**Commissioning High-Performance Residential Buildings: Lessons from the NIST Net-Zero Energy Residential Test Facility**

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Synopsis

This paper provides an overview of important considerations for commissioning (Cx) high-performance residential buildings, including recommendations based on lessons learned from designing, constructing, and operating the Net-Zero Energy Residential Test Facility (NZERTF). Common quality assurance practices in residential construction are reviewed, and the benefits of applying commissioning processes from commercial buildings to ensure proper system performance in high-performance residential buildings are described. Although the National Institute of Standards and Technology (NIST) NZERTF was only partially commissioned in a formal sense, a review of the processes employed is conducted, including initial commissioning considerations for each of the major NZERTF building systems: thermal envelope, heating ventilating and air-conditioning (HVAC), water heating, solar photovoltaic, and lighting. Specific recommendations are made for key performance assurance measures to form the basis of an ongoing commissioning plan for the NZERTF.

About the Author

Natascha Milesi Ferretti is a Mechanical Engineer at the National Institute of Standards and Technology. Her current research is focused on building commissioning for improved energy performance. She has worked on several projects in the areas of commissioning and fault detection and diagnostics, including two International Energy Agency research projects on building commissioning (Annex 40 and Annex 47).

# Overview of Residential Commissioning

The residential construction industry already voluntarily performs a variety of quality control measures, such as visual inspections and functional performance checks of mechanical equipment. However, many factors that influence installation quality cannot be controlled under field-construction conditions and can result in deficiencies. For example, in a review of 17 houses with an average fan flow of 1495 m3/h (880 cfm) built by the same design and construction crews in the same subdivision, Walker et al (1998) found variations in duct leakage on the order of 170 m3/h (100 cfm) for supply ducts and 85 m3/h (50 cfm) for return ducts and concluded that the specific installation, rather than system design, was the determining factor for duct leakage. Matson et al. (2002) studied the potential benefits of commissioning homes in California and estimated the resulting savings of HVAC-related energy to be 15 % to 30 % in existing houses, 10 % to 20 % in new conventional houses, and up to 8 % in advanced energy efficient houses.

The use of a formal Cx procedure to identify and correct deficiencies can improve building performance, but is rare in residential construction. This is in part due to the inherent difficulty in quantifying avoided costs, and the belief that quality assurance is already part of the construction contract. Assumptions are often made that new construction means excellent energy performance, and that any potential problems would be visible to and resolved by the builder. However, since performance cannot be tested over the full range of operating conditions, the identification of issues often falls to the individual owner or occupant; without the owner calling for the builder to address a warranty, maintenance, or service issue, the deficiencies will not be addressed. The problem with this situation is that homeowners do not generally have the expertise to identify performance issues associated with the building envelope (including the roof, exterior walls, windows, doors, and foundation), ventilation system and ductwork, controls, and appliances (including furnaces, air-conditioners and water heaters). It is often only during the purchase of an existing home that buyers will contract a licensed home inspector to conduct a detailed home inspection to identify problems, including issues that could have been corrected during the construction process but these inspectors focus on functionality and safely, rather than efficiency. There is a benefit in reviewing the design as part of the commissioning as it is most cost-effective to correct potential issues on paper than during construction or after completion.

Within residential construction, there are niche applications, such as high-performance buildings, where system complexity and risk of not achieving the full potential of the design more clearly justify the investment in a formal commissioning process for quality assurance. Lukachko et al. (2011) presented Building America Program case studies showing how systems engineering of residential buildings, including applying specific construction requirements and performance metrics, reduced 50 % of heating-related energy and 30 % of cooling-related energy consumption relative to code-compliant construction. An advanced building design, such as the NZERTF, employs strategies to improve system and equipment efficiency on a component-by-component basis and its success is dependent on ensuring that the home is designed, built and operated properly. Pettit et al. (2015) present ten design principles for net-zero energy homes, which includes coordinating and commissioning systems as part of the project plan. Integrated commissioning for residential construction considers the house as a system of interacting subsystems, auditing and testing components and systems, and implementing improvements to energy efficiency and occupant comfort.

For commercial buildings, ASHRAE Guideline 0-2013 (ASHRAE 2013) presents the commissioning process to verify that the systems meet the owner’s project requirements. Commissioning extends into the operations phase in order to verify performance under a full range of operating conditions and seasonal differences, to ensure that the performance of both the heating and cooling systems are verified. The main activities are to: identify the Cx team, identify the performance requirements, update the Cx plan, verify achievement of current facility requirements, investigate unacceptable performance or outcomes, implement corrective actions, update systems manual and facility personnel training, write/deliver a Cx report, and obtain owners acceptance. For residential buildings, the process is simpler because houses have less complex control systems, fewer elements, and no formal operations and maintenence personnel. Wray et al. (2004) present three phases for residential commissioning as follows:

* Survey the house performance using audit and diagnostic techniques
* Perform ‘on the spot’ tuning and tweaking to improve system performance
* Identify opportunities for potential repair or retrofit

In the case of high-performance residential buildings, the increased complexity and risk warrants a hybrid approach. Lukachko et al. (2008) present a quality assurance roadmap for the construction of high performance buildings which includes seven steps:

1. Review of past construction and risk assessment
2. Setting performance goals
3. Changes to drawings, specifications, contracts and trades scopes-of-work
4. Training for site supervision and trades
5. On-site inspections, verification, and trouble-shooting
6. [[1]](#footnote-1)Commissioning (testing the mechanical systems and other equipment)
7. Post construction evaluation

Although it has become more commonplace to have service contracts for home HVAC systems, the same type of tune-up and assessment is needed for a broad variety of systems to ensure persistence of good operation and performance.

The NZERTF was commissioned during the design phase as part of the requirements of the Leadership in Energy & Environmental Design (LEED) certification process, but was not fully commissioned using the recommended hybrid approach. The objective of this paper is to take a retrospective look at what was done to commission the NZERTF, and consider what could have been done differently to improve the process. The recommendations for initial commissioning presented in the next section are based on industry best practices as well as the experience gained from the design, construction and two years of operating the NZERTF. The subsequent section presents a plan for the ongoing commissioning of the NZERTF. It is anticipated that the recommendations and ongoing Cx plan can be more broadly applied to other high-performance residential buildings projects.

# Initial Commissioning Considerations for the NIST Net Zero Energy Residential Test Facility

The Net Zero Energy Residential Test Facility (NZERTF) shown in Figure 1 is a LEED Platinum-designed facility with state-of-the-art building components including thermal envelope, solid state lighting, high-efficiency space conditioning equipment, solar water heating, and solar photovoltaics (NIST and BSC 2011).



Figure 1: NIST NZERTF (Photo Credit: B. Young)

Fanney et al. (2015) describe the design and performance of the NZERTF, a 252 m2 (2700 ft2), two-story residential building with a basement, attic, and rooms typical of what is found in a house in the state of Maryland, plus a detached 65 m2 (700 ft2) garage. The entire house, including the unfinished 135 m2 (1450 ft2) basement and the attic, is conditioned. The unconditioned garage serves as the facility control room, housing the extensive instrumentation that is used to monitor the performance of the building and its various components/systems. The facility also emulates the energy and hot water consumption of a “simulated family of four,” using programmed occupancy and energy use profiles. The sensible and latent heat loads of the simulated occupants, lights turning on and off, showers starting and stopping, and cooking and other systems are all controlled from the garage (Omar and Bushby 2013).

NIST envisions using this facility for many years to address the measurement science challenges associated with a range of building systems as well as the whole building system performance as buildings approach net-zero operation (Davis et al. 2014). The project successfully demonstrated net-zero operation of the NZERTF over the course of one year with simulated occupancyand currently serves as a research and development test facility where additional mechanical and design features are being evaluated. The NZERTF was initially commissioned in 2012 by Thierren Waddell, which provided points to qualify for the LEED Platinum rating. The scope of the commissioning effort was limited to design and construction phase. Only the photovoltaic system was commissioned separately by the supplier, which also included basic operator training. Third-party testing was limited to evaluating airtightness and did not address functional performance testing of all systems. Instead, a team of NIST researchers carried out the work of monitoring the system, once the building was put into operation. Their expertise, combined with the tremendous monitoring capabilities of the facility instrumentation, enabled very effective surveillance of system performance that would likely only have been found through active testing as a part of commissioning building operations. As a result, some of issues that negatively impacted the energy efficiency performance were identified during the net-zero demonstration period, (Kneifel et al. 2015).

The following subsections give a high-level overview of the various systems in the NZERTF, along with specific commissioning tasks and lessons learned. In each subsection, a table lists the recommended commissioning activites. Shaded items were not originally part of the NZERTF commissioning activities but would add value to the process. These form the basis for the key recommendations for the ongoing commissioning plan found in the last section of this paper.

## Thermal Envelope

The building envelope consists of the major systems intended to separate the indoor spaces from outdoors in terms of heat transfer and airflow, including the roof, exterior walls, foundation, windows, and doors. In residential buildings, the building envelope is the primary system responsible for heating and cooling loads, with internal loads being secondary. In a high performance building, the building envelope must include a continuous air barrier to minimize infiltration of unconditioned air, and a continous insulation system to minimize conductive losses. These goals include minimizing mechanical penetrations through the envelope that can compromise its thermal integrity. The building envelope must be properly designed to achieve high levels of airtightness, insulation, moisture control and glazing performance, and subsequently verified. Improper design, material selection, or faulty installation can result in poor performance in any or all of these respects. Table 1 presents the plan for commissioning the thermal envelope of the NZERTF.

At design, a simple way to confirm continuity of the building envelope is to perform a ‘pen-test’, tracing the water barrier, thermal barrier, air barrier, and vapor barrier from roof to slab. At no point should there be a break in the continuity of these barriers. these barriers must also be inspected at the time of installation, focusing on envelope subsystem interfaces (e.g., wall-window, wall-wall), insulation type, placement of the air barrier and vapor barrier, any damage during construction, and other potential issues (e.g., blocked ventilation pathways).

Visual inspections must be carried out to inspect the envelope for wetness, microbial growth, color or texture changes, decay, or structural dislocation, paying special attention to plumbing system leaks. This inspection extends to construction materials before they are installed. Pressurization testing to determine air leakage rates, also known as blower-door testing, can identify the existence of construction deficiencies but does not pinpoint the air leakage locations.

Table : Recommendations for commissioning the NZERTF thermal envelope \*

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| Element | Test Description |
| Envelope Design | Perform a ‘pen-test’, tracing the water barrier, thermal barrier, air barrier, and vapor barrier from roof to slab. At no point should there be a break in the continuity of these barriers. |
| Insulation Quality | Visual inspection- framing, insulation type, installation, placement of air and vapor barrier, barrier damage, blocked ventilation pathways etc.3rd-party testing, check for gaps and voids pre-insulation and post insulation per specifications, tested thickness/density pre-drywall. |
| 1. Thermographic survey/Infrared inspection-

Check for thermal bridging, air leakage, air intrusion, missing, displaced, or improper insulation. Check under pressurized and depressurized conditions |
| Windows |  Visual Inspection -framing, glazing type, installation |
| Handheld Spectrometer to determine window emittance classANSI 1105 test method for air/water leakage |
| Airtightness | Pressurization testing to determine air leakage per ASTM E779. test after the moisture barrier without any penetrations is installed and repeat when windows/doors are installedperform air leakage test on windows, doors and other moisture barrier penetrations |
| Envelope Moisture | Visual inspection for wetness, microbial growth, color or texture changes, decay, or structural dislocation. Special attention to plumbing system leaks. |
|  Electrical inspection (for detection or diagnosis of any moisture problem)surface scanning dielectric meters emit low frequency electromagnetic waves and detect their disturbance to determine average moisture content determine moisture content for building framing. |

\*Shaded items were not part of the original NZERTF commissioning activities.

Airtightness testing is recommended at various stages in the construction process: 1) after air barriers are in place, but before any penetrations are made, 2) once windows and doors are installed, but before drywall is installed, 3) at substantial completion, and 4) at final completion. For the NZERTF, a total of four separate blower door tests were performed as quality control during construction and to confirm that the thermal envelope airtightness met the design targets. The early tests provided valuable information on the construction of the NZERTF at times when corrective measures such as improving building seals, or reducing air leakage could be taken with minimal impact on costs. For troubleshooting, a thermographic survey or infrared inspection carried out under pressurized and depressurized conditions can help identify thermal bridging, air leakage, and missing, displaced or improper insulation, but such an evaluation of the envelope was not conducted in the NZERTF. Thermographic surveys were carried out later during operation to identify potential issues with the photovoltaic system.

In the case of the NZERTF, the blower-door testing conducted at final completion with the kitchen vent and clothes dryer vents sealed and all the results showed high levels of building airtightness. Nevertheless, visual inspections for wetness led to the discovery of improperly manufactured window seals that failed to maintain the moisture barrier and were replaced under warranty by the manufacturer. A pressurized water spray test, such as ASTM E1105 (2015) water penetration test would have identified this deficiency earlier in construction, but are not typically carried out in residential construction.

## Heating Ventilating and Air-Conditioning (HVAC) Systems

The NZERTF was designed as a laboratory, with the ability to use one of four different HVAC configurations: 1) a centrally-ducted system with a dehumidifying, air-to-air heat pump or gas furnace/AC; 2) a small-duct, high-velocity heat pump system; 3) two, smaller, multi-split heat pump units with minimal ducting; or 4) a ground-source heat pump using one of three, independent in-ground heat exchangers (vertical, straight line horizontal, and a horizontal slinky coil) and the traditional air ducts. Additionally, a heat recovery ventilator (HRV) was selected and installed to provide constant-volume airflow with air-to-air heat recovery to minimize energy losses associated with ventilation, while ensuring that the space provides the ventilation rate required to meet ASHRAE Standard 62.2-2010 (ASHRAE 2010) requirements.

For the first two years of operation, HVAC Configuration 1, with a dedicated, dehumidifying, air-to-air heat pump was installed as shown in Figure 2. The dehumidification function is provided by control algorithms and a hot gas bypass arrangement, with an additional reheat heat exchanger placed within the indoor air handler. Studies during the third year of operation are comparing a modified Configuration 1 (without dehumidification) to Configuration 2 (small duct, high velocity system). The additional ducts and ground-source loops for Configurations 3 and 4 were constructed for use in future experiments and have not yet been commissioned. This section will address commissioning of the vapor compression equipment, air distribution ducts, heat pump and HRV, as well as the future commissioning of the geothermal systems. Table 2 presents the plan for commissioning the NZERTF HVAC systems.

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Figure . Air-source heat pump installed at NZERTF

Key factors for meeting capacity and efficiency targets for vapor compression equipment include refrigerant charge levels, airflow across coils, and proper control. Domanski et al. (2015) found that duct leakage, refrigerant undercharge, oversized heat pumps, low indoor airflow due to undersized ductwork and refrigerant overcharge had the greatest potential for causing significant performance degradation and increased energy consumption. For duct leakage, the impact on air distribution systems can be particularly significant if leakage is into unconditioned space. Jump et al. (1996) found that duct losses on the order of 35 % are common for residential construction, and measured an average 18 % decrease in HVAC energy use after sealing and insulating ducts. Testing and balancing is important to ensure that the designed air flows actually are provided at each vent is key. Otherwise it leads to over/under heating/cooling of some areas, which leads to inefficiency and thermal discomfort. Other ventilation systems, such as those installed in bathrooms, kitchens and attics can increase heat loads, can increase the likelihood of moisture problems, and degrade indoor environmental quality if not properly commissioned. For ground-source heat pumps, the system loop integrity, control of the loop flow rate and to loop thermal response characteristics are critical.

In terms of commissioning activities for ducts, Walker and Sherman (2002) indicate that total duct leakage should be measured by one of two means:

1. Duct pressurization test: this can be done in unfinished or finished houses using a small fan-assisted flow meter, and in some cases a blower-door as well, to determine duct leakage by pressurizing the duct system to 25 Pa with the supply and return grilles sealed, or
2. Delta Q duct leakage test: changing airflows through the distribution system by turning the air handler on and off while pressurizing and then depressurizing the building envelope to various pressure differentials using a blower-door.

Walker and Sherman propose that testing must show that the duct leakage is less than 5 % of the rated flow for the total air handling system. Two compliance mechanisms are acceptable: one can test total duct leakage to the exterior at finish stage, or test total duct leakage at duct rough-in stage. When more than one air handler exists, each air-handling system must individually meet the requirement. If zoning is used, all zone dampers must be open and any motorized outside air ventilation dampers must be closed. The system must also be properly balanced, with the forced-air system providing balanced distribution of airflow to all conditioned spaces and zones of the house.

In the NZERTF, duct pressurization tests were done by the design-build firm, together with NIST. Each duct run was individually tested in the rough-in stage. In addition, special care was taken in design of the NZERTF to minimize the impacts of duct leakage, to run ducts in conditioned space, and to implement good construction practices. These efforts included ensuring the following: duct work is covered and dry before installation; filters are in place during construction and then changed before occupancy; the house is kept clean to minimize contaminants; the house is sealed before bringing in the drywall to reduce the likelihood of moisture problems, and testing and balancing is conducted for each room with return air vents.

Following industry best practices, heat pumps should be commissioned, including conducting a full inspection to confirm proper installation, verifying that the flow measurements are complete and accurate, and performing functional performance tests with controls calibration, as well as basic heating and cooling performance tests. There are several publicly-available industry references that provide useful guidance and templates for heat pump comissioning (Seattle City Light 1999, PTSC 2013). In the case of the NZERTF, this process was not applied. Instead, a control issue that could have been identified in functional performance testing was discovered during system monitoring in the first-year demonstration period. The design was for a single-zone system with a thermostat located at the first floor, while the heat pump was located in the basement. In heating mode or defrost mode, the indoor unit controller can energize up to 10 kW of electrical resistance heat. During operations, it was seen that the heat pump ran on low speed for 40 min, and if the temperature setpoint was not met, the heat pump shifted to high-speed operation. If the setpoint was still not met after another 40 min, the electrical resistance heat was activated. It was determined that the non-adjustable thermostat time periods of 40 min were such that the system was frequently using this electrical resistance heat, having a significant impact on the energy use of the house (Kneifel et al. 2015). In the NZERTF, this was detected by the engineer monitoring the system within 12 d but was not changed until after the demonstration period. Because comfort conditions are maintained and without a baseline to indicate the inefficiency, a typical homeowner would not be aware of the increased energy use, or the benefit to replacing the thermostat. NIST researchers replaced the thermostat in the second year of operation and saw that use of the electric resistance heat was reduced, producing a 27 % reduction in degree-day normalized energy use from 1555 Wh °C-1 day to 1136 Wh °C-1 day.

To commission the HRV, NIST engineers began with a review of the equipment selection. The HRV had been selected to ventilate the house with a nominal airflow rate of of 256 m3/h. However, in design review, the minimum outdoor air requirement to meet ASHRAE Standard 62.2-2010 (ASHRAE 2010) was calculated to be 137 m3/h. The standard allows for reducing that requirment if infiltration is found to exceed 0.01 m3/s per 100 m2, however, this was not applicable in the NZERTF due to the tight construction. When the installed system was brought into operation, NIST engineers used a hot wire anemometer traverse to measure the actual outdoor air flow rate provided by the HRV. It was evident that the HRV could not meet the minimum ventilation requirements with the lowest fan setting due to pressure drops in the ducts associated with the geometries of the final installation. Therefore, to meet the ventilation requirements, the system was operated using a constant speed fan that was measured to provide 171 m3/h (the airflow rate coresponding to the next highest fan setting). This higher rate provides greater ventilation for the occupants, but at a greater energy cost.

Finally, we consider the future commissioning needs for the geothermal heat pump, as this system was not operated during the first two years of testing of the NZERTF. An important commissioning test for the geothermal installation is to measure the change in temperature across the ground loop and ensure that there is a 2.7 ºC to 5.6 ºC (5 ºF to 10 ºF) drop in cooling season, or rise in heating season. The supply air temperature during cooling season should also be in the range of 10 ºC to 12.8 ºC (50 ºF to 55 ºF) to ensure sufficient latent cooling to maintain comfort. In general, the most effective data point to measure or trend is the temperature of the water or heat transfer fluid entering the heat exhanger in the house, which should usually be below 35 ºC (95 ºF) in summer and above -6.7 ºC (20 ºF) in winter. This measurement sensor is a cost-effective investment as it will enable the identification of faults that would negatively impact energy efficiency, and that would likely go undetected since comfort conditions are not significantly degraded.

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| Table 2. Recommendations for commissioning the NZERTF HVAC systems |
| **Element** | Test Description |
| Duct Leakage | Test for duct leakage using Duct Pressurization or Test Delta Q duct leakage test (Wray and Sherman 2002). Total space conditioning system duct leakage must be less than five percent of the total air handling system rated air flow at high speed determined by pressurization testing at 25 Pa (0.1 WIC). Two compliance mechanisms are acceptable: (1) test total duct leakage to the exterior at finish stage, or (2) test total duct leakage at duct rough-in stage. When more than one air handler exists, each air handling system must individually meet the requirement. If zoning is used, all zone dampers must be open. Motorized outside air ventilation dampers must be closed.  |
| Mechanical Ventilation Airflows | 1. Mechanical ventilation airflows: local and whole house mechanical ventilation system airflows must be tested during commissioning of the building. \*Determine airflow as a function of the fan’s external static pressure and speed setting
2. Balanced airflow: check that inter-zonal air pressure differences, when doors are closed, must be less than 3 Pa using passive transfer grilles or jump ducts, or active return ducts.
3. External Static Pressure: Air handler external static pressure must be within manufacturer specifications (125 Pa (0.5 WIC) maximum typically).
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| Heat Pump Diagnostics  | Heat pump inspection Test and balance report reviewed for completion of flow measurementsNo unusual noise or vibration identifiedAdequate access for service & filter change verifiedRoom thermostats/sensors confirmed to be in appropriate locationsElectrical connections confirmed to be tightPiping configuration match designCondensate drains are unobstructed, properly sloped, & trappedNo visible water leaks presentFilter is clean and tight-fittingDuctwork appears tight, with no obvious leaksDuct insulation appears in good condition where visibleO&M manuals are on siteRefrigerant properly charged |
| Functional performance tests (e.g., Seattle City Light 1999) Controls calibration testsBasic heating and cooling performance tests |
| Ground-source loops | Manufacturer testing requirements: Sustained Pressure Hoop Stress test (ASTM D-1598) Pressurization test- Testing shall be by water pressure at 100 psi for a minimum of 30 minutes. Flush the loops and filter particulates. |
| Indoor Air Quality | Investigate generation, transport, and removal of pollutantsVolatile organic compound testing of samples conducted periodically |
| Radon |
| Make-up air  | Check barometric activation of motorized damper to kitchen exhaust and dryer exhaust |

\*Shaded items were not part of the original NZERTF commissioning activities.

## Water Heating Systems

The hot water system consists of two solar-thermal preheat loops that used an active, indirect forced circulation system that is suitable for cool climates. Each preheat loop uses two solar thermal flat-plate collectors installed on the porch roof facing true south. A pump is energized to circulate loop fluid when sensor temperatures exceed a 10 ºC differential and turned off when the differential temperature is below 3 ºC. A 302 L (80 gal) tank provides storage for the water heating system. The solar collectors, heat exchangers, circulators and controls are identical for the second solar thermal system, though the storage tank is 454 L (120 gal) and is intended for future use with the basement radiant floor heating system and ground source heat pump system. Davis et al. (2014) describe the two-collector circulation loop, hot water storage, and heat pump water heater that was used in year two. The heat pump water heater downstream of the solar water heating system provides hot water in the event that demand exceeds the capacity of the solar water heating system. The heat pump water heater is a 189 L(50 gal) tank having electric auxiliary heating and multiple operating modes: heat pump, hybrid and standard electric. Energy data is stored in the control unit which has a Wi-Fi hub for communication, including to report errors.

Table 3 presents the commissioning plan for the water heating systems in the NZERTF. It includes steps to verify clean piping; visual, pH, and performance checks of the solar thermal system; and visual, mechanical, and performance checks of the heat pump water heater. During the first-year of operation, a loose control wire at the solar loop pump resulted in control failure that effectively put the solar thermal system out of service, leading to a greater demand on the heat pump water heater and auxiliary water heating components. This was a result of NIST’s intervention to obtain the control signal for monitoring purposes. The fault was detected by the engineer monitoring the system and resolved within 10 d; a typical homeowner would only be aware of the error (and the increased energy use) by connecting to the Wi-Fi interface to review error messages. An installation error from the manufacturer led to another fault, i.e., loose controller wiring that led to the inoperability of the heat pump compressor. For 10 d, this fault increased the demand on the auxiliary water heating element. Furthermore, a review of the piping installation for the solar thermal loop led engineers to shorten the length of the pipe connecting the solar loop tank to the heat pump water heater and to improve insulation in that section. The issue of unnecessary or inefficient piping layout is important as it leads to greater heat losses than more direct piping and is best been carried out prior to operations, as it is unlikely that a homeowner would make these changes post-occupancy due to cost.

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| Table 3. Recommendations for commissioning the NZERTF water heating systems  |
| **Element** | Commissioning Activity |
| Piping | Verify clean piping. 1. For the NZERTF this included flushing the system, then chlorinating to sanitize the system, then re-flushing the system, pressurizing the system, connecting appliances and finally adding a filter to the open loop and a screen in the closed loop.
 |
| 1. Perform annual checks for particles on closed loop.
 |
| Solar thermal  |  Visual Inspection of collector installation1. Verify equipment selection
2. Check the mechanical integrity of components, proper fastening to support collector weight and wind/snow loads
3. Check that the system has been wired correctly
4. Check waterproofing and air sealing of all pipe penetrations

Inspection of plumbing connections in solar loop1. Verify equipment selection and installation (e.g., expansion and pressure relief valves are properly sized, check valves are in place to prevent reverse circulation
2. Ensure there are no leaks in the circulation loop through which the heat transfer fluid is pumped by pressurizing the system with all valves closed. See if gauge pressure reading drops.
3. Verify that the external piping is properly insulated and that connections are secure
4. Determine system operating pressure, recording the gauge reading at the initial commissioning stage and monitor any large system pressure drops (e.g., 50 kPa) as system runs.
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| 1. Perform pH testing as a part of yearly maintenance as high operating temperatures can lower the pH of the heat transfer fluid.
2. Check the functional performance of the system.
 |
| Determine troubleshooting procedures after system installation and operation. |
| Heat pump water heater | Visual inspection of equipment selection1. Check for mechanical integrity of all system components.
2. Check all plumbing connections
3. Ensure unit is installed on flat surface and close to drain. Provide connection between condensate port on water heater to drain.
4. Ensure fan vents are unobstructed and filter is checked and changed periodically.
 |
| Functional performance tests |

\*Shaded items were not part of the original NZERTF commissioning activities.

Solar Photovoltaics

The NZERTF has 32 solar photovoltaic (PV) panels installed on the south half of the main roof. The PV modules are installed in the same plane as the roof, in four horizontal strings of eight panels each. Two strings or sixteen panels are then connected to one of two DC-to-AC inverters located in the main attic area, and the thermal energy released by the inverter enters the attic space. There is no battery storage. In total, the peak capacity of the **solar photovoltaic array is 10.2 kW. It is designed to** provide 15 % more electricity than is required over the course of an average year.

In the case of the photovoltaic system, the system installers carried out most commissioning activities, including training system operators. The Florida Solar Energy Center provides a valuable reference for the industry on installing photovoltaic systems (FSEC 1999.) It documents in detail the process for carrying out design review, performance verification, key metrics to evaluate the system visual inspections of the installation, and operation and maintenance procedures. Table 4 presents the high-level commissioning plan for the NZERTF photovoltaic systems and provides greater detail for checks that the system operators should do on an ongoing basis. Due to the distinctive nature of the design, having two identical collector strings operating in parallel, operators are able to make performance comparisons as a means to identify gross deviations from normal operation. During the first test year, one combiner box was determined to have a defective connection and was repaired. In the NZERTF, this fault was found by the engineer monitoring the system and resolved under a service contract with the installation company. A typical homeowner may not be aware of the performance degradation without a benchmark for normal operation such as a normal energy bill for the season.

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| Table 4. Recommendations for commissioning the NZERTF Photovoltaic systems |
| **Element** | Commissioning Activity |
| Solar photovoltaics |  Visual Inspection of equipment selection and installation 1. Verify installation is as per contract documents, manufacturer’s instructions, and local code and document with photographs the condition of the PV array and the balance-of-system components.
2. Verify system is safe and is performing as designed.
3. Measure the open circuit voltage of each series string of PV modules under relatively constant irradiance conditions and verify consistency.
4. Prior to inverter start-up, measure the following voltages at the AC disconnect: line-to-line, line-to-neutral, neutral-to-ground and line (hot)-to-ground (expected values are 240 V, 120 V, 0 V and 120V, respectively).
5. Start-up the inverter and confirm normal operation
6. At each inverter, use a DC clamp-on meter to measure the current in the ungrounded conductor of each series string of PV modules. Make these measurements while the irradiance on the array is relatively steady. Verify that all four strings are producing the same maximum power point current levels.
7. Verify that the measured AC voltage output from the inverter equal the inverter’s indicated value.
8. Measure the instantaneous AC power, module temperature, and instantaneous plane-of-array irradiance at nearly the same time and/or when the irradiance is changing very slowly (e.g., clear day near solar noon) and repeat to create multiple (e.g., 10 to 15) datasets.
9. Develop and implement operation and maintenance procedures.
10. Take detailed IR scan of PV array and inverters to identify normal operating temperatures and profiles, avoiding reflection from solar-thermal panels.
 |
| 1. Take periodic scans of the PV array and inverters to identify potential issues
2. Perform occasional (e.g., biannual) cleaning of panels
 |
| 1. Train the system owners on the basic system operation.
2. Conduct “walkthrough” noting disconnect locations and procedures.
3. Review inverter operations, including display screens and status lights.
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\*Shaded items were not part of the original NZERTF commissioning activities.

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## Lighting

Adequate and appropriate lighting (whether daylighting, artificial lighting, or a combination) should be provided so that people are able to perform visual tasks efficiently and accurately. General illumination is provided for visual comfort and for safety. Commissioning tasks verify whether the design specifications and performance criteria have been met. The lighting system must be checked to verify that the proper lighting fixtures have been installed appropriately and in the correct locations. Furthermore, measurements of actual light levels are needed to confirm that the performance criteria have been met. In the NZERTF, lights are remotely controlled to simulate occupancy. A photosensor is installed that can be used in Year 3. Illuminance testing can determine the number or combination of lights that are required to meet the needs of the user. Table 5 presents the commissioning plan for the lighting systems, which is applicable to lighting projects in general.

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| Table 5. Recommendations for commissioning the NZERTF lighting systems  |
| **Element** | Test Description |
| Solid state lighting | Visual inspection of equipment selection |
| Wiring review to check switches control lights according to the design |
| Illuminance testing to confirm requirements have been met. |

\*Shaded items were not part of the original NZERTF commissioning activities.

# Plan for ongoing commissioning of the NZERTF

This section presents the plan for ongoing commissioning of the NZERTF. It is based on industry guidelines for commissioning existing buildings (ASHRAE 2015) and presents a summary of the people, activities and reporting that will be important in ensuring proper system performance. The first subsection identifies the Cx team and their responsibilities. The second subsection lists the Cx activities. The third section outlines the process to review performance under current facility requirements, investigate issues, and document findings and recommendations.

Identify the Commissioning Team and Project Goals

The NZERTF is a federal facility and as such, the development process, including design and construction requirements, is uncommon for a net-zero energy home, as is the availability of an operations and maintenance staff. The Cx team listed in Table 6 includes the NIST scientists and engineers who helped design the systems, and they also have an extensive network of sensors to monitor the performance of each building subsystem and the environmental conditions (Davis et al. 2014).

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| Table 6. Roles and responsibilities for the NZERTF commissioning team |
| Roles  | Responsibilities |
| Owner | NIST is the owner of the building and controls its use and pays for its operations and maintenance. |
| Owners representative | The NIST Principal Investigator for the project has knowledge of the research needs and serves as the Owner’s representative. The Owners representative is responsible for providing information required for updating the current facility requirements, establishing the Cx project goals and priorities, and monitors the process and provide resources to support the Cx team. |
| Operations Staff | Because of the unique nature of the facility, both NIST Facilities personnel and research staff that operate the systems must work together to monitor and report systems performance, identify and implement recommendations, and help ensure the persistence of benefits. This includes NIST Plant and Research Staff |
| Commissioning Authority (CxA) | The CxA is responsible for the management of the Cx Plan and for updating the Cx priorities. The CxA can be a third-party, or the role may be assigned by the Principal Investigator if all activities are kept in-house. |
| Cx team (All) | The Cx team will design the testing procedures and plan data collection/analysis. They will report on the year-long evaluation of the NZERTF’s energy-consuming systems to identify energy reduction recommendations. They will help to direct the implementation of energy reduction recommendations.The Cx team will work with the CxA to update the documentation in the event that any components are introduced or changed and will also develop relevant training to help increase the persistence of benefits. The Cx team includes: the CxA, operation staff, maintenance staff, representative from researchers, service contractors |

Maintaining or continually improving energy efficiency, indoor environmental quality, and system control are the three project goals to be addressed by the on-going commissioning efforts. The Cx team will review current building operation, confirm the previously implemented initial commissioning recommendations are still in place, using both passive monitoring and active functional testing, and adjust these recommendations to meet the Cx goals. Testing will be similar to what would normally be carried out in the inital Cx, with sensor data and trending capabilities leveraged to verify performance.

## Review current facility requirements and update the commissioning plan

In the case of the NZERTF, facility requirements are expected to change from year to year as the building systems are used in different ways to address a wide range of research issues. The commissioning plan specifies which tests are to be conducted along with the testing interval. One major consideration is the need for data. In the NZERTF, there are over 200 sensors, generating thousands of points daily and analyzed weekly. For ongoing commissioning of other projects, it is recommended that data for normal operation and functional performance testing be analyzed for a minimum of two weeks in heating season, cooling season, and swing season. This frequency would be adequate to establish a benchmark for proper operation. Stand alone measurements with trends can be used when such detailed sensing is not available.

For the NZERTF, several Cx steps are combined because the project is smaller than typical commercial applications and because in many cases the same individual is responsible for carrying out the performance review, investigating any potential issues, and implementing improvements. Much like any other construction project, there was time pressure to get the construction completed and the occupancy period initiated. Although it was noted that design and construction phase commissioning activities were carried out by the commissioning authority to meet the LEED certification requirements, not all systems were fully commissioned. Instead, functional performance testing was carried out at the discretion of installers and NIST researchers.

The experiences of the occupants and building staff are valuable inputs into the comfort and performance of the house for the ongoing commissioning process. However, in the NZERTF, the occupants are simulated with latent and sensible loads and sensors located throughout the house provide a record of comfort conditions. The NIST team that monitored data over the one-year demonstration period has a wealth of knowledge regarding system design and performance issues. Their experience will be leveraged to carry out commissioning activities for the various subsystems and the whole building system. These include the inspections, trend reviews and utility statement reviews from the real world operation of the systems under the normal range of operating conditions and exercised in a way that is impossible during initial commissioning. A retrospective comparison was made of the NZERTF initial commissioning activities and the recommendations presented in the last section to determine the gaps and ensure that any remaining tasks become part of the ongoing commissioning plan. The NZERTF Cx activites listed in Table 7 are identified as important, based on the operating experience, and demonstrate how the Cx plan must be tailored to meet the needs of the individual application. The activities are organized by system and when appropriate, recommendations for testing frequency are listed. Activities denoted with an asterisk were not originally part of the NZERTF commissioning plan, but would add value to the process.

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| Table 7. Ongoing commissioning plan for the NZERTF |
| System/Subsystem | Commissioning Activity  | Frequency |
| Monitoring System | 1. Check sensor placement and reading accuracy and frequency, calibrate key sensors.
 | Annually |
| Insulation and Glazing Systems | 1. Visually inspect building envelope for wetness, microbial growth, color or texture changes, decay, or structural dislocation. Pay special attention to plumbing system leaks
2. Perform air leakage testing and compare to initial commissioning results. (ASTM 2010)
3. \*Perform a thermographic survey/Infrared inspection- Check for thermal bridging, air leakage, air intrusion, displaced insulation. Check under pressurized and depressurized conditions
 | SeasonallyInitially |
| HVAC System | 1. Perform duct pressurization test and compare to initial commissioning results
2. Perform functional performance test for heat pump
3. \*Check barometric activation at 10 pa of motorized damper to kitchen exhaust and dryer exhaust
4. Perform a functional performance test of the heat recovery ventilation system.
5. \*Perform a functional performance test of a high-velocity air distribution system before the system is used in research studies.
6. \*Perform a functional performance test of the ground source loops before the system is used in research studies.
 | InitiallyInitiallyInitiallyInitially |
| Water Heating System | 1. Visually inspect collector installation, check for damage/debris, waterproofing of penetrations
2. Review functional performance and compare to initial commissioning results.
3. Perform checks for particles on closed loop.
4. Perform pH testing.
5. Perform check for refrigerant leaks in heat pump using a soap solution or other leak detection method
6. Conduct a functional performance test of the solar pumps to verify proper control.
 | SeasonallyAnnuallyAnnuallyInitially |
| Photovoltaic Systems | 1. Visually inspect collector installation, check for damage/debris, waterproofing of penetrations
2. Review energy monitoring and trending compare to initial commissioning results
3. Review functional performance.
4. Inspect the inverter using an infrared camera to identify hot spots or other changes that may occur over time.
5. Make performance comparisons of the two identical collector strings operating in parallel as a means to identify gross deviations from normal operation.
 | Seasonally |
| Lighting System | 1. \*Conduct illuminance testing (Table 3, Item 3-3)
2. Evaluate the lighting layout based on the results of illuminance testing.
 | Initially, following changes. |

## Review Performance, Investigate Issues and Documenting Findings in OCx Report

Throughout the commissioning process, findings will be documented and information will be presented in Commissioning Reports, including the findings, a listing of recommendations that were implemented, a plan to implement additional corrective actions, updates to the systems manuals, including new/revised maintenance actions that are needed, and the results of any additional functional performance tests. Many of the low-cost and no-cost recommendations such as tuning the sytem or tweaking parameters can be carried out on the spot. These changes must be documented along with any additional recommendations for additional repairs or retrofits. In the event that any systems are added or modified, as is likely the case for the research facility, the systems manual must be updated and the staff working with the system should be informed and trained. Any tasks to be added as preventative maintenance should be added along with the corresponding frequency.

Although as-built documentation for residential applications is rare, such records provide important data for operation and maintenance (O&M) efforts as well as for future renovations, upgrades or repairs. Technical reports and other commissioning documents serve as benchmarks for future system testing, re-commissioning and maintenance or renovation activities. Systematic development of commissioning documentation facilitates knowledge transfer from one phase of delivery to the next, and from the delivery process to the ensuing ongoing operation of the facility.

# Summary

This report discusses the practice of residential commissioning and investigates the motivation for commissioning the NIST Net-Zero Energy Residential Test Facility (NZERTF), a high-performance residential house/test facility located in Gaithersburg, MD. The NZERTF was partly commissioned in 2012 by a registered commissioning authority, with activities focused on design and construction. A review of best practices led to the conclusion that this level of commissioning was not sufficient. The unique nature of the facility, a complex and high-risk residential application, led to a hybrid adaptation of existing commissioning approaches. Guidelines for both commercial and residential building commissioning processes were reviewed and used to form the basis of the commissioning plan for the NZERTF.

A review of the subsystems was carried out in consultation with NIST experts to form recommendations for commissioning the various subsystems, and tables are presented that document these activities for each subsystem. A commissioning plan was developed and presents each of the major elements, established the roles and responsibilities for the Cx team members, defined the goals for the process, outlined the measurement and verification plan, and the use of functional testing to verify proper system performance. This collectively provided guidance as to what should be done for this type of facility to help ensure that the specifications of the design intent are met, and that the testing and inspection of the systems identify issues so that corrective measures can be undertaken before developing into serious operational flaws that impact comfort, efficiency or equipment life. The testing activities, which extend into the operation phase, verify performance under a full range of operating conditions.

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1. The ASHRAE definition of commissioning process is broader, encompassing the tasks associated with these seven steps listed here and defines the tasks described in Step 6 as Functional Performance Testing: [↑](#footnote-ref-1)