# Commissioning and Optimization of On-Site Renewable Energy Systems

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## ABSTRACT

Today, many electrical contractors and photovoltaic (PV) integrators engineer and install custom systems on a variety of existing and new construction. These systems are designed specifically to the building configurations and to required utility interconnection. Each system therefore becomes a unique challenge to design, install and commission.

This paper will present a detailed review of pre-commissioning activities, followed by the formal commissioning and startup of PV systems. A step by step list of activities, including a review of compliance to the National Electrical Code®, will be presented with examples from actual completed installations. Proper understanding and installation of these systems will ensure the safety of all personnel during the commissioning and subsequent operation by the end user.

One of the often overlooked benefits of the commissioning is to include the client in the overall review of the system and provide an explanation of the rational for the design, installation and operation of the system. This is not a substitute for the final hand over of the system, but rather a way for the client to become knowledgeable with the completed project.

Finally, the commissioning procedure provides a view into the operation and maintenance (O&M) of the completed project. The commissioning process therefore presents a safe and thorough procedure for the final testing and evaluation of the system prior to hand over to the client.

## INTRODUCTION

The design and construction of a photovoltaic (PV) power system can take several weeks to many months depending on the system size.
Unfortunately, the commissioning activity is rarely included in the initial design process. Commissioning and system start-up requires specific tasks that involve direct access to the individual components of the system. Measuring and recording operational parameters requires physically touching the components. This simple task can be made difficult and unsafe by a poorly thought out system configuration with poor access to the components being tested. The first order of business is to formulate a plan that will keep everyone safe and meeting all requirements of the local facility and authority having jurisdiction.

Figure 1 shows commercial PV installation.

Figure 2 shows a block diagram of a typical solar PV system.

Figure 1. Commercial PV Installation

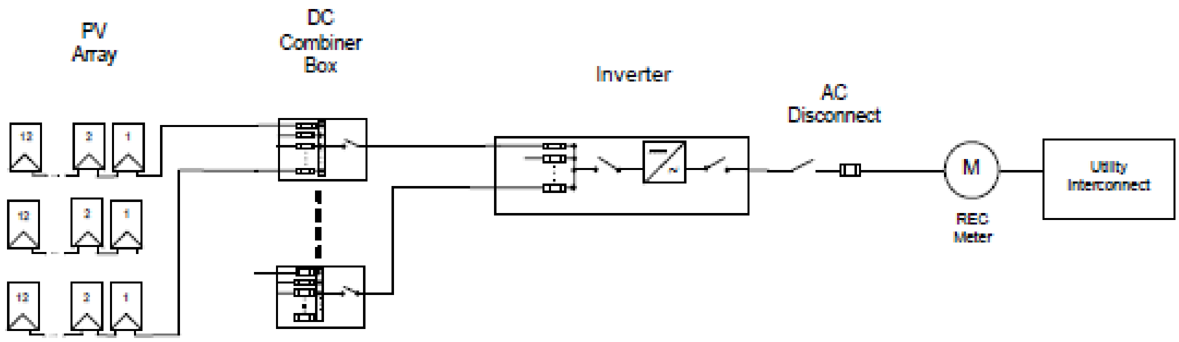


Figure 2. Block Diagram Typical PV System

Figure 2 shows a typical PV system consisting of (from left to right) PV Array (solar panels), fused combiner boxes (all PV circuits are terminated in the combiner box), the inverter (takes direct voltage/current) and converts it to alternating voltage/current), AC disconnect (master disconnect for the system), Renewable Energy Credit Meter (PV production), Utility Point of Connection.

**COMMISSIONING PROCESS**

Commissioning begins with a review of the design, based on AS BUILT drawings provided by the design group and the installation crew, followed by a walk through to insure the system is installed mechanically and electrically to the drawings. Drawings and photos of the installation in advance helps to speed this process. Depending on the size of the project, it can take anywhere from ½ to 1 or 2 days to review the design documents and walk the project to compare the actual mechanical and electrical installation to the documents provided. If there are substantial differences between the design documents and the installation, a meeting is scheduled with the installation supervisor and hopefully the lead design engineer. It may be necessary to delay the commissioning until the installation is brought up to the documents provided.

At this point, the system is energized in steps to verify the electrical design. This procedure starts at the solar modules and works its way to the inverter and finally to the interconnection with the building electrical system.

**THE DETAILS**

The Pre-Commissioning Checklist:

- Design documents
- Preliminary voltage and current readings
- Digital Camera & spare batteries
- Laptop
- Safety Equipment (Hard hats, gloves, Fall protection
- Testing and measuring equipment
  - Multimeter
  - Pyranometer (Solar-irradiance
  - Temperature
    - Ambient (digital thermometer)
    - Module (IR thermometer or attached thermocouple)
- Tools
- Two ladders
- Spare fuses (DC – combiner box & DC disconnect switch, AC – AC disconnect switch)
- Keys (Inverter, combiner boxes, disconnect switches)
- Access to all required areas and restrooms
- Personal items (water, hat etc.)

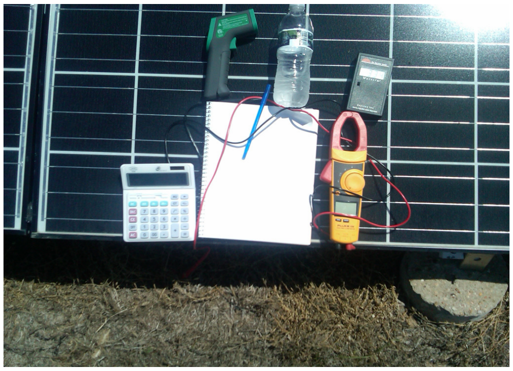

Figure 3. Tools of the trade

Figure 4 shows a typical commissioning process flowchart

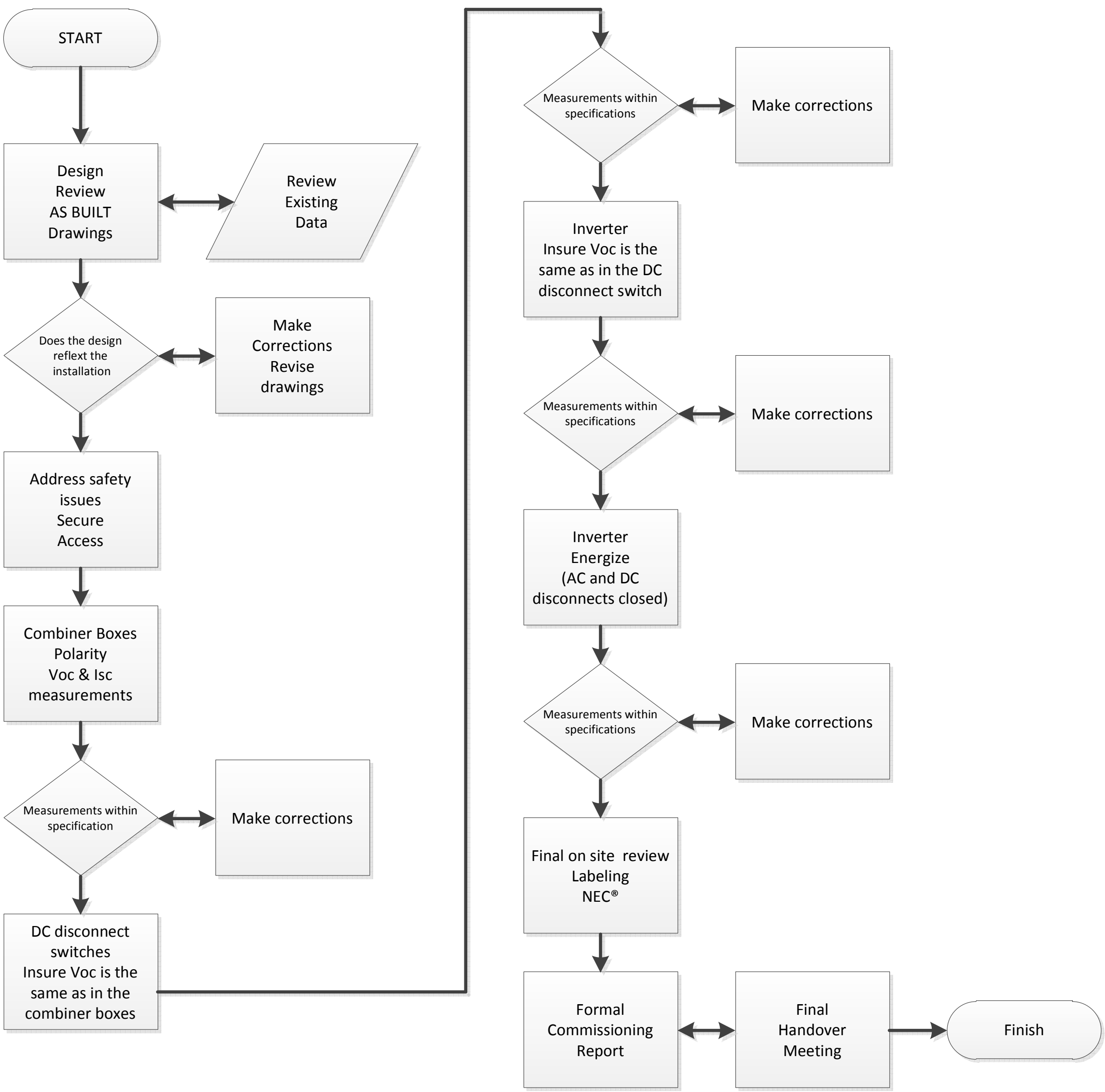


Figure 4. – Commissioning Flowchart

Commissioning Checklist:

- Verify system matches final drawings
- Verify system is safe per OSHA standards
- Verify system is aesthetically acceptable to the client
- Verify components are robust and permanent
- Verify system performance and operation by comparing measurements to design specifications
- Verify NEC® Code compliance

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Pre-Commissioning Checklist

Pre-Commissioning begins with a review **of** the design, final AS BUILT drawings and voltage and current readings and photos from the installation crew. The data recorded during final system testing is a very important and should be compared to the design specifications for voltage and current. If these readings are not within specifications, sample measurements should be taken to verify the accuracy of the original data. Estimated design parameters (string voltage and currents) are part of the initial design. The field measurements should be within +/- 10% except in the case of extreme weather conditions. Another important piece of information needed prior to the formal commissioning is certified conductor insulation resistance (meggar) readings of all underground and long conduit runs. If this data is not provided, all the terminations must be disconnected and the resistance measured between the conductor and ground. The walk through is to insure the system is installed mechanically and electrically to the drawings and to determine safety requirements for recording operational data. Prior to the visit, it is important to advise the facility personnel responsible for contractor safety plans. Access to all areas on site must be secured in advance. Be sure to have all the keys to inverters, disconnect boxes, meter boxes, AC combiner boxes etc.

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Commissioning Checklist

Electrical data in the form of AC and DC voltages and current measurements are taken at each enclosure throughout the system and comparing them to the design operating parameters adjusted with respect to the environmental conditions (temperature and available sunlight).

One of the most important issues during system commissioning is NEC® code compliance. Article 690 of the National Electrical Code®, SOLAR PHOTOVOLTAIC SYSTEMS (Figure 5), must be followed to insure safe installation and acceptability by the local inspectors. Articles throughout the NEC®, particularly Article 250 on grounding are standard practice for a well built, quality installation. It is important to determine prior to design and construction which version (year) of the code is to be used. Local jurisdictions are not always on the latest issue of the NEC®.


Figure 5. 2011 NEC®

Commissioning Procedures:

Actual measurements to the recorded

- Meggar
- Check DC polarity of module strings
- Open circuit voltage (Voc)
- Short circuit current (Isc)
- Vac (Inverter)
- DC voltage under load (Vmp)
- DC current under load (Imp)
- Irradiance
- Module & ambient temperature
- Combined currents and voltages
- Inverter KW
- Inverter input (DC) current
- Inverter output (AC) current
- Recheck questionable values

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Commissioning Steps:

Document all deviations from the final drawings. This will be the beginning of a punch list before final turnover to the system owner. If there are issues that prevent the commissioning, a return visit must be scheduled.

Data is recorded beginning at the combiner boxes. Polarity of the DC circuits (strings) terminated in the combiner box should be checked first. This is a common issue. Prior to recording open circuit voltage (Voc) for each string, record the ambient temperature, module temperature (back of module if accessible) and solar irradiance. This should be done before each set of recordings. Pull all fuses from the combiner box before taking measurements to prevent inaccurate readings. Check the fuses to make sure they are rated 600 VDC. Repeat for each combiner box. Take pictures of the inside and outside, including the required label, of each combiner box.

Upon completion of all combiner boxes, re-install all the DC fuses and move on to the DC disconnects. Close the switch and measure Voc for the combined strings. Record ambient and modules temperatures and solar irradiance before each set of readings.

The next step is to move to the DC connection point in the inverter. Remove the fuses and record DC volts for each incoming supply. Assuming temperatures and irradiance are near those recorded at the DC disconnect switch, the readings in the inverter should be about the same.

If all these readings are within tolerances it is time to energize the inverter. Close the circuit breaker or disconnect switch supplying AC (grid) voltage to the inverter. Re-install DC fuses in the inverter, close the inverter AC disconnect switch, then the DC disconnect. Wait the required time for the inverter to run through its start up procedure. Record all inverter data from the display.

A final review of the system is to insure all labeling is in compliance with the NEC®, the local utility and the local authority having jurisdiction (AHJ). A typical DC disconnect label that meets ART. 690 of the NEC® are shown in Figure 6.

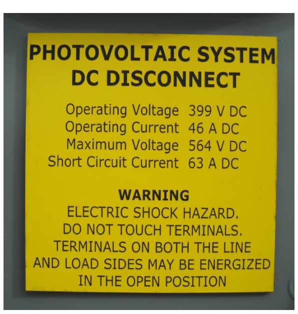


Figure 6. DC disconnect label

**INCLUDING THE CLIENT**

- Design review
- Operation and maintenance
- Safety

Design Review

It is important to include the client in the commissioning process so they become familiar with the system components and their function. Walk the client through all the system components starting at the PV array to the interconnection with their electrical system. This does not need to be highly detailed, which will be covered in the handover meeting, but enough to answer any question they may have.

Operation and Maintenance

The operation and maintenance of the system can be discussed as part of the overall system description. An operation and maintenance manual with all equipment operating manuals and specification sheets is normally provided as part of the non material requirements for the job and is part of the final handover meeting.

Safety

It is important to specify all safety issues when working with the system. The operating voltages are typically 400 to 600 volts AC and DC. Emphasize the use of proper safety equipment including personal protective equipment (PPE) requirements.

One of the most common questions asked by the system owner is will the PV system continue to operate if the facility loses utility voltage for a period of time. UL and IEEE standards for PV inverters require that they disconnect from the building electrical system to prevent voltage from being back fed into the system that may injure maintenance personnel. The inverter will respond to a sudden change in voltage or frequency by disconnecting and will not re-connect until these parameters have been within specification for a specified period of time. The UL and IEEE standards specify the inverter shall disconnect is 2 seconds. This can be demonstrated to the system owner as well as the utility by disconnecting the circuit breaker or disconnect switch, Figure 7, feeding the inverter.


Figure 7. Inverter interconnect circuit breaker

**COMMISSIONING REPORT**

Since commissioning rarely if ever is performed on a day with weather conditions that match the standard test conditions (STC) that were used to evaluate the performance of the solar modules at the factory, it is necessary to predict the system performance, based on actual irradiance and ambient temperatures to the ideal Standard Test Conditions.

The calculation for AC power is given by: AC Output Power = Pstc x Ksys x Ktemp x K irrad.

- Pstc = DC power (KW) of the system (nameplate watts)
- Ksys = de-rate factor based on module tolerance, inverter efficiency, wire loses and soiled condition of the modules
- Ktemp = factor to accommodate for ambient and modules temperatures above or below the STC temperature of 25 deg. C.
- Kirrad = factor to accommodate for irradiance measurements above or below the STC irradiance of 1000W/m2.

The installed DC rating of the system in kilowatts (KW) is multiplied by these various factors to provide a "predicted" system output under the actual conditions. This is then compared to the actual inverter power (KW) readings. New systems typically will be operating at 10% to 15% higher than the "predicted" value. A sample commissioning report is included in the Appendix.

**FINAL HANDOVER MEETING**

This meeting is typically a joint meeting between the installation contractor and the system design company and the client. Inclusion of facility managers and maintenance personnel at the handover meeting helps to insure that all personnel will be knowledgeable regarding the day to day operation of the system A formal presentation of the system operation, safety and maintenance parameters will be provided. Complete operation and maintenance documentation along with final stamped drawings are turned over to the client representatives. A well run project will have included all the people in this meeting from the beginning.

<u>Performance Review</u>

Often a performance review, which may include a follow up commissioning, is included in the contract. This is usually a scaled down version of the process described above. This often takes place on the one year anniversary of the system start up.

**CONCLUSION**

The paper has presented a step by step guide to the commissioning process. Although some steps appear redundant before and during the commissioning, they insure accurate data taken in a safe manner. It cannot be stressed enough to include the planning and execution of the commissioning throughout the design and installation. Be sure to include all appropriate personnel, including the facility representatives, in review meeting during this process. The commissioning report is as important a document at the design drawings. The data recorded in the commissioning report is the initial reference to which all subsequent performance measurements are compared. Although many voltage and current measurements are recorded in the report, it is the final calculation of predicted power of the system that is the keystone of the report. This is what the system owner is looking for and what the design and installation contractors have waited for to be officially verified. After all the hard work designing the PV system and getting it installed, it comes down to the final commissioning to complete the project.

The PV system is designed and intended to provide solar power for 25 to 30 years. This means every aspect of the system from design to the materials of construction must meet the requirements for this intended lifespan.

This makes the commissioning process a vital step to insure everything possible was done to make this a reality. Projects may be small or large, easy or complicated; but the process of commissioning is the same. Often, on larger projects, a 3rd party commissioning company, independent from the design and installation contractor is required to meet contractual obligations.

Even though commissioning is just another part of the job, it is indeed very exciting to "bring a system to life". It certainly makes everyone involved with the process feel very good.

## REFERENCES


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## VITA


John C. Gardner graduated from Texas A&I University with a BSEE and is a Professional Engineer in the states of Texas and Arizona. He is a senior member of IEEE and a member of the IEEE Power and Energy Society. He has authored five IEEE papers. He is a member of the American Solar Energy Society, American Wind Energy Association and Past Chairman of the Texas Solar Energy Society. John has made many presentations on renewable energy including past Hot and Humid Building conferences. John's energy efficient home has been featured several years on the Houston Solar Tour and has been the subject of articles in the Wall Street Journal and the local paper. John is employed by ONTILITY as a Solar Design Engineer.

**APPENDIX**

# Commissioning Report

**John Gardner**

**30 April, 2010**

# Project Description

The project consists of a solar PV system located on the roof of Building B located in Any town, USA.

The system is made up of 252 Kyocera, KD 210; 210 Watt solar panels mounted on the western edge of the south facing roof of Building B with a 183 degree Azimuth at a 10 degree tilt. The arrays connect to a PV Powered 75 kW inverter. The PV array is electrically divided into two (2) sub arrays. Power from each array runs to a DC combiner box and DC disconnect switch. The DC wiring continues across the roof in metallic conduit through a roof penetration into electrical room 35.021 and to the inverter. AC power is run in metallic conduit to an AC disconnect switch and REC PV production meter before connecting to a back fed breaker in an existing Cutler Hammer 480V service panel (D4N530).

**The system was completed and energized on Tuesday, April 20, 2010**

# Commissioning Summary

This report records the information obtained by a performance verification that took place on the 20th of April between 12:00 pm and 1:30 pm. The commissioning was performed by:

- John Gardner – Standard Renewable Energy
- Robert Helms – Standard Renewable Energy

These verification tests conducted under sunny conditions and a temperature of 67 deg. F.

**Calculated Acceptable AC Output Power = 35.86 kW**

**Actual AC Output Power = 42.6 kW**

**Actual AC Output Power was 18.7 % higher than the calculated acceptable value.**

# System Observations and Measurements

### *Weather Conditions*

Weather for the day was mostly sunny with ambient air temperatures of 68 °F to 75 °F and wind at 10 to 15mph.

### *PV System: Array with Kyocera Crystalline Modules*

Array measurements on roof were taken between 12:00 and 1:00 pm.

| **Measurement** | **Value** |
|---|---|
| In plane Irradiance<br>(180 °Azimuth, 10 °slope) | 830 - 930 W/m2<br>880 (Ave.) |
| Module Temperature | 107°F to 119 °F (42°C to 49°C)<br>46°C (Ave.) |

| **Measured Values** | **Inverter** |
|---|---|
| DC Input voltage | 325 Vdc |
| DC Input current | 138 A |
| DC Input power | 44.85 kW |
| AC Output voltage | 479 Vac |
| AC Output power | 42.61 kW |

| Combiner Box #1 (South) | | | Combiner Box #2 (North) | |
|---|---|---|---|---|
| **String** | **Current (A)** | | **String** | **Current (A)** |
| 1 | 6.9 | | 1 | 7.6 |
| 2 | 7.0 | | 2 | 7.9 |
| 3 | 7.2 | | 3 | 7.8 |
| 4 | 7.3 | | 4 | 7.5 |
| 5 | 6.3 | | 5 | 7.0 |
| 6 | 6.4 | | 6 | 7.3 |
| 7 | 6.4 | | 7 | 7.5 |
| 8 | 6.3 | | 8 | 7.7 |
| 9 | 6.8 | | 9 | 7.5 |
| Total 1-9 | 60.6 (Ave. 6.73) | | Total 1-9 | 67.8 (Ave. 7.53) |

Irradiance = 830 +/-10%
Operating voltage = 322 VDC

Irradiance = 930 +/-10%
Operating voltage = 324 VDC

Current variations are caused by irradiance changes over the period of measurement.

# *System Calculations:*

## ***System Output: Array with Kyocera Crystalline Modules***

*AC Output Power* = $P_{STC} * K_{Sys} * K_{Temp} * K_{Irrac}$

$\mathbf{P_{STC}}$ **= 52.92 kW**

$\mathbf{K_{Sys}}$ **= Product of table values**

| System Factor Components | Values | Notes |
|---|---|---|
| PV Module Tolerance | 0.95 | Refer to KD module spec sheet, +/- 5% |
| Inverter and Transformer | 0.955 | Refer to inverter spec sheet |
| Module Mismatch | 0.985 | Based on module tolerance, see note* |
| DC Wiring losses | 0.98 | Refer to wire calculations in design package |
| AC Wiring losses | 0.99 | Refer to wire calculations in design package |
| Soiling of modules | 0.98 | Modules already show signs of being dirty |
| Shading | 1.00 | No shading |
| Aging | 1.00 | Modules were new |
| **Total** $\mathbf{K_{Sys}}$ | **0.850** | |

$\mathbf{K_{Temp}}$ = 1 – ($T_P$ *( $T_{cell}$ – 25 °C))
1 – (0.0045*(46 – 25))
1 – (0.0045*(21))
1 - 0.0945
**0.906**

$\mathbf{K_{Irrad}}$ = 880 W/m2 / 1000 W/m2 = **0.880**

**Calculated Acceptable AC Output Power = 35.86 kW**

**Actual AC Output Power = 42.6 kW**

**Actual AC Output Power was 18.7 % higher than the calculated acceptable value.**