Early Experiences with a High-Elevation Off-Grid Solar Residence in Colorado

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Abstract

A new off-grid high-elevation solar residence located in Colorado is described. Key design objectives were to size the solar/battery storage system to provide reliable power without the need for power backup. The residence features high R values for the walls and ceiling and low U values for the windows and uses highly efficient lighting and appliances. To date, the key lessons learned are: 1) The high building efficiency and its passive features, efficient appliances, and careful load management practices, have led to an off-grid system that in most cases does not require backup power; 2) Nevertheless, despite a favorable solar resource, adequate battery storage is mandatory at times of prolonged cold, cloudy, and snowy weather; 3) Selection of a design-build team with a deep understanding of sustainable building practices and making good use of incentives of the Inflation Reduction Act go a long way to ensuring a successful and cost-effective installation.

Keywords: Off-grid residence, rooftop PV, battery storage, net-zero plus, residential load management

1. Introduction and Design Considerations

During the spring of 2020, the authors purchased a 7.5-acre parcel of forested land just east of the Continental Divide near Nederland, Colorado. The parcel is part of an old gold-mining claim. Although the authors have yet to find the motherlode that early settlers had anticipated, they did set forth to build an off-grid solar-powered mountain home on the property. Construction began in the Spring of 2022 and was completed in late summer 2023. This paper provides early results of the performance of the residence as a case study for off-grid home design.

A local design-build team experienced in designing and building energy-efficient homes that perform extremely well in the harsh Colorado mountain winters was commissioned. The final design was a 1000-ft^2 main level with a kitchen, a utility room, a full bathroom, a bedroom, a living room, and an entryway plus a second-level 308-ft^2 open loft with a half-bath. The roof rises from the south to the north at a ~22° angle (somewhat less than ideal for this latitude). Most of the windows are located on the south and western side of the house, providing an effective passive heat source during winter. The site is flat, at an elevation of 8850 ft (~2700 m).

Water is supplied by a well. A septic system was required. Both systems require pumps, which add to the overall electricity load of the residence.

2. The Final Build

The final structure (see Figures 1 and 2) is a highly energy-efficient residence. High R values for the exterior walls (R = 27) and ceiling (R = 54) and low U values for the windows (U = 0.16), along with the use of highly efficient electrical appliances and the

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installation of a wood stove, result in a Home Energy Rating System (HERS) Index of -53.

The solar system was sized based on estimated annual loads of approx.10,000 – 12,000 kWh. The result is a 7.3-kW rooftop solar system (twenty 365 kW_p rooftop-mounted panels totaling 36.6 m^2 in area) and a 24-kWh lithium ferrous phosphate battery storage system, using a 15 kW, 200-amp inverter.

Photo courtesy Andrew Finanger, IPS Solar

Fig. 1. Aerial view of residence, looking NE

Fig. 2. Authors in front of recently completed residence

Although the original plan was to install the majority of the house on a concrete slab, the excavation work necessary to allow for burial of water pipes and a septic system resulted in the opportunity to place the entire dwelling over a fully conditioned crawl space. A ducted HVAC (Heating, Ventilating and Air conditioning) system using a centralized 3-ton (36K-BTU) variable-speed heat pump was installed. The heat pump provides both heating and cooling through an air handler located in the crawl space.

A 10-kW resistance heat backup system is included inside the air handler, but has not been commissioned, since adequate interior temperatures are generally maintained through the heat pump and the wood stove. Because the efficiency of the residence results in such an air-tight structure (ACH50[1] = 1.73), an auxiliary Energy Recovery Ventilator (ERV) is required to maintain fresh air. Although the ERV and the air handler add to the electricity load, the conditioned crawl space, which must be kept above freezing due to the fire sprinkler system, provides a "passive" geothermal heat source, causing temperatures in the space to remain well above freezing. Thus, the conditioned crawl space itself can be a source of heat to the house in winter, as well as cooling during summer, serving to moderate high temperature fluctuations inside the residence.

The well water head is approximately 80 feet (~26 m) from the house. A submersible 110-volt pump delivers water from the well to the house via a buried water conduit. A

[1] Air Changes per Hour at 50 pascals pressure differential

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high-efficiency 40-gal. hybrid heat pump water heater is used to provide hot water to the residence.

The solar system was commissioned on August 21, 2023, and the HVAC system on September 7. The hybrid water tank was commissioned on September 11. The house was winterized in mid-November 2023 and the water turned back on in late April 2024.

3. Site Climatic and Solar Resource Characteristics

The site can be characterized as a cool montane continental climate. The site is near the top of the western side of a ridge that comprises part of the eastern Colorado Rockies foothills. To the west is a deep valley (Caribou Ranch), and further to the west is the Continental Divide. The site experiences frequent snowfall, sometimes heavy, from October to May. Summer rainfall comes primarily as afternoon thunderstorms. High winds are common, especially following winter storm events.

A Davis VantagePro2™ weather station was installed on a tripod in an open area near the residential site on August 16, 2020. The weather parameters (air temperature, barometric pressure, humidity, wind speed and direction at 2 m above ground, rainfall totals and rainfall rates) transmitted to a home computer on an hourly basis during the first year of operations, and since then have been transmitting at 15-minute intervals. The data are publicly available through a Davis WeatherLink™ subscription.[2]

The three full years of measurements (2021–2023) show a mean annual temperature ranging from 40.8˚F to 42.6˚F (4.9˚C to 5.9˚C). The warmest month is July, ranging from 62.6˚F to 63.5˚F (17.0˚C to 17.3˚C). But the coldest month in 2021 and 2022 was January (21.7˚F and 22.0˚F, or -5.7˚C and -5.6˚C), while in 2023 it was February (21.1˚F, or -6.1˚C). To date the highest recorded temperature was 89.6˚F (32.0˚C) in June 2021 and the lowest was -20.3˚F (-29.1˚C) in February 2021.

Heating Degree Days are tabulated for the site. These values are useful for assessing the heating requirements in a structure. Figure 3 provides the monthly average heating degree days along with the mean monthly temperatures over the 3 ¾ -year period that data are available. Annual average heating degree days (in ˚F) have ranged from 8410 to 8924, similar to regions in the upper Midwest and northern New England of the United States (Nadal and Fadali, 2024).

[2] Accessible at www.weatherlink.com; site name is "County Road 103, Nederland".

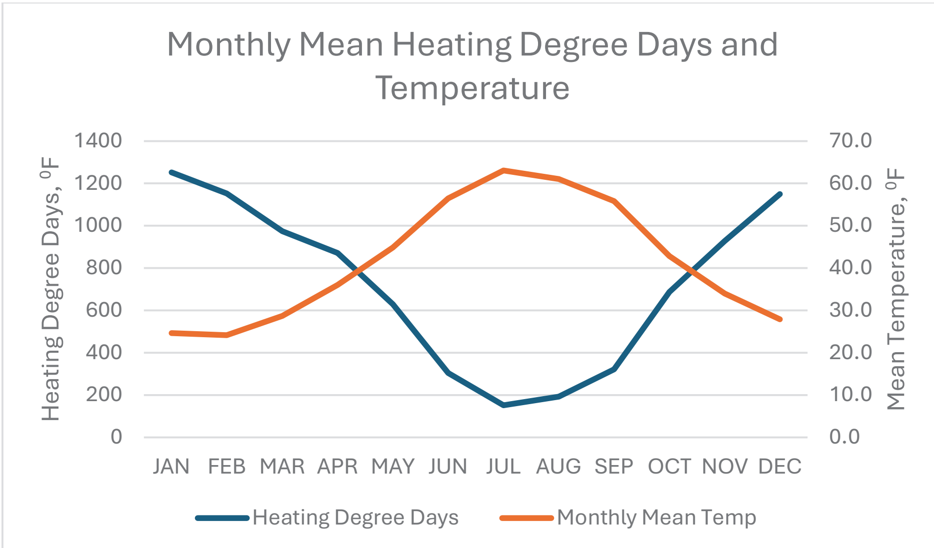

Fig. 3. Average total monthly heating degree days and monthly temperatures at the off-grid residence for the period August 2020 – May 2024, based on onsite measurements.

Average measured precipitation varied from 15.96 in (40.4 cm) in 2022 to 21.32 in (54.2 cm) in 2023. A significant source of annual precipitation is winter snowmelt.

There are no direct solar resource measurements at or near the site. Satellite-derived SolarAnywhere™,[3] data have been provided by Clean Power Research (2021).All historic hourly data (2013 – 2023), in units of W/m^2 for the tile in which the site resides, were downloaded using the most recent Version 3.7 of SolarAnywhere. Figure 4 provides information on the monthly average daily total values of Global Horizontal Irradiance (GHI) for each of the 11 years in which data are available.

[3] https://www.solaranywhere.com/

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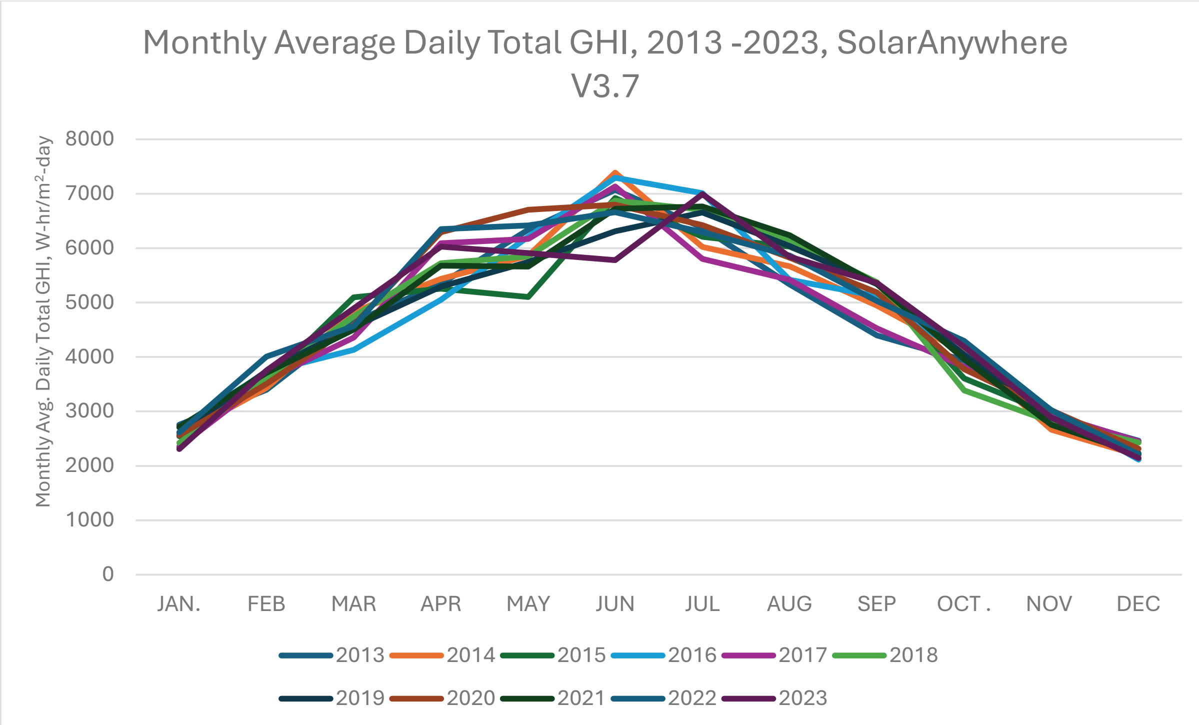

Fig. 4. Satellite-derived monthly average daily total GHI values at the location of the residence for the years 2013-2023. Data are from SolarAnywhere Ver. 3.7.

4. Early Results on Residential Energy Performance

This section provides a preliminary analysis of system performance on the degree to which the domestic loads are met directly from the solar panels vis-à-vis the storage batteries. The intention is for this analysis to continue in the future, so that the residence can serve as a relevant case study for off-grid solar living.

Several apps are available to monitor the performance of the inverter, water heater, and HVAC systems in the residence. These include 1) PowerView™, an app[4] provided by the inverter manufacturer, which offers 5-minute data on the performance of the solar system (inverter, PV output, battery storage, backup generator output, residential loads, and numerous other parameters); 2) the ecobee™ app[5] that provides 5-minute digital data of the HVAC performance; and 3) EcoNet™, an app that monitors the performance of the hybrid hot water heater. More information regarding the solar and HVAC systems is provided in the Appendix. A NETGEAR Nighthawk™ wireless router was installed at the residence to provide subscription-based internet service through the regional 5G network, enabling the performance of the solar, water heating, and HVAC systems to be monitored remotely.

[4] https://pv.inteless.com/plants; recently renamed https://www.solarkcloud.com/plants
[5] https://www.ecobee.com/consumerportal/index.html#/devices/thermostats/

Fig. 5 shows an example of electrical flow information provided by the PowerView app.

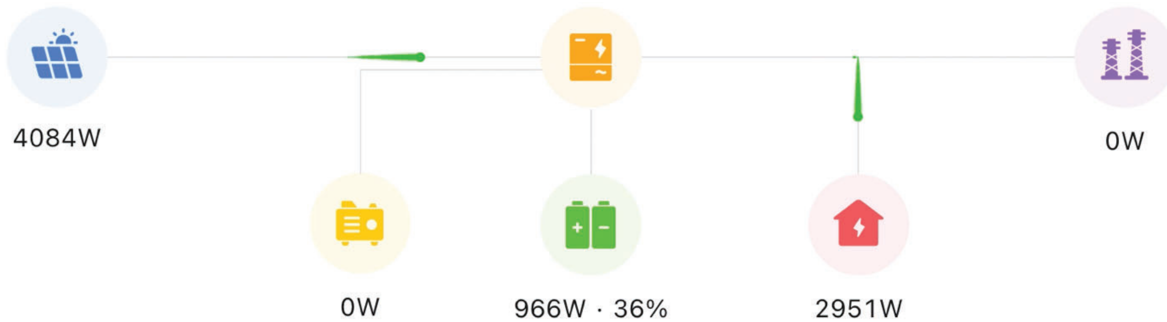

Fig. 5. Example PowerView power flow chart for the residence, taken on a sunny day in February when the HVAC system is operating. PV power flows from the panels (blue icon) to the inverter (orange icon), which then distributes the power to the batteries (green icon) and the electrical load (red icon). The backup generator (yellow icon) is not operating, and the grid (purple icon) is always zero since the residence is off the grid.

The app also provides daily summaries of these power flows. However, the app does not explicitly provide data on a "phantom load," ranging from 60–90 W, that is required for the internal operation of the inverter and batteries. This phantom load must first be calculated from the daily data that are available, which includes the household load, L, total PV power output, PV_{OUT}, and the charge and discharge of the batteries. The total phantom load$L_{PH,}$ can be expressed as the sum of the phantom load met by the PV system ($PV_{L,PH}$)) and the battery system ($B_{L,PH}$)):

$$L_{PH} = PV_{L,PH} + B_{L,PH} \quad (1)$$

The PV_{OUT} reported by PowerView represents only that output being used to meet the load (PV_L)), charge the battery (PV_{BAT})) or meet the phantom load: $PV_{OUT} = PV_{BAT} + PV_L + PV_{L,PH}$ or:

$$PV_{L,PH} = PV_{OUT} - PV_{BAT} - PV_L \quad (2)$$

Similarly, since battery charge comes exclusively from the PV when there is no external power source, the battery discharge (B_{OUT} is used to meet that portion of the load not met by the PV, plus the phantom load: $B_{OUT} = B_L + B_{L,PH}$, or:

$$B_{L,PH} = B_{OUT} - B_L \quad (3)$$

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Combining (2) and (3) into (1), the total phantom load can be determined from:

$$L_{PH} = (PV_{OUT} - L) - \Delta B \qquad (4)$$

Where ΔB is the difference between the reported daily charge and discharge of the battery.

Once the phantom loads are calculated from (4) the relative daily contribution of PV vs. battery to meeting the total household load, L_T , which is the sum of the reported load and the phantom load, can be calculated as follows:

$$PV\ contribution\ to\ load = L_T - B_{OUT} \qquad (5)$$

$$Battery\ contribution\ to\ load = B_{OUT} \qquad (6)$$

Although the solar and HVAC systems were commissioned in late summer 2023, performance data available from the residence are limited due to a variety of reasons: 1) the residence has been primarily unoccupied, limiting the electrical loads to the HVAC and a few small appliances, such as the mini-fridge; 2) the residence was winterized in mid-November, further reducing the load requirements, except for the HVAC, which remained on with low indoor temperature settings; 3) the inverter failed on December 3, 2023 and was replaced on January 11, 2024, resulting in a loss of nearly seven weeks of performance data.

For this analysis, data on those occasions when the backup generator is running are excluded; data are evaluated only for those conditions when the batteries are being charged by the PV, and the battery discharge is being used to meet that portion of the load (including the phantom loads) not met by the PV_{OUT} . Figure 5 shows that PV_{OUT} is used both to charge the batteries (that is, until they are fully charged) and meet the residential and phantom loads.

Figure 6 provides an analysis of the monthly average contribution of PV and batteries in meeting residential loads for those days in which no backup generation is required, and power is fully available throughout the day. Due to the 7-week inverter failure, data for December 2023 and January 2024 are quite limited. Also, measurements did not begin until Aug. 21, limiting data availability for August 2023. Nevertheless, the figure shows a pattern of the household being much more reliant on battery storage during the cooler, cloudier winter months than the warmer spring, summer, and fall months, as would be expected.

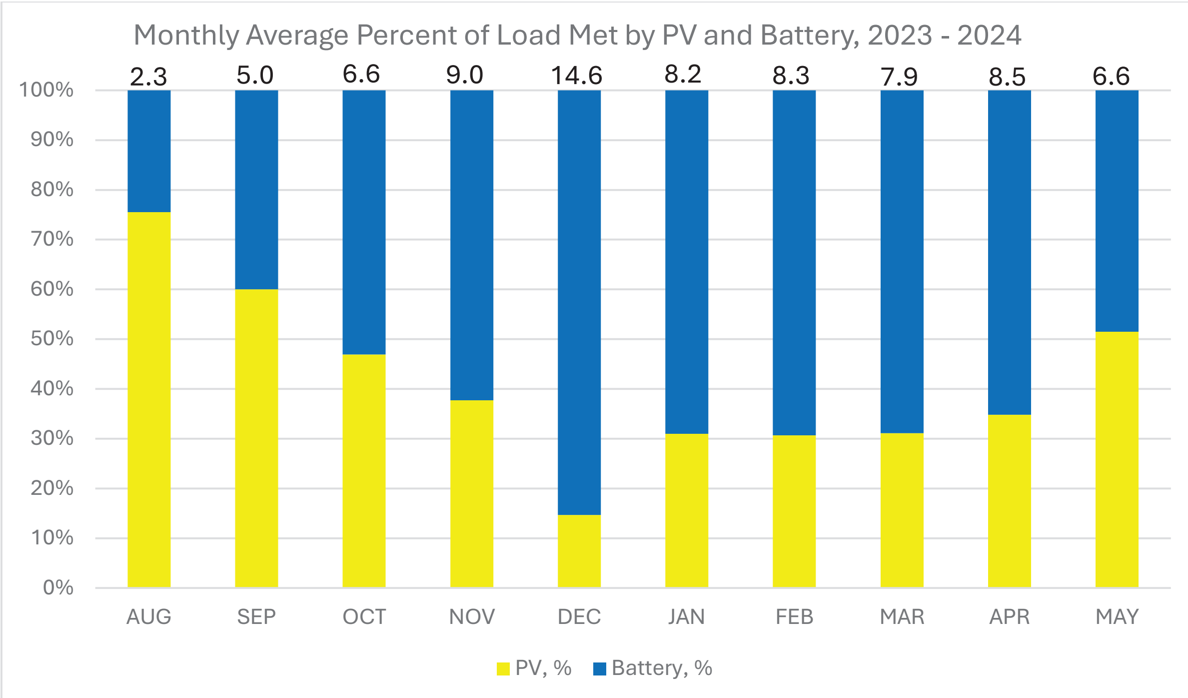

Fig. 6. Percentage of total monthly loads met by PV (yellow) and batteries (blue) when no external generator is used and inverter power to the house is fully on. Numbers above each bar represent the average daily load (kWh/day) for those days used in the analyses.

5. Summary and Future Plans

Some preliminary analysis of the performance of the off-grid solar system can be summarized here:

- ***Active load management is essential:*** On a typical sunny day, the State of Charge (SOC) of the battery storage system can reach 100% well before noon. This means that any further production of solar from the panels is "curtailed", other than what is used to meet the current loads. Accordingly, activities requiring high electricity use (e.g. clothes washing, EV charging, etc.) should be done during this period of full charge. In late afternoon and evening hours, electricity demand should be minimized to avoid too much reduction in SOC. Alternatively, during times of extensive cloudiness or snow-covered panels, electricity usage must be minimized at all times to avoid SOC dropping below 20%, at which point the inverter is designed to shut power off to the house to protect the batteries.

- ***Steps need to be taken to minimize the impacts of long-term curtailment of electricity production***: A significant problem in this environment is caused by multi-day periods when the solar panels are covered with snow, or during periods of prolonged cloudiness. Under these conditions the batteries are unable to build

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up a sufficient charge to meet all electricity demands, especially those associated with HVAC operations. This situation can be mitigated only through extreme load management practices or adding additional backup storage capacity to the solar system.[6] Of course, a backup generator can bridge these extreme events, although the overall goal of the residence is to be able to rely completely on a 100%-renewable energy system, independent of the regional grid.

- ***The solar system and electrical loads need to be designed and planned appropriately for the intended use of the dwelling:*** Although the house is not yet fully occupied, and the load patterns have not yet been clearly established, early indications are that the solar system may have been oversized while the battery storage system is significantly undersized.

- ***Make full use of local expertise and state and federal incentives:*** The authors commissioned an architectural firm knowledgeable in net-zero and passive home design and local building requirements and a contractor familiar with modern-day construction methods required for highly efficient homes. Although these efficiency measures can result in a higher initial cost for the build, the Inflation Reduction Act, along with State of Colorado incentives, have helped significantly in keeping initial costs at a manageable level and encouraging the use of only the most energy-efficient building materials and appliances.

In summary, despite the challenges, a properly functioning and well-designed off-grid system is cost-effective in the long run and provides a highly desirable place to call home.

6. Conflicts of Interest

This research is self-funded. There are no conflicts of interest.

[6] Plans are underway to install an additional 8 kW of battery storage.

References

Clean Power Research (2021). *Solar anywhere system check*. https://go.cleanpower.com/rs/369-HBZ-605/images/Solar-Data-Lifecycle-Overview_FINAL-LINKS_060421.pdf

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Appendix: Building and Equipment Specifications

Construction	Company/Manufacturer	Comments
Design; Contractor	Rob Ross, AIA, TRAD Design/Build; Jacob Neathawk, Neathawk Building Company LLC	Business located in Boulder, CO
External wall insulation	Johns Mansville™	ClimatePro Blow-in fiberglass + foam
Ceiling insulation	Johns Mansville™	ClimatePro Blow-in fiberglass + HFO closed cell foam
Roofing material	GAF™	Timberline Armor Shield ASII
Siding material	James Hardie™	Fibre-cement, board and batten style
Bldg. eff. ratings	Scott Home Services LLC, Boulder, CO	HERS Index Score = -53 (Note: A zero-energy grid-tied home would be HERS = 0)
Solar System	**Manufacturer**	**Comments**
Solar Panels	REC™ 365 N-Peak 2 monocrystalline n-type, black https://www.recgroup.com/de/products/rec-n-peak-2	Each panel rated at 365 W_p; 20% efficiency; 7.3 kW_p total; 36.6 m^2 total area; roof-mounted, south-facing at 22^0 tilt
Inverter	Sol-Ark™ 15-2p-N https://www.sol-ark.com/sol-ark-15k-all-in-one/	15 kW Max Power delivered to batteries; 200 amp service; suitable for both off-grid and on-grid
Battery storage	Blue Planet Energy™ Blue Ion HI https://www.blueplanetenergy.com/	24 kWh in two cabinets; expandable to 32 kWh (expansion will take place in 2024)
HVAC	**Manufacturer**	**Comments**
Heat Pump	Bosch™ BOVA-36HDN1-M20G https://www.budgetheating.com/Bosch-3-Ton-20-SEER-Inverter-BOVA-36-BVA-36-p/52077.htm	3-ton (36K BTU) variable speed inverter system
Air handler	Bosch™ BVA2.0 https://www.bosch-homecomfort.com/us/en/ocs/residential/bva20-air-handler-unit-1115667-p/	Includes 10 kW resistance auxiliary heat (not used)
Thermostat	Ecobee™ Smart Thermostat Premium https://www.ecobee.com/en-us/smart-thermostats/smart-thermostat-premium/	Extra room sensor installed in crawl space

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Hot water supply	Rheem™ Performance Platinum Hybrid https://www.rheem.com/products/residential/water-heating/	40-gallon; heat pump with resistance heating coil backup
Wood Stove	Lopi™ Evergreen NexGen-Fyre https://www.lopistoves.com/product/evergreen-nexgen-fyre/	12,772 – 70,720 BTU (EPA Tested); up to 77.1% efficiency

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