Design and Development of a Grid-Tied Solar Photovoltaic Training Infrastructure

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Abstract

Renewable Energy (RE) related course work is becoming an important part of the science, engineering, and technology curricula. Hands-on training in RE-related coursework is a major part of engineering technology-related technical coursework. RE courses typically require hands-on laboratory experiments for the students, unless the course is being taught in business and education related programs. Laboratory experiments for the related courses necessitate two major laboratory tools, first, a good laboratory workbook pertaining to what is being taught in the lectures and second, the related laboratory equipment. There is a variety of laboratory equipment available on the market for the RE related courses. The cost of the equipment varies between $2,500-$100,000 or more depending on what is expected required in the course. Some of the training/laboratory equipment companies offer manuals/workbooks to accompany their equipment. Those technical and engineering programs covering specific renewable energy curricula, but lack funding to purchase necessary lab equipment, seek ways to build their own equipment and prepare related laboratory activities. This research describes design and development of a 3-Phase Grid-Tied Solar Photovoltaic Training Unit using micro- and string-inverters. The unit is completely designed and built in the design and production laboratories of an engineering technology program by faculty and students. The available lab equipment is used in lab sections of two renewable energy courses offered in the program.

Introduction

Technology and engineering programs in many higher education institutions are developing alternative energy-related curricula in classes, projects, training, and certification programs. RE teaching systems and projects help students to better comprehend complex concepts by including a renewable energy project or series of laboratory experiments. The importance of experiential activities such as laboratory sessions is highlighted by many authors [1-8]. Energy knowledge and renewable energy-based projects are important in order to prepare students to be competitive for careers in the growing fields of energy related engineering, science, and technology. Preliminary projections from the Bureau of Labor Statistics state that the number of expected energy related green jobs is expected to increase by 11% by 2018, and most of that growth is expected to be in the environmental or energy related sectors [9-10].

Edgar Dale's cone of learning shows that participating in discussions or other active experiences may increase retention of material by up to 90% [11]. Richard Felder and Linda Silverman recommend several teaching techniques to address all learning styles, one of which is to provide the students with demonstrations that address sensing and visual learning styles, and hands-on experiments for students with active learning styles [12]. According to Moore [13], there is a direct correlation between in-class performance, laboratory attendance, and performance. In renewable energy courses, active learning can be achieved through a variety of activities which include lab and project experiments with hands-on projects and hands-on laboratory experiments [14-17].

There are recent RE-related projects that have been created to focus on student learning and promotion of clean energy sources. According to a recent project report, an integrated electric power system was designed and installed in the Taylor Wilderness Research Station in central Idaho by a team of undergraduate and graduate students under the supervision of faculty. Projects included establishment of a hydroelectric generator, a photovoltaic array, a fossil fuel generator, and control units. The results of this project and previous attempts were shared with academia in an engineering education conference in 2010 [18-20].

Students first became involved in this project in the spring 2015 semester during a solar photovoltaic course (17 students) at Sam Houston State University (SHSU). During the course, students were tasked with building a portable grid-tied solar photovoltaic lab equipment after extensive lectures to learn the theory. Students worked in teams to prepare an action plan for the project. Four teams were created for the initial steps of the project. The assignments of the teams are (a) estimates and quotes for the materials; (b) computer aided design (CAD); (c) production of the portable stand; (d) purchasing of solar photovoltaic related equipment and supply; and (e) building the unit-system design (all students participated). Each team was asked to share their accomplishments and progress with the other teams on regular basis. The accomplishments of each team are explained below.

Materials

The materials team consisted of 5 students, a faculty, and an independent The Interstate Renewable Energy Council (IREC) certified contractor who was funded by the South-Central Region of Solar Instructor Training Network (SITN). This was a federal grant from the Department of Energy. Necessary components for the unit were identified by the students and approved by the course instructors. The actual training unit components were identified after extensive market research. The compatibility of the components was confirmed, and specification sheets were stored in a database to draw actual components using CAD software. The design layout helps to locate drilled holes and to make cuts to place and align the components on the board. The specifications of the components for the metal frame are summarized in Table 1.

Table 1. The Specifications of the Components for Training Unit Stand

Portable Stand Materials List

Item	Description	Quantity	Units	Unit Cost	Amount	Source
1	1.5" x 3" x 14 ga rec. Steel Tube	96	LF	2.38	228.48	local steel supplier
2	1/2" Sande Plywood	2	ea	31.95	63.9	Home Depot
3	5" x 2" Plate Caster Set (1120 LBS)	4	ea	16.95	67.8	www.surpluscenter.com
4	1/4"-20 x 1" FH Machine Screw	16	ea	0.23	3.68	local hardware store
5	Spray Cold Galvanizing Compound	2	ea	5.27	10.54	Home Depot
6	Enamel Spray Paint	2	ea	5.26	10.52	Home Depot
				TOTAL	**$384.92**	

The total price of materials to build the portable stands was $384.07 dollars. This amount can change dramatically depending on the building materials required for the training unit stand. In our prototype, some metal tubing was donated by a local steel company. Students worked closely with local companies and Engineering Technology program secretaries in every phase of ordering, purchasing, and delivery of materials.

Computer Aided Design (CAD)

The design team consisted of 5 design students and a faculty member. The CAD designs of the portable metal stand (frame) layout was completed using Microsoft Visio and Autodesk AutoCAD software packages. The purpose of the CAD was to find out the size of the portable unit with all the equipment included. Dimensions of each piece of equipment was considered for the design work. During the design work, the center of gravity was considered due to the portable nature of the units and the heavy equipment required, such as an inverter unit. In the design work, the location of each component was determined to identify the distance of parts to make patch-cords and conduit connections. Both Microsoft Visio and AutoCAD layouts are shown in Figures 1, 2, and 3 consequently.

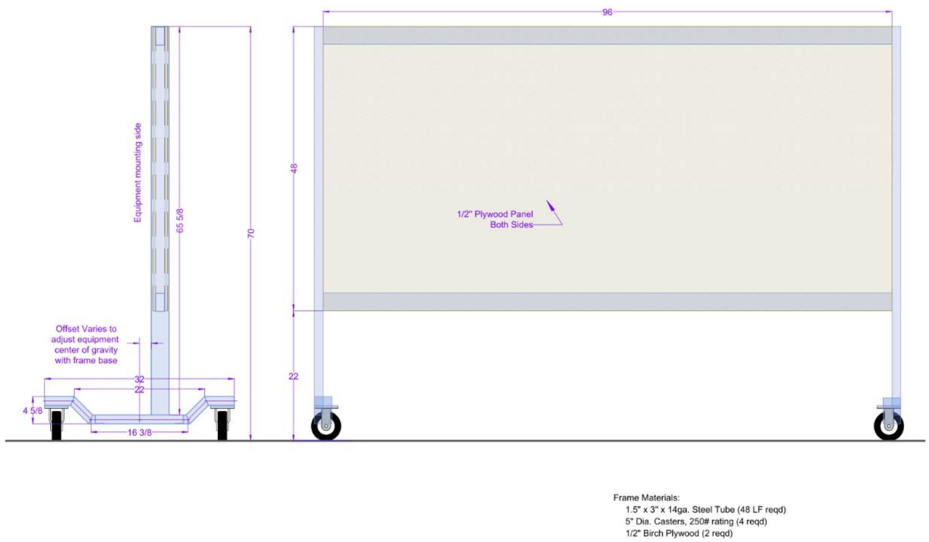

Figure 1. AutoCAD layout of the metal stand (frame) without equipment

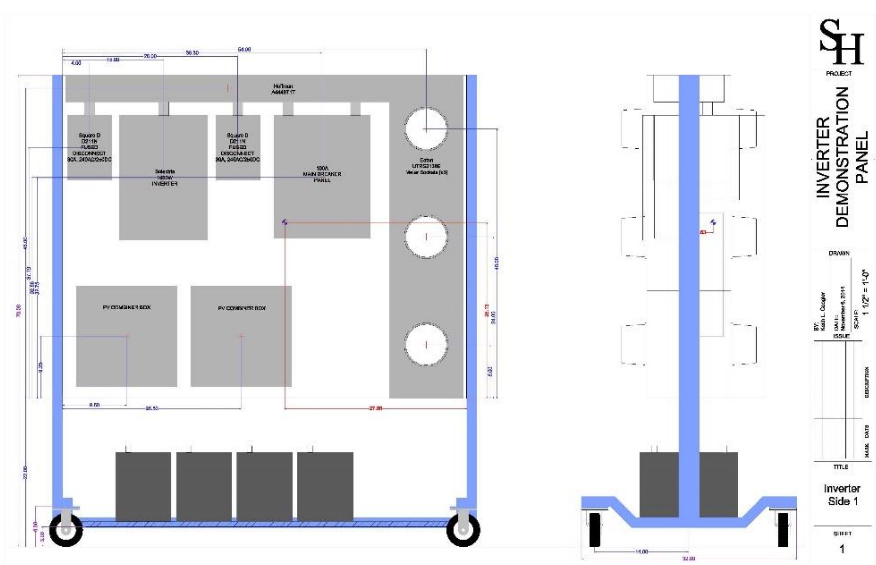

Figure 2. AutoCAD layout of the metal stand (frame) with equipment

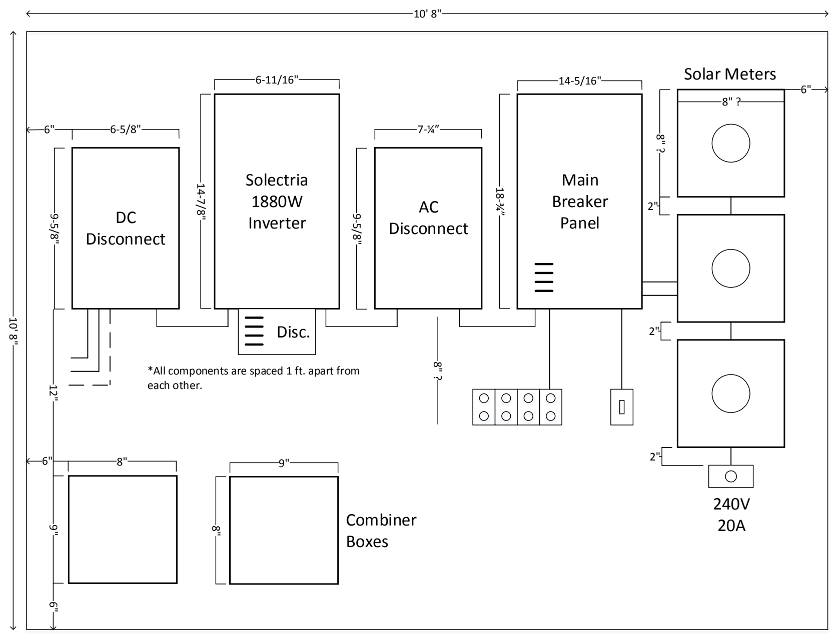

Figure 3. Microsoft Visio layout of the metal stand (frame)

The first two concepts drawings were done by design and development students; many of the components and other parts were put into digital form so that they could be used for the CAD design. After measuring the board and placing all of the components into this CAD file, the project progressed quickly. Many of the concepts that developed from this point were to address due to the CAD files which allowed us to change design without incurring cutting and mounting parts. There are many components that comprise this training unit; all of these components were drawn on a 1:1 annotation scale which allowed us to properly place the components on the board as if it were in a real time situation. This made for optimum assembly of these parts, allowing for maximum space utilization of the training board.

Production

A team consisting of 6 students and a faculty member worked on the production process of the unit. Figure 4 shows a photo of the portable unit without any components mounted.

Figure 4. Photo of portable metal stand (frame)

In this step, student experienced reading engineering drawings, working with metal and wood working equipment, welding, safety requirements in a production lab, painting etc.

Purchasing

Four students and three faculty members conducted a for the materials and supply for the grid-tied solar photovoltaic system before the design of the portable stand in the previous sections occurred, in order to determine the dimension of the all equipment would be used. In this section, students experienced purchasing new materials and supply, and they checked for the compatibility of existing equipment in the labs. As mentioned in the previous sections, this project was mainly funded by the SITN. Some of the equipment was transferred from other Institutions who were SITN partner Institutions. The list of the components is shown in Appendix A (The list of solar photovoltaic related equipment and supply). These components were obtained from a variety of resources and the list was merged into one table.

Assembly and Testing Process

After receiving all of the components, all of the students were involved in the assembly and testing process of the unit. Students were assigned individual components so that they could learn more about the specific component(s) by studying the specifications and assembly procedures. For example, two of the students are assigned to three different electric meters for further study (net metering, one way metering, two ways metering). Two of the inverters were assigned four students for further study of the specifications, assembly, and testing of the equipment. The photos of the assembly and testing process are shown in Figure 5.

Figure 5. Assembly and Testing of Individual Components

A laboratory experiments workbook is being written to explain the training unit capability, operation, and parts used to conduct several lab experiments including troubleshooting. All the experiments are being written so that they can be conducted in the renewable energy-related classes and potential workshops to be offered on campus. A folder with the specifications data for each component on the training unit was prepared to check the operations of each component and as a reference for students. During the laboratory experiments, students can refer to this folder to find the specifications of each component to conduct the lab experiments; this will eliminate connection difficulty. There are already fifteen laboratory experiments written; general titles in the workbook are listed in Table 3.

Table 3. Experiments using training unit

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<tr><td>Experiment 1</td><td>Basic Electricity & Measurements (Voltage, Current, Resistance, and Power)</td></tr>
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Brief descriptions of each lab is listed below. Not all the details for each lab experiment are provided in this paper.

Experiment 1: Students learn basic electricity measurements (V, I, R) using a multimeter, a watt-meter.
Experiment 2: In this experiments, student learn to identify solar photovoltaic electrical and mechanical system components (Balance of the system components).
Experiment 3: Students learn how to use a solar path finder for shading analysis to locate the potential shadings throughout the year. In this lab students are divided into groups and pick specific locations an arrays on campus.

Experiment 4: Student learn I-V curve (Power characteristics) of solar modules based on temperature and irradiation changes.
Experiment 5: Batteries are important components of solar photovoltaic systems. Student learn how to connect (series-parallel) batteries, battery safety and protection.
Experiment 6: Student measure ambient temperature and solar module temperatures and observe voltage output with temperature changes. Student also measure irradiation using a solar insolation meter and observe current based on solar irradiation change.
Experiment 7: Inverters and DC to AC conversions are introduced to students with this activity.
Experiment 8: In this experiment, charge controllers are introduced. Students are given opportunity to connect different types of charge controllers to the solar photovoltaic system.
Experiment 9: In this activity, students learn how to build a basic stand-alone system without any grid power.
Experiment 10: In this activity, students learn how to build a basic grid-ties solar photovoltaic system with and without battery backup.
Experiment 11: Student learn variety of electric meters and their connections such as traditional, dual, and net metering.
Experiment 12: In this activity, students are given an opportunity for instrumentation and interfacing of solar photovoltaic outputs (V, I, P) using several data acquisition devices provided by inverter, charge controller, and third party manufacturers. This experiment also allows students to store the power, temperature, irradiation outputs.
Experiment 13: Students are given opportunity to connect a wind turbine and a generator with the solar panels to study hybrid systems.
Experiment 14: In this activity, students are asked to troubleshoot a non-working (purposely prepared) system by using motoring and testing devices such as multimeter.

As an example, the description of Experiment 3 (Solar Pathfinder) is detailed here. In the experiment, students are divided in three groups and are provided three Solar Pathfinders, assistive software, and laptops to use software. A short description of the equipment, summary of the experiment, and questions are provided in the experiment paper work. A sun path calculator is used to view the solar window for a particular location for assessing shading. Other means can be used to evaluate shading, but sun path calculators are usually the quickest and easiest to use. The Solar Pathfinder™ is a popular type of sun path calculator that consists of a latitude-specific sun path diagram covered by a transparent dome. The dome reflects the entire sky and horizon on its surface, indicating the position and extent of shading obstructions. The sun path diagram can be seen through the dome, illustrating the solar window. The solar window is compared to the obstruction reflections to determine the dates and times when shading will occur at the site. When a sun position is overlapped by an obstruction, the sun would appears behind the obstruction, and the location is shaded. The pictures of the solar path calculator are shown in Figure 6.

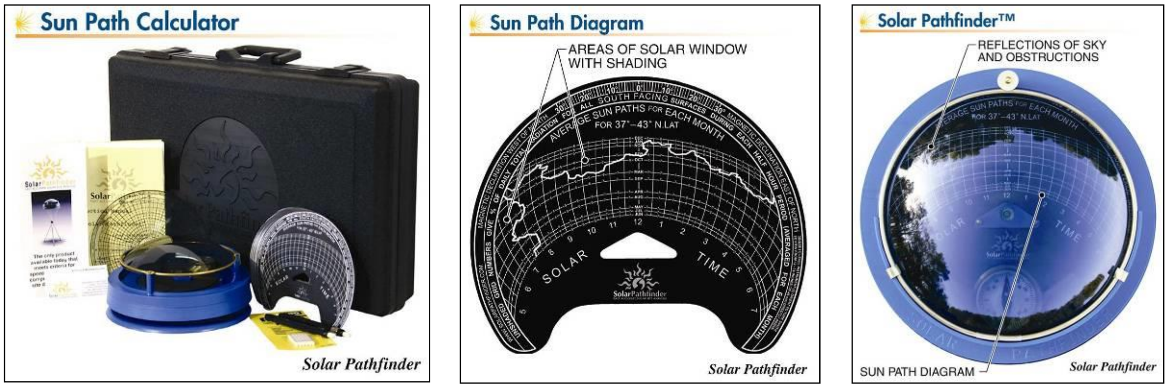

Figure 6. Solar pathfinder

To use the Solar Pathfinder™, the unit is located at the proposed array site. It is leveled and oriented to true south with the built-in compass and bubble level. (The compass reading may require adjustment for magnetic declination.) Looking straight down from above, the user observes reflections from the sky superimposed on the sun path diagram and traces the outlines of any obstructions onto the diagram. Students draw shading areas in different locations and identify obstructions around the solar modules. Students are required to submit a detailed report and suggestions for the given experiment.

Necessary improvements on this manual will be made summer, 2016 by obtaining a class survey from students. Also, any errors identified during the laboratory experiments will be noted by an instructor, and necessary actions will be taken for updates to the manual. This lab manual will be updated to include more experiments such as hydrogen fuel cell systems, mechanical to electrical energy conversion, biofuel etc., and the training unit will be upgraded with necessary components. Adding more components to the training unit may lead to a design change of the system to enlarge the board space.

Student Learning

Students involved in this project conducted structured independent research, used creative thinking, and shared hands-on experiences that also were beneficial to their gained knowledge. The training unit was used to develop an understanding of the way that the energy is collected and stored. Establishing methods to present alternative energy teaching and to research interactive training units will help to involve our undergraduate and graduate students, faculty, and the community in future alternative energy projects and training. A fully functional training unit provides for applied energy education workshops for local community colleges, secondary/high school science/technology teachers and students, and an interested citizen population who are not otherwise exposed to state-of-the-art renewable energy. Students can obtain valuable knowledge by doing research related to their major/minor.
In terms of student learning and satisfaction, the projects were a success. With the increasing importance of renewable energy resources in present and future energy scenarios, an ability to design and analyze renewable energy systems becomes essential for engineering and technology educators and students. All students in the projects showed improvement in learning and understanding concepts about renewable energy sources since the theory-based lecture was

complemented by hands-on experiments, and we are hoping to increase the number of experimental projects to address additional renewable sources that increase the students' learning possibilities. The hands-on experience from the projects provided the students with the opportunity to demonstrate the knowledge that they have gained in previous courses. Students learned about various aspects of renewable energy including problem identification, technical, social and environmental constraints, multidisciplinary team management, communications, and documentation skills. These projects also provided the student with an opportunity to view their designs from an ethical and sustainability awareness perspective, thus realizing a lifelong learning opportunity. Through practice, the students realized that the key success for a design project is team work, industry interaction, and collaboration.

Discussions

The outcome of this project was an efficient, easy to build and operate, cost-efficient alternative energy training unit which works as a stand-alone mini-lab. The reliability of these types of projects will lead other institutions to develop their own systems. The project engaged student participation from different disciplines (electronics technology, construction management, safety management, design and development, and electronics & computer engineering technology). The team leader (faculty advisor) set up meetings to organize working schedules, progress reports, and the implementation was conducted as part of the initial project. All necessary construction and production tools are located at the production lab building; therefore, this location was used to construct the training unit. The computer models of the system were designed using Computer Aided Design and Drafting software tools by the Design and Development Majors in the Design and Drafting Lab. The Electronics Majors used equipment in the electronics laboratory for the electrical part of the structure and for testing the system. The determination of the system reliability and safety was tested with detailed calculations and measurements by Industrial Safety Management Majors and Minors. Students involved in this project participated in hands-on experiments that will benefit their future careers.

Conclusion

Building a renewable energy teaching and research training unit as a mini-lab will help to establish a laboratory and involves our undergraduate/graduate students, faculty, and community in learning about alternative energy. This lab and the hands-on renewable-energy related classes will promote alternative energy education at Sam Houston State University. A fully functional laboratory training unit will augment applied energy education workshops for local community colleges, secondary/high school science/technology teachers, students, and especially interested population who are not exposed to state-of-the-art renewable energy. During the development of this project, students of the university's engineering technology programs became involved. They were able to participate in real-world problem solving, and to suggest their own solutions. This allowed them to further their skills in research and troubleshooting.

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Appendix A: The list of Solar Photovoltaic related equipment and supply

Part #	Quantity	Description
H361NRB	1	SQUARE D SAFETY SWITCH, HEAVY DUTY
		NON-FUSIBLE, 3-POLE, 600VAC, 30A, NEUTRAL, NEMA 3R
CS6P-230P	6	CANADIAN SOLAR CS6P 230 WATT MODULES
PVI 1800 - 240V	1	SOLECTRIA PVI 1800W SOLAR INVERTER
10-01XLPUSE BK	500	USA WIRE AND CABLE 10AWG USE-2
002103C*1	20	UNIRAC MID CLAMP DK, CLR
004002C*1	20	UNIRAC 2 FLANGE HD W/SCREWS/BUTYL
003001S*1	4	UNIRAC SPLICE KIT HD W/GRND MILL
WEEB-UMC	20	WILEY WEEB GROUND PLATE. WASHER, ELECTRICAL
304000C*1	20	UNIRAC L-FOOT, SERRATED, CLR
QMSC A	10	QUICK MOUNT ROOF FLASHING 12 X12 MILL
302101C*1	20	UNIRAC MID CLAMP ABCDK, CLR, HD
303001C*1	2	UNIRAC SPLICE BAR SERRATED, CLR
WEEBL-6.7	10	WILEY GROUND LUG WEEB 6.7
ACC-PV	50	WILEY ACME CABLE CLIP HOLDS 1 OR 2 USE-2 CABLES OR 1 PV CABLE
308001S*1	20	UNIRAC GROUNDING CLIP NO.
PF-TC	1	SOLAR PATHFINDER FULL KIT W/TRIPOD, SHADE SURVEY
DS-05	1	DAYSTAR DIGITAL SOLAR METER
PV-670508-000	1	AMPHENOL CRIMP TOOL - ATTACH CONNECTOR CABLE
DU221RB	1	SQUARE D SAFETY SWITCH, GENERAL DUTY, NON-FUSIBLE, 30A, 240V, 3-POLE
FP1-1	1	OUTBACK FLEXPOWER ONE - PREWIRE INVERTER SYSTEM - VFX3524
PV-100506-00	50	AMPHENOL MALE & FEMALE H4 PAIR
SOCSRV-ID-LCDOD	1	SolrenView, PVI 1800-7500 Outdoor w/LCD
OUTMATE3		MATE3 System Controller
OUTFW-MB3		FW-MB3 Mate 3 Side Mounting Bracket
OUTFW-MB3-F		FW-MB3-F Mate3 Flat Mount Kit
OUTMATE3USB		MATE3 USB Card
8G27-DEKA	4	MK Powered 12V 88/99.5 AH Deka Gel Battery
CSUN250-60P	4	CSUN 250W Polycrystalline Silver Frame Solar Module w/MC4 Compatible Connectors
DS-05	3	DayStar Digital Solar Meter
PF-TC	2	Solar Pathfinder Full Kit w/ Tripod
0786-41	1	SolaDeck Roof Mount Combiner/Enclosure w/ 6” Slotted Din
CCS-04-15-4XP	1	SolarBOS 600 VDC Compact Combiner per the following specifications (listed to UL-1741): 1) Fuse sizes are: 4 x 15 amp
PSX-240	2	OUTBACK 6KVA RATED W/ ENCLOSURE AND COOLING FAN(INCLUDES DUAL POLE 25AMP AC BREAKER)
BARE6S0L315	50	6 SOLID BARE COPPER-315'

31062	1	50FT FISHTAPE W/EYELET
8432	50	3/4" NM L/T 100' COIL
8405	6	3/4" SEALTIGHT STRAIGHT N
8420	6	3/4" SEALTIGHT 90 DEGREE
1X4	5	1" X 4" RIGID NIPPLE
GLL3	8	1" MALLEABLE INSULATED GR
103S	10	1" STEEL LOCKNUT
BR1220B100	3	12/20C 100A 1PH MB LOADCE
BR120	6	1P 20A 120/240 BREAKER
BR215	1	2P 15A 120/240V BREAKER
BR250	1	2P 50A 120/240V BREAKER
TP414	4	4" SQ MOLDED COMBO 1/2 &
TP438	2	4" SQ 2 1/8" DEEP MOLDED
TP518	2	4" SQ CVR (1) 30A-50A SGL
TP514	2	4" SQ CVR (1) 20A SGL RCP
ALF1	10	1" ALUMINUM FLEXIBLE COND
410DC2	2	1" FLEX STRAIGHT DIECAST
ALF34	100	3/4" ALUMINUM FLEXIBLE CO
903	10	1-INCH ONE-HOLE MALLEABLE
TP594	2	1 7/8" DEEP 1/2" KO HANDY
660IG	2	SP 15A TOG SWITCH
TP618	2	HANDY BOX TOGGLE SWITCH P
TP278	4	4" OCTAGON 1/2" & 3/4" KO
3232I	8	15A 125V DUPLEX RECPT
TP510	4	4" SQ CVR (2) DUP RCPT
902S	50	3/4" ONE HOLE RIGID STRAP
SE00W124BK250	40	12/4 SEOOW 600V BLACK COR
SE00W84BK250	40	8/4 SEOOW 600V BLACK CORD
L1420P	2	20A 4W 125/250V TL PLUG
EMT34	100	3/4" EMT CONDUIT
241DC	5	3/4" EMT SET SCREW DIECAS
231DC2	5	3/4" EMT SET SCREW DIECAS
1451	2	1451 3P4W 50A125/250V PLU
IT04	10	#4-#14 POLARIS INSUL-TAP
ADR1121	8	1/0 AL/CU 2 CONDUCT. LUG
THHN10STBK500	500	10 THHN STR BLACK-500'
THHN10STWH500	500	10 THHN STR WHITE-500'
THHN10STGN500	500	10 THHN STR GREEN-500'
THHN4BK500	500	4 THHN STR BLACK-500'
408DC2	12	3/4" FLEX STRAIGHT DIECAS