of high importance to the Tribe, but its inclusion into the NAEPA model has not yet been performed (see the Future Work section).

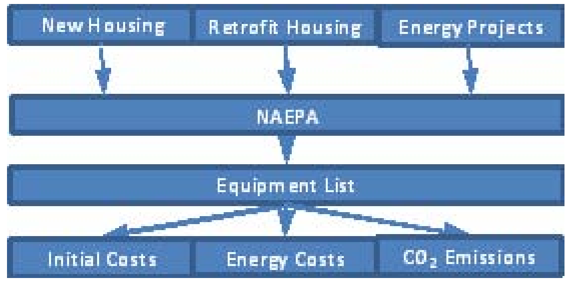

Figure 2: INPUTS AND OUTPUTS TO NAEPA MODEL.

Initial and recurring energy expenditures were disaggregated due to the separation of funding sources for PPN homes; while it is typically federal agencies which provide the initial installation costs, it is Tribal members living in the homes that pay the energy bills. Lifetime expenditure as a single number was not a relevant metric, either to the government agencies paying for the home, nor for the Tribal members residing in them. For this reason, analysis of cost in NAEPA is disaggregated into initial and recurring costs rather than summed into a single lifetime cost.

Each of the multiple objective functions in NAEPA below is dependent on the three sustainability strategies in the TELUS plan: improvements in retrofit housing, construction of new housing, and implementation of a renewable energy generation system. The analysis presented here is a special case, for housing systems.

Total Initial Costs, X_I

This term is the sum of all the initial costs, including such items as construction costs, costs of new equipment, and etc. Data sources include information from suppliers, and estimates from engineering firms.

Energy Expenditures, X_R

This term is the sum of all financial energy expenditures of to be incorporated into the TELUS plan, on an annual basis over the course of the plan's 40-year lifetime. This total lifetime cost is a net present value, using a discount rate of 7%. Information includes cost points from PG&E, local propane provider, as well as projections on energy generation estimates from the renewable energy system (rooftop photovoltaic and solar water heating arrays). For all cases, the lifetime of the house projects presented here are taken as 40 years.

Lifetime Carbon Emissions, E

This quantity is based on a life-cycle assessment of all components going into the TELUS plan. An economic input-output life cycle assessment model is used in this calculation to estimate initial carbon emissions [11]. Using emission factors for grid power from the local utility (PG&E), and for combustion of propane and natural gas, use phase emissions were also created for homes the renewable energy systems [12,13,14]. Use phase emission factors for the combustion of propane and natural gas also included manufacturing and distribution emissions. Table 1 contains information on the source of calculations for the carbon emissions.

Table 1: LIFE CYCLE ASSESSMENT DATA SOURCES AND SCOPE.

Scope	Includes	Data Source
Scope 1	Natural Gas and Propane Combustion	Emission Factors from Energy Information Administration [14]
Scope 2	Electricity Consumption (PG&E)	Electricity Source Factors from Pacca & Horvath [12], with PG&E Fuel Mix [13]
Scope 3	New Equipment, Construction, Manufacture of Natural Gas and Propane	EIO-LCA model [11]

The calculations for X_I, X_R, and E, for improvements to existing housing stock and construction of new housing, depend on a variety of equipment and appliance inputs, and design considerations. The equipment choices in the house designs which can be varied are given in Appendix A. The table presented there shows all of the design variables that can be varied in the TELUS plan, and what data points differ for each selection. Table 10 and equations 5, 6, and 7 (in the Appendix) represent the analysis methodology of NAEPA.

The NAEPA model is in Excel spreadsheet format, and was used to select the systems used in the prototype roundhouse design, constructed on land in Ukiah. This allowed for quick comparisons of the costs and emissions of several design options, to determine the best selection of equipment for this specific home design.

RESULTS

The NAEPA model was used to evaluate initial costs, energy expenditures, and lifetime CO_2 emissions (X_I, X_R, and E) for a single home, as well as to conduct a preliminary evaluation of an integrated housing plan, including two new homes and two existing ones in Ukiah, California.

Comparative monetary savings and carbon reductions to conventional home construction are also presented, variables which will be referred to as C_I, C_R, and R.

Lifetime energy expenditures are calculated using a discount rate of 7%.

Case Study: Roundhouse

The equipment list for the prototype roundhouse was selected using the NAEPA Tool. The roundhouse included non-standard features such as a solar hot water (SHW) and photovoltaic (PV) array, straw-bale insulation, and a ground-source heat pump (GHP) for the heating, ventilation, and air conditioning (HVAC) system. A comparison is made to a conventional house construction. The equipment options selected that are different from the conventional home design are listed in Table 2.

Key metrics for the roundhouse are given in Table 3. In addition calculating X_I, X_R, and E for the whole home, values were assessed for the individual engineered systems in the home; these values are shown in Table 4.

Table 2: ROUNDHOUSE EQUIPMENT OPTIONS. (Variables not shown are identical in roundhouse and conventional design. See table and equations in Appendix for description of decision indices and associated equations.)

Decision Index	Roundhouse	Conventional
NEM	Straw Bale insulation	Fiberglass Insulation
NEPV	5 kW PV Array	No PV Array
NESHW	2 collector SHW system	No SHW system
NEHC / NECC	GHP, closed loop	Propane furnace, conventional air conditioning
NEDS	Desuperheater	No desuperheater
NEWH	Electric 91% AFUE	Propane 59% AFUE
FOE	No fuel	500-gal propane tank
SHWOE	119-gal water storage tank	No extra storage
NETWH	3.9 GPM electric	No tankless water heater
NEAPP	Energy star appliances	Not energy star appliances

Table 3: RESULTS FROM NAEPA FOR ROUNDHOUSE DESIGN. (A 40-year lifetime is assumed for all results.)

Objective	X_I (Savings)	Annual X_R (Savings)	Lifetime X_R (Savings)	Lifetime E (Savings)
Units	USD 2009$	USD 2009$	USD 2009$	MT CO_2e
Round-house	270,000 (-70,000)	410 (1,800)	5,200 (22,000)	170 (200)

Table 4: ENGINEERED SYSTEMS FOR ROUNDHOUSE DESIGN.

Objective	X_I (Savings)	Annual X_R (Savings)	Lifetime X_R (Savings)	Lifetime E (Savings)
Units	USD 2009$	USD 2009$	USD 2009$	MT CO_2e
PV Array	36,000 (-36,000)	-1,400 (1,400)	-18,000 (18,000)	-102 (102)
SHW array Heating	8,200 (-6,200)	85 (340)	1,000 (4,300)	10 (62)
HVAC	8,300 (0)	160 (270)	2,000 (3,300)	18 (57)

Case Study: Community Housing Plan

NAEPA was used on two proposed new construction and retrofit projects, both of which the PPN are considering for its TELUS plan. The retrofit buildings are both located in Lakeport, California, while the proposed new homes are located in Ukiah. New Home 1 is identical to the roundhouse; New Home 2 differs from New Home 1 only in the HVAC and SHW systems, which incorporate a conventional electric furnace and A/C and one-panel system, respectively. Retrofit 1 and retrofit 2 are based on actual buildings. Differences in equipment options and home design are given in Table 5.

Table 5: COMMUNITY PLAN EQUIPMENT OPTIONS FOR RETROFIT BUILDINGS. (Variables not shown are identical.)

Decision Index	**Retrofit 1**	**Retrofit 2**
BH (kWh/yr)	2,400	25,000
BC (kWh/yr)	600	11,000
BWH (kWh/yr)	14,000	16,000
NEPV (existing)	No PV Array	4 kW PV array
NESHW (existing)	4 collector system (No SHW system)	4 collector system (No SHW system)
NEHC AFUE (existing)	Propane furnace 92% (Propane 80%)	Electric furnace 99% (Elec. furnace 99%)
NECC COP (existing)	A/C 4.10 (A/C 2.93)	A/C 4.10 (A/C 2.93)
NEWH AFUE (existing)	Propane WH 59% (Propane WH 59%)	Electric WH 92% (Electric WH 87%)
SHWOE (existing)	2x 119-gal tanks (No SHWOE)	2x 119-gal tanks (No SHWOE)
NEAPP (existing)	Propane appliances (No change)	Electric appliances (No change)

The results of this community plan are shown in Table 6. The expenditures per home unit are shown in Table 7.

Table 6: RESULTS FROM COMMUNITY HOUSING PLAN.

Objective	X_I (Savings)	Annual X_R (Savings)	Lifetime X_R (Savings)	Lifetime E (Savings)
Units	USD 2009$	USD 2009$	USD 2009$	MT CO_2e
Commun-ity Plan	600,000 (-200,000)	14,000 (10,000)	170,000 (130,000)	1,600 (830)

Table 7: RESULTS FROM NAEPA FOR COMMUNITY HOUSING PLAN, BY HOUSING UNIT.

Objective	X_I (Savings)	Annual X_R (Savings)	Lifetime X_R (Savings)	Lifetime E (Savings)
Units	USD 2009$	USD 2009$	USD 2009$	MT CO_2e
New Home 1	270,000 (-70,000)	410 (1,800)	5,200 (22,000)	170 (200)
New Home 2	270,000 (-68,000)	700 (1,500)	8,700 (18,000)	200 (170)
Retrofit 1	18,000 (-18,000)	5,200 (3,200)	64,000 (40,000)	550 (160)
Retrofit 2	43,000 (-43,000)	7,500 (3,800)	94,000 (48,000)	670 (300)

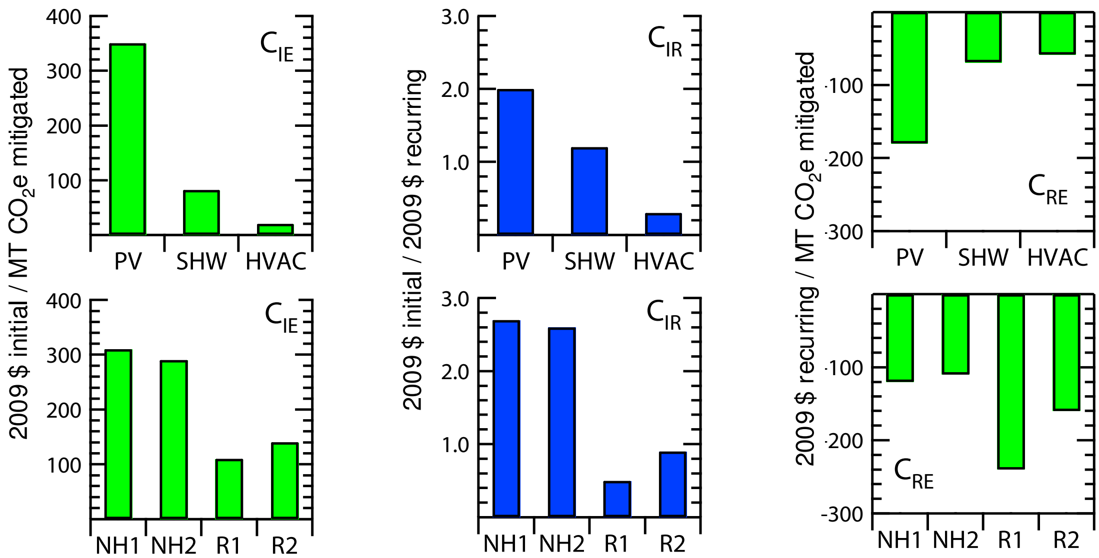

Figure 3: PLOTS OF SUBSIDIARY METRICS. (PV = photovoltaic array, SHW = solar hot water system, HVAC = heating and cooling systems, NH1, NH2 = New Homes 1 AND 2, R1, R2 = Retrofit Homes 1 AND 2.)

Results from the retrofit improvements vary case-by-case; as can be seen, retrofit 2 has dramatically higher energy consumption overall, resulting in its higher emission savings seen in Table 7.

DISCUSSION

A set of subsidiary metrics was developed, to identify the most beneficial financial outlays for reducing energy expenditures and carbon dioxide emissions. These metrics are based on the comparative values of X_I, X_R, and E.

1. C_I is the initial cost difference (USD 2009 $) between proposed project and conventional (or existing) project.
2. C_R is the lifetime energy cost difference (USD 2009 $) between proposed project and conventional (or existing) project.
3. R is the lifetime carbon dioxide mitigation (in metric tons) between proposed project and conventional (or existing) project.

Three subsidiary metrics are developed, based on C_I, C_R, and R:

1. C_{IR} : Initial costs per unit lifetime energy cost savings.
2. C_{IE} : Initial costs per unit CO_2e reduction.
3. C_{RE} : Lifetime energy cost per unit CO_2e reduction.

The first and second metric are a measure of the cost-effectiveness of various systems, at reducing Tribal energy expenditures, and lifetime carbon emissions. The third is a unit cost-effectiveness of Tribal expenditures at reducing carbon emissions. Subsidiary metrics are presented for both the roundhouse and community projects.

$$C_{IR} = \frac{C_I}{C_R} \quad (1)$$

$$C_{IR} = \frac{C_I}{R} \quad (2)$$

$$C_{RE} = \frac{C_R}{R} \quad (3)$$

The subsidiary metrics were also applied to the individual engineered systems and home projects for the roundhouse and community housing plan.

Case Study: Roundhouse

As shown in Table 8, it is the alternative heating and cooling system (a ground-source heat pump) that results in the most cost-effective use of federal funding. Each investment of $0.30 into this system results in $1.00 of energy savings over the lifetime of the home, while each investment of $20 results in one ton of CO_2e emission reductions.

The difference from the Tribal perspective is notable; all of the systems result in energy savings, the PV array being the most cost-effective at emissions reductions.

Table 8: SUBSIDIARY METRICS FOR ROUNDHOUSE PROJECT.

Objective	C_{IR}	C_{IE}	C_{RE}
Units	2009$ / 2009$	2009$ / MT CO_2e	2009$ / MT CO_2e
PV Array	2.0	350	-180
SHW Array	1.2	82	-69
HVAC	0.3	20	-58

Case Study: Community Housing Plan

The retrofit projects are more cost-effective than the new home projects, for reducing the financial burden on Tribal members, as well as in reducing carbon emissions. This is true for federally and Tribally provided funding. **Error! Reference source not found.** and **Error! Reference source not found.** contain the subsidiary metrics for the roundhouse and community plan projects.

CONCLUSIONS AND FUTURE WORK

The importance to Native American Tribes of three types of investments was discussed; retrofits to existing homes, construction of new buildings, and investments in energy systems. The Native American Energy Plan Analysis (NAEPA) tool was introduced as a way for Tribes to create diversified and cost-effective energy plans. The Tribal Energy and Land Use Sustainability (TELUS) plan, and the NAEPA model's results for a single home, as well as for a set of homes, was introduced. Expected savings in energy expenditures and reductions of carbon emissions were discussed, and broken down by separate engineered system to be incorporated into the housing.

Water consumption was left out of NAEPA; this will be included in future versions of the model, as being of high importance to the Pinoleville-Pomo Nation. The NAEPA model will also be expanded to include renewable energy portfolio systems, so that the optimal equipment mix, to minimize all metrics of importance, can be identified.

Full operation and maintenance costs were not included in NAEPA, due to lack of data. This will be addressed as soon as the data can be obtained.

The NAEPA analysis tool will be integrated into a multi-objective mathematical optimization tool to minimize initial costs, energy costs, carbon emissions, and water consumption, according to equation 4. X_I, X_R, and E are defined as in NAEPA; W is the end-use water consumption.

$$f = \rho_U \cdot X_I + \rho_R \cdot X_R + \rho_E \cdot E + \rho_W \cdot W \quad (4)$$

These four primary metrics have different importance to the PPN. The weighting factors $\rho_U, \rho_R, \rho_E, \rho_W$ account for these variations. The factors are chosen to normalize the units in each quantity, so that they are comparable; the magnitude of the weighting factors also determines the importance of each quantitative metric. Development of the least carbon-intensive TELUS plan, for example, would mean setting $\rho_U = 0, \rho_R = 0, \rho_W = 0, \rho_E = 1$, which would mean only the minimization of carbon emissions (*E)* would be of importance.

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APPENDIX A

The table presented shows all of the design variables that can be varied in the TELUS plan, and what data points differ for each selection.

Table 9: EQUIPMENT OPTIONS AND PARAMETERS USED IN CALCULATION OF X_I, X_R, AND E.

Decision Index	Equipment Description	Data Variables	Data Includes
NEM	Construction Material	NEM_I NEM_{EFF} NEM_{CO2}	Initial cost per square foot (2009 $ / psf) HVAC efficiency Pre-use phase CO_2 emissions (kg CO_2e)
NESHW	Solar Hot Water Collectors (SHW)	$NESHW_I$ $NESHW_G$ $NESHW_{CO2}$ $NESHW_{NO}$	Initial cost per collector (2009 $) Energy generation (kWh/yr) Pre-use phase CO_2 emissions (kg CO_2e) Number of collectors
NEPV	Photovoltaic (PV) Panels	$NEPV_I$ $NEPV_G$ $NEPV_U$ $NEPV_{CO2}$ $NEPV_{NO}$	Initial cost per panel (2009 $) Panel output (W) Utilization factor Pre-use phase CO_2 emissions (kg CO_2e) Number of collectors
NEPVI	Inverter for PV Array	$NEPVI_I$ $NEPVI_{EFF}$ $NEPVI_C$ $NEPVI_{CO2}$	Initial cost (2009 $) Transmission efficiency Annual energy consumption (kWh/yr) Pre-use phase CO_2 emissions (kg CO_2e)
NEPVC	Load Controller for PV Array	$NEPVC_I$ $NEPVC_{EFF}$ $NEPVC_C$ $NEPVC_{CO2}$	Initial cost (2009 $) Transmission efficiency Annual energy consumption (kWh/yr) Pre-use phase CO_2 emissions (kg CO_2e)
NEPVD	Manual Disconnect for PV Array	$NEPVD_I$ $NEPVD_{CO2}$	Initial Cost (2009 $) Pre-use phase CO_2 emissions (kg CO_2e)
NEB	Battery Array	NEB_I NEB_{EFF} NEB_{CO2} NEB_{NO}	Initial cost (2009 $) Storage efficiency Pre-use phase CO_2 emissions (kg CO_2e) Number of batteries
NEGT	Grid-Tie Option	$NEGT_I$ $NEGT_{CO2}$	Connection cost (2009 $) Pre-use phase CO_2 emissions (kg CO_2e)
NEHC	Space Heating Equipment	$NEHC_I$ $NEHC_{EFF}$ $NEHC_F$ $NEHC_{CO2}$	Initial cost (2009 $) Furnace efficiency Fuel type Pre-use phase CO_2 emissions (kg CO_2e)
NEDS	Desuperheater (Heat pump system)	$NEDS_I$ $NEDS_G$ $NEDS_{CO2}$	Initial cost (2009 $) Heat generation (kWh/yr) Pre-use phase CO_2 emissions (kg CO_2e)
NECC	Space Cooling Equipment	$NECC_I$ $NECC_{EFF}$ $NECC_{CO2}$	Initial cost (2009 $) Cooling efficiency (COP) Pre-use phase CO_2 emissions (kg CO_2e)
NEWH	Direct Water heating	$NEWH_I$ $NEWH_S$ $NEWH_{EFF}$ $NEWH_F$ $NEWH_{CAP}$ $NEWH_{CO2}$	Initial cost (2009 $) Tank size (gal) Heating efficiency Fuel type Heating capacity (Btu/hr) Pre-use phase CO_2 emissions (kg CO_2e)
NEVS	Ventilation System	$NEVS_I$ $NEVS_F$ $NEVS_{EFF}$ $NEVS_{CO2}$	Initial cost (2009 $) Fuel type Efficiency Pre-use phase CO_2 emissions (kg CO_2e)
SHWOE	Additional Equipment for SHW System	$SHWOE_I$ $SHWOE_{CO2}$	Initial cost (2009 $) Pre-use phase CO_2 emissions (kg CO_2e)
FOE	Additional Equipment for Gas Fuels	FOE_I FOE_{CO2}	Initial cost (2009 $) Pre-use phase CO_2 emissions (kg CO_2e)
NAWP	Water Pump	$NAWP_I$ $NAWP_C$ $NAWP_{CO2}$	Initial cost (2009 $) Annual energy consumption (kWh/yr) Pre-use phase CO_2 emissions (kg CO_2e)
NATWH	Tankless Water Heater	$NETWH_I$ $NETWH_{EFF}$ $NETWH_F$ $NETWH_{CO2}$	Initial cost (2009 $) Heating efficiency Fuel type Pre-use phase CO_2 emissions (kg CO_2e)
NEAPP	Appliances	$NEAPP_I$ $NEAPP_C$ $NEAPP_{CO2}$	Initial cost (2009 $) Annual energy consumption (kWh/yr) Pre-use phase CO_2 emissions (kg CO_2e)

The equations below show the mathematical formulation of the NAEPA model.

$$X_I = SF \times NEM_I + NESHW_{NO} \times NESHW_I + NEPV_{NO} \times NEPV_I + NEPVI_I + NEPVC_I + NEPVD_I + NEB_{NO} \times NEB_I + NEGT_I + NEHC_I + NEDS_I + NECC_I + NEWH_I + NEVS_I + SHWOE_I + FOE_I + NAWP_I + NETWH_I + \sum NEAPP_I \tag{5}$$

$$\begin{aligned} X_R = {} & (BWH - NESHW_{NO} \times NESHW_G - NEDS_G) \times [NEWH_{EFF}]^{-1} \times FC_i + \\ & BH \times [NEVS_{EFF} \times NEHC_{EFF}]^{-1} \times FC_i + BC \times [NEVS_{EFF} \times NECC_{EFF}]^{-1} \times FC_i + \\ & (NEPVC_C + NEPVI_C + NAWP_C) \times FC_{electricity} + NATWH_C \times FC_i + \sum FC_i \times NEAPP_C \\ & - (NEPV_{NO} \times NEPV_G \times NEPV_U \times NEPVI_{EFF} \times NEPVC_{EFF} \times NEB_{EFF}) \times FC_{electricity} \\ & + SF \times L \times FC_{electricity} \end{aligned} \tag{6}$$

$$\begin{aligned} E = {} & SF \times NEM_{CO2} + NESHW_{NO} \times NESHW_{CO2} + NEPV_{NO} \times NEPV_{CO2} + NEPVI_{CO2} + NEPVC_{CO2} + \\ & NEPVD_{CO2} + NEB_{NO} \times NEB_{CO2} + NEGT_{CO2} + NEHC_{CO2} + NEDS_{CO2} + NECC_{CO2} + NEWH_{CO2} + NEVS_{CO2} + \\ & SHWOE_{CO2} + FOE_{CO2} + NAWP_{CO2} + NETWH_{CO2} + \sum NEAPP_{CO2} + \\ & (BWH - NESHW_{NO} \times NESHW_G - NEDS_G) \times [NEWH_{EFF}]^{-1} \times FE_i + \\ & \begin{bmatrix} BH \times [NEVS_{EFF} \times NEHC_{EFF}]^{-1} \times FE_i + BC \times [NEVS_{EFF} \times NECC_{EFF}]^{-1} \times FE_i + \\ (NEPVC_C + NEPVI_C + NAWP_C) \times FE_{electricity} + NATWH_C \times FE_i + \sum FE_i \times NEAPP_C \\ - (NEPV_{NO} \times NEPV_G \times NEPV_U \times NEPVI_{EFF} \times NEPVC_{EFF} \times NEB_{EFF}) \times FE_{electricity} \\ + SF \times L \times FE_{electricity} \end{bmatrix} \times H \end{aligned} \tag{7}$$

Constants

SF = square footage of home
BH = base space heating needs
BC = base space cooling needs
BWH = base water heating needs
L = lighting needs of home per square foot
FC_i = fuel cost for fuel type i (electricity, propane, or natural gas)
FE_i = fuel emissions factor for fuel type i (electricity, propane, or natural gas)
H = time horizon of interest