Deliverable 6

Development of Low Voltage/Extended Runtime Signalized Intersection Using Backup Power after the Loss of Utility Power Due to Hurricanes

Agreement No. BE703

Deliverable 6 – Final Report

Prepared For

Florida Department of Transportation

August 2021

2021 CUTR CENTER FOR URBAN TRANSPORTATION RESEARCH CUTR.USF.EDU UNIVERSITY OF SOUTH FLORIDA

Deliverable 6: Final Report

Agreement No. BE703

Submitted to:

Mr. Derek Vollmer, P.E.
Project Manager (PM)
Manager, Traffic Engineering Research Lab (TERL)
605 Suwannee St. MS 26S
Traffic Engineering & Operations Office
Florida Department of Transportation
Tallahassee, FL 32399
E-mail: Derek.Vollmer@dot.state.fl.us

Prepared by:

Dr. Pei-Sung Lin, P.E., PTOE, FITE
Principal Investigator (PI)
Program Director – ITS, Traffic Operations and Safety
Center for Urban Transportation Research (CUTR)
University of South Florida
4202 E. Fowler Avenue, CUT100
Tampa, FL 33620
Phone: (813) 974-4910
E-mail: lin@cutr.usf.edu

Dr. Achilleas Kourtellis (Co-PI)
Assistant Program Director – ITS, Traffic Operations and Safety, CUTR
University of South Florida

Dr. Zhixin (Lee) Miao (Co-PI)
Associate Professor, Smart Grid Power Systems (SPS) Lab
University of South Florida

Dr. Zhenyu Wang (Co-PI)
Research Faculty, CUTR
University of South Florida

Miao Zhang
Graduate Research Assistant, CUTR
University of South Florida

August 2021

Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

Metric Conversion

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	M
yd	yards	0.914	meters	M
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	G
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of Low Voltage/Extended Runtime Signalized Intersection Using Backup Power after the Loss of Utility Power Due to Hurricanes		5. Report Date August 2021
		6. Performing Organization Code
7. Author(s) Pei-Sung Lin, Achilleas Kourtellis, Zhixin Miao, Zhenyu Wang, Miao Zhang		8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Urban Transportation Research University of South Florida 4202 E Fowler Avenue, CUT 100 Tampa, FL 33620		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. FDOT BE703
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report January 30, 2019–August 31, 2021
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract
This research study investigated the applicability of backup power systems to provide extended backup power to traffic signals after power loss due to hurricanes. CUTR researched available and experimental technologies and recommended three systems for testing to the Florida Department of Transportation (FDOT). The three selected systems were acquired and installed at a test intersection at the FDOT Traffic Engineering Research Lab (TERL) in Tallahassee. A liquid propane generator was tested that successfully provided constant power without issues; the only limitation was the availability of fuel. A lithium battery system also was tested, which powered the test signalized intersection for 20 hours, more than enough to cover nighttime operations. A system that included a battery + solar backup was tested successfully and provided power for several days without issues. This system uses smaller battery capacity but requires sunny weather to charge the battery and power the intersection during daytime; this is not usually an issue after hurricanes, especially if adequate solar energy generation is provided to charge the battery during available daytime hours. These systems are recommended to be approved and placed on the FDOT Approved Product List (APL) for future use by agencies in Florida.

17. Key Word	18. Distribution Statement
Backup power, solar energy, solar panels, lithium batteries, batteries, BPS, UPS, LPG generator, extended backup power, traffic signal, power loss	No restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	110	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgments

The project research team at the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF) sincerely thanks FDOT Project Manager Mr. Derek Vollmer and Mr. Matt DeWitt for their full support, guidance, and assistance on this important research project and thanks TERL staff for their help and support, insights, and feedback. CUTR also thanks former FDOT Project Manager Mr. Jeff Morgan for his support and guidance. Our appreciation also goes to FDOT Research Center Manager Mr. Darryll Dockstader, Research Development Coordinator Jennifer Clark, Performance and Workforce Coordinator Jason Tuck, and Business Systems Coordinator Amanda Ulmer for their support and assistance. Finally, CUTR thanks Mr. Tracy Forester and Mr. Lucas VanSickle of Halff Associates, Inc., for their help and support during system acquisition, installation, and testing.

Executive Summary

Lessons learned after recent Florida hurricanes revealed that although most traffic signal infrastructure withstood the impacts of the storms, signalized intersections were not operational due to lack of utility power. Because of this and problems associated with the use of generators to run intersections, such as purchase and replacement costs, storage issues, and costs of placement in the field after a storm, the subject needs further research for viable solutions.

The project team researched and developed recommendations for specific technologies for consideration in testing extended backup power for traffic cabinets in case of power loss especially during and after hurricanes. Current traffic cabinets employ a standard uninterrupted power supply (UPS) system, which is powered by lead acid batteries, an outdated technology that provides power for only up to eight hours of operation.

After coordination with staff at the Florida Department of Transportation (FDOT) Traffic Engineering Research Lab (TERL) and the FDOT Project Manager, the team selected a liquid propane (LPG) generator system, a lithium battery system, and a lithium battery with solar backup system for testing. Testing was conducted at the TERL in Tallahassee; the systems were installed at a test signalized intersection and connected to the traffic cabinet.

After installation, the team tested a generator that provided power to the traffic cabinet without issue for as long as it had fuel. The generator can be set up as a standby backup power source similar to those at commercial buildings, hospitals, etc. The generator has a lower initial cost but requires maintenance that might increase operation costs in the long term. In addition, the LPG generator needs a fuel tank, which can be hazardous if hit during a traffic crash. Therefore, additional safety precautions must be taken, such as breakaway lines, an automatic shutoff valve, or concrete barriers, to ensure safe storage close to a signalized intersection.

The tested lithium battery system transferred the load instantaneously and without delay. It requires no maintenance and is self-charging and maintains charge when needed. The battery-only system is an applicable solution to the problem of providing extended power to traffic cabinets. A major drawback with a battery-only system is that if the battery runs out of energy and grid power is not restored, the signalized intersection will go dark. To ensure a longer runtime, a larger battery capacity is required, which increases cost.

To minimize the cost of the batteries, a solution is to provide backup power using additional solar power in addition to the batteries. The team installed and tested a solar-powered setup that provided enough solar power to charge a 10-kWh battery used to power a 0.45-kW load an average of 14 hours overnight (from 6:00 pm to 8:00 am). The solar power available in the morning powered the load and charged the battery to be ready for the next night. The number of solar panels depends on their rated power generation, the size of the battery, and the available space for installation at the site. In real-world applications, a specific design needs to be

implemented for each signalized intersection to assess power needs, available space, and budget to install a battery + solar battery system.

The systems tested showed great promise in providing backup power in case of power loss for an extended period due to a hurricane. The selection and availability of each system will be the responsibility of each agency once the systems are approved and listed on the FDOT Approved Product List (APL).

Table of Contents

List of Figures

List of Tables

1 Introduction

Lessons learned from recent hurricanes revealed that although most traffic signal infrastructure withstood the impacts of the storms, signalized intersections were not operational due to lack of utility power. Because of this and problems associated with the use of generators to run intersections, such as purchase and replacement costs, storage issues, and costs of placement in the field after a storm, the subject needs further research for viable solutions.

Due to the large number of hurricanes and other storms experienced in Florida and their impact on Florida's transportation system, the Florida Department of Transportation (FDOT) strives to be the nation's leader regarding extended or self-sustaining power at signalized intersections. This research project aimed to assist FDOT in being at the forefront of the application of this technology and lead the nation in its implementation. The advantages of having a signalized intersection that can continue to operate during long hours of power outages during or after hurricanes could be substantial.

Implementation of backup power systems on a wide scale is needed, especially for traffic signals on major arterials or at major signalized intersections. Resources needed for implementation may be high for new signalized intersections and low for existing ones. Testing of backup power technologies needs to be performed to find the best solution, and standards and specifications for backup power systems need to be developed, as does a testing procedure to allow certification of associated components.

Some current practices may need to change, such as delivering generators to intersections, etc. Lack of a solution for this problem means continuing to have non-operational (dark) signalized intersections during normal daily traffic after loss of utility power during and after a storm. Currently, a dark intersection is treated as a four-way stop, which contributes to traffic congestion and safety concerns.

1.1 Project Objectives

The primary objective of this research was to improve safety and efficiency at signalized intersections during utility power loss during or after hurricanes. This project investigated the most appropriate methods for developing an extended runtime signalized intersection that would operate for a minimum of three days (72 hours) using backup power. The original goal was to provide power for five days (120 hours), but this was later modified due to the high costs of the available systems. Other areas of interest were low voltage intersection development and technologies that would lengthen battery backup runtime such as solar assist or other energy sources. Implementation is expected to be for new intersections and a retrofit solution that could be used with existing 120 VAC-powered intersections so benefits can be experienced immediately for many signalized intersections.

2 Literature Review

This section provides a detailed description of existing and emerging low voltage or extended runtime systems and emerging technologies that potentially could be used for signalized intersections and other signals. Data resources included Google, Google Scholar, scholarly articles, the Transportation Research Information Database (TRID), technical reports, conference proceedings, vendor websites, user manuals, and white papers.

2.1 Traffic Signal Backup System Requirements

The objective of this study was to explore backup power technologies to supply extended runtime of traffic signal systems at a typical signalized intersection during a power outage for a minimum specified time period, such as three or five days. The existing alternating current voltage level used for traffic signal power is 120 VAC. For example, the intersection of E Fowler Ave & Bruce B Downs Blvd in Tampa has 21 traffic signals and 8 pedestrian signals. The average LED traffic signal power is 9 W, and the pedestrian signal power is 6 W. This computation is based on specifications from Dialight LEDs [1], which is on the FDOT APL [2]. The estimated power required is 0.3 kW (kilowatts), including powering all traffic signals, the communication system, vehicle detection in operation, etc. Table 1 shows the detailed computation.

Table 1. Traffic Intersection Calculated Power

Device Used for Power Calculation	Full Operation Power (watts)	Flashing Mode Power (watts)
Dialight LED signal heads (x21)	189	90
Dialight Pedestrian (x8)	18	18
McCain 170 Controller (1x1)	40	40
EMX Detection loops (x21)	30	30
Allied Vision Monitoring equipment (x4)	10	10
Total	**295**	**188**

Table 2 shows the total capacity of the designed backup power source system. The total capacity is 36 kWh (kilowatt-hours) for 5 days of full operation. If the system runs in flashing mode from 10:00 PM to 6:00 AM (8 hours), the demanded capacity is 31.5 kWh. If the system runs in flashing mode at all times, the capacity reduces to 22.8 kWh.

Table 2. Traffic Intersection Power Needs

Running Modes	Full Operation, 5 Days	Flashing Mode on at Night, 5 Days	Flashing Mode On, 5 Days
Total Capacity	36 kWh	31.5 kWh	22.8 kWh

Backup power must be immediate and automatic; no person will be sent to a signalized intersection to start the backup system, and no activity will be performed when a hurricane approaches, such as setup. The backup system should start once power is lost; the system will have everything in place beforehand and will automatically start and last ideally for five days, with a minimum of three days.

2.2 Interconnection Requirements

Based on the output electricity form, distributed generators (DGs) can be classified into two categories—alternating current (AC)-based or direct current (DC)-based. Output electricity from a fuel cell, a solar panel, and a battery are in DC form. DC/AC converters are employed if these energy sources are to be integrated into an AC grid; DC/DC converters are required if they are to serve DC loads. However, synchronous machine-based DGs such as gas turbine DGs output AC electricity.

2.2.1 Low Voltage Backup System Topology

Figure 1 shows the interconnection topology of a traffic signal backup power system. The traffic signal devices are connected and controlled by a controller cabinet and are powered by DC power from the uninterruptible power supply (UPS) in the controller cabinet. The AC power sources are connected to an AC/DC converter, and the DC sources (fuel cell or photovoltaic) can be imported to the controller cabinet directly or through a DC/DC converter.

During normal conditions, the system is powered by a grid network, which provides an AC 120V power source. Once the grid is out of power, such as during a hurricane or storm, the switch will connect the system to the backup power source automatically. If the backup power is an AC source, it will go through an AC/DC converter; if it is a DC source, it can be used to power the system directly.

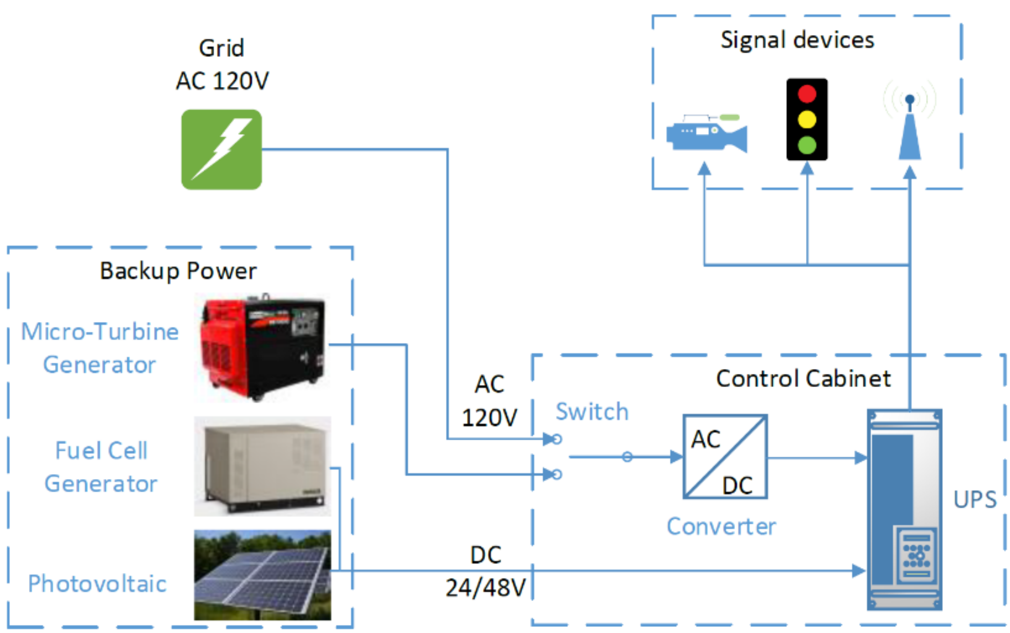


Figure 1. Concept of traffic signal backup system

2.2.2 Extra Low Voltage (ELV) System

The use of Extra Low Voltage (ELV) signal drives is now standard in the United Kingdom, where controlled pedestrian facilities are provided. However, the widespread use of ELV technology across whole intersections has not materialized, largely due to severe limitations on cable lengths and the number of signals that can be illuminated if traditional incandescent signals are used at ELV levels [3]. The development of more efficient LED signals [4] now allows ELVs to be used without imposing significant limitations on intersection cable runs or the number of signals that can be driven, allowing all potential benefits of ELV systems to be realized in the Siemens ST900 ELV system, as shown in Figure 2.

Figure 2. Siemens ST900 ELV system

ELV solutions can improve safety, reduce CO_2 emissions, reduce raw material usage, and easily integrate with DC solar/battery power source. An ELV system should be considered when designing the backup power interconnection based on the above benefits.

An 48V cabinet has been applied in some locations. Development of more efficient LED signals allows ELV to be used. Siemens Automation Company has ELV traffic controller cabinets, such as its ST750P ELV system shown in Figure 2, that can integrate with both low voltage (230 VAC) and ELV (48VDC) drive levels. This means that LED signals can be integrated with the ELV controller directly. Benefits include (1) much simpler LED modules needed in signal heads; (2) a smaller load switch size that allows a much smaller cabinet, which is good for restricted rights-of-way; (3) reduced load, which opens up opportunity for solar-powered signalized intersections at remote locations; (4) reduced load that allows longer battery backup; and (5) less of an electrical hazard in a knockdown. Therefore, a 48V cabinet could allow the same backup power system to provide longer extended time for a traffic signal operation after loss of utility power.

2.3 Alternative Storage Technology: Supercapacitor

A supercapacitor (SC) (also called a supercap, ultracapacitor, or Goldcap) is a high-capacity capacitor with capacitance values that are much higher than other capacitors (but with lower voltage limits) that bridge the gap between electrolytic capacitors and rechargeable batteries. They typically store 10–100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver a charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries.

Supercapacitors are used in applications requiring many rapid charge/discharge cycles rather than long-term compact energy storage, such as in cars, buses, trains, cranes, and elevators, for which they are used for regenerative braking, short-term energy storage, or burst-mode power delivery. Supercapacitors compete with electrolytic capacitors and rechargeable batteries, especially lithium-ion batteries.

2.3.1 Background

Supercapacitors can be applied to consumer electronics with fluctuating loads, such as laptop computers, GPS, portable media players, hand-held devices [5], photo flashes in digital cameras, LED flashlights [6], and portable speakers [7]. They also can be used for transportation non-linear loads, such as electric vehicle (EV) chargers and hybrid EVs [8]. Additionally, supercapacitors can be implemented as an interface between load and grid to act as a buffer [9, 10]. Sado City in Japan's Niigata Prefecture has streetlights that combine a stand-alone power source with solar cells and LEDs. Supercapacitors store the solar energy and supply two LED lamps, providing 15 W power consumption overnight [11]. This is the closest application to the purpose of this project; however, there is no proof that it can provide power continuously for more than one day.

Supercapacitors are used in applications requiring many rapid charge/discharge cycles rather than long-term compact energy storage, such as five-day continuous power supply for traffic systems.

2.3.2 Pros and Cons

- Pros:
    - Virtually unlimited cycle life; can be cycled millions of times
    - High specific power; low resistance enables high load currents
    - Charges in seconds; no end-of-charge termination required
    - Simple charging; draws only what it needs; not subject to overcharge
    - Safe; forgiving if abused
    - Excellent low-temperature charge and discharge performance

- Cons:
    - Low specific energy; holds fraction of regular battery
    - Linear discharge voltage prevents using full energy spectrum
    - High self-discharge; higher than most batteries
    - Low cell voltage; requires series connections with voltage balancing
    - High cost per watt

2.3.3 Conclusion

Ultracapacitors or supercapacitors are best suited for situations in which much power is needed quickly. For electric cars, this means they would be better than batteries when the vehicle needs bursts of energy, such as during acceleration. Toyota, PSA Peugeot Citroen, and Mazda use supercapacitors for short-term energy storage at acceleration and deceleration. This project requires a long-term but low-power energy storage system; thus, a battery system would be more suitable than supercapacitors.

2.4 Battery Backup Systems

Most agencies use widely-available battery backup systems. A battery backup system can be installed in parallel with grid power to allow a traffic signal system to run on battery power during a power outage. The battery cells are charged by utility power and expel their electricity when a power outage occurs (see [12] for information on how a battery stores and releases energy). Many agencies currently use UPS system for backup power for short-term losses of utility power; however, a much more efficient and larger battery system is needed for meeting the requirement of five days of operation of a typical signalized intersection after the loss of utility power due to a hurricane.

2.4.1 Background

Dr. Zhixin Miao's research group conducted much research related to battery analysis and implementation. Reference [13] investigates modeling and control of a battery management system used in a microgrid. Mixed integer programming (MIP) formulations are proposed in [14] to obtain the optimal capacity of a battery energy storage system (BESS) in a power system. Reference [15] presents data analysis results based on four-year data from photovoltaic (PV) panels and lithium-ion batteries and [16] presents the topologies of three types of charging systems. In [17], system identification is carried out for a 20 kWh battery using real-world measurement data. Reference [18] applied a general Benders Decomposition to solve a stochastic mixed integer programming formulation (SMIP) to obtain the optimal sizing of a PV system and BESS. Reference [19] developed an unbalanced current (UC) and harmonic current (HC) controller for battery inverters based on the structure of a proportional-resonance (PR) controller. In [20], a real-time model of a microgrid with an energy storage system was implemented in the RT-Lab and [21] investigated the control strategies for a lithium-ion battery to operate in a microgrid.

Lithium-ion batteries provide lightweight, high-energy-density power sources for a variety of devices. To power larger devices such as electric cars, connecting many small batteries in a parallel circuit is more effective and more efficient than connecting a single large battery [22] in portable devices, power tools [23], and EVs in transportation [24].

Most of the world's lead-acid batteries are used for automobile starting, lighting, and ignition (SLI). Wet cell stand-by (stationary) batteries designed for deep discharge are commonly used in large backup power supplies for telephone and computer centers, grid energy storage, and off-grid household electric power systems [25]. Valve-regulated lead acid batteries cannot spill their electrolytes and are used in backup power supplies for alarm and smaller computer systems (particularly for UPS) and for electric scooters, electric wheelchairs, electrified bicycles, marine applications, battery electric vehicles, micro hybrid vehicles, and motorcycles.

Currently, the UPS units inside a traffic control cabinet are lead-acid batteries. Lithium-ion batteries are made from a better, stronger balloon material when compared to lead acid. In addition to depth of discharge benefits, lithium-ion batteries have a longer useful life and can cycle more times without significant loss of capacity [26].

2.4.2 Pros and Cons

- Pros
  - Can switch from utility power to battery power within milliseconds without a noticeable interruption in signal operations
  - Generate no noise and guarantee zero emissions
  - May provide full-operation or flash-operation depending on power requirements

- Cons
  - Battery bank with a capacity of five days for normal operation requires high cost for installation
  - Battery degradation over time and storage temperature impact should be considered

2.4.3 Battery Types

As shown in Figure 1, a 120VAC 60Hz inverter is required to convert a DC battery output to AC. The major battery chemistries are described below:

- **Nickel Cadmium (NiCd)** – Chemistry is mature and well understood but relatively low in energy density. NiCd is used where long life, high discharge rate, and economical price are important. Main applications are two-way radios, biomedical equipment, professional video cameras, and power tools. NiCd contains toxic metals and is not environmentally-friendly.

- **Nickel-Metal Hydride (NiMH**) – Chemistry has a higher energy density compared to NiCd but at the expense of reduced cycle life. NiMH contains no toxic metals. Applications include mobile phones, laptop computers, and hybrid electric automobiles.
- **Lead Acid** – Chemistry is the most economical for larger power applications where weight is of little concern. A lead acid battery is the preferred choice for hospital equipment, wheelchairs, emergency lighting, automotive, and UPS systems.
- **Lithium Ion (Li-ion)** – Chemistry is the fastest-growing battery system. Li-ion is used where high energy density and light weight are of prime importance; its chemistry is more expensive than other systems and must follow strict guidelines to ensure safety. Applications include laptop computers, cellphones, hybrid electric vehicles, and any electronic device that needs a battery.
- **Lithium-Ion Polymer (Li-ion polymer) –** Chemistry is a potentially lower-cost version of Li-ion chemistry; is similar to Li-ion in terms of energy density, enables very slim geometry, and allows simplified packaging. Main application is mobile phones.

Table 3 compares the characteristics of the six most commonly used rechargeable battery systems in terms of energy density, cycle life, exercise requirements, and cost. Exotic batteries with above average ratings are not included.

Table 3. Comparison of Battery Technologies [27]

Feature	NiCd	NiMH	Lead Acid	Li-ion	Li-ion Polymer	Reusable Alkaline
Gravimetric energy density (Wh/kg)	45–80	60–120	30–50	110–160	100–130	80 (initial)
Internal resistance (includes peripheral circuits) in mW	100 to 200[1] 6-V pack	200 to 300[1] 6-V pack	<100[1] 12-V pack	150 to 250[1] 7.2-V pack	200 to 300[1] 7.2-V pack	200 to 2000[1] 6-V pack
Cycle life (to 80% of initial capacity)	1500[2]	300 to 500[2,3]	200 to 300[2]	500 to 1000[3]	300 to 500	50[3](to 50%)
Fast charge time	1 h typical	2–4 h	8–16 h	2–4 h	2–4 h	2–3 h
Overcharge tolerance	Moderate	Low	High	Very low	Low	Moderate
Self-discharge / month (room temperature)	20%[4]	30%[4]	5%	10%[5]	~10%[5]	0.3%
Cell voltage (nominal)	1.25 V[6]	1.25 V[6]	2 V	3.6 V	3.6 V	1.5 V
Load current: • Peak • Best result	20 C 1 C	5 C 0.5C or lower	5 C[7] 0.2 C	>2 C 1 C or lower	>2 C 1C or lower	0.5 C 0.2C or lower
Operating temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance requirement	30–60 days	60–90 days	3–6 month[8]	not req.	not req.	not req.
Typical battery cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per cycle (US$)[9]	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10–0.50
Commercial use since	1950	1990	1970	1991	1999	1992

Notes:

1. Internal resistance of battery pack varies with cell rating, type of protection circuit, and number of cells. Protection circuit of Li-ion and Li-polymer adds about 100 mW.
2. Cycle life based on battery receiving regular maintenance. Failing to apply periodic full discharge cycles may reduce cycle life by factor of three.
3. Cycle life based on depth of discharge. Shallow discharges provide more cycles than deep discharges.
4. Discharge highest immediately after charge, then tapers off. NiCd capacity decreases 10% in first 24h, then declines to about 10% every 30 days thereafter. Self-discharge increases with higher temperature.
5. Internal protection circuits typically consume 3% of stored energy per month.
6. 1.25V is open cell voltage; 1.2V is commonly used value. No difference between cells, simply method of rating.
7. Capable of high current pulses.
8. Maintenance may be in form of “equalizing” or “topping” charge.
9. Derived from battery price divided by cycle life. Does not include cost of electricity and charger.

2.4.4 Applications in Traffic Signals

- **San Angelo, TX** – The San Angelo City Traffic Operations Department is working to place battery backup systems at all intersections with traffic lights. Full installation of one unit takes 1–2 hours, with 4 units per day the average. In Phase 1 of this project, 42 battery backups were installed, bringing the current total to 70 traffic signals that have this system, according to the Traffic Operations Superintendent. Phase 2 funding will add 49 signals to complete the project for 100% of the city's traffic signals [28].
- **Brooklyn, OH** – The Brooklyn City Council is expected to proceed with an $80,000 expenditure aimed at keeping 12 traffic light intersections operational during emergency electricity outages. The 12 battery-backup and generator panels cost roughly $70,000, and the City will spend $9,400 to purchase 120 foldable STOP signs to be used at minor intersections during power outages. According to the Brooklyn Police Chief, a Cleveland-based company will do most of the installation work. Each traffic light battery should last 3–6 hours, depending on the number of lights running and how often it cycles [29].
- **Jonesboro, AR** – Jonesboro's battery backups can keep traffic signals working for up to 12 hours after the power goes out. Each backup battery costs about $4,000. The City uses traffic volume to determine which intersections get the batteries first. When there is a power outage, often if the signal is dark, it takes 1–2 officers to run the intersection, per the City Traffic Operations Engineer. In the event of an emergency when the power is out, the battery backups keep officers from having to spend their time directing traffic and, rather, can help other citizens (Figure 3) [30].

Figure 3. Battery backup system for traffic signal in Jonesboro, AR

- **Tesla Powerwall** – A Tesla Powerwall, as shown in Figure 4, is a fully-integrated AC battery system for residential or light commercial use. Its rechargeable lithium-ion battery pack provides energy storage for backup, with every Powerwall battery offering

13.5kWh. Based on total capacity calculation, three Powerwall packs (40kWh) would be enough for five days of full operation; two Powerwall packs would be enough if signals are operating on flash mode at night.

Figure 4. Size dimensions for Tesla Powerwall

According to Tesla's Powerwall performance specifications, as shown in Table 4, the voltage, capacity, and power provided meets the system requirement. In addition, Tesla supplies 10-year warranties. The Powerwall has a good ingress rating, so it can be installed outdoors. Based on this information, using a Tesla Powerwall would need three packs of batteries to provide the capability to supply five days of continuous power.

Table 4. Tesla Powerwall Specifications [31]

PERFORMANCE SPECIFICATIONS

AC Voltage (Nominal)	120/240 V
Feed-In Type	Split Phase
Grid Frequency	60 Hz
Total Energy[1]	14 kWh
Usable Energy[1]	13.5 kWh
Real Power, max continuous[2]	5 kW (charge and discharge)
Real Power, peak (10s, off-grid/backup)[2]	7 kW (charge and discharge)
Apparent Power, max continuous	5.8 kVA (charge and discharge)
Apparent Power, peak (10s, off-grid/backup)	7.2 kVA (charge and discharge)
Maximum Supply Fault Current	10 kA
Maximum Output Fault Current	32 A
Overcurrent Protection Device	30 A
Imbalance for Split-Phase Loads	100%
Power Factor Output Range	+/– 1.0 adjustable
Power Factor Range (full-rated power)	+/– 0.85
Internal Battery DC Voltage	50 V
Round Trip Efficiency[1,3]	90%
Warranty	10 years

[1] Values provided for 25°C (77°F), 3.3 kW charge/discharge power.
[2] In Backup mode, grid charge power is limited to 3.3 kW.
[3] AC to battery to AC, at beginning of life.

ENVIRONMENTAL SPECIFICATIONS

Operating Temperature	–20°C to 50°C (–4°F to 122°F)
Optimum Temperature	0°C to 30°C (32°F to 86°F)
Operating Humidity (RH)	Up to 100%, condensing
Storage Conditions	–20°C to 30°C (–4°F to 86°F) Up to 95% RH, non-condensing State of Energy (SoE): 25% initial
Maximum Elevation	3000 m (9843 ft)
Environment	Indoor and outdoor rated
Enclosure Type	NEMA 3R
Ingress Rating	IP67 (Battery & Power Electronics) IP56 (Wiring Compartment)
Wet Location Rating	Yes
Noise Level @ 1m	< 40 dBA at 30°C (86°F)

- **Alternatives to Tesla** – Even though energy storage for homes or other facilities is a relatively new technology for that market, it continues to garner interest. Over the past few years, new and exciting opportunities within the energy industry have emerged. There are similar backup power systems produced from several manufacturers in addition to Tesla's Powerwall, including Sonnen, LG, Smart Harbor, and ElectrIQ. The backup power systems developed by these manufacturers provide alternatives to Tesla's Powerwall. A comparison of battery type, capacity and warranty among manufacturers is shown in Table 5.

Table 5. Comparison of Battery Type, Capacity, and Warranty among Manufacturers

Manufacturer	Tesla	Sonnen	LG	Smart Harbor	ElectrIQ
Battery type	Lithium-ion	Lithium-ion	Lithium-ion	Lithium-ion	Lithium-ion
Capacity	13.5 kWh	4–16 kWh	3.3–9.8 kWh	10.6–15.9 kWh	10 kWh
Warranty	10 yrs	10 yrs @ 70% capacity	10 yrs @ 60% capacity	10 yrs	10 yrs @ 60% capacity

2.4.5 **Source:** https://www.allhomerobotics.com/best-tesla-powerwall-alternatives/

2.4.6 Battery Backup System (BBS) Capacity Assessment

Research has been conducted on maximizing return on investment (ROI) for a BBS, and a methodology was developed to assist BBS capacity investment by considering both traffic signal operation and budget requirements [32]. The hazard-based duration models were developed to aid in evaluating the potential benefit of BBS and in optimizing the BBS investment by understanding the attributes of traffic signal power failures. An analysis comparing the volume and functional class weighted annual signal downtime at different intersections could help to select BBS installation locations and determine the installation priority.

2.4.7 Conclusion

According to the existing battery backup system cases researched, many agencies currently use UPS for backup power. However, the battery-powered UPS in traffic signal systems can work for no more than 12 hours in most cases. To satisfy system requirements, a much more efficient and larger battery system is required to be installed in parallel with grid power to allow a traffic signal system to run on battery power during a power outage. The Tesla Powerwall, with its rechargeable lithium-ion battery pack, provides energy storage for backup, with every Powerwall battery offering 13.5kWh. Three Powerwall packs (40kWh) would be enough for five days of full operation of a typical traffic signalized intersection; two Powerwall packs would be enough if signals are operating on flash mode at night. The Tesla Powerwall is a promising solution for a battery backup system for a signalized intersection and an excellent candidate for testing and evaluation in this project. In addition to the Tesla Powerwall, other alternative systems should be considered.

2.5 Fuel Cell

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions. Fuel cells are different from most batteries in requiring a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery, the chemical energy usually comes from metals and their ions or oxides that are commonly already present in the battery, except in flow batteries. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. A hydrogen fuel cell and a liquid methane fuel cell recently were designed for signal systems.

2.5.1 Background

Stationary fuel cells are used for commercial, industrial, and residential primary and backup power generation. Fuel cells are very useful as power sources in remote locations such as spacecraft, remote weather stations, large parks, communications centers, and rural locations such as research stations and in certain military applications [33]. A fuel cell system running on hydrogen can be compact and lightweight and have no major moving parts. As of 2017, about 6,500 fuel cell electric vehicles (FCEVs) had been leased or sold worldwide [34]. Fuel cells have been applied to buses, forklifts, motorcycles, and airplanes. Portable fuel cell systems are generally classified as weighing under 10 kg and providing power of less than 5 kW [35].

A pilot program is operating on Stuart Island, Washington; the Stuart Island Energy Initiative [36] has built a complete, closed-loop system–solar panels power an electrolyzer, which makes hydrogen, and the hydrogen is stored in a 500-U.S.-gallon (1,900 L) tank at 200 pounds per square inch (1,400 kPa) and runs a ReliOn fuel cell to provide full electric back-up to the off-the-grid residence.

There are very limited fuel cell applications on traffic signal backup systems, but they still are a potential backup technology, as a fuel cell system running on hydrogen can be compact and lightweight and has no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability, which equates to less than one minute of downtime in a six-year period [37].

2.5.2 Pros and Cons

A fuel cell traffic signal backup system will not cause pollution, as it is an environmentally-friendly power source. Additionally, it has advantages such as high efficiency and high power. The only concern is the safety of the fuel cell storage at a signalized intersection. Two types of fuel cells have been used in traffic signals and in railroad signals— a hydrogen fuel cell and a liquid methane fuel cell. Information on fuel cell vendors and backup power systems is provided in Appendix A.

- Pros – Renewable and abundant, no emissions, very powerful, environmentally-friendly, fuel-efficient [38]
- Cons – Expensive to extract, difficult to replace present infrastructure, difficult to transport, highly flammable, difficult to store

2.5.3 Applications in Traffic Signals

- **Alexandria, VA** – A report by the Fuel Cell & Hydrogen Energy Association (FCHEA) shows that hydrogen fuel cells have been used for traffic signals in Alexandria, as shown in Figure 5. In Summer 2017, Alexandria became the first U.S. East Coast city to use a hydrogen fuel cell as a backup power source for traffic lights. Through the City's Hydrogen Fuel Cell Traffic Signal Pilot, the heavily trafficked intersection that connects King Street, Quaker Lane, and Braddock Road now has a reliable, green-energy backup for traffic signals to remain in operation without interruption. According to the City, the pilot was spurred by the cost savings, reliability, and reduced maintenance of fuel cell technology compared to traditional battery backup systems [39].

Figure 5. Intersection hydrogen fuel cell backup generator, Alexandria, VA

2.5.4 Conclusion

A fuel cell can be used to provide backup power for traffic signals. It is a type of clean and efficient energy and has been shown to be able to provide power for several days with enough fuel. With proper and safe storage (e.g., flameshield tank) of hydrogen or liquid methane fuel cells or installed underground, a fuel cell backup power system could be a good candidate to provide backup power for traffic signals.

2.6 Natural Gas/Liquid Propane

Natural gas (NG) and liquid propane gas (LPG) typically work like their gasoline-powered counterparts—an internal combustion engine injects a mixture of fuel and air into a combustion chamber, where a piston compresses the mix. A spark plug ignites the fuel, driving the piston down and turning a crankshaft. The crankshaft, in turn, spins the generator's rotor in an electromagnetic field, generating an electric current that can charge batteries, power appliances or even run high-wattage tools, depending on the generator's size.

The differences between LPG and NG are clear in their physical properties. LPG has a higher energy content than NG (93.2MJ/m3 vs 38.7MJ/m3), and LPG is denser than NG, at a specific gravity of 1.5219:1 vs 0.5537:1, among other differences, as shown in Table 6.

Table 6. LPG (Propane) vs. NG (Methane) [40]

Gas Properties	LPG (Propane)	Natural Gas (NG) (Methane)
Chemical formula	C3H8	CH4
Energy content: MJ/m3	93.2	38.7
Energy content: Btu/ft3	2572	1011
Energy content: MJ/kg	49.58	52.5
Boiling temp: Cº	-42	-161.5
Flame temp: Cº	1967	1950
Flame temp: Fº	3,573	3,542
Gas volume: m3/kg	0.540	1.499
Specific gravity	1.5219	0.5537
Density @15ºC: kg/m3	1.899	0.668

Note: Some numbers rounded.

2.6.1 Background

For power generators, burning natural gas produces only about half the carbon dioxide per kilowatt-hour that coal does [41]. Natural gas-generated power increased from 740 TWh in 1973 to 5140 TWh in 2014, generating 22% of the world's total electricity, approximately half as much as generated with coal [42]. In transportation, energy efficiency is generally equal to that of gasoline engines, but lower compared with modern diesel engines. Gasoline/petrol vehicles converted to run on natural gas suffer because of the low compression ratio of their engines, resulting in a cropping of delivered power while running on natural gas (10–15%). CNG-specific engines, however, use a higher compression ratio due to this fuel's higher octane number of 120–130 [43]. Manufacturers such as PowerUp Electric implement natural gas generators for traffic signal backup systems; a utility supplies the gas to the standby natural gas generator to power the traffic signal system during a power outage.

2.6.2 Pros and Cons

NG burns more cleanly than other fuels, such as gasoline and diesel, because burning it produces both water and carbon dioxide. Propane is also considered a "green fuel" and is eco-friendly before and after combustion, which means that propane and NG are both environmentally safe. They also are less expensive than other non-renewable fuels and are very efficient. NG does not need to be stored, as it is supplied through gas pipelines; at times of natural calamities, the supply of NG is disrupted, causing a lack of fuel needed to operate generators. NG and liquid propane also are extremely explosive and can be a serious fire hazard should a pipeline burst [44].

- Pros – Renewable and clean, no toxic emissions, cheaper, environmentally-friendly, fuel-efficient
- Cons – Expensive to run, limited or non-renewable energy resource, difficult to transport, flammable, difficult to store

2.6.3 Applications in Traffic Signals

- **Shreveport, LA** – PowerUp Electric designed a system called Auto Traffic Cop for Shreveport in 2006, a self-contained natural gas system that provides continuous backup power for traffic intersections. Its units use GPS monitoring technology to check the system's health every six seconds, perform automatic exercise cycles each week, send run and stop reports, and communicate other important information. Users can access system data from any location via the Internet. Initially, the City installed three Auto Traffic Cop units that operated exactly as predicted. Based on the high success of the first three units, the City installed an additional 17 units and is installing 30 more. The unit is now specified as standard equipment on new signal installations.
- Auto Traffic Cop can operate all signal and camera operations at full power to maintain ITS capabilities for an intersection. City officials have concluded that Auto Traffic Cop is cheaper than a battery backup system in terms of the initial cost and routine maintenance costs. Its monitoring system allows City officials to know when the units are running, a feature that already has proven to be valuable. At one location, the system ran for 16 hours after a power outage; because the power circuit had only street lights and traffic signals, the power company received no calls from businesses or citizens due to the outage until the City notified the company as a result of the generator reporting the outage.

The Auto Traffic Cop unit, called the PowerUp Traffic System, as shown in Figure 6, is detailed in [45]. The system is natural gas-powered generator and designed to supply backup power to stoplight intersections and railroad crossing gates. It features a 6-kW brushless commercial generator and will supply power to any location that needs 50 amps or less of backup power.

Figure 6. PowerUp Traffic System

The PowerUp Traffic System comes with a 100-amp 120/240-volt, single-phase outdoor automatic transfer panel that is used to activate the generator when it senses a loss of power. The system assumes the full load in less than 20 seconds. When utility power is restored, the generator shuts off and signal operation is automatically returned to the normal utility power source. The transfer switch is equipped with a feature that allows testing of the unit with or without load from the transfer switch. It is also equipped with a state-of-the-art monitoring system that reports every five seconds to guarantee up to the minute accuracy and maximum reliability. The PowerUp Traffic System will completely run the signalized intersection.

- PowerUp Traffic System engine info:
  - Overhead valve commercial quality engine
  - Brushless alternator provides clean and efficient power
  - Run-time meter helps maintain regular maintenance intervals
  - Battery charger keeps battery charged to ensure starting
  - Automatic starting method
  - 7-day exerciser runs ATC for 20 minutes, weekly
  - Overcrank protection
  - Engine start-up/transfer – 20 seconds
  - Weight – 407 lbs.
  - Warranty – 3 years
- Diagnostic Control Center Alerts + remote system status panel includes alerts for:
  - Low oil shutdown
  - Engine fail to start
  - Low frequency
  - Engine over-speed
  - Low voltage
  - Run time reporting
  - Automatic Transfer Switch 100 amp, 120/240V, one-phase with generator exerciser-load/no load

The PowerUP-100 Automatic Transfer Switch has a unique exerciser LOAD/NO LOAD test feature that allows maintenance crews to test the unit without utility outages. It complements remote start generator sets allowing the PowerUp Standby Power System to be fully automatic. This switch is perfect for applications where adjustable voltage and time delay settings are not required. Settings are fixed at values that are suitable for many different applications. The PowerUp Auto Switch-100 Automatic Transfer Switch combines reliability and flexibility in a small package for transferring loads between the utility and PowerUp Power Systems. The controller in the switch monitors utility and emergency standby power. When utility power fails or is unsatisfactory, the controller starts the PowerUp System and transfers the load. When the controller senses that utility power is restored, it automatically transfers back to utility power, shutting down PowerUp Traffic Systems unit and instantly resetting itself for the next power interruption. No action is required by site staff. The PowerUP Traffic System can provide backup power up to 1–2 weeks if needed.

2.6.4 Conclusion

Although there are only a few NG/LPG-powered generator applications in traffic signals, some companies offer 6–10 kW size NG/LPG generators (Kohler [46], Generac, Altergy [47]). Their generators are compatible with both natural gas and liquid propane. Information on NG/LPG systems is provided in Appendix A. Compared with other types of generators, NG/LPG-powered generators are cleaner and more efficient and have less expensive fuel consumption. However, they have the same storage and transportation concerns as hydrogen fuel cells, which is not a problem if pipeline or underground installation is under consideration or a flameshield tank is provided. The PowerUp Traffic System is a potential solution for this project, as it can meet the requirements for providing backup power for more than five days.

2.7 Portable Gasoline/Diesel Generators

Portable generators can produce power ranging from 2 kW to 8 kW. These are popular as home backup generators for homeowners and can be secured into the back of a truck and driven to where they need to go. They work like the engine in vehicles, and gasoline and diesel are affordable and easy to get.

2.7.1 Pros and Cons

- Pros – Inexpensive fuel, portable and small in size, inexpensive, easy to maintain, quick installation [48]
- Cons – Produce exhaust fumes and heat, require separate fuel storage, noisy when running, require manual start, and can be easily stolen. Would need to deliver to each intersection, hook up to a cabinet, keep refueling (with 30-minute shutdown) and be retrieved when utility power is restored; also need to be regularly serviced to be operational.

2.7.2 Applications in Traffic Signals

- **Weston, FL** – The City purchased 34 generators, one for each intersection, to operate traffic signals during a power outage. About $475,000 was spent on the purchase, installation, cabinets, and connections for the 34 generators. The City also purchased 8 generators for $182,448 to help power sewage-lift stations in hopes of preventing outages [49].
- **Palm Beach County, FL** – Hurricane Irma's mammoth winds and relentless rain knocked out traffic lights at 600 of Palm Beach County's 1,200 intersections, leaving

employees on a search for backup until Florida Power & Light could put them back on the grid. They funded 15 generators and deployed them at some of the 125 most critical intersections, as shown in Figure 7. The County used money in reserves to buy the 5,500-watt generators at about $725 each, for a total of approximately $10,875 [50]. Many counties in Florida and FDOT Districts have used portable generators to power signals in case of extended power loss.

Figure 7. Portable generator in Palm Beach County

Challenges encountered in Palm Beach County with portable generators include the following:

- Need time to be setup and need personnel to deliver and connect them to the cabinet
- Require manual hookup; at each intersection, generators were placed next to the control box and were chained and locked to a signal pole
- Easily stolen; when Palm Beach County deployed the generators after Hurricane Wilma in 2005, approximately 25 were stolen; now, County Sheriff deputies and City police officers watch them 24/7
- Require shutdown for at least 30 minutes before refueling
- Generators (especially low-end) produce "dirty" power that cannot provide the required power needed by the electronics of the cabinet
- Less expensive generators do not last long (usually rendered Beyond Economical Repair after a few sessions)
- Need a large warehouse to be housed and maintained

2.7.3 Conclusion

An effective backup system should not be the use of portable generators; gasoline/diesel portable generators were not considered in this study. Additionally, the requirements of gasoline/diesel portable generators are extremely high during a large area power outage. A major concern is that they could be stolen from an intersection, which would not occur with other generators, as people can get gasoline and diesel easily.

2.8 Solar Power and Batteries

Florida has sufficient sunshine year-round, and solar panels are widely used in commercial and residential areas. A solar-powered system includes a battery for sustained operation in the absence of adequate solar power. Additionally, DC/AC converters can be included to supply traffic signal systems. Solar-power systems with a strong mounting structure and connection would potentially be a very good solution to provide backup power for traffic signals to meet the requirements of this project. Currently, a few vendors have traffic systems designed to be supplied by solar systems, with most geared towards warning lights for signs. Two vendors that provide solar backup power systems for traffic signals are provided in Appendix A for reference. Additionally, installations of solar panels on mast arms, poles, traffic signal cabinets, or sidewalks could be options for consideration to reduce solar panel damages during hurricanes. A system using solar power and batteries could be a good solution.

2.8.1 Background

A PV system is a power system designed to supply usable solar power by means of photovoltaics. It consists of an arrangement of several components, including solar panels to absorb and directly convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, and mounting, cabling, and other electrical accessories. PV systems range from small, roof-top mounted or building-integrated systems with capacities from a few to several tens of kilowatts to large utility-scale power stations of hundreds of megawatts.

Typically, residential rooftop systems have small capacities of around 5–10 kW, whereas commercial rooftop systems often have capacities of several hundred kilowatts. Although rooftop systems are much smaller than ground-mounted utility-scale power plants, they account for most of the worldwide installed capacity [51]. Dr. Miao's PV research works on PV system modeling can be found in [18, 52, and 53].

In this project, the purpose is to power a less than 1kW traffic backup system for five days, so a residential rooftop size solar system was considered. Through integration with battery packs, a solar-powered system has the capability to support a traffic backup system for one week of operation. Follow-up research should focus on designing a solar and battery backup system. A solar panel mounting and installation should be carefully designed to ensure that the frame is strong enough to survive a hurricane. In addition, solar roadway and bifacial solar modules can be potential options to save installation space at intersections.

2.8.2 Pros and Cons

- Pros – Clean and safe energy, unlike fuel cells or automatic generators; no fuel costs, extremely reliable, durable, can last at least 10 years; no emission or noise generated in operation
- Cons – System big enough to power an intersection requires large area of solar panels, unless minimized to charge a battery system

2.8.3 Wind Load & Mounting

ASTM International (formerly known as the American Society for Testing Materials) has standards in place for testing PV modules. ASTM E1830-15(2019) [54] shows that a minimum static load test to 2,400 pascals (equal to 65 psi or a 139.9 mph wind) is used to simulate wind loads, and a static load test to 5,400 pascals (equal to 113 psi or 209.8 mph wind) is used to simulate heavy snow and ice accumulation. In Florida, although there is little concern about ice and snow, there exists the challenge of withstanding hurricane-force winds, which can be above 157 mph (Category 5).

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy issued a report [55] outlining the issues observed with fastening and securing PV modules and their failures after a hurricane or other severe weather event. The report shows that the PV modules are mostly undamaged, but the securing methods and materials can cause the systems to experience major damage. There are at least three ways to mount solar panels [56], as described below.

2.8.3.1 Side of Pole Mounting

The panels can be mounted on rails directly connected to a pole, as shown in Figure 8.

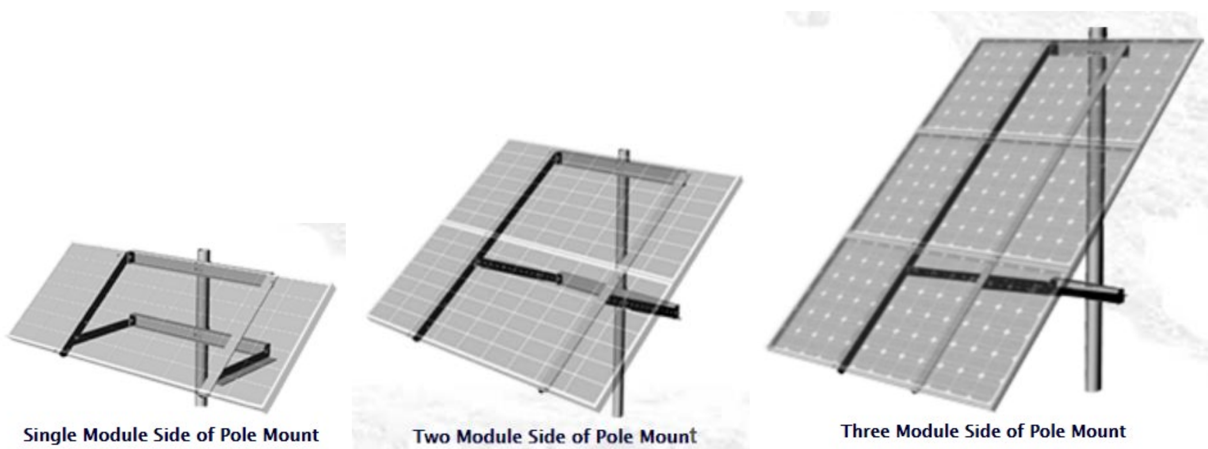


Figure 8. Solar panel mounting types

- Strengths:
    - Standard design 90 MPH; 130 MPH and higher available
    - TIG welded aluminum pole channels
    - 5000 & 6000 series structural aluminum mounting rails
    - Stainless steel module mounting hardware
    - Zinc-plated rack assembly hardware
    - High strength stainless steel band clamps or U bolts

- Applications:
    - Support from 1–4 solar modules
    - Standard pipe size clamps supplied; custom sizes available for any pole type
    - Adjustable from 30° to 90° tilt angle
    - Support up to 1000 watts on single structure
    -

2.8.3.2 Top of Pole Mounting

The Power-Fab® Top-of-Pole Solar Panel Mount is designed to install quickly and provide a secure strength welded steel components and corrosion resistant hardware for long-term reliability. Seasonal adjustability for maximizing production is provided by six different tilt angles, as shown in Figure 9.

- Strengths:
    - Standard mounts designed to withstand 90 MPH wind zones
    - MIG welded steel strong backs and mounting sleeves
    - Two coats of industrial urethane enamel paint
    - 6000 series structural aluminum mounting rails
    - Stainless steel module mounting hardware
    - Zinc plated rack assembly hardware

Figure 9. Solar panel top of pole mounting

- Applications:
    - Several sizes available from 1–24 modules
    - Installs over standard Schedule 40 or 80 rigid steel pipe (installer-supplied)
    - 15°–65° tilt angle settings (10° increments)
    - Mount up to 4.1kW on a single pole

2.8.3.3 Multi-Pole Ground Mounting

The Power-Fab® MPM-G2 ground mount is designed to install quickly and provide a secure mounting structure for PV modules on a single row of vertical pipe. The module-specific design reduces the number of components and provides for easier assembly. The MPM-G2 uses high-strength welded steel components and corrosion-resistant hardware for long-term reliability. Seasonal adjustability for maximizing production is provided by nine positive locking tilt angle settings, as shown in Figure 10.

Figure 10. Power-Fab® Multi-Pole PV Mounting (MPM-G2) System

- Strengths:
  - Designs available to withstand up to 130 MPH wind zones
  - MIG welded steel pipe caps and rail brackets with powder-coat finish
  - Stainless steel module mounting hardware
  - 6000 series structural aluminum mounting rails
  - Stainless steel module clamps
  - Stainless steel rack assembly hardware
- Applications:
  - Several sizes available, from 2–4 modules high in landscape orientation
  - Structures designed for standard 3", 4", or 6" Schedule 40 or 80 vertical steel pipe and 4" x 4" square or 5" x 4" rectangular horizontal steel tube (installer-supplied)
  - Ideal for shade and carport structures
  - Capable of significant ground clearance
  - Adjustable elevation brackets available with 0°, 10°, 20°, 25°, 30°, 35°, 40°, 45°, and 55° positive locking tilt angles

2.8.3.4 Top and Sides of Traffic Signal Cabinet Mounting

To reduce the possibility of damage during major hurricanes, solar panels can be installed on the top and sides of a traffic signal cabinet (Figure 11).

Figure 11. Solar panels mounted on top and sides of traffic signal cabinet

Most solar panels are manufactured to withstand 2,400–3,000 pascals, which is the same as winds of approximately 140–156 MPH. Theoretically, solar panels should have the capability to withstand Category 4 hurricanes. Current applications of solar panels have indicated that most solar panels survive hurricanes, but failures are attributed to substandard brackets and installation. Appropriate techniques can be used to ensure that the panels have the lowest failure during a hurricane.

2.8.4 Hurricane Weather History Data

To investigate weather conditions after a hurricane, local weather history data were reviewed from Weather Underground [57] for the days after hurricanes Harvey, Irma, and Michael made landfall. Tables 7, 8, and 9 show the first day each hurricane made landfall at each city.

Table 7. Weather Data after Hurricane Harvey (August 2017), Houston, TX

Time	Temperature (° F)			Wind Speed (mph)			Precipitation (in.)		
Aug	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min
25	80	78	76	23	-	9	-	0.28	-
26	79	77	75	37	-	7	-	3.83	-
27	77	76	74	25	-	0	-	11.82	-
28	74	73	71	37	-	6	-	1.74	-
29	74	73	72	31	-	18	-	2.4	-
30	86	80	73	24	-	7	-	0	-
31	92	83	73	15	-	0	-	0	-

Table 8. Weather Data after Hurricane Irma (September 2017), Naples, FL

Time	Temperature (° F)			Wind Speed (mph)			Precipitation (in)		
Sep	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min
10	79	76	73	62	-	7	-	9.02	-
11	84	80	75	45	-	5	-	0.35	-
12	87	80	75	13	-	0	-	0	-
13	90	82	75	10	-	0	-	0	-
14	93	86	78	13	-	0	-	0.21	-
15	91	83	75	12	-	0	-	0	-
16	91	84	77	13	-	4	-	0	-

Table 9. Weather Data after Hurricane Michael (October 2018), Panama City Beach, FL

Time	Temperature (° F)			Wind Speed (mph)			Precipitation (in)		
Oct	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min
10	80	78	75	46	-	7	-	2.62	-
11	88	83	77	14	-	7	-	0	-
12*	138	0	138	13	-	8	-	0	-
13*	0	0	0	8	-	0	-	0	-
14*	0	0	0	10	-	0	-	0	-
15*	0	0	0	10	-	0	-	0	-

* Reported data show outliers.

By reviewing the amount of precipitation, an assumption can be made for sun activity. For Hurricane Harvey, there were several days of heavy rain, which had low sun activity; for Hurricane Irma, there were only two rainy days after hurricane landfall; for Hurricane Michael, there was no precipitation after the hurricane. An accurate prediction about available sun cannot be made, which will affect the decision to include solar panels. A worst-case scenario should be considered if using solar panels are to be considered as the power source for traffic signal systems.

2.8.5 Efficiency

Most solar panels are about 5.5 ft tall and a little more than 3 ft wide. Figure 12 shows the scale of a standard panel. As of 2018, a typical solar panel produces around 320 watts of power, but panels come in many different wattage ratings. The top 10 residential solar panels for 2018 includes panels rated to produce 285–360 watts.

Figure 12. Solar panel size [58]

Table 10 shows the most popular solar panels used in 2018 by order of number installed. The average-sized solar panel has a surface area of 17.6 square feet (sf) and produces 320 watts under direct sunlight, or just over 18 watts per sf.

Table 10. Popular Solar Panels Rated Power in 2018 [58]

Rank	Manufacturer	Model No.	Rated Output (watts STC)
1	SolarCity	SC325	325
2	SunPower	SPR-X22-360-D-AC	360
3	Jinko Solar	JKM290M-60B	290
4	SunPower	SPR-X21-335-BLK-D-AC	335
5	SunPower	SPR-X21-345-D-AC	345
6	SunPower	SPR-E20-327-D-AC	327
7	Mission Solar Energy	MSE295SQ5T	295
8	LG Electronics	LG330N1C-A5	330
9	Jinko Solar	JKM290M-60	290
10	REC Solar	REC285TP2 BLK	285

Considering the requirement of at least 36 kWh for 5 days, a total of 7.2 kWh is required every day in sunshine weather. According to [59], there are 5.67 peak sun hours per day in Florida. Using 5 hours of full sun gives an equation of $320\text{ W} * 5\text{ hr} = 1.6\text{ kWh}\ (1{,}600\text{ W})$ in a day per 320-watt panel. Hence, 5 solar panels should be installed, which takes up an area of about 88 sf. Considering the space limitation at intersections and the worst weather scenarios (no sun), a 36-kWh battery is required, regardless of the efficiency of the solar panels.

2.8.6 Bifacial Solar Modules

Bifacial modules, as shown in Figure 13, produce solar power from both sides of the panel. Whereas traditional opaque-backsheeted panels are monofacial, bifacial modules expose both the front and back of the solar cells. When bifacial modules are installed on a highly reflective surface (such as a white roof or on the ground with light-colored stones), some bifacial module manufacturers claim up to a 25% increase in production just from the extra power generated from the rear [60]. Bifacial modules come in many designs, some framed, others frameless. Some are dual-glass, and others use clear backsheets. Most use monocrystalline cells, but there are polycrystalline designs.

Figure 13. Lumos Solar GSX bifacial modules

2.8.7 Solar Roadways

Solar tiles have debuted recently, and some testing and proof-of-concept deployments have been funded to show effectiveness. These tiles can be used on either a roadway surface or on sidewalks. Their proof-of-concept technology combines a transparent driving surface with underlying solar cells, electronics, and sensors to act as a solar array with programmable capability. Road panels are made from recycled materials and incorporate photovoltaic cells.

Rear-world implementations of solar roadways include the following:

- **SolaRoad, The Netherlands** – SolaRoad is the world's first bike path made from solar panels and is a prototype project testing the feasibility of various proposals for smart highways. The 72m (236 ft) path opened in October 2014 and was designed by a consortium of organizations that built the pathway in Krommenie, Netherlands [61]. Figure 14 (left) shows the SolaRoad.
- **Tourouvre au Perche, France** – This was one of the first solar roads to be installed and has a maximum power output of 420 kWs, covers 2,800 m², and cost €5 million ($5.8 million) to install ($14,000 per installed kW) (Figure 14, right). Although the road is supposed to generate 800 kWh per day, recently-released data indicate a yield closer to 409 kWh/day or 150,000 kWh/yr [62]. This highly-publicized road (340 kW) produced an average of 409 kWh per day during 2017, indicating a load factor of 5% compared to 12% for conventional solar photovoltaic in Normandy and much more in the south of the country. Each square meter of Norman solar road (surface of 2800 square meters) delivers 0.14 kWh per day on average, enough to power a bulb of 70 W for 2 hours.

Figure 14. SolaRoad in The Netherlands (*left*), solar road in France (*right*)

- **Solar Roadways, Sandpoint, ID** – The U.S. version of WattWay has been championed by a company called Solar Roadways. An Idaho-based husband-and-wife team raised $2.2 million in an Indiegogo campaign fed by a video entitled "Solar Freakin' Roadways!" proclaiming the technology's ability to light LEDs and melt snow with the energy it collects from the sun. The project used 30 of the company's SR3 panels, each capable of generating 48 watts, for a total of about 1,440 kW. However, its 2016 ribboncutting revealed that many of the panels did not work, and further reports indicate that the panels have not generated nearly their stated nameplate capacity [63]. Solar photovoltaic technology is becoming cheaper, more efficient, and more resilient, but it currently is not a good replacement for asphalt.

The concept of installing special solar panels on sidewalk, as shown in Figure 15, to support and supply backup power along with batteries is appealing. If successful, it can overcome potential space constraints for solar panel installation and eliminate the possibility solar panel damages due to hurricane-force wind.

Figure 15. Solar roadway panels on sidewalk near traffic signal cabinet

2.8.8 Applications in Traffic Signals

- **Hillsborough County, FL** – Hillsborough County's Division Director of Transportation Maintenance noted that to head off potential accidents after a major power outage, Hillsborough County Public Works is installing solar-powered signal flashing beacons at some of its intersections. Of the 316 intersections, 40 have been identified by the County as the busiest in the area and were scheduled for completion by October 2019; the remaining 276 were projected for completion by the end of 2020. The County has experience with solar power beacons and familiarity with their performance as it has used the same product for school (crosswalk) flashers.

  The full cost of the project is about $3,160,000, roughly $10,000 for each intersection. Emergency beacons consist of single indication, flashing LED beacons installed at the center of each approach aligned for each approaching direction. Solar panels installed at the top of the uprights charge the batteries for the beacons, as shown in Figure 16. The beacons remain unlit in normal operation but are wired to automatically replicate the intersection's flashing red or yellow pattern if the traffic signals lose power and the universal battery system is exhausted. The beacons will be tested and serviced annually during routine preventive maintenance for each intersection [64, 65].

Figure 16. Solar-powered signal system in Hillsborough County, FL

- **Miami-Dade County, FL** – In the wake of Hurricane Irma, power outages shut down almost 70% of traffic lights in Miami-Dade County. Power was lost at more than 1,900 intersections, and it took many days to get them all back online, according to a Miami-Dade County Commissioner. Solar traffic lights could make the county more resilient to storms, save money, protect the motoring public, and ensure that the police can fight crime instead of direct traffic. The solar-powered signals are still in Miami-Dade County's plan, and a resolution has been proposed asking the County Mayor's office to study the cost [66].
- **Coral Springs, FL** – Coral Springs used solar-powered traffic lights while its grid power was down after Hurricane Irma, placing traffic lights on 13 major thoroughfares throughout the city. Two small batteries were placed beneath a solar panel that powered the light, which was placed on the ground at an intersection, according to a Coral Springs Traffic Officer, as shown in Figure 17. The batteries were used at night so the lights would stay on during nighttime [67].

Figure 17. Temporary solar traffic signals in Coral Springs, FL

2.8.9 Conclusion

Solar-powered signals have been used and studied in multiple counties in Florida. Existing cases show that solar panels can be installed at existing traffic signal poles, and the traffic signals can be powered mainly from a battery system, with solar power charging the batteries. With advancement of battery technologies and solar panel mounting methods, the use of solar power with efficient battery offers a practical and promising solution in Florida for providing backup power for at least five days after the loss of utility power due to hurricanes.

2.9 Solar-powered Hydrogen Fuel Cell

At its Takahama City, Japan, plant, Toyota Industries installed the H2Plaza, which charges fuel-cell (FC) forklifts with hydrogen, as shown in Figure 18, produced by using solar electricity [68]. The H2Plaza has functions to produce, compress, store, and supply hydrogen and supplies CO_2-free hydrogen to 13 FC forklifts operating in the plant. Toshiba Energy Systems & Solutions provided hydrogen-related facilities with a hydrogen production capacity of 10 Nm^3/h, and Mitsubishi Electric supplied solar panels with a total output of 190kW. Toyota solar hydrogen has not been commercialized; therefore, this technology was not considered further.

Figure 18. Solar-powered hydrogen fuel cell, Japan

2.10 Wind Generators

Wind power is a clean, renewable energy and is now used in many parts of the U.S. A wind turbine (wind energy converter) converts the wind's kinetic energy into electrical energy.

2.10.1 Background

Dr. Miao's group has conducted research on wind turbine generators; [69] details modeling and analysis of double-fed induction generator wind energy systems, and Chapter 19 in [70] discusses wind farm with HVDC delivery in inertial and primary frequency response. Wind farm system stability issues are addressed in [71-73].

The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or for power traffic warning signs. Larger turbines can be used for making contributions to a domestic power supply while selling unused power back to a utility supplier via the electrical grid. As of 2009, wind had the "lowest relative greenhouse gas emissions, the least water consumption demands and ... the most favorable social impacts" compared to photovoltaic, hydro, geothermal, coal, and gas [74].

Small wind turbine blades are usually 1.5–3.5 m (4 ft 11 in.–11 ft 6 in.) in diameter and produce 1–10 kW of electricity at their optimal wind speed [75]. Small wind turbines can be applied to power traffic signal systems; however, a sufficient wind source is a precondition for implementation. Some small wind turbines can be designed to work at low wind speeds, but, in general, small wind turbines require annual average wind speeds of at least 5 m/s [75].

2.10.2 Pros and Cons

- Pros – Green and renewable energy source, enormous potential, space-efficient, low operational costs
- Cons – Unpredictable, cost-competitiveness is debatable, threat to wildlife, and noise problem

2.10.3 Applications in Traffic Signals

- **Lincoln, NE (wind)** – A team of researchers at the University of Nebraska–Lincoln worked on a pilot project funded by USDOT in 2011 that would use wind and solar energy to power street and traffic lights while putting excess electricity back into the grid. A small wind generator was installed at an intersection in Lincoln, and a small wind turbine was installed to provide electricity for traffic lights, as shown in Figure 19. A project report in 2013 provided a design of an alternative signal head mast with a wind generator included at the top to provide backup power [76] (Figure 20). The pilot was successful, and wind power was able to generate enough electricity to power the intersection. Considerations included the height of the turbine tower and the surroundings of the turbine site, which affect wind energy production.

Figure 19. Wind-powered traffic lights in Lincoln, NE

(Photo courtesy of Colin Wood)

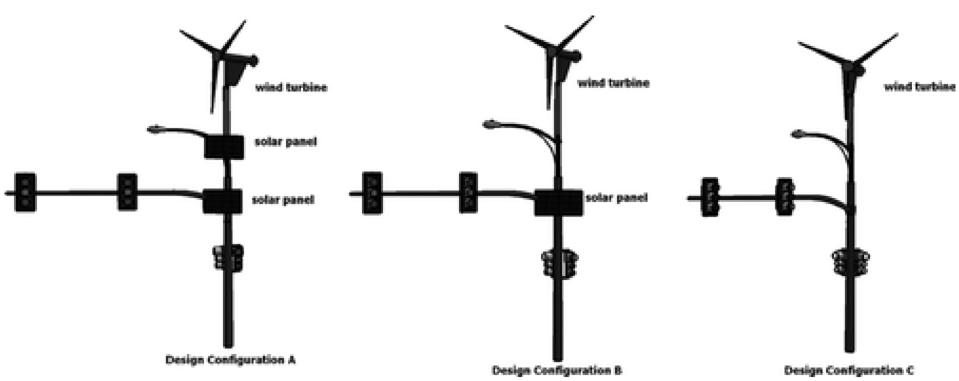


Figure 20. Signal head mast with solar panels and wind generators

- **Lincoln, NE (wind/solar hybrid)** – A team from the University of Nebraska–Lincoln and Iowa State University conducted wind/solar hybrid power generation for traffic signals and street lights [77] (Figure 21). Power generated is consumed locally by roadway/traffic-signal light; excess power is stored in a battery system or delivered through RHPS microgrid. System cost was $9,656.

Figure 21. Test site in Lincoln, NE—one 1.0-kW wind turbine, two 210-W PV panels, four 6-V 305-Ah lead-acid batteries

2.10.4 Conclusion

According to the U.S. DOE, for wind energy to be a viable option, an area needs to experience wind speeds with an annual average of 6.5 m/s (21 fps) at a height of 80 meters (262 ft). Figure 22 shows that Florida experiences an annual average wind speed below 5 m/s (16 f/s). Utility-scale, land-based wind turbines typically are installed at a height of 80–100 m (262–328 ft) to have a resource suitable for wind generation. Considering that traffic signal poles are lower than 5 m (16 ft), wind-powered generators are not suggested to mount on traffic signals as backup power.

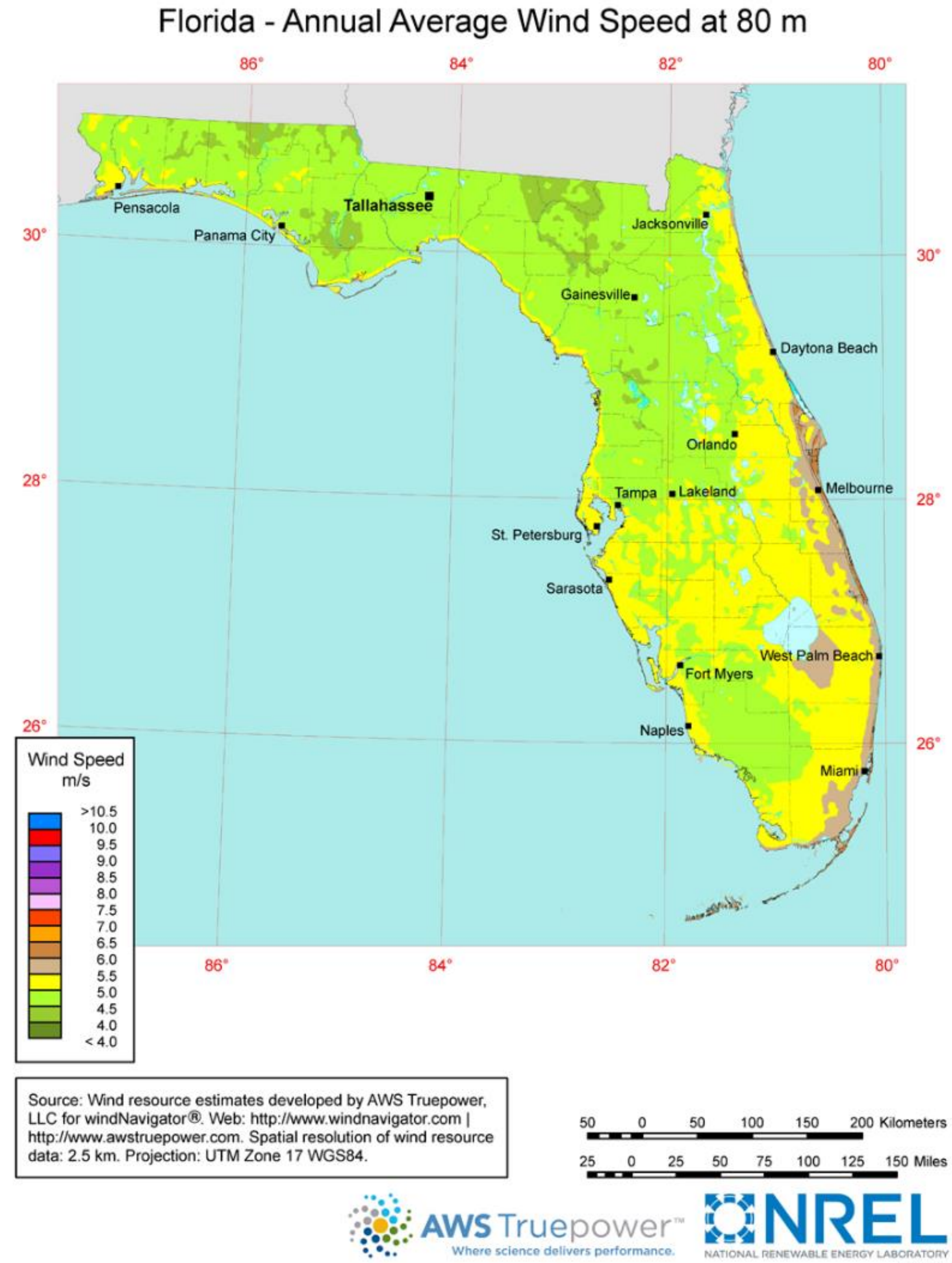


Figure 22. Florida 80-meter (262 ft) wind resource map

2.11 Technology Summary

This section reviewed literature on existing and emerging backup power technologies and associated systems for traffic signals. For Florida, major promising backup power technologies for meeting needs for five days include battery, fuel cell, natural gas/liquid propane, and solar power with battery.

Existing and emerging backup power technologies and systems have many potential applications. Several promising backup power technologies have been commercialized and successfully applied to specific fields in several industries, but in the traffic signal field, some are in the early stages of testing or pilot implementation. These technologies and associated systems could be excellent candidates for testing and evaluation. A simple comparison of backup power technologies on their applications is shown in Table 11.

Table 11. Backup Power Technology Applications

Backup Power Technology	Industrial Applications	Commercialized?	Applied in traffic signal systems?
Supercapacitor	Rapid and short-term charge/ discharge, e.g., vehicles, elevators	Yes	Not used
Battery (lithium-ion)	Electric vehicles, emergency power, off-grid power systems, energy storage, smart house	Yes	Limited or in early stage
Battery (lead acid)	UPS, emergency lighting, hospital equipment	Yes	Often
Hydrogen fuel cell	Transit buses, backup power for facilities and homes	Yes	Limited or in early stage
Natural gas/liquid propane	Standby generators for facilities and homes, clean energy vehicles	Yes	Limited or in early stage
Portable generators (gasoline/diesel)	Backup power for small-size facilities and homes	Yes	Often
Solar power	Power generation in grid farm and home rooftop	Yes	Often; mostly used in flashing beacons or LED signs and lights
Solar-powered hydrogen fuel cell	Hydrogen-powered forklifts	No	Not used or not yet
Wind generator	Power generation in wind farm	Yes	Limited or in early stage

3 Recommended Backup Power Technologies

Based on the assessment of technologies and associated backup power systems, the CUTR team recommended four candidate backup power technologies and associated systems to the FDOT Project Manager for consideration for testing at the TERL—(1) battery backup system, (2) solar + battery backup system, (3) hydrogen fuel cell backup system, and (4) natural gas or propane generator backup system.

The CUTR team visited the FDOT TERL facility in October 2019 and held a comprehensive discussion with the FDOT Project Manager and TERL engineers regarding Deliverable 1 findings, selection of backup power technologies, TERL test site setup, testing scenarios, test procedure, and evaluation criteria. Backup power capacity, efficiency, cost, safety, implementability, and compatibility were important factors for inclusion in selection for testing. In December 2019, the CUTR team and FDOT held a web meeting with fuel cell vendor Altergy, who presented its fuel cell solutions, provided examples, and answered questions. The meeting provided useful information on the fuel technologies, especially the hydrogen fuel cell backup system.

The FDOT Project Manager noted important factors for consideration of final recommendations and selection of backup power technologies for field testing at TERL, including the following:

- Prioritizing of recommendations based on technologies best suited for new signalized intersections and retrofitting of existing signalized intersections.
- Recommendations for the most cost-efficient and practical backup power technologies.
- Recommendations for multiple technologies to be used together or separately.
- Consideration of backup power technologies suitable for certain intersections, such as urban or rural intersections.

Based on the literature review and investigation, communication with backup power system vendors, backup power technology assessment, consultation with the FDOT Project Manager and TERL engineers, and discussion among the CUTR team, four backup power technologies were recommended for the field testing at the FDOT TERL facility: 1) battery backup system, 2) battery and solar backup system, 3) hydrogen fuel cell backup system, and 4) natural gas/liquid propane backup system. This section describes the recommended technologies/ systems for testing and provides supporting information.

3.1 Battery Power System

A battery backup system can be installed as the main energy buffer to allow a traffic signal system to run on battery power during a power outage. The battery cells are charged by utility power and expel their electricity when a power outage occurs.

3.1.1 Pros and Cons

FDOT currently uses UPS systems for backup power for short-term loss of utility power, thus allowing the UPS to be replaced by a larger power battery capacity. Due to the large capacity needed for a five-day extended run time, high-energy density rechargeable batteries (lithium-ion and nickel-zinc) should be considered for the following reasons:

- They are compatible with existing traffic signal control cabinets and can replace current UPS.
- Switching time from utility power to battery power is milliseconds; thus, there is no noticeable interruption to traffic signal systems.
- Battery cells generate no noise and guarantee zero emissions.
- Most traffic agencies use widely-available battery backup systems and are familiar with battery backup systems.
- Battery backup power systems for long extended runtimes are available and produced by several key manufacturers.
- The system does not use much space and is especially suitable for urban downtown signalized intersections with tight space for installation of a backup power system.

Drawbacks of a battery backup system are as follows:

- Battery cost increases dramatically when scaling up system capacity. One pack 13.5 kWh Tesla Powerwall costs $6,500, which is not comparable to a hydrogen fuel cell ($0.15 per kWh) or liquid propane ($0.1 per kWh).
- The battery will experience capacity degradation over time and eventually will need to be replaced if degradation becomes serious. For comparison purposes, the life cycle of a battery system is assumed to be as long as the manufacturer's warranty, after which the batteries should be replaced.
- There will be no power after battery depletion; unlike other generators, there is no way to recharge the battery backup system during a power outage.

3.2 Battery + Solar Power System

Florida has sufficient sunshine year-round to make solar power an ideal renewable energy source to be used with a backup power system. A solar-powered system includes a battery for sustained operation in the absence of adequate solar power. Additionally, DC/AC converters can be included to supply traffic signal systems. Solar-power systems require a strong mounting structure and connection to ensure survivability in a hurricane. With advancements in technologies, various types of solar-power systems have become or will be available for installation.

3.2.1 Pros and Cons

Compared to a battery-only backup system, a battery + solar power system can be less expensive, as fewer batteries are required. The most important aspect is that solar is renewable energy and can last for weeks with sufficient sunshine.

In addition to the aforementioned advantages of a battery system, reasons for considering a solar-powered system include the following:

- Common backup source in current traffic signal systems, according to investigation in Task 1; particularly common power source in Florida, has been implemented in many industries.
- Different potential types of solar panels, such as bifacial modules, flexible modules, and solar roadways; solar roadways piloted in Europe and the U.S.
- Clean and safe energy has no fuel cost or emissions; panels can last for 10+ years.
- System may require more space for solar panels, so it is suitable for urban, suburban, and rural areas where space is not an issue and there is no major blockage of sunshine from tall buildings.

In addition to the disadvantages noted, solar panel installation requires a significant amount of space in an intersection. The size of a general solar panel is 65" x 39" x 1.5". According to the CUTR team's estimation, six panels would be required to ensure one day of consumption; therefore, a 105-sf space, equivalent to the size of an office, would be required at an intersection. Another issue is ensuring that the solar panels are clean and free of shadows so energy generation does not decrease.

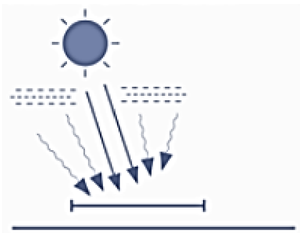
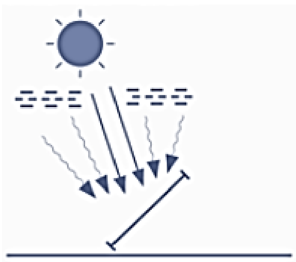
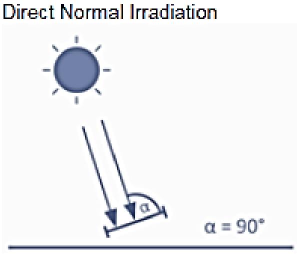
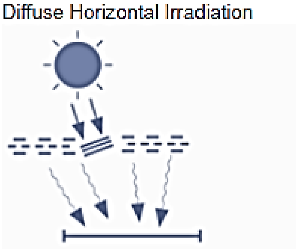
3.2.2 Solar Radiation

According to the National Renewable Energy Laboratory (NREL) National Solar Radiation Database (NSRDB), to ensure well-founded decisions in designing profitable solar power plants, sun irradiation should be measured at the planned site. It is also recommended to measure the produced electrical energy to keep the energy yield high. PV or Concentrated Solar Power (CSP) each require specific measurements to obtain relevant irradiation information. The sun's radiation on the earth's surface combines Direct Normal Irradiation (DNI) and Diffused Horizontal Irradiation (DHI), both linked in the formula for Global Horizontal Irradiation (GHI):

$$GHI = DHI + DNIcos(\theta)$$

Where θ is the solar zenith angle. Normally, on a sunny day, insolation is 100% GHI with 20% DHI and 80% DNI*cos (θ). According to NREL's Data View map, the average DNI is above 5 kWh/sq.m/day. Table 12 shows the different types of irradiations and the measurement instruments necessary to measure irradiation.

Table 12. Types of Irradiation

Type of radiation	Descpition	Measurement instrument
GHI Global Horizontal Irradiation 	The total amount of radiation received from above by a horizontal surface. This value includes both Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiation (DHI). Application: ▪ Fixed PV installations ▪ Comparisons with solar data bases to perform MCP (Measure Correlate Predict) evaluations	▪ Pyranometer (horizontal) ▪ Reference cell
GTI Global Tilted Irradiation 	The total amount of direct and diffuse radiation received from above by a tilted surface. GTI is an approximate value for the energy yield calculation of fixed installed tilted PV panels. Applications: ▪ Fixed PV installations	▪ Pyranometer tilted in the same angle as the solar module ▪ Reference cell
DNI Direct Normal Irradiation 	Direct Normal Irradiation is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line form the direction of the sun at its current position in the sky. Applications: ▪ Concentrated Solar Power (CSP) ▪ Concentrated PV (CPV) ▪ Fixed PV installations	▪ Pyrheliometer installed on a sun tracker ▪ Rotating Shadowband Irradiometer
DHI Diffuse Horizontal Irradiation 	Diffuse Horizontal Irradiation is the amount of radiation received per unit area by a surface (no subject to any shade or shadow) that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere and comes equally from all directions. Applications: ▪ Fixed PV installations ▪ Redundancy calculations of GHI → GHI = DHI + DNI · cos(θ)	▪ Pyranometer with shadow ball or shadow ring, installed in a sun tracker ▪ Rotating Shadowband Irradiometer

3.2.3 Solar Data Search and Analysis

To further establish the feasibility of using solar power as a backup system, daily GHI values were collected for several days after previous hurricanes in which loss of power was reported, including Hurricane Irma in Florida in 2017**,** Hurricane Harvey in Texas in 2017, Hurricane Wilma in Florida in 2005, and Hurricane Charley in Florida in 2004.

3.2.4 Hurricane Irma 2017 Power Outage

Figure 23 shows the Florida counties that experienced power loss during and after Hurricane Irma, and Table 13 shows the GHI values. After Hurricane Irma, most locations in Florida had sunshine such that sufficient solar energy could be generated. Starting from the second day (9/10/2017), the daily total GHI was more than 5,000 Wh/m2, as shown in Figure 24, for the three areas with the highest percent of power loss.

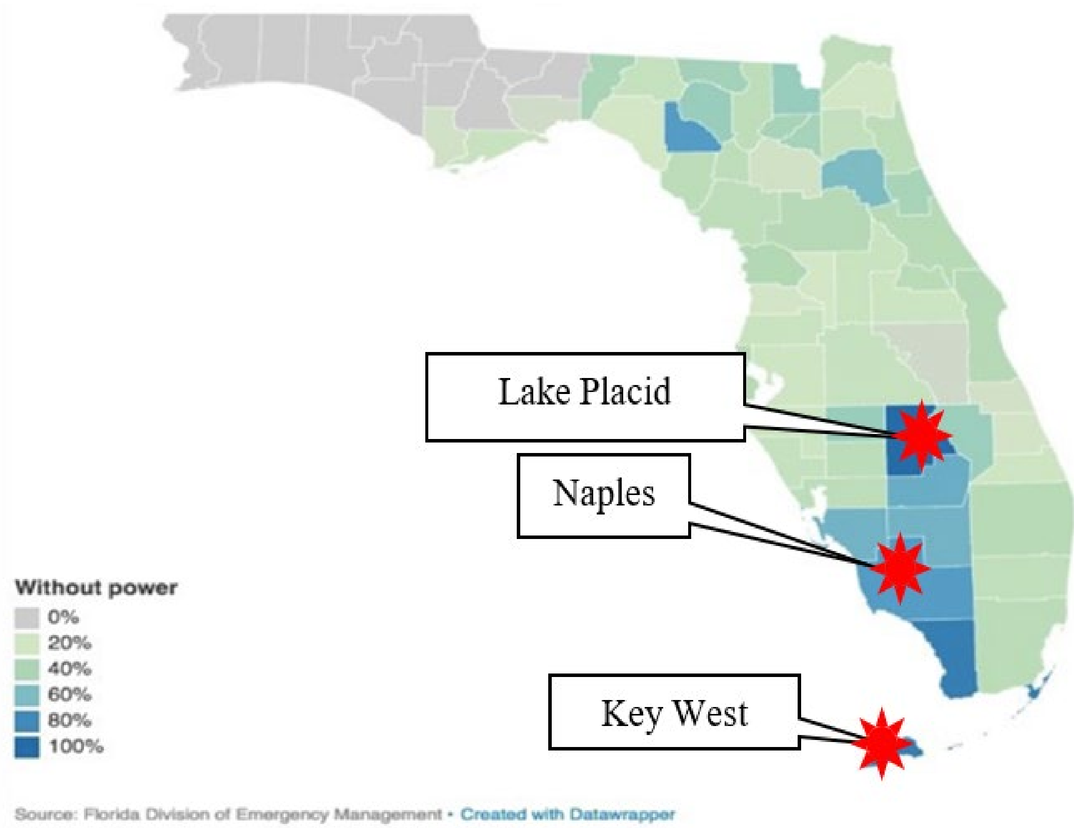


Figure 23. Florida power outages caused by Hurricane Irma

Table 13. Daily GHI after Hurricane Irma

Date	Naples (Wh/m2)	Lake Placid (Wh/m2)	Key West (Wh/m2)
9/9/2017	3,604	4153	2,622.5
9/10/2017	865	1,064.5	1,483.5
9/11/2017	5,081	5,823	5,072
9/12/2017	6,955	6,151.5	6,313.5
9/13/2017	5,581.5	6,549	6,690
9/14/2017	6,604.5	5,992.5	5,988.5
9/15/2017	6,365.5	6,285.5	6,617.5

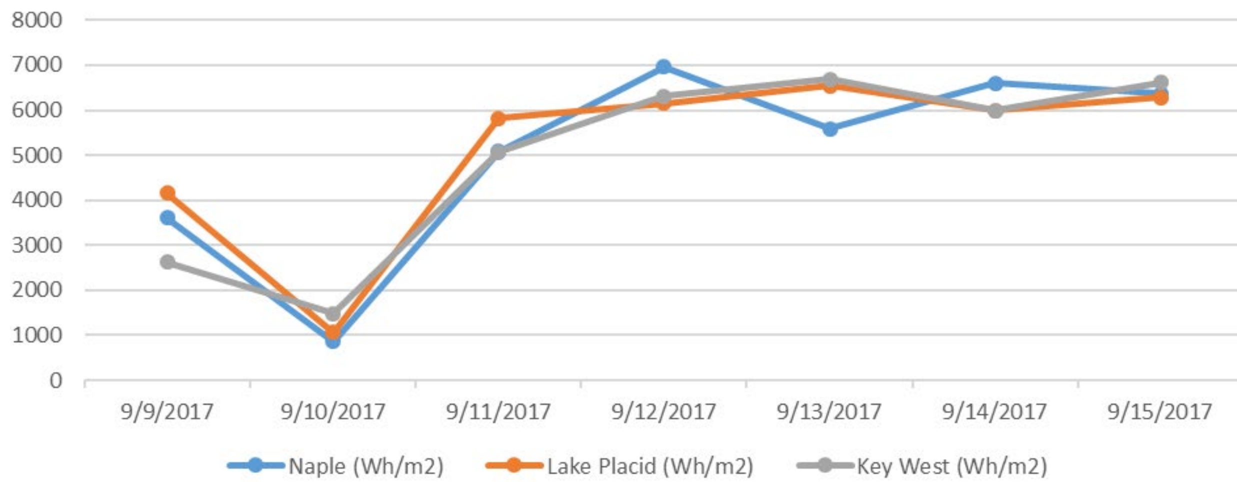


Figure 24. Daily GHI after Hurricane Irma

3.2.5 Hurricane Harvey 2017 Power Outage

Figure 25 shows power outages during and after Hurricane Harvey in Texas, and Table 14 shows the GHI values.

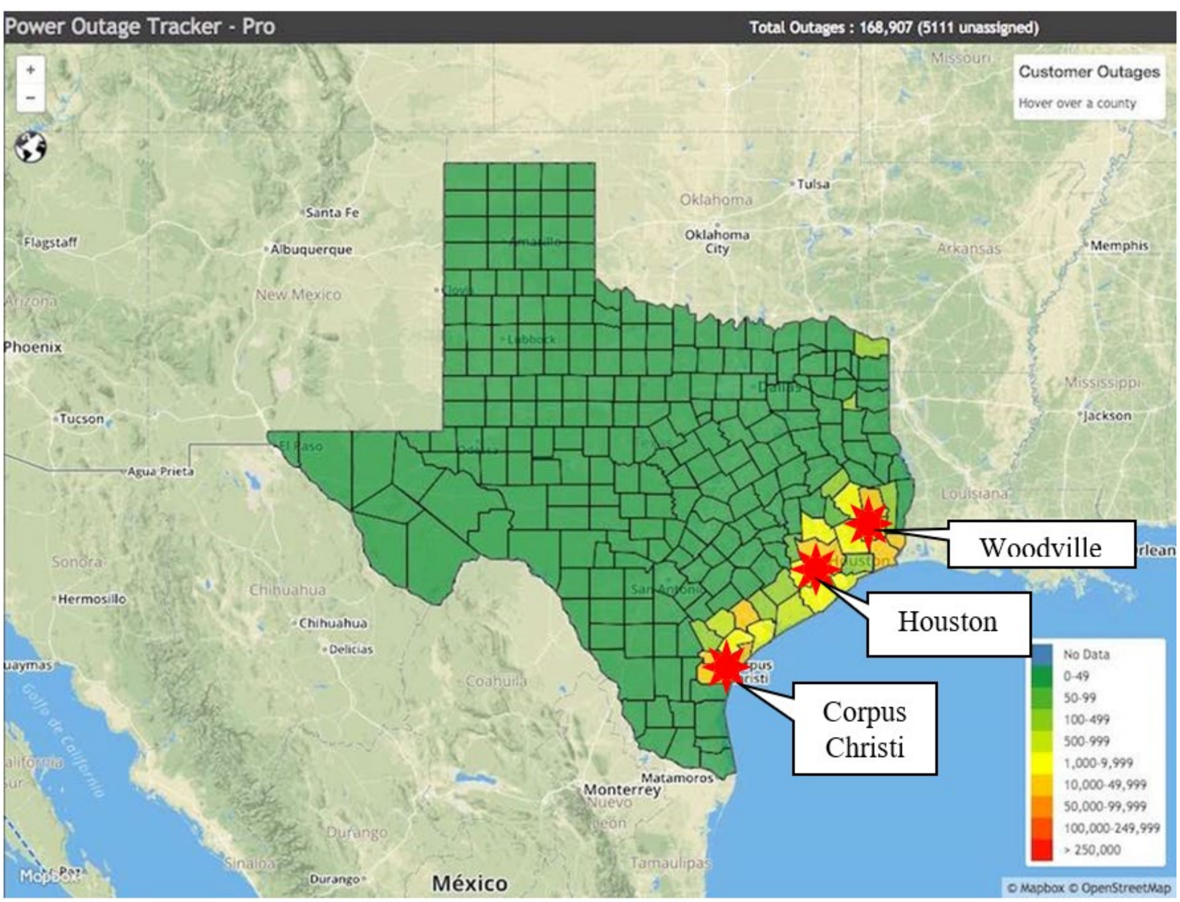


Figure 25. Texas power outages after Hurricane Harvey

Table 14. Daily GHI after Hurricane Harvey

Date	Corpus Christi (Wh/m2)	Houston (Wh/m2)	Woodville (Wh/m2)
8/25/2017	979.5	1,714	2,503
8/26/2017	2,431.5	2,262.5	943
8/27/2017	2,468	1,572	1,321.5
8/28/2017	2,502	1,047.5	1,616
8/29/2017	6,734	1,731.5	997.5
8/30/2017	7,161	5,052	1,150.5
8/31/2017	7,038.5	6,444.5	6,163
9/1/2017	6,964.5	6,361.5	6,348.5
9/2/2017	6,445	6,518	6,298
9/3/2017	5,321	5,905	6,456

Hurricane Harvey in 2017 lingered over Texas for a couple of days, which caused most areas in Texas to have cloudy weather and resulted in relatively low GHI for couple of days. Daily total GHI reached above 5,000 Wh/m2 after one week, as shown in Figure 26.

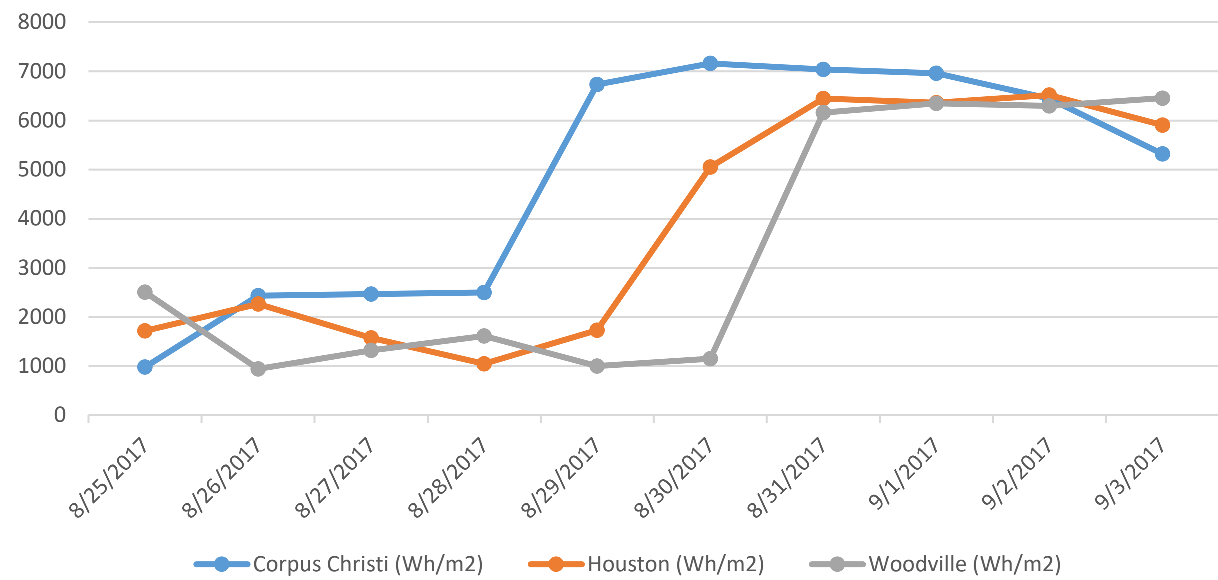


Figure 26. Daily GHI after Hurricane Harvey

3.2.6 Hurricane Wilma 2005 Power Outage

After Hurricane Wilma in 2005, three major cities in Florida over which the hurricane's center passed (Figure 27) experienced the GHI daily values shown in Table 15. Three selected cities showed sufficient solar energy; starting from the second day (10/25/2005), daily total GHI reached above 5,000 Wh/m2, as shown in Figure 28.

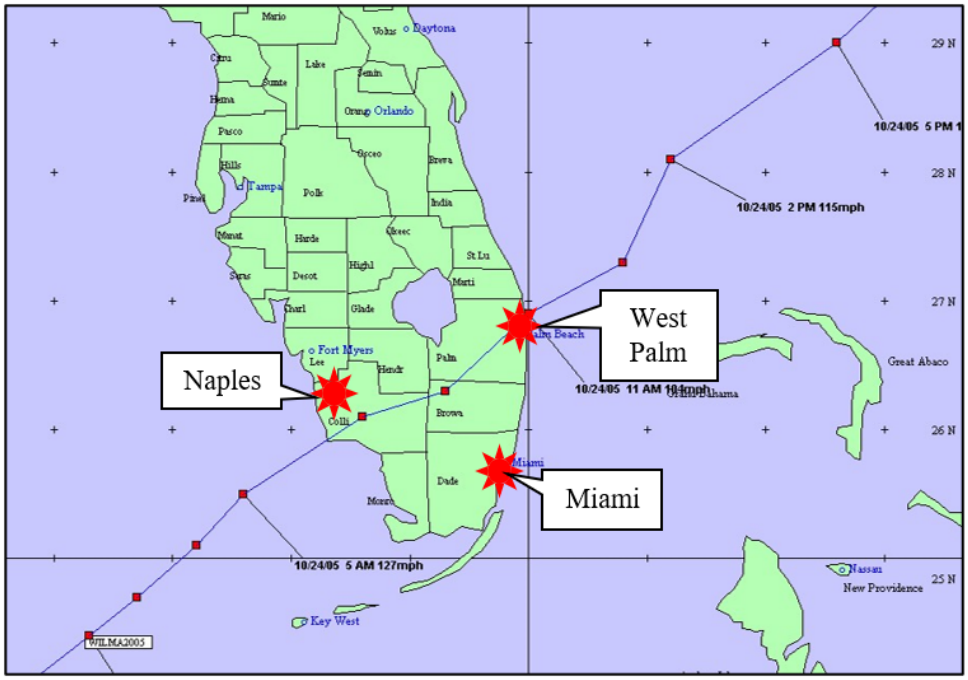


Figure 27. Power outages after Hurricane Wilma

Table 15. Daily GHI after Hurricane Wilma

Date	Naples (Wh/m2)	Miami (Wh/m2)	West Palm Beach (Wh/m2)
10/24/2005	3,434	2,304.5	1,603.5
10/25/2005	5,495	5,637.5	5,622.5
10/26/2005	5,671	5,768.5	5,700.5
10/27/2005	5,704	5,510	5,504
10/28/2005	5,560.5	5,194.5	4,698
10/29/2005	5,433	4,321.5	3,200
10/30/2005	5,405.5	4,598	4,600

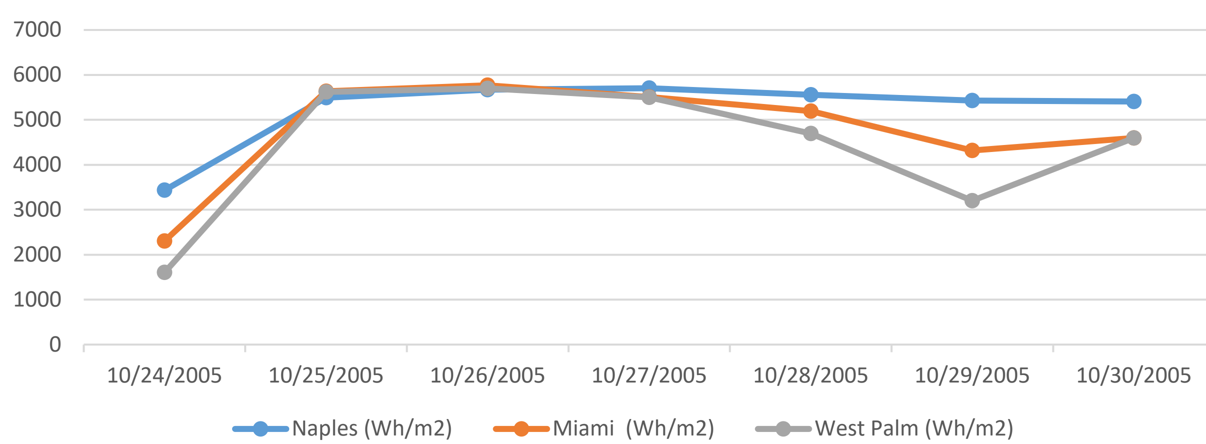


Figure 28. Daily GHI after Hurricane Wilma

3.2.7 Hurricane Charley 2004 Power Outage

Hurricane Charley in 2004 passed through Florida and affected several cities. GHI values for three selected cities (Figure 29) are shown in Figure 30 and Table 16. After Hurricane Charley, Fort Myers experienced sufficient solar energy; however, Orlando and Daytona Beach did not until after three days.

Figure 29. Path of Hurricane Charley

Table 16. Daily GHI after Hurricane Charley

Date	Fort Myers (Wh/m2)	Orlando (Wh/m2)	Daytona Beach (Wh/m2)
8/13/2004	1,851.5	2,336.5	2,532.5
8/14/2004	5,704.5	4,127	3,846.5
8/15/2004	6,461	3,996	3,395
8/16/2004	6,515	5,776	5,833
8/17/2004	6,337	5,480.5	6,531
8/18/2004	5,777	6,864	6,553.5
8/19/2004	5,524.5	6,266.5	7,208.5

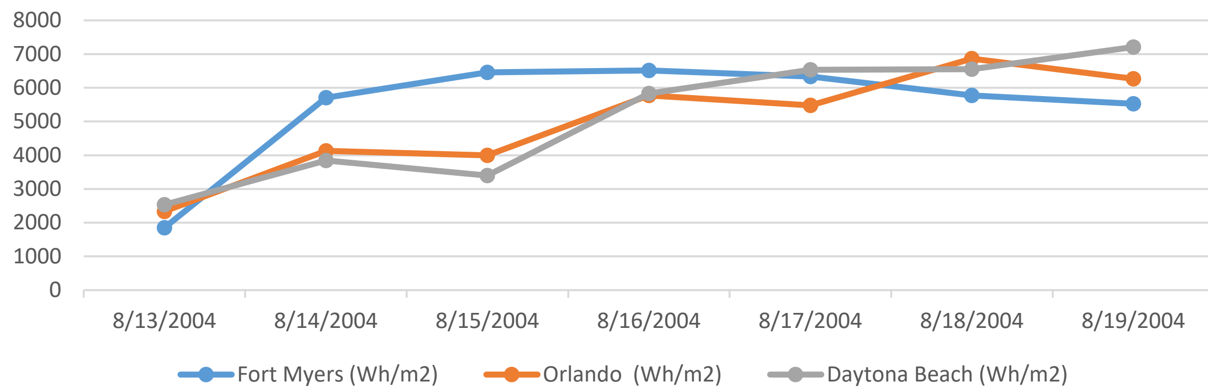


Figure 30. Daily GHI after Hurricane Charley

3.2.8 Conclusion

Historical GHI data from the NSRDB were analyzed for four hurricanes. Some areas had sunny weather and sufficient solar radiation just after a hurricane; however, in some instances, several cloudy days after a hurricane did not provide enough solar irradiation for solar charging. Adding solar energy as a source for a backup system should be balanced with cost and the risk of not experiencing adequate sunny days to charge the system after a hurricane. Solar panels available currently gain only about 15–20% efficiency—for example, solar panels can produce, at most, 1 kWh for each square meter per day if daily GHI is 5,000 Wh/m^2 or more.

3.3 Hydrogen Fuel Cell Backup Power System

3.3.1 Pros and Cons

Hydrogen-powered fuel cells are being advanced in the telecom, aerospace, automotive, and other sectors. After a rapid breakthrough, fuel cells have become the clean power source of choice. (Detailed information on fuel cell backups is provided in the Deliverable 1 report for this project.) There are many advantages to using hydrogen-powered fuel cell backup systems; reasons for considering and selecting hydrogen fuel cell backup power system are the following:

- Already implemented in traffic signal backup systems.
- Long service life and life cycle, can be refueled without disruption in service, low maintenance costs; design life generally more than 20 years.
- Installation price low and acceptable.
- Suitable for urban, suburban, and rural intersections; due to low maintenance needs, especially suitable for rural intersections.
- Can maintain expected performance in extreme hot or cold temperatures, can provide uninterrupted power.
- Can provide sufficient specified runtimes after loss of utility power due to hurricanes.

- Requires minimum maintenance, replacement of air filters once per year.
- When compared to a battery backup power system, can avoid battery/ maintenance/ monitoring.

However, there are some concerns related to a hydrogen fuel cell system:

- Highest initial cost
- Largest footprint
- Hydrogen fuel might not be readily available (especially after a hurricane)
- Fuel safety
- Needs monitoring for fuel level

3.4 NG/LPG Backup Power System

3.4.1 Pros and Cons

Detailed information on NG/LPG backups is provided in Section 2.6. There are many advantages to using hydrogen-powered fuel cell backup systems, as follows:

- Widely used as residential and commercial backup power; variety of generators available to consider.
- Lower cost than hydrogen fuel cell or battery system; 6–10kW generator costs are $2,000–$4,000, with some additional equipment required for specific application.
- Cheap energy source; generally, price is $2.5 per gallon or $0.1 per kWh.

Cons of using NG/LPG generators include the following:

- Efficiency extremely low if generator running at 25% load; smallest NG/LPG generator is 6 kW; traffic devices need only 0.3 kW; if run at 25% load, most generated power will be wasted.
- Large space required to install; requires 53-gal liquid gas for 3 days of full operation.

3.5 Technologies Matrix

Table 17 provides a comparison of the four different backup power systems: battery only, battery + solar backup, hydrogen fuel cell, and NG/LPG generator.

Table 17. Backup Power Systems Comparison Matrix[1]

Technology	Battery	Battery + Solar	Hydrogen Fuel Cell	NG or LPG
Brand	2 Tesla Powerwalls	1 Tesla Powerwall + Sunpower Solar	Altergy	Kohler 6VSG, Alpha[78] Gen, Power Up
Rated Power (W)	7kW peak / 5kW continuous	7kW peak / 5kW continuous	1kW to 2.5kW	5–9kW
Energy Storage (kWh)[2]	27[3]	13.5[4]	Up to 54[5] Can be customized to required length of time	Can be customized to required length of time[6]
System Voltage	Converted to 120 VAC	Converted to 120 VAC	48 VDC or converted to 120 VAC	24/36/48 VDC or converted to 120 VAC
Efficiency	75%	75%	50%	2% (25% load)
Noise	0 dBA	0 dBA	<60 dBA	68 dBA
Working Condition	-20 °C to 50°C	-20 °C to 50°C	-40 °C to 74 °C	Up to 65 °C
Warranty	10 yrs	10 yrs	10 yrs	10 yrs
Initial Cost[7]	$17K	$14K	$22K with fuel cabinet	$9–15K with fuel cabinet
Fuel Cost	No fuel needed	No fuel needed	$0.15 /kWh	$0.1 /kWh
Switch ON	Within milliseconds	Within milliseconds	Within seconds	Within seconds
Life	10 yrs based on warranty	10 yrs based on warranty	> 10 yrs	> 10 yrs
Deployment	Residential and commercial applications	Small-scale in traffic applications	Thousands in telecom industry, some in traffic and rail signals	Thousands in other industries, some in traffic
Cost Comparison among Systems	High capital cost for longer life	Lower than battery alone	Higher cost for low number of units (12% discount for 20+)	Higher cost for low number of units
Space Needed among Systems	Smallest footprint	Smallest but requires solar panels on mast arm or other poles	Larger size with fuel cabinet	Larger size with fuel cabinet
Maintenance	None	Clean solar panels	Check air filter and inlets every 6 mo/100 hrs	Replace oil, check air filter after 100 hrs
Fuel	N/A	N/A	Need to refuel after use	Need to refuel after use
Safety	Some safety concern if vehicle crashes on batteries or overheats	Some safety concern if vehicle crashes on batteries or overheats	Moderate safety concern if vehicle crashes or overheats, has shutoff system	High safety concern if vehicle crashes or overheats, has shutoff system

Table 17. Backup Power Systems Comparison Matrix (cont'd)

Technology	Battery	Battery + Solar	Hydrogen Fuel Cell	NG or LPG
Pros	Small footprint, fast power switch, no maintenance, no fuel needed	Small footprint, fast power switch, low maintenance, no fuel needed, lower cost than battery alone, can last longer with sun	Low maintenance, can last longer than 3 days with refuel or more tanks	Can last longer than 3 days with refuel or more tanks, fuel readily available
Cons	High initial cost for larger system, no power after depletion	High initial cost for large system; if smaller than battery alone, needs sun to provide power for up to 3 days	Highest initial cost, largest footprint, hydrogen fuel might not be readily available, fuel safety concern, if fuel depleted during normal operation and power lost, needs monitoring for fuel	Highest maintenance, large footprint, fuel safety concern, if fuel depleted during normal operation and power lost, needs monitoring for fuel

[1] Power calculations based on 3 days runtime: 400W X 72h = 28.8kWh
[2] Although calculated power requirement is 400W, actual power needed is less.
[3] Based on footnote 1, battery system likely to provide enough power for 72 hrs, as actual power needed less than calculated 28.8kWh.
[4] System uses one battery pack; can be increased to 2 packs, therefore will meet three-day requirement.
[5] Capacity can be adjusted by adding more storage for fuel.
[6] Capacity can be adjusted by adding more storage for fuel.
[7] Does not include installation costs for any system.

4 Testing and Evaluation of Selected Technologies

The test site at the FDOT TERL in Tallahassee was used to evaluate three FDOT-approved recommended backup power technologies for extending traffic signal operations after the loss of utility power supply in hurricane events. Before testing, data were collected at a live signalized intersection in Hillsborough County, Florida, on the voltage, current, and power data for a traffic control system in full operation and in flashing mode.

Following a pretest, the three selected and approved backup power technologies were installed and tested at the TERL following the proposed evaluation plan. The testing data were recorded and fully analyzed to compare the selected systems.

4.1 Pretest at Hillsborough County Intersection

Prior to testing the selected backup systems at the TERL, the CUTR team established a testing and evaluation plan and data collection procedures. In cooperation with Hillsborough County Traffic Operations, a pretest was conducted at a live intersection in Hillsborough County with two major objectives:

- Test AC data logger reliability on logging AC voltage and AC current from a traffic cabinet.
- Validate data collection methodology with collected data.

Data were collected in the pretest for six days (12/4/20–12/9/20). The data logger sampling rate was set at 30 sec to collect AC voltage and AC current data to obtain information to calculate the power needed to operate the traffic cabinet. At the same time, Hillsborough County Traffic Operations staff remotely monitored the traffic system working condition of the UPS. The current UPS used in traffic cabinets provides the data needed to observe changes in voltage and current levels as the UPS transitions from grid power to UPS backup power.

4.1.1 Intersection Overview and Connection Setup

The pretest was conducted at Progress Blvd and S. Falkenburg Rd in Tampa (Figure 31), a large traffic intersection with five signal heads in each direction and a traffic controller, sensors, cameras, and network switch in the traffic cabinets. This intersection was a candidate for a backup power system after loss of grid power due to a hurricane.

Figure 32 shows the AC data logger connected in the control cabinet. The UPS has an APC system, which has the capability to regulate voltage, and four lead acid batteries that can support full operation for 10–12 hours. The UPS system switches to flashing mode when the battery voltage drops below 48 VDC. The AC data logger is connected to the UPS output and logs voltage and current every 30 sec.

Figure 31. Pretest intersection at Hillsborough County

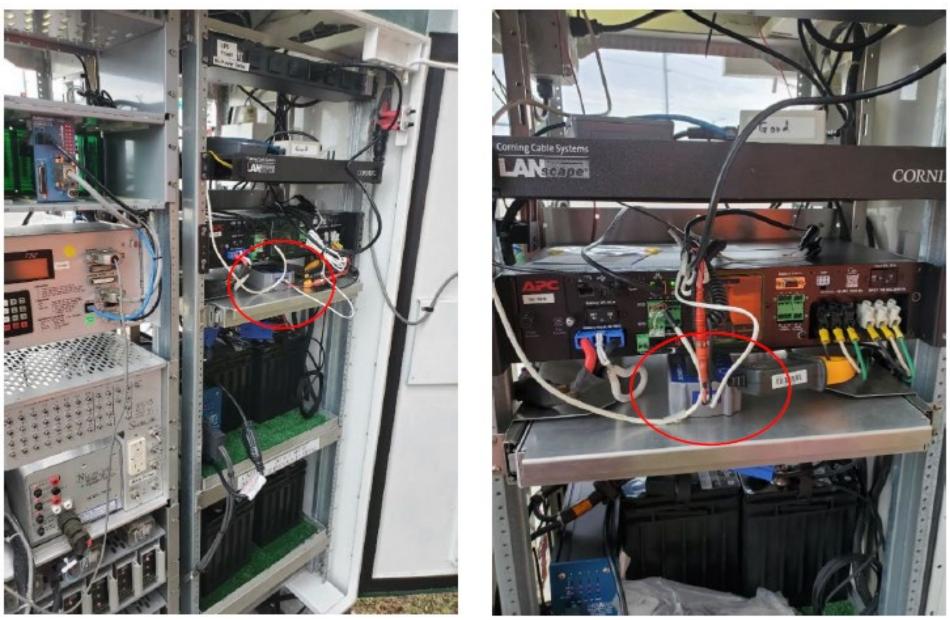


Figure 32. AC data logger connection in control cabinet

4.1.2 Data Analysis

Data collected from the logger were reviewed for accuracy. Figure 33 shows that the logger successfully logged all data for six days; the load power was 384–432 W under full operation, and 168–264 W under flashing operation. During the data collection period, three main events occurred, two planned and one unplanned, as described in the following sections.

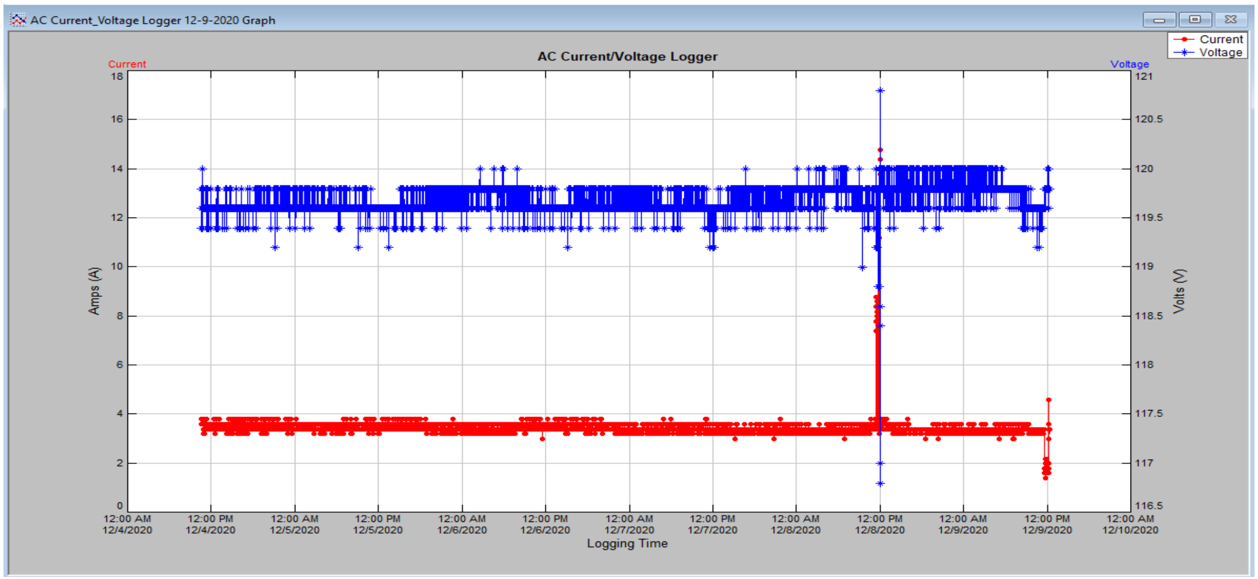


Figure 33. Voltage and current from data logger

4.1.2.1 Event 1: Switch to UPS Power from Utility Power in Full Operation Mode

The cabinet was switched to UPS power from 11:01 to 11:20 AM on 12/7/2020. The working condition during this time was kept at full operation with the help of Hillsborough County Traffic Operations staff. Figure 34 shows the transition and full operation during this switch. There was no change in the measured data when operating under the UPS.

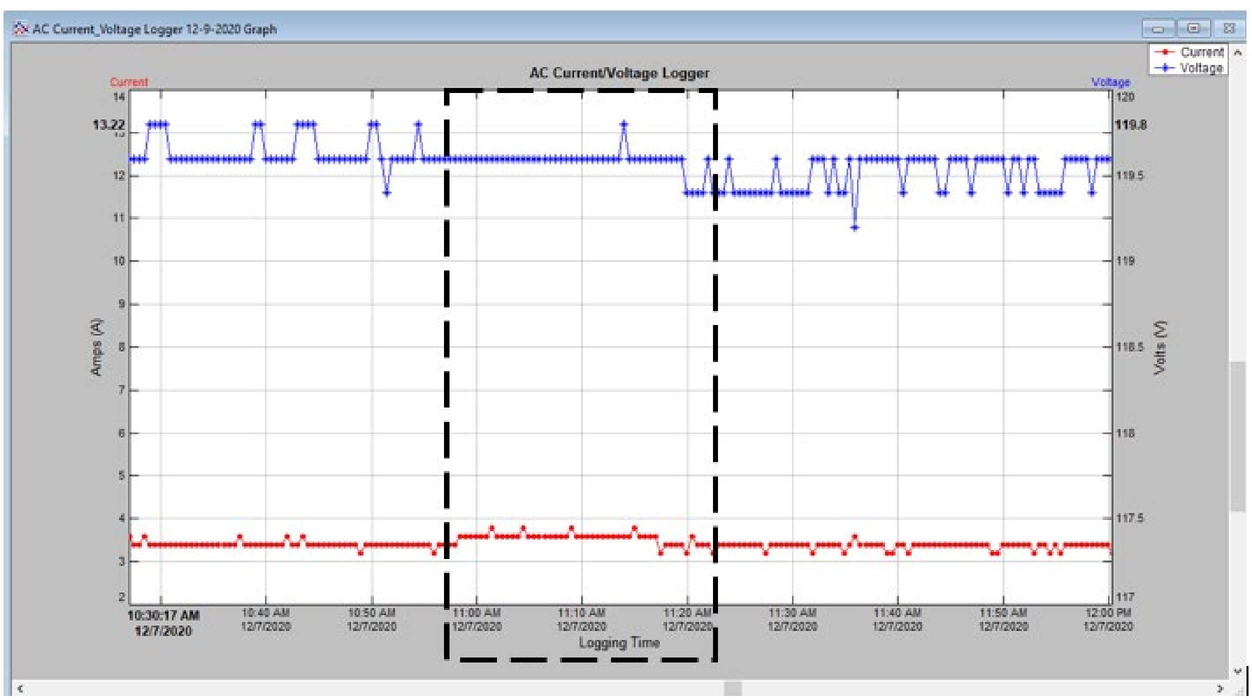


Figure 34. AC logger data when switching to UPS battery power

4.1.2.2 Event 2: Power Increase due to Use of Power Drill

During the data collection period, there was construction at the location, and a construction worker connected a power drill in the cabinet, which caused the current and voltage to vary, as shown in Figure 35. The current varied from 11:30 AM to 12:10 PM on 12/8/2020. At the same time, the recorded voltage dropped from the average of 119.7 V to various values up to 117 V. This shows the level of sensitivity of a traffic cabinet in operation and the effectiveness of the logger in identifying these events.

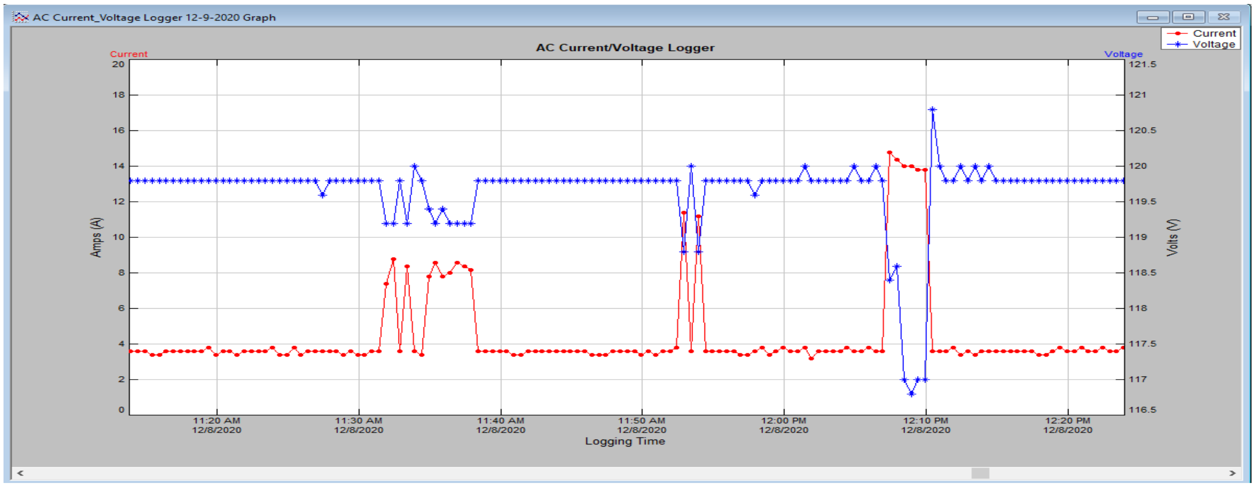


Figure 35. AC logger data when power drill connected

4.1.2.3 Event 3: Switch from full operation to flashing mode under UPS power

The control cabinet was switched to flashing mode at 11:43 AM on 12/9/2020 due to the UPS battery voltage reaching the threshold (48 VDC). Full operation was restored at 12:18 PM on 12/9/2020. As shown in Figure 36, the current dropped 50% when in flashing mode. This confirmed that if an intersection is operating in flashing mode, it can save power, as the current needed is about half of that in full operation.

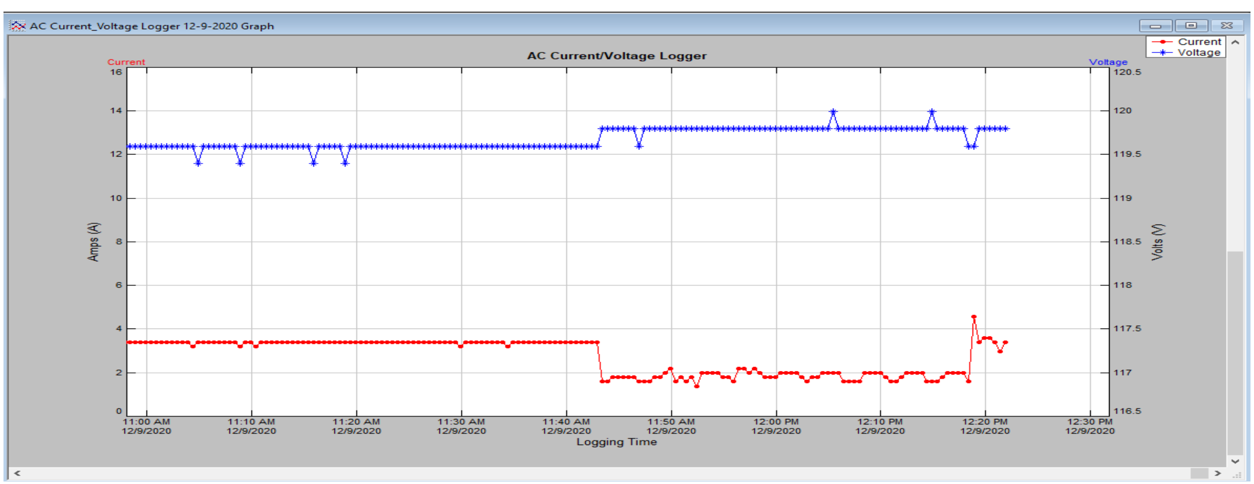


Figure 36. AC logger data when switching to flashing mode

4.1.3 Comparison with Data Collected via UPS

The data collected using the data logger was compared with the Smart-UPS measured data on voltage, current, and power. Figure 37 shows the voltage, Figure 38 shows the current, and Figure 39 shows the power calculated using the data collected from the logger and as provided by UPS logging for comparison. Both logged data every 30 min. The data show that both methods provide data that are close to each other and can be used for evaluation of the backup systems.

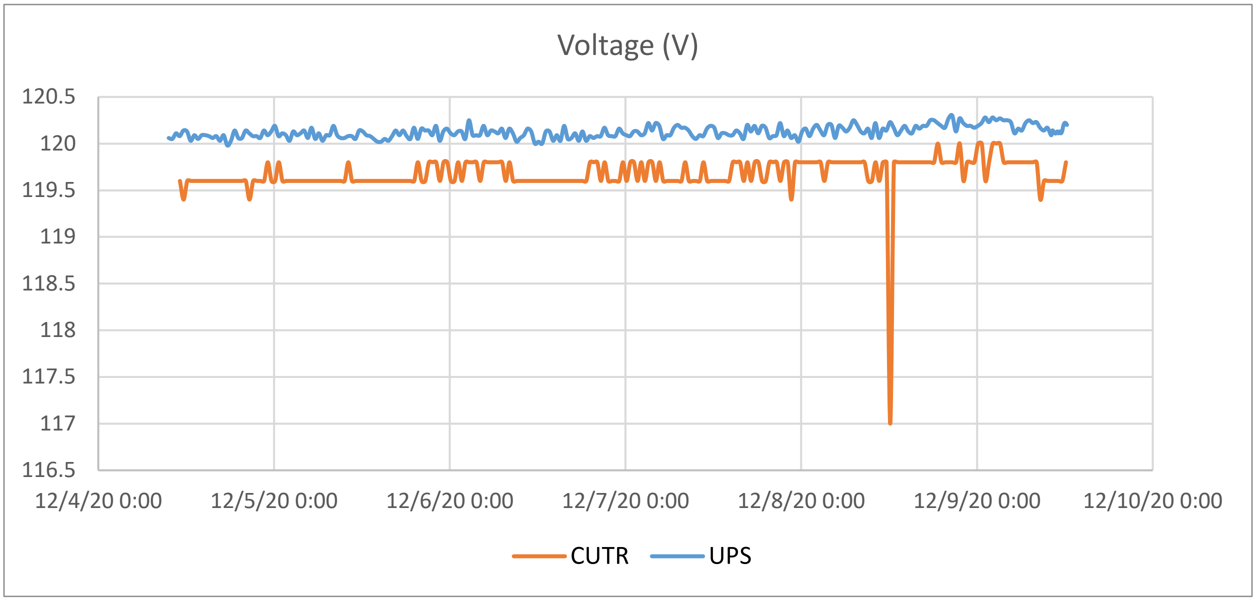


Figure 37. Voltage comparison – CUTR logger and UPS data

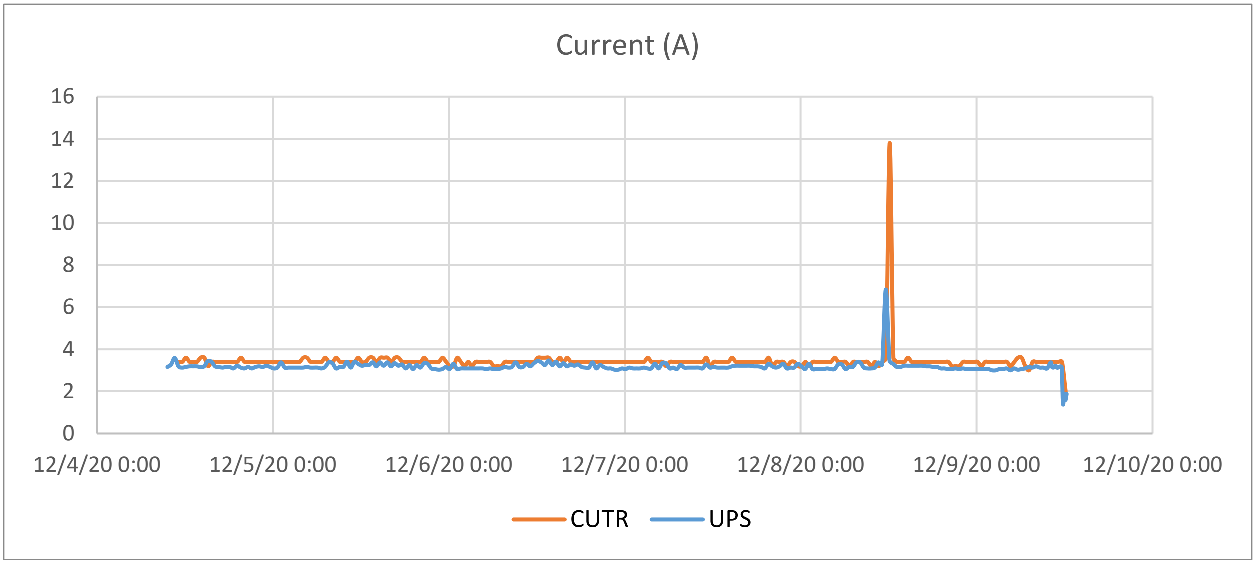


Figure 38. Current comparison – CUTR logger and UPS data

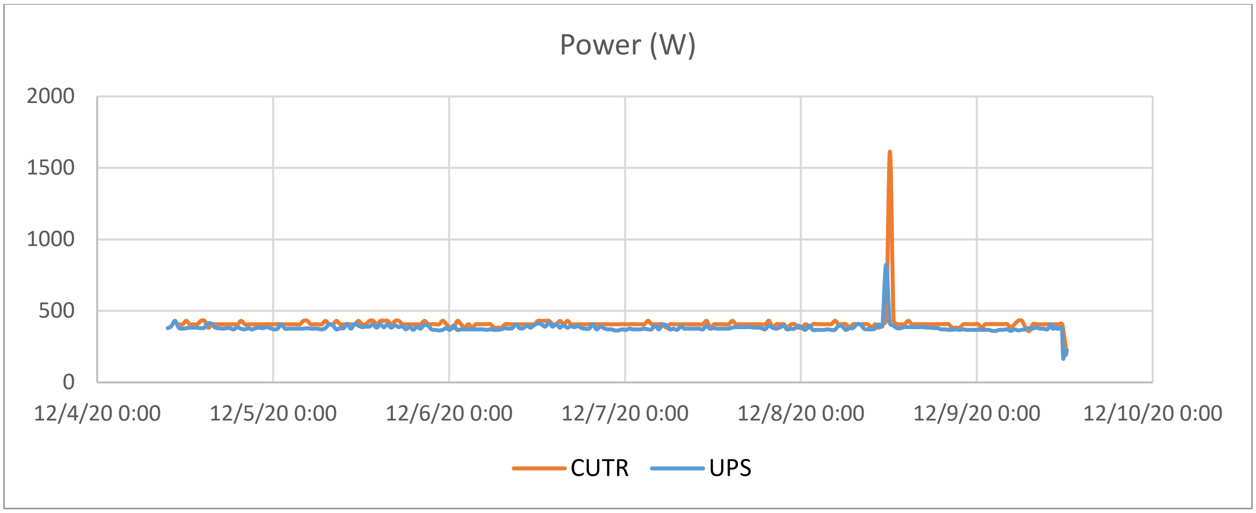


Figure 39. Power comparison – CUTR logger and UPS data

4.1.4 Pretest Conclusion

The pretest was successful in providing information on voltage, current, and power of an active intersection with 20 signal heads and other devices in the cabinet. In addition:

- The measured data showed no difference between using utility power and UPS power in full operation mode.
- The data logger could be used during testing at the TERL. Switching from full operation to flashing mode reduced the current to 50%, and the current will drop to zero once the battery has no more power.
- The AC data logger collected accurate data, which was validated with the data logged by the UPS system in the cabinet.

4.2 Selected Power Backup Systems

In coordination with the TERL manager, three systems were selected for testing:

- Battery backup system
- Battery + solar backup system
- Liquid propane generator backup system

The first two systems could be acquired together and connected such that the solar system could be separate from the battery, thus providing for independent testing; the third system was a stand-alone generator. Following are vendor quotes on the systems.

4.2.1 Battery + Solar Backup System

The first system was a solar and battery integrated backup power system. Quotes from five vendors were acquired to aid in system selection. One vendor supplied a battery system only, and the other four offered solar panels and battery banks together. Their quotes are shown in Table 18.

Table 18. Battery + Solar System Vendor Quotes

Vendor	Price	Battery Cap. (kWh)	Battery Bank Size (in.)	Battery Type	Solar Power (kW)	Solar Panel Size (ft²)	Solar $/W	Battery $/kWh	Delivery	Recom-mend?	Notes
Electriq Power	$9,720	10	27.5 × 50 × 9	Lithium-ion	NA	NA	NA	$972	4-6 wks	No	Professional battery company
Ameresco Solar	$32,175	19.2	(29.1 × 19.6 × 15.7) * 2	Lithium-ion	2.4 (305W * 8)	132	$5.39	$1,675	6 wks	No	Products implemented in Hillsborough County
Wholesale Solar	$14,024	19	(11.61 × 7.05 × 16.69) * 8	Lead-acid	3.84 (320W * 12)	214.7	$3.64	$736	4 wks	No	Lead-acid battery, not as durable/reliable as lithium-ion
CED Greentech	**$10,809**	**10.4**	**(17 × 17 × 8.75) * 2**	**Lithium-ion**	**3.2 (400W * 8)**	**229.3**	**$3.37**	**$1,040**	**6 wks**	**Yes**	Manager gave detailed, reasonable quote; most products in stock; pick up at Milton, FL or $150-350 charge for freight
Enphase Energy	$13,600	10	42.13 × 26.14 × 12.56	Lithium-ion	2.92 (365W * 6)	116.7	$6.21	$1,360	13 wks	No	Delivery time after 13 wks; order first, then will ship ASAP
Notes: 10 kWh battery can support normal operation for 1 day (24 hr); price of lithium-ion batteries $9K–$10K per 10 kWh. Quotes do not include installation fee. Inverter, cable, and solar panel mounting dimensions may vary depending on test site.											

The CUTR team conducted several phone calls with each vendor on system requirements and product selections. The system from CED Greentech was eventually recommended considering many aspects:

- Large company with warehouses in Florida, carries many products from known manufacturers.
- Supplied detailed quote on each component and parts needed, was responsive to CUTR team requests, met requirements in a timely fashion.
- Battery module price reasonable and within project budget.
- Delivery time acceptable for project schedule.

4.2.2 Propane Generator System

Two propane generator system vendors provided quotes and information for their products, as shown in Table 19.

Table 19. Propane Generator System Quotes

Vendor	Price	Power Capacity (kW)	Output Voltage (V)	$/W	Delivery	Recommend?	Notes
Alpha	$17,889	7.5	48 VDC	2.39	3-6 wks	No	Includes Alpha UPS with cabinet ($4000), concrete pad, propane tanks
Kohler	**$5,333**	**8**	**120 VAC**	**0.67**	**1-3 wks**	**Yes**	**Does not include pad or tanks**

Note: Quotes do not include installation cost ($1,500–$4,000).

Both vendors are manufacturers of backup generators. Kohler was selected as the propane generator supplier for the following reasons:

- System needs to provide 120 VAC to power existing traffic cabinet; Alpha's propane generator output voltage is 48 VDC, suitable for a 48 VDC low-voltage traffic control cabinet; Kohler generator more feasible for integrating with current cabinets.
- Kohler well-known brand in both commercial and residential generators.
- Price and delivery time of Kohler generator more competitive than Alpha.

4.3 Evaluation Plan

CUTR developed an evaluation plan to describe experiment details, including test scenarios, procedure, performance measures, data collection, and evaluation methods. The CUTR team followed the evaluation plan proposed in Task 2 to conduct the experiment for assessing the recommended backup power technologies.

4.3.1 Test Schedule

Two backup power systems were acquired by CUTR to test at the TERL—a standby propane generator and a battery + solar backup system. Table 20 shows when each system was acquired, installed, and tested.

Table 20. Test Schedule

System	Acquired	Installed	Tested
Propane generator	2/3/2021	2/11–12/2021	2/22–25/2021
Battery only	3/29/2021	6/28/2021*	7/2–3/2021
Battery + solar	3/29/2021	6/28/2021*	7/7–14/2021

*Battery/solar system initially installed on 4/21/2021 but experienced faulty Battery Management System (BMS) and had to be changed. Also, inverter/charger changed to different model due to inadequately providing required data.

4.3.2 Evaluation Procedure

The CUTR team conducted a pretest after each installation to ensure that all components and the signal system were fully functional. Any issues found at the debugging stage were resolved prior to testing. The technology vendors and contractors provided technical support to complete system assembly and debugging.

As noted in Task 2, each backup system was tested under full operation as well as in flashing mode if the runtime in full operation mode was not satisfied. Full operation testing took priority, as the goal was to ensure that the traffic system was working normally as long as possible. Figure 40 presents the operational condition decision logic used, and Figure 41 shows the connection diagram for the system test. Descriptions of elements of Figure 40 are as follows:

- *System fully charged* – Energy storage device of test system, either battery or propane fuel tank, will be charged to maximum capacity.
- *Full operation* – Set traffic controller to full operation mode and enable all devices in cabinet, e.g., video cameras and controller; system is working in normal operation similar to when connected to utility power.
- *System down* – When storage energy runs out, system will shut down; usually means that power backup system is unable to supply required voltage, which causes system failure.
- *Flashing operation* – Set traffic controller to flashing operation mode, which allows only yellow/red signal heads flashing; power consumption will be decreased to 50% level compared to full operation mode.
- *Analyze runtime* – Calculate runtime from beginning to system failure.
- *Runtime satisfied* – If runtime satisfies requirements, system meets requirements.

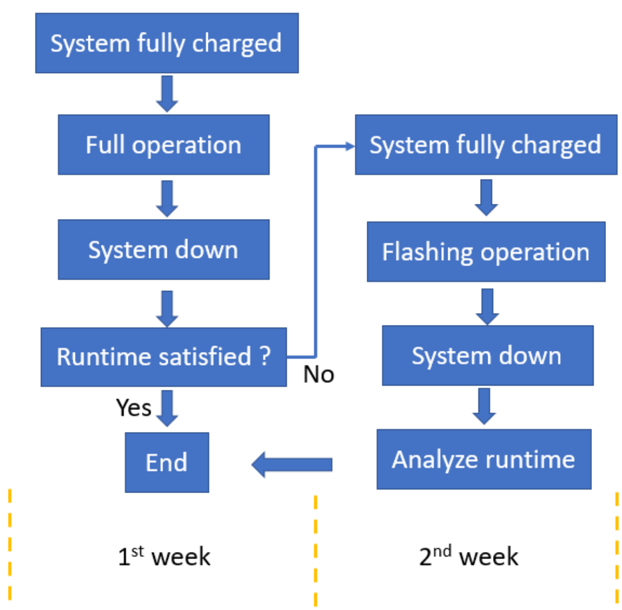


Figure 40. Operational condition decision

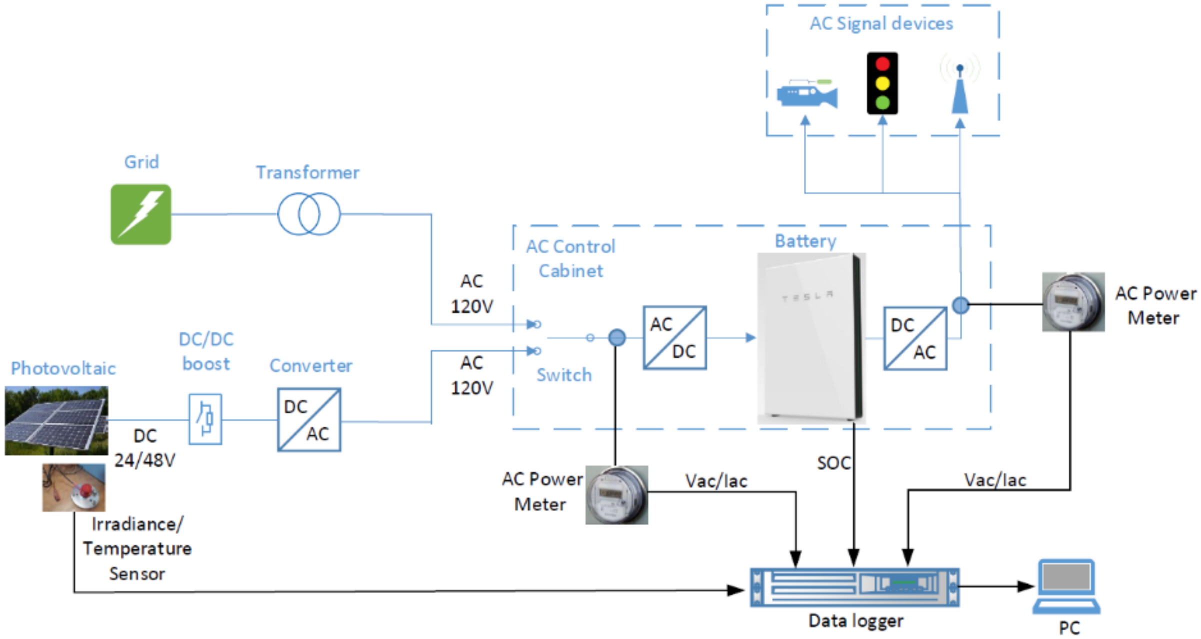


Figure 41. 120 VAC system assembly and data logger connection

4.3.3 Data Collection and Analysis

With voltage and current data from the tested system, the operational condition could be evaluated via data analysis. Figure 42 shows the logic flowchart used to make a judgment.

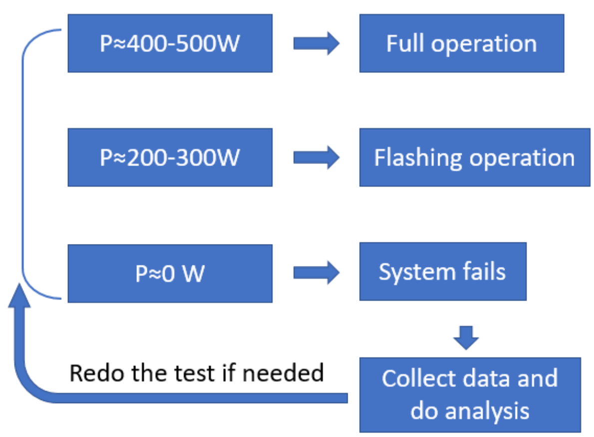


Figure 42. Operation condition evaluation flowchart

Based on the electric-required specification in FDOT Standard Specifications for Road and Bridge Construction, 685-2.2.4, the voltage should be in the range of 85–154 VAC. Therefore, the system will be in full operation if the voltage is within the normal range and the calculated power is close to full power. The system will be in flashing operation if the voltage is within the normal range and calculated power is decreased to 50% level.

4.4 Propane Generator Test and Data Analysis

This section introduces the test site and traffic load included in the system and provides a description of the propane generator, data logger connection, and data collection. Test data also are presented and analyzed.

4.4.1 Test Site Overview

The traffic intersection test site was at the TERL, which has a four-leg approach intersection with 12 signal heads (44 LED bulbs). A fully-functional cabinet was present and included a traffic controller, four video detection cameras, a video controller, and two network switches. Figure 43 shows the test intersection.

Figure 43. Traffic intersection test site at TERL

The first backup power technology tested was the Kohler propane generator, model 12RESV, and was installed with a 57-gal fuel tank. Figure 44 shows the components installed at the site. The propane tank was fueled at 80% capacity for safety reasons, as propane tanks need space for the fuel to expand under high temperatures. The initial fuel capacity was about 80% (shown in Figure 45). As the total tank capacity was 57 gal, the estimated initial propane fuel was approximately 45.6 gal of fuel with a predicted runtime of 2–3 days under full operation condition.

Figure 44. Propane generator backup power supply system at test site

Figure 45. Initial propane fuel capacity approximately 80%

Table 21 shows the Kohler 12RESV generator fuel-rated consumption under different conditions; its rated power is 12kW for 100% load operation. For the tested 400–500 W system, this generator was expected to work in 25% load operation. According to fuel conversion factors, the predicted runtime was approximately 51.3 hours with 45.6 gallons of LPG.

Table 21. Kohler 12RESV Generator Fuel Consumption

Fuel Type	% Load	Fuel Consumption, f^3 /hr. (cfh)
Natural Gas	100	6.1 (216)
	75	4.5 (160)
	50	3.6 (128)
	25	2.8 (99)
	Exercise	2.1 (74)
LPG	100	2.9 (103)
	75	2.2 (76)
	50	1.6 (57)
	25	1.2 (42)
	Exercise	0.8 (30)

Notes: Nominal fuel rating: Natural gas – 37 MJ/m3 (1000 Btu/ft.3); LPG – 93 MJ/m3 (2500 Btu/ft.3). LPG conversion factors: 8.58 ft.3 = 1 lb; 0.535 m3 = 1 kg; 36.39 ft.3 = 1 gal.

4.4.2 Electric Devices in Traffic Cabinet

Before starting the test, all involved electric loads in the traffic cabinet were investigated; their estimated power is shown in Table 22. Figure 46 shows the layout of the traffic control cabinet and each device.

Table 22. Equipment in Traffic Cabinet and Required Power

Load	Quantity	Estimated Power (W)
LED signal head (switches)	9	100–150
ITERIS camera	4	80
Intelight X3 traffic controller	1	25
Conflict monitor	1	10
WAVETRONIX radar interface with 2 sensors	1	30
SMARTMICRO TMIB-AB radar interface with 1 sensor	1	20
GRIDSMART camera system	1	80
AXIS camera and ethernet switches	1	60
Real-time measured power: 400–500 W		**405–455**

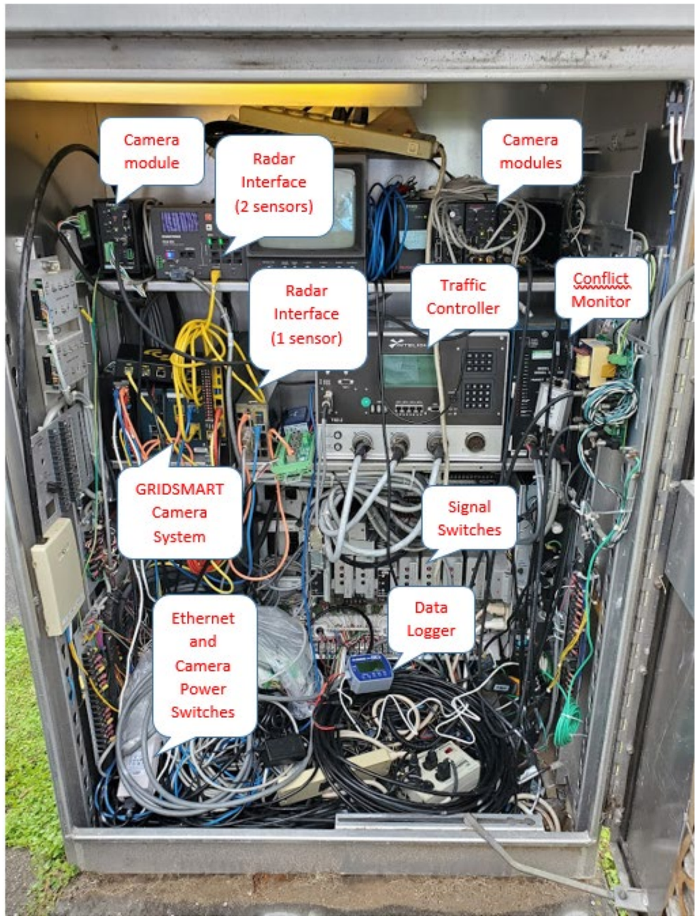


Figure 46. Traffic control cabinet equipment

4.4.3 Data Logger Connection

Two AC voltage/current data loggers were used during the testing period for redundancy and were connected at the total power point, as shown in Figure 47. The logger sampling rate was 30 sec, and the reading power was within the range of 400–500 W, which was consistent with the estimated power.

Figure 47. Data loggers connection for propane generator test

4.4.4 Collected Data

The test started at 1:59 PM on 2/22/21. A CUTR team member monitored the system status periodically until the propane fuel was depleted. Recording status included traffic system working condition (i.e., if normal operation), fuel level, logger operation, circumstance temperature, and weather, as shown in Table 23.

Table 23. Propane Generator Test Data

Time	Logger 1 (W)	Logger 2 (W)	Fuel	Cycling	Temperature (°F)	Weather
2/22/2021 13:59	432	432	80%	Yes	65	Rainy
2/22/2021 16:05	456	456	74%	Yes	64	Cloudy
2/23/2021 9:10	480	480	47%	Yes	50	Sunny
2/23/2021 12:03	432	432	42%	Yes	63	Sunny
2/23/2021 16:09	456	456	37%	Yes	70	Sunny
2/24/2021 8:55	432	432	12%	Yes	48	Sunny
2/24/2021 10:50	432	432	9%	Yes	64	Sunny
2/24/2021 12:01	456	456	7%	Yes	69	Sunny
2/24/2021 14:47	432	456	3%	Yes	73	Sunny
2/24/2021 15:33	432	432	2%	Yes	73	Sunny
2/24/2021 16:56	456	456	0%	Yes	72	Sunny

Figure 48 shows the propane fuel level during the test. The fuel consumption is in a linear relationship with time, and the total generator running time was 51 hours. Thus, the propane generator used 0.87 gal/hr when supporting the traffic signal system. Actual fuel consumption was also compared with predicted fuel consumption; as shown in Table 21, the Kohler 12RESV generator fuel rated consumption under different conditions. The Kohler 12RESV rated power is 12 kW for 100% load operation. For the tested 400–500 W system, this generator was expected to work in 25% load operation. According to fuel conversion factors, the predicted runtime was approximately 51.3 hours with 45.6 gallons of LPG.

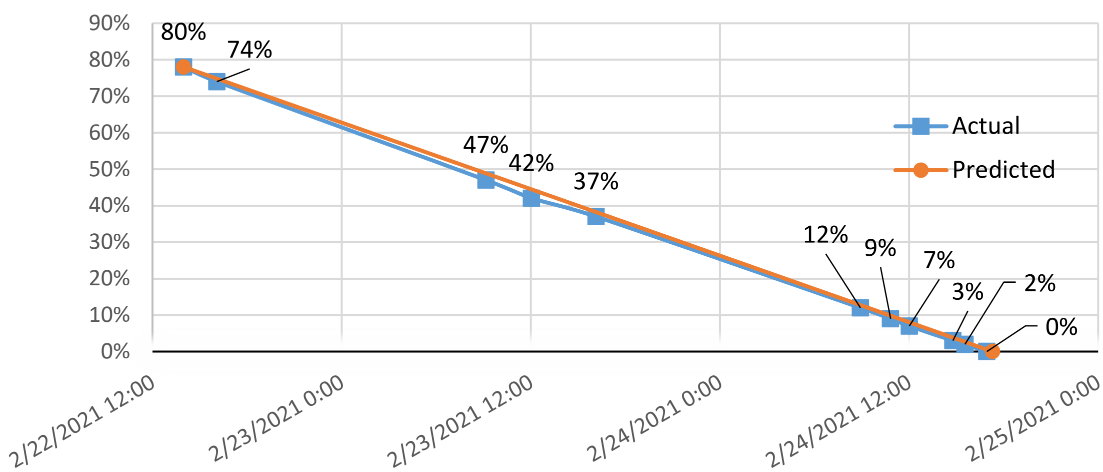


Figure 48. Propane fuel consumption during test

In addition to the consumption and operation test, generator-produced AC voltage was measured by oscilloscope. Figure 49 compares propane generator output AC voltage and utility pure voltage sinewave. As shown, the propane generator-produced voltage had some noise, but it did not affect all traffic devices working normally.

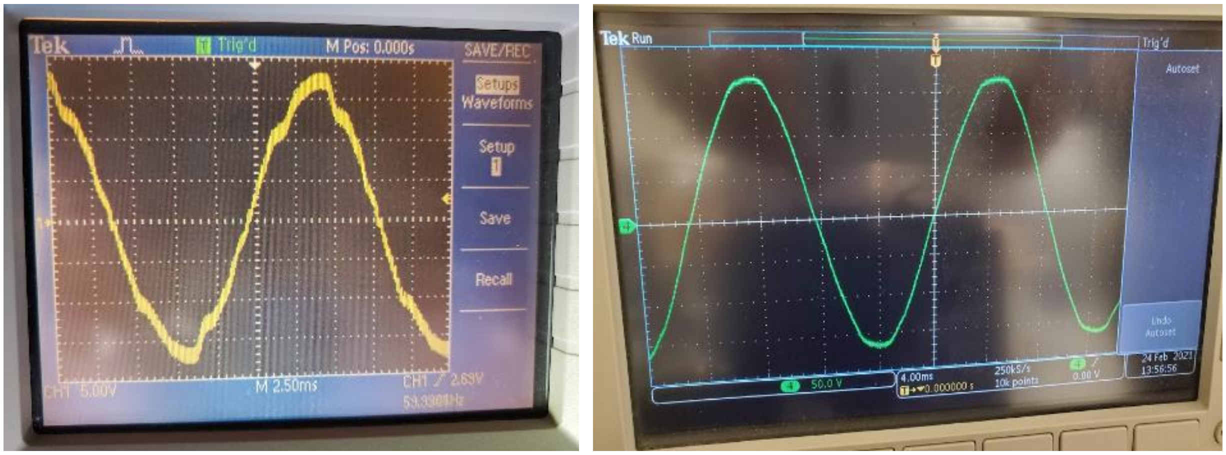


Figure 49. Oscilloscope-measured propane generator output AC voltage (*left*) vs. utility AC voltage (*right*)

4.4.5 Logger Data Analysis

Two AC data loggers collected data successfully. The measured AC voltage and current are shown in Figure 50, and the voltage/current-based computed power is shown in Figure 51. During the test, the traffic cabinet worked under normal operations, as shown in Figure 51. The power rate was within the expected range of 400–500 W.

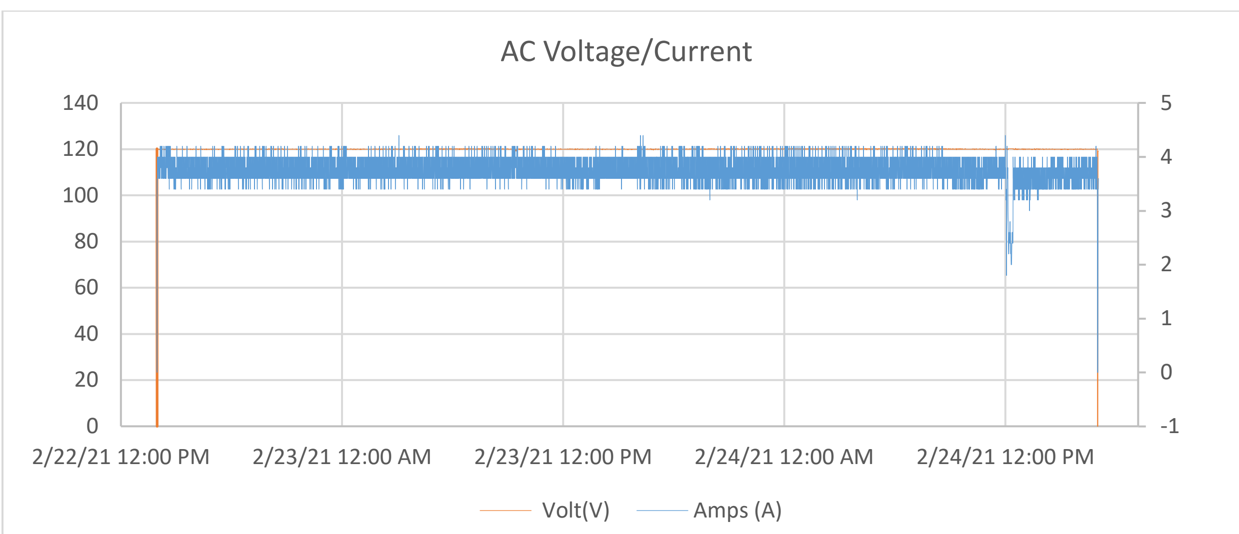


Figure 50. AC voltage/current logger collected data in propane generator test

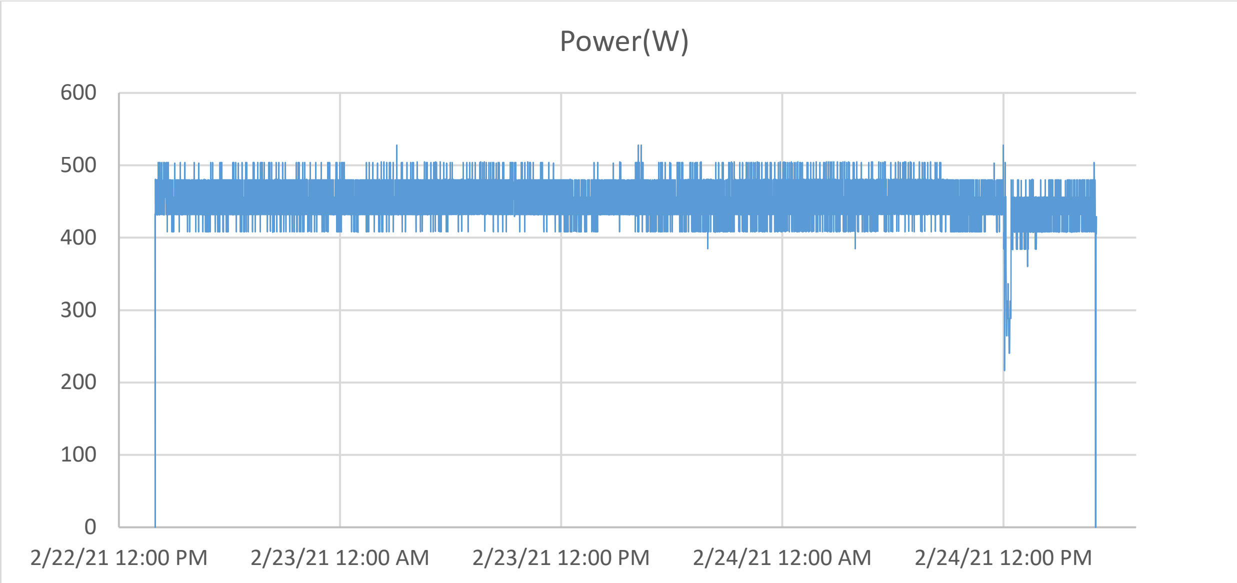


Figure 51. Computed power in propane generator test

Figure 52 shows that the traffic control cabinet was disconnected from utility power on 2/22/21 at 1:57 PM; the propane generator started to power the traffic system within 1 min. During the transition, the intersection was dark for 10 sec, and the signals went to flashing mode for one cycle; within 30 sec, the traffic signals were back to fully operating mode. Figure 53 shows the propane generator shut down on 2/24/21 at 4:58 PM and the switch back to utility power at 5:00 PM.

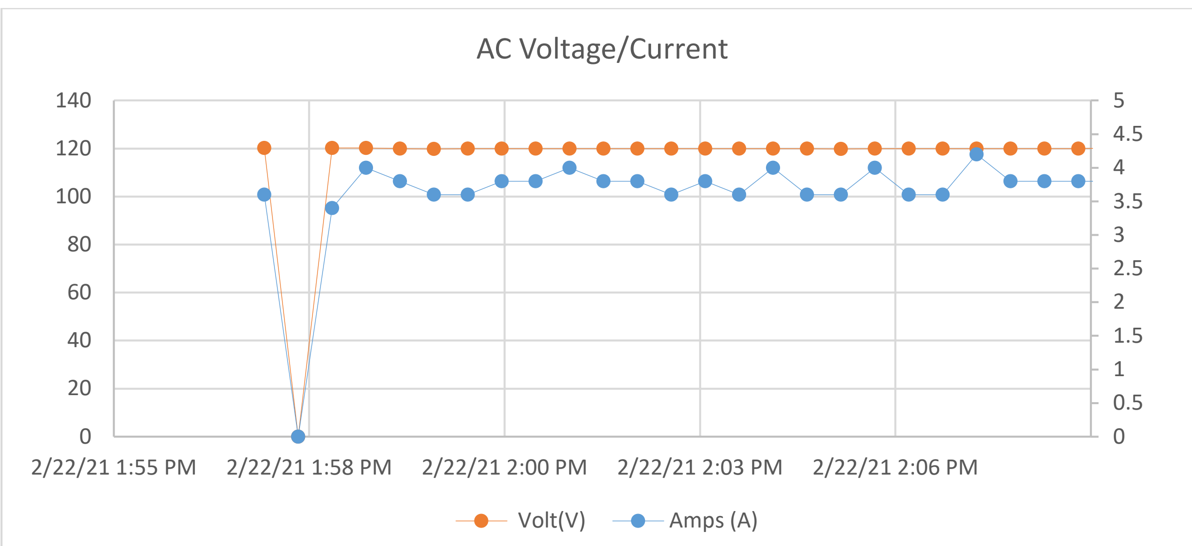


Figure 52. AC voltage/current data when switching from utility power to propane generator

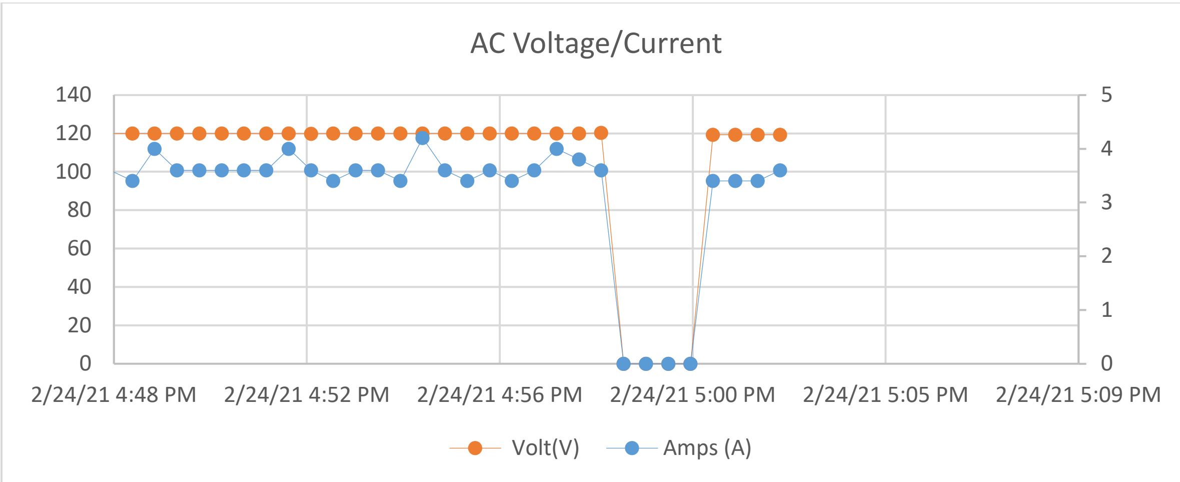


Figure 53. AC voltage/current data when switching from propane generator to utility power

4.4.6 Conclusion

The propane generator was tested as the backup power supply for the traffic cabinet; results were as follows:

- With the automatic transfer switch (ATS), the generator system showed the capability to switch power when utility power is lost.
- The propane generator worked reliably for the duration of the test. Although the signal was not as clean as utility power, all traffic devices inside the cabinet worked without issue during the test.
- The generator produced loud noise, which reached more than 70dB when measured near the generator. A dB limit should be considered by FDOT in the specification for generators.
- In total, 45 gallons of propane fuel supported this system for 51 hours under full operating conditions.

To further extend the runtime to a desired level, more fuel should be used. The corresponding LPG and cost under different runtime assumptions are shown in Table 24. The values are for reference only, and fuel tank protection (poles, concrete barrier, or other measures) is not included. The incremental difference is for fuel only, which varied about $220 for 1–5 days of runtime.

Table 24. Propane Generator Backup System Cost Estimation

Propane System Runtime	LPG (gal)	Cost
1 day	22	$8,669
2 days	44	$8,725
3 days	66	$8,779
4 days	88	$8,834
5 days	110	$8,889

4.5 Battery + Solar System Test and Data Analysis

A 10-kWh capacity battery and 8 solar panels with 2.8-kW maximum power were installed at the TERL for testing as a backup power system. In this section, the battery + solar system and test procedure are described, and collected data and analysis are presented.

4.5.1 Test Site Overview

Figure 54 shows the installed solar panels and the additional cabinet housing the solar inverter and batteries for the system at the TERL intersection. The solar panels were mounted on a steel and aluminum structure next to the traffic intersection; an inside view of the inverter and battery cabinet is shown in Figure 55. TERL staff worked with the CUTR team to provide an empty ITS cabinet to house the inverter and batteries, which were installed next to the existing traffic cabinet; electrical connections to the system were via a buried conduit.

The battery + solar system integrated solar panels, batteries, and traffic load. The system was not connected to the grid but was installed in an "off-grid" configuration in which the batteries are charged from solar power only and the solar power is pushed to the grid. When solar power is available, the solar panels generate power to charge the batteries (if needed) while they power the load. The system had a real-time monitoring system that provided data logging and remote monitoring capabilities, as shown in Figure 56.

Figure 54. Battery + solar system at test site

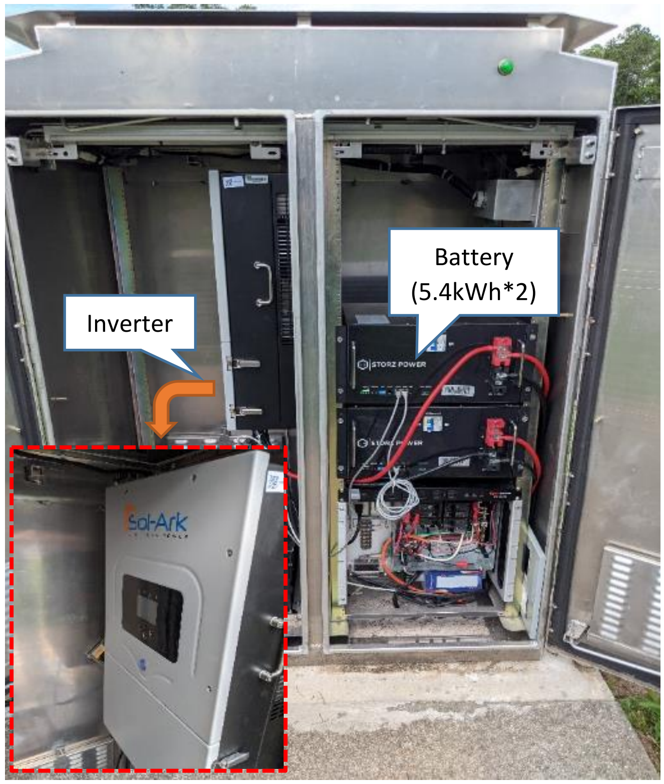


Figure 55. Inverter and battery cabinet

The battery capacity was calculated to last approximately 24 hours, which for the backup system is more than enough to power the intersection overnight when no solar power is available. The assumption was that the depleted batteries will charge the next day during solar power availability. As an example, as shown in Figure 56, the solar panels provide 543 W of power, of which 439 W are required for the load (red house icon) and the remaining 104 W are used to maintain the battery charge at 100%.

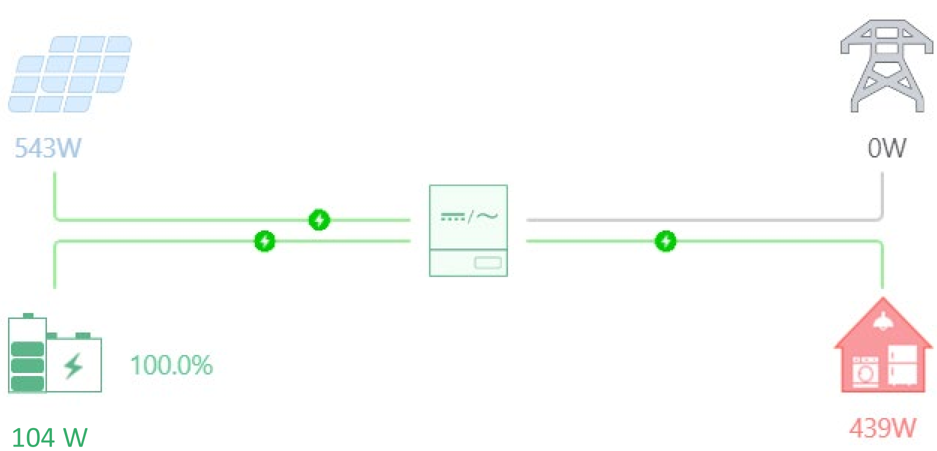


Figure 56. Battery + solar system

The inverter output AC voltage was examined via oscilloscope similar to the generator test and showed pure sinewave (Figure 57). Hence, the battery + solar system output voltage quality was better than the generator and equal to the grid power signal.

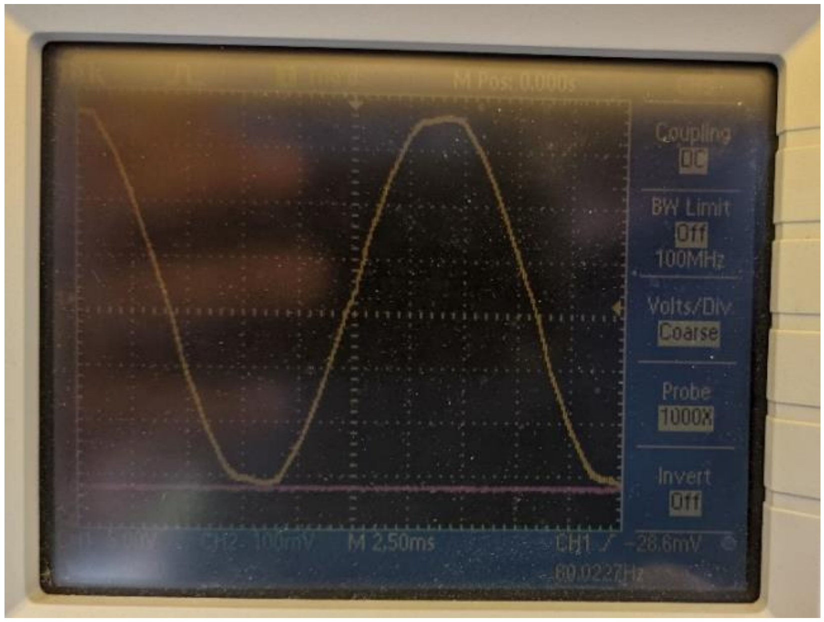


Figure 57. Inverter output AC voltage sine wave

Two kinds of tests were conducted using this system: (1) using power from the battery only without any solar panels connected and (2) with the solar panels connected. These are described in the following sections.

4.5.2 Battery-Only Test and Data Analysis

A backup system used to power a traffic cabinet can include only a battery and no solar panels. The battery can be charged using utility power; when a loss of utility occurs, the battery can provide the required power for a certain amount of time. A battery-only test was conducted to verify battery performance and calculations of required power and runtime. According to estimations, the 10-kWh capacity battery can support a 450-W load for 20–22 hours.

The battery test started at 9:51 AM on 07/02/2021. Traffic cabinet power was switched from utility to battery power with solar panels off. The battery operated at 53 VDC, and power was converted to 120 VAC via the inverter. To protect the battery from damage, a minimum threshold was set to 46 VDC. If the battery voltage drops to this level, it shuts down and stops providing power until it is charged again to 52 VDC.

The battery state of charge (SOC) in percentage and monitored load power during the test are shown in Figure 58. As the traffic load power was in the range of 400–550 W, the SOC dropped at a constant rate, providing a linear relationship between charge and time.

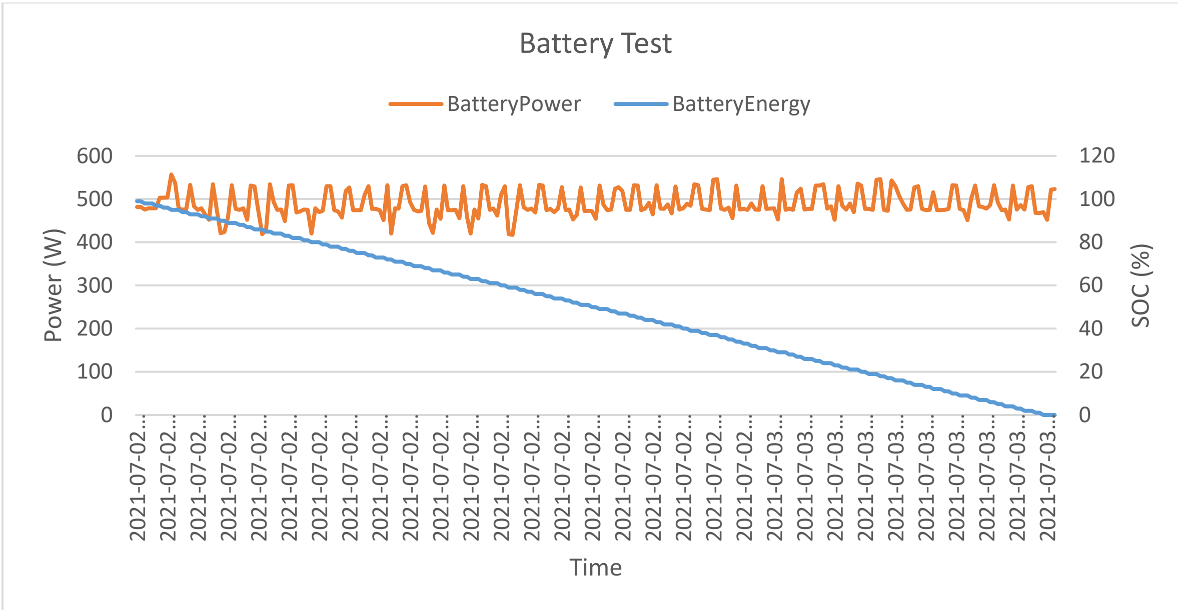


Figure 58. Battery test data

The battery DC voltage and SOC relationship is shown in Figure 59. Battery voltage drops dramatically when SOC reaches a low level. After about 20 hours, the SOC decreased to zero, and the battery system shut down. This test result matched the expectation of the battery supporting the load for 20 hours runtime. This runtime is to be expected every time the battery needs to fully support the cabinet; it does not depend on time of day. With this knowledge, a second test was conducted with battery + solar together. After depletion of the battery, the solar panels were switched on to charge the battery to 100%.

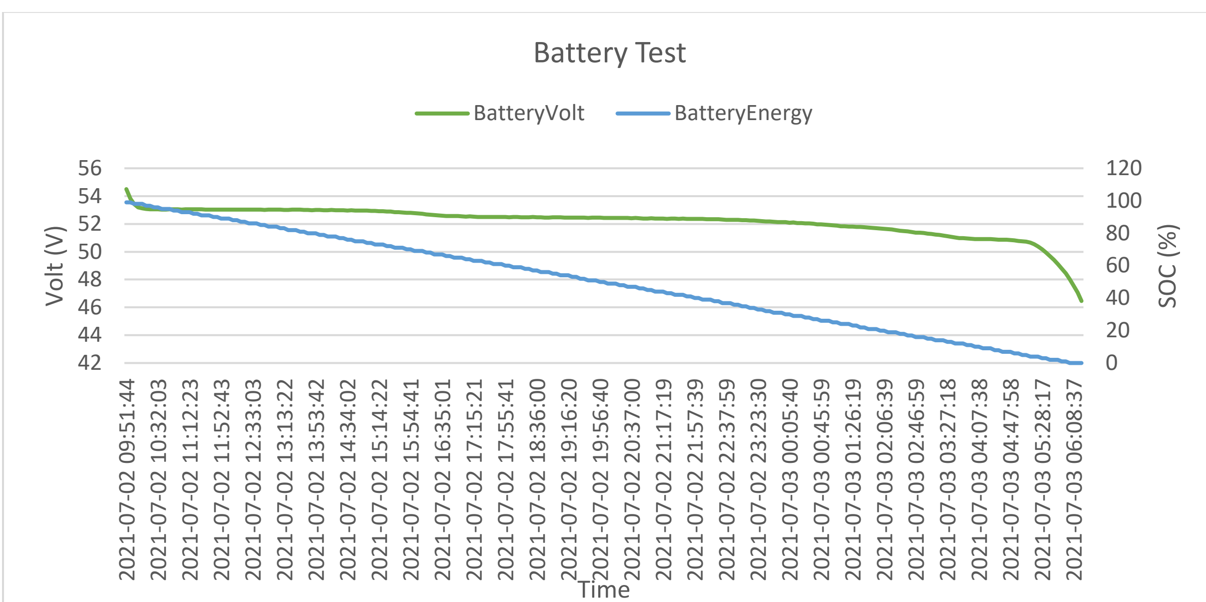


Figure 59. Battery voltage vs. SOC relationship

4.5.3 Battery + Solar Test and Data Analysis

This test was conducted after the battery was 100% fully charged and was conducted twice, with different outcomes. Test 1 included experiment data for a bad weather scenario, and Test 2 included experiment data for a good weather scenario, which affected how much solar power was available to charge the batteries and support the required runtime. The solar irradiance historical data were downloaded from the SOLCAST webpage (https://solcast.com/).

Figure 60 shows one week of data for reference. During the testing week, the first two days had cloudy and rainy weather, and the following five days had fewer clouds and more sunny weather. The two tests were run separately on 07/11/2021 and are shown as a dashed line in Figure 60.

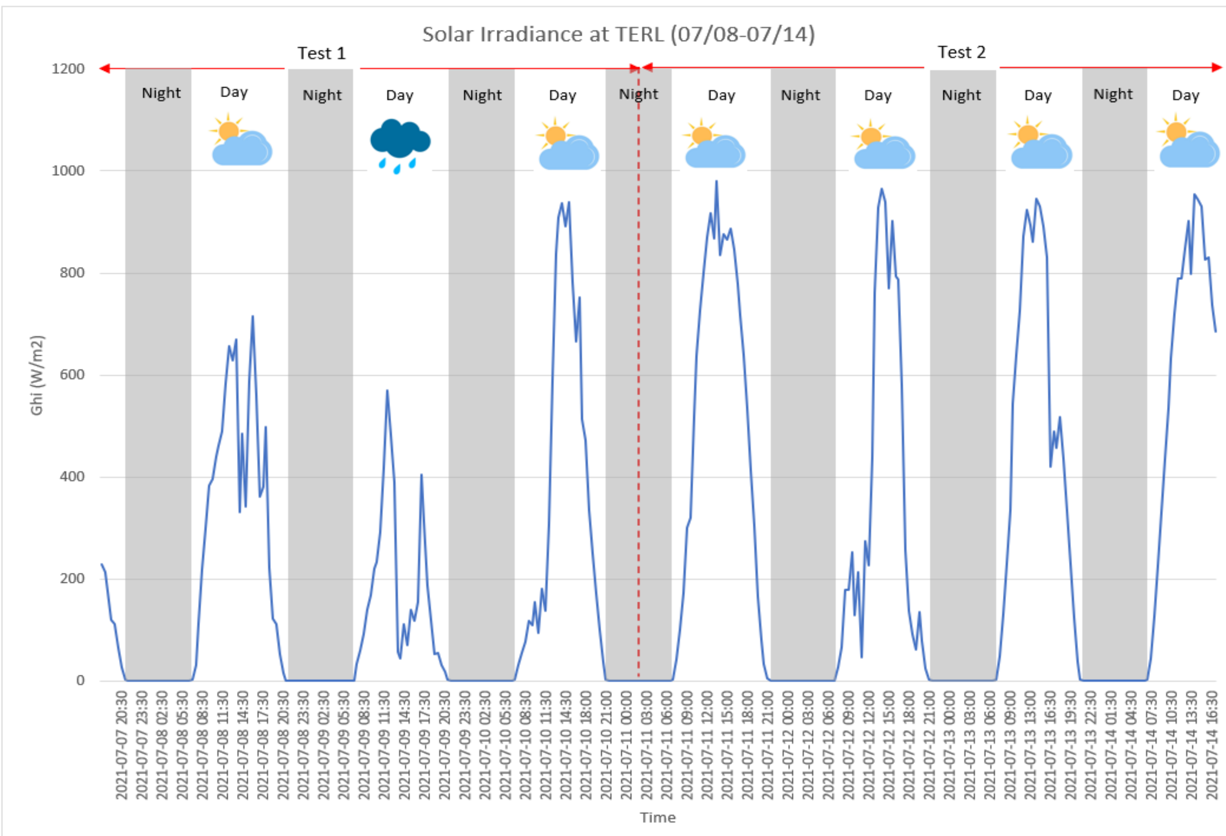


Figure 60. Solar irradiance data at TERL

4.5.3.1 First Battery + Solar Test and Data Analysis

The first battery + solar-powered system test started at 10:04 AM on 07/07/2021. The battery's initial SOC was 100%, and the traffic load was switched on. Eight 400W solar panels were available to generate up to a rated 3.2 kWp. The test runtime was expected to be a minimum of 72 hours from start, which is the desired outcome of such systems. Solar power, load power, and battery SOC during this test are shown in Figure 61.

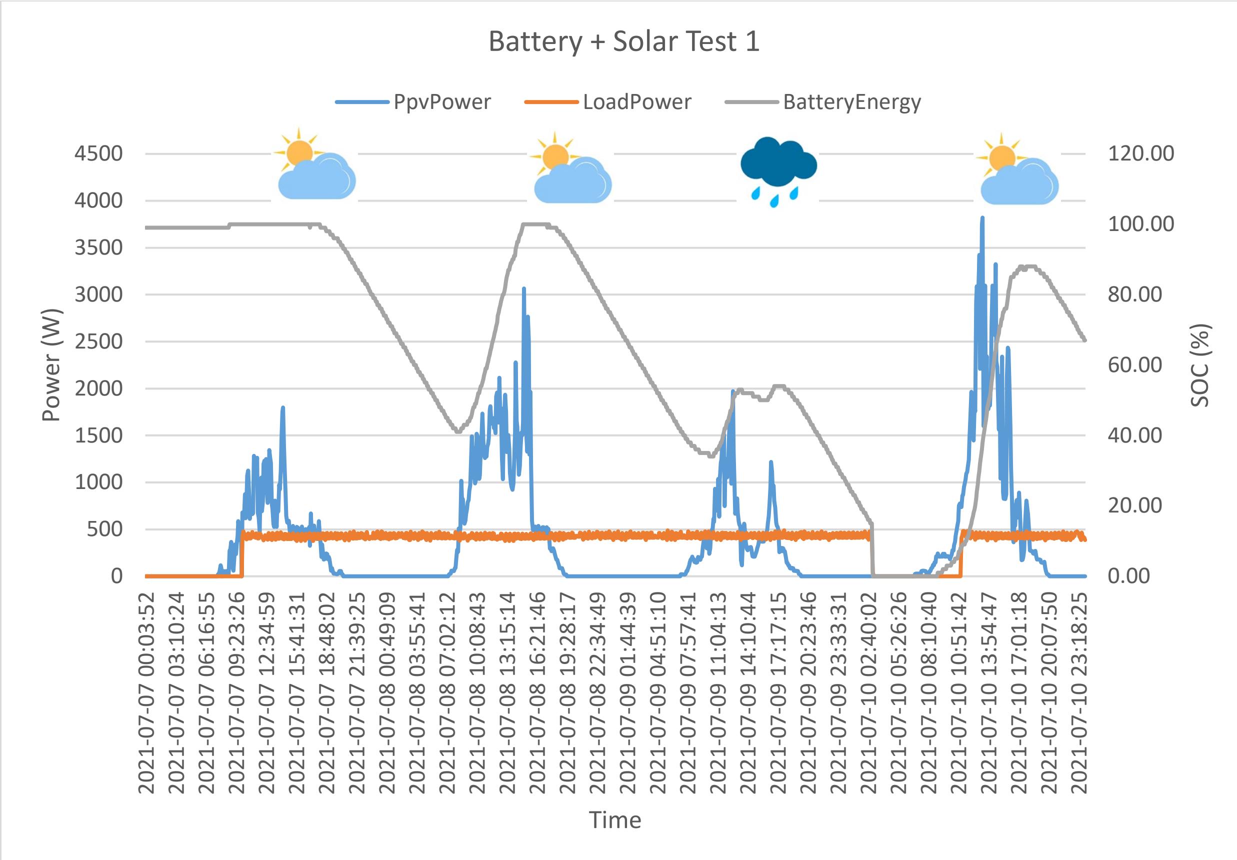


Figure 61. Battery + solar test 1 data

The solar power shown in Figure 61 reflects the weather conditions during the first three days. Although there was not sufficient solar energy during the first day (07/07/2021), the solar panels were able to keep the battery charged 100% until 6:15 PM. From 6:15 PM to 9:13AM the next day, the load was served by the battery with no solar power (nighttime). The next day, the solar panels were able to recharge the battery to 100% only briefly (3:21–5:42 PM). At 5:42 PM, the battery started to serve the load until the next morning at 8:53 AM when the solar panels started to produce energy. This time, however, the panels were not able to charge the battery, which reached a maximum of 63%. At 6:50 PM, the battery started to serve the load for the night and dropped to 15% at 3:00 AM, at which time the system shut down to protect the battery. The system remained shut down until 11:00 AM when the solar panels were able to charge the battery enough to switch back on. The gap between 3:00 AM and 11:00 AM was due to the previous cloudy day when the battery was not charged more than 53%. The runtime requirement would have been met if the system had been operational for another seven hours (3:00–10:00 AM).

In this test, the battery and the eight solar panels supported the traffic system working in full operation for 2 days and 17 hours. The combination of battery capacity and amount of solar power provided can greatly affect the characteristics of the system related to how fast it discharges or charges and how long it can power the intersection without solar power. The test showed that the system used approximately 60–70% of the battery capacity overnight; however, this value was not accurate, as cloudy days mean that solar power was late to start charging in the morning or early to drop at night and a longer battery runtime was required.

4.5.3.2 Second Battery + Solar Test and Data Analysis

After the first test, the system continued to power the cabinet for the following days. A second test was recorded, in which solar irradiance at the TERL was relatively better and the battery was fully charged during daytime as a best-case scenario. The data collected from 07/11/2021 to 07/14/2021 are presented in Figure 62.

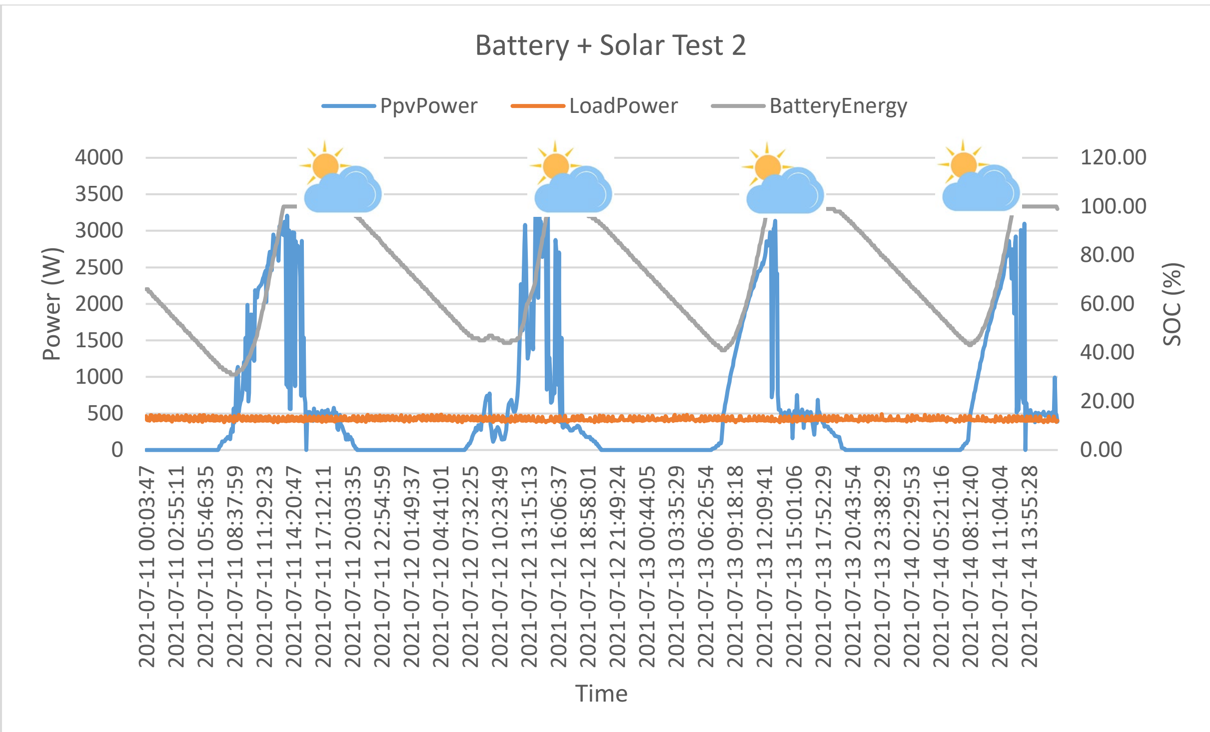


Figure 62. Battery + solar test 2 data

The setup was the same as in Test 1; the only difference was the weather during the three testing days. This time, the test did not start with a 100% battery charge; the initial battery SOC was about 30% before solar power started charging. Due to sufficient solar irradiance, the battery was fully changed at 2:00 PM the next day while also powering the cabinet. The battery remained at 100% until the solar power could not provide enough power and dropped overnight from 100% to 44%. The second day, the solar panels charged the battery to 100% at 4:30 PM; subsequently, the battery took the load overnight and reached a low 41%. On the last day of the test, the solar panels charged the battery from 41% to 100% in five hours, the shortest time of all test days. The battery remained charged until nighttime operations. As shown in Figure 62, the load was constant at all times, with no loss of power (unlike Test 1). This test showed the expected pattern of charge and discharge cycles when the weather is clear enough such that the solar panels can provide enough energy to charge and maintain the system.

4.6 Test Summary

During testing, three different backup systems were acquired, installed, and tested at the TERL test intersection—a propane generator, a battery system, and a battery + solar system. All tests successfully showed the capability of the systems to extend traffic load runtime after losing power from the main grid. Comparison of the tested systems is summarized in Table 25.

Table 25. Comparison of Tested Technologies

Attribute	Propane	Battery	Battery + Solar
Cost	$9k	$16k	$17k
Power quality	Adequate	Good	Good
Runtime	2–3 days	20 hrs	Up to 5 days
Startup time	30 sec	Milliseconds	Milliseconds
Weather impact	No	No	Yes
Noise level	High	Low	Low
Air pollution	No	No	No
Maintenance	Quarterly	Yearly	Yearly
Refuel	Yes	No	No
Data monitor	Yes	Yes	Yes

Based on the comparison in Table 25, the following conclusions can be drawn:

- A **propane generator** is a low-cost backup power technology that will not be impacted by weather conditions; however, power quality is not as clean as utility power, and it might not be able to support sensitive electronic devices. A propane generator is loud and requires maintenance and refuel. In addition, transfer time was not adequate for uninterrupted power supply, but it can be adjusted. A standard UPS can fill the gap between utility power loss and generator fully operational mode.
- A **lithium battery system** (ion or Li-PO) provides reliable power quality and can be switched on within milliseconds without noticeable signal noise. It does not need refuel and requires less maintenance, and diagnostics can be monitored remotely. It is a more expensive system, especially when a larger-capacity battery is required.
- A **battery + solar system** has all the advantages of a battery system and can extend runtime at a very low-cost rate, as solar panels are inexpensive. Solar panels can charge the battery during the day, which discharges during the night, and this cycle can be sustained until the batteries need to be changed. The number of solar panels and battery capacity will vary depending on required load, available space, desired runtime, and available budget for this type of system.

4.7 Data Analysis

To provide further information about the battery + solar system, a brief estimation and comparison for different capacity batteries and different solar generation sizes based on the experimental data was conducted and included in this section.

4.7.1 Battery System Analysis

An additional test was conducted for the 10-kWh battery system. The traffic signal at the TERL was placed in flashing operation to measure the power level required and confirm findings from the data collected in Hillsborough County. The data collected are presented in Figure 63; the first is a 0.45 kW load under full operation mode and the second is a 0.34 kW load under flashing operation mode. The data show that the 10-kWh battery supported a 0.45 kW load for 20 hours and supported a 0.34 kW load for 24 hours. The load value for flashing operation was not half the load of the full operation found in Hillsborough County. This is due to the traffic cabinet including many devices not normally found in a live intersection. Also, the number of signal heads was lower than the 20 signal heads found in the pre-test intersection in Hillsborough County.

It is important to note that the relationship between battery runtime and load size is nonlinear—it is inaccurate to assume that the battery runtime will be doubled if the load size is reduced by half. This, however, should be verified with additional data collection with varying load values.

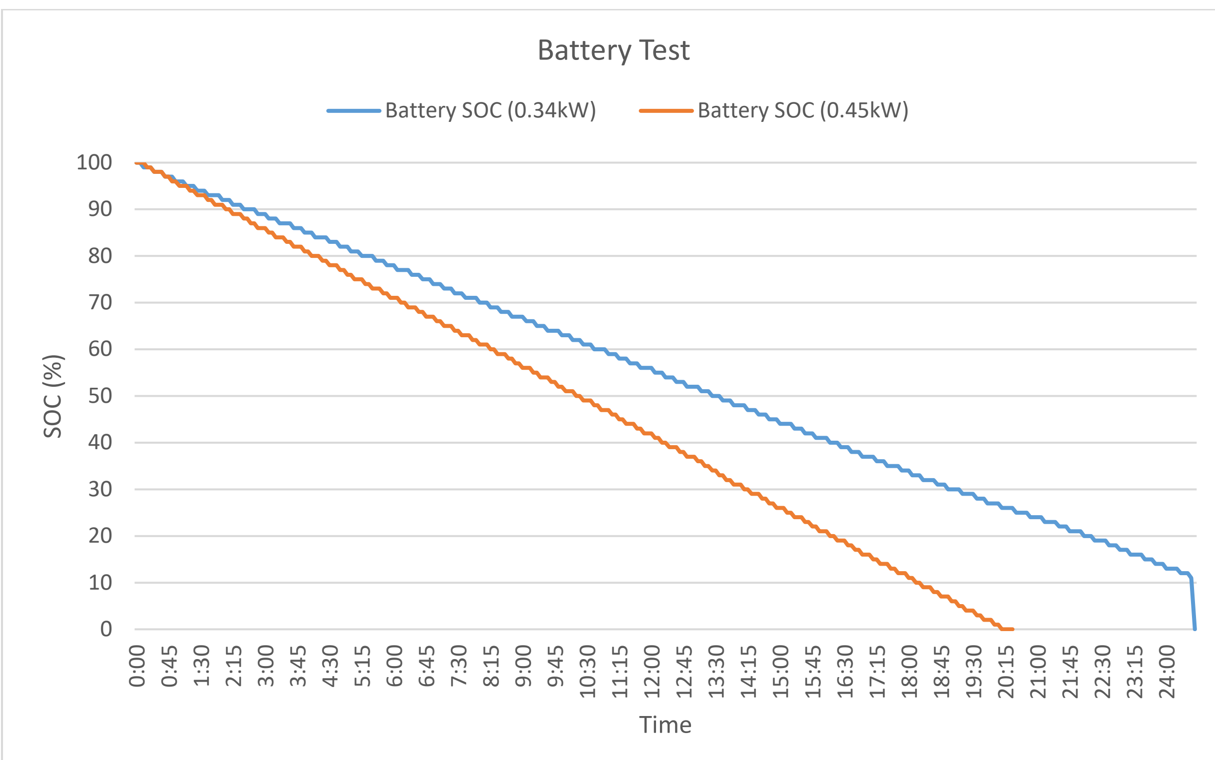


Figure 63. Battery performance under different load sizes

Estimation of different battery capacities and load sizes is shown in Table 26. The test at the TERL included only the 10-kWh battery with 0.45 kW load and 0.34 kW load. Additional scenarios were calculated using the same rates of discharge. If a system is equipped with a 15-kWh battery capacity, it is expected to run 30–44 hours depending on the load. Similarly, a 20-kWh battery is expected to run for up to 72 hours if it supports a 0.22 kW load (the flashing power level of the pretest intersection in Hillsborough County). In the future, if such a system is implemented, a decision will need to be made on the battery capacity based on the power level of the cabinet in question.

Table 26. Runtime Regarding Different Batteries and Loads

Battery	0.45 kW load	0.34 kW load	0.22 kW load
10 kWh	20 hrs	24 hrs	36 hrs*
15 kWh	30 hrs*	36 hrs*	44 hrs*
20 kWh	40 hrs*	48 hrs*	72 hrs*

* Estimate

4.7.2 Solar System Analysis

All solar tests conducted at the TERL adopted a maximum of 3.2 kW solar generation size, based on eight 400 W solar panels. As the relationship between solar power generation and number of solar panels is linear, it is necessary to extrapolate the number of solar panels needed for a certain system based on their rated power generation. Table 27 shows solar power generation for varying numbers of solar panels of the same type as those used for the test. This analysis was based on the monitored solar data on 07/06/2021, as shown in Figure 64. During charging, it was shown that the solar panels with 3.2 kW maximum generation could fully charge a 10-kWh battery during daytime with relatively sunny weather. The solar generation will decrease linearly with reducing solar size.

Table 27. Solar Generation Power and Capacity Based on 07/06/2021 Irradiance

Panel Number	Max Solar Power	1-day Generation	% of 10 kWh Battery
PV x 8	3.2 kW	10 kWh	100
PV x 6	2.4 kW*	7.5 kWh*	75*
PV x 4	1.6 kW*	5 kWh*	50*
PV x 2	0.8 kW*	2.5 kWh*	25*

* Estimate

Figure 64 shows the battery charging process via solar energy. The load was disconnected, so all energy produced was used to charge the battery. It took approximately 9 hours for the battery to reach 100% SOC from 0%. The cloudy weather observed on 07/06/2021 is typical for Florida in the summer. As shown, the solar power varied due to the cloud-shading effect on the panels. More solar panels will be needed to fully charge a 10-kWh battery if the weather is worse or the load consumption is considered (in addition to charging the battery).

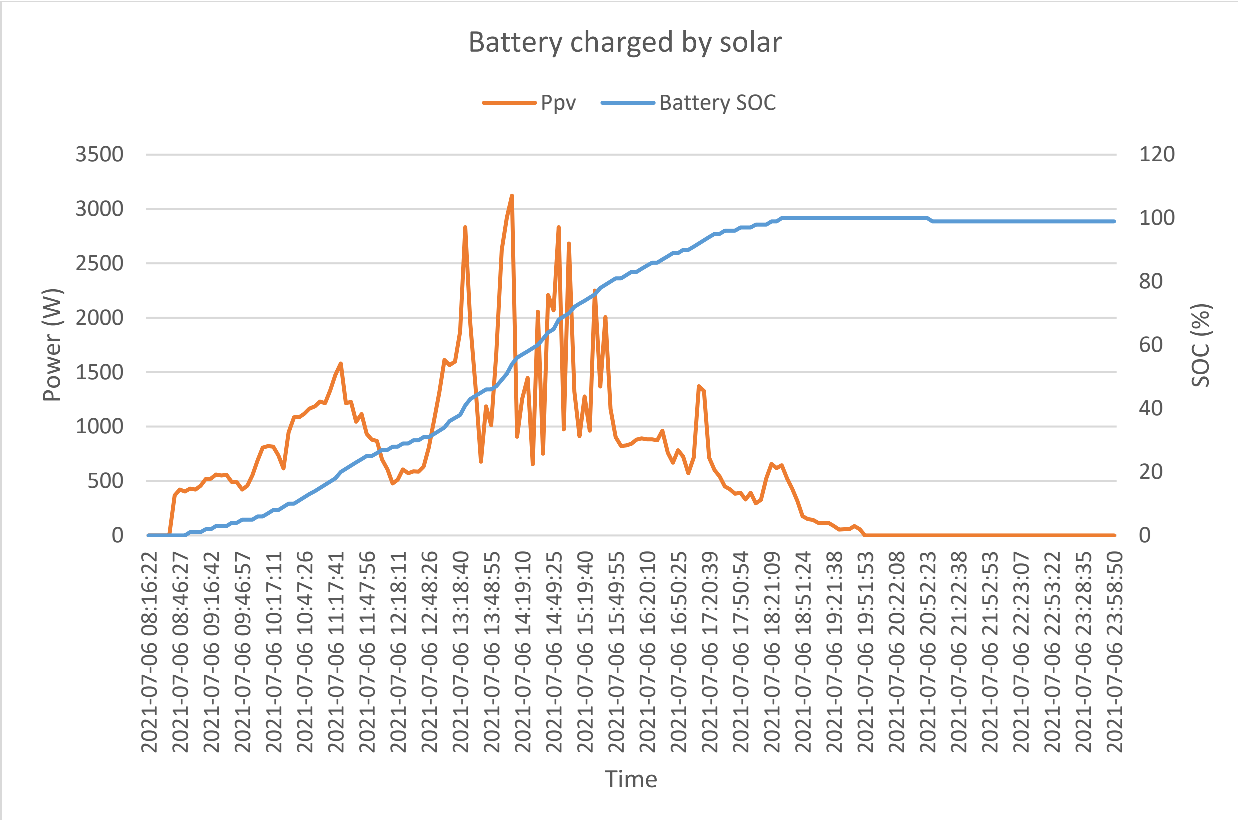


Figure 64. Battery charging process by solar on 07/06/2021

5 Conclusions

The CUTR team conducted detailed literature review and recommended four specific technologies for consideration in testing for extended backup power for traffic cabinets in case of power loss. Current traffic cabinets use a standard UPS system, which is powered by lead acid batteries, an outdated technology that provides power for up to eight hours of operation. After discussion and coordination with the FDOT Project Manager and TERL staff, the following three backup power systems were approved and selected for testing:

- LPG generator system
- Lithium battery system
- Lithium battery + solar backup system.

An LPG generator is a tested technology used in many applications, including telecommunications, rail, and other industries with remote facilities. The CUTR team installed and tested a generator that provided power to a traffic cabinet without issue for as long as it had fuel. During the switch, the generator took 13 seconds to transfer power, which would require further adjustments or the use of a small UPS to cover the gap between power loss and the generator fully supporting the load. In addition, the LPG generator requires a fuel tank, which can be hazardous if hit during a traffic crash; therefore, additional safety precautions must be taken (breakaway lines, automatic shutoff valve, or concrete barriers) to ensure safe storage close to a traffic intersection.

The lithium battery system is a relatively newer technology widely used in commercial and residential applications as energy storage and for off-grid applications. Recent advances in battery technology used in electric vehicles and energy storage allow for a compact form factor with high energy capacity. These batteries have a higher initial capital cost but a longer life cycle, with up to a 10-year warranty compared to other batteries. The battery-only system transferred the load instantaneously and without delay and is an applicable solution to the problem of providing extended power to traffic cabinets. A major drawback of the battery-only system is that if the battery runs out of energy and grid power is not restored, the intersection will go dark. To ensure a longer runtime, a larger battery capacity is required, which increases cost.

To minimize the cost of the batteries, a solution is providing backup power using additional solar power. In Florida after a hurricane, typically there are sunny days that can provide enough solar power to recharge a smaller battery discharged during the night and cycle for the next day, a pattern that can go indefinitely. The CUTR team installed and tested this setup, providing enough solar power to charge a 10-kWh battery used to power a 0.45 kW load an average of 14 hours overnight, from 6:00 PM to 8:00 AM. The solar power in the morning powered the load and charged the battery to be ready for the next night. The number of solar panels depends on their rated power generation, the size of the battery, and the available space for installation at the site. This is an appropriate way to minimize costs (using smaller capacity batteries), with the risk that there might not be enough solar power to re-charge the battery the next day. In real-world applications, a specific design needs to be implemented for each intersection to assess power needs, available space, and budget to install a battery + solar battery system.

The systems tested showed a great promise in providing backup power in case of power loss due to a hurricane for an extended period. Selection and availability of each system will be the responsibility of each agency once the systems are approved and listed on the FDOT APL.

The CUTR team provided specification recommendations for the TERL to include in the certification process of backup power systems; these specifications are provided in Appendix B. In addition, a testing procedure is provided in Appendix C for adoption and use in conjunction with internal procedures from the TERL.

References

1. Dialight. 12" ITE Compliant XL15 Long Life LED Traffic Signals Brochure. Available from www.dialightsignalsandcomponents.com/Assets/Brochures_And_Catalogs/Signaling/Traffic_new/Dialight_Traffic_data_12inXL15_Feb2019.pdf.
2. FDOT, FDOT Approved Product List (APL): 650 – Vehicular Traffic Signal Assemblies. 2019.
3. Siemens. Extra low voltage solutions. Available from https://www.siemens.co.uk/traffic/en/index/productssolutionsservices/elv.htm.
4. Dialight. 48VDC LED signal modules brochure. Available at http://www.dialightsignalsandcomponents.com/Assets/Brochures_And_Catalogs/Signaling/Traffic_new/Dialight_Traffic_bro_48VDC_Nov2017.pdf.
5. Pitcher, G. How supercapacitors can help to solve power problems in portable products. Portable Products, 2015.
6. Rattner, E. Light for life flashlight. TheFutureofThings.com, 2008.
7. Ridden, P. Helium Bluetooth speakers powered by supercapacitors. New Atlas.com, 2013.
8. First one up the drive: A new sort of storage device gives lithium-ion batteries a run for their money. *The Economist*, *Science and Technology Edition, The Economist.com, July 12th,* 2014. Available at https://www.economist.com/science-and-technology/2014/07/10/first-one-up-the-drive
9. Farhadi, M. and O. Mohammed, Adaptive energy management in redundant hybrid DC microgrid for pulse load mitigation. *IEEE Transactions on Smart Grids,* 2014.
10. Farhadi, M., Performance enhancement of actively controlled hybrid DC microgrid with pulsed load. 2014 IEEE Industry Application Society Annual Meeting, 2014.
11. Nippon Chemi-Con Corp. Nippon Chemi-Con, Stanley Electric and Tamura announce: development of "Super CaLeCS," an environment-friendly EDLC-powered LED street lamp. Press release, 2010.
12. Schmidt-Rohr, K., How Batteries store and release energy: Explaining basic electrochemistry. *Journal of Chemical Education*, 2018. **95**(10): p. 9.
13. Z. Miao, L. Xu, V. R. Disfani and L. Fan, "An SOC-Based Battery Management System for Microgrids," in IEEE Transactions on Smart Grid, vol. 5, no. 2, pp. 966-973, March 2014, doi: 10.1109/TSG.2013.2279638.
14. Alhaider, M., Fan, L. Mixed integer programming based battery sizing. *Energy Syst 5, 787–805 (2014)*. https://doi.org/10.1007/s12667-014-0118-4.
15. M. Zhang, Z. Miao and L. Fan, "Data Analytics of Real-World PV/Battery Systems," *2019 IEEE Power & Energy Society General Meeting (PESGM), 2019*, pp. 1-5, doi: 10.1109/PESGM40551.2019.8973970.
16. Bao, L., L. Fan, and Z. Miao, Real-time simulation of electric vehicle battery charging systems. 2018 North American Power Symposium (NAPS).
17. Zhang, M., Z. Miao, and L. Fan, Battery identification based on real-world data. 2017 North American Power Symposium (NAPS).
18. Alhaider, M., L. Fan, and Z. Miao, Benders Decomposition for stochastic programming-based PV/Battery/HVAC planning. 2016 IEEE Power and Energy Society General Meeting (PESGM).

19. Xu, L., Z. Miao, and L. Fan, Unbalance and harmonic mitigation using battery inverters. 2015 North American Power Symposium (NAPS).
20. Khazaei, J., et al., Real-time simulation and hardware-in-the-loop tests of a battery system. 2015 IEEE Power & Energy Society General Meeting.
21. Xu, L., Z. Miao, and L. Fan, Control of a battery system to improve operation of a microgrid. 2012 IEEE Power and Energy Society General Meeting.
22. Andrea, D., Battery Management Systems for Large Lithium-Ion Battery Packs. Artech House, Norwood , MA, 2010.
23. Resende, C. A guide to choosing best power tool battery for your cordless tools. PowerToolLab.com, 2018, Available at https://www.powertoollab.com/best-power-tool-battery/.
24. Miller, P., Automotive lithium-ion batteries: State of the art and future developments in lithium-ion battery packs for passenger car applications. Johnson Matthey Technology, 2015.
25. Hagerty, K. Deep cycle batteries introduction. altE store.com. Available at https://www.altestore.com/diy-solar-resources/deep-cycle-batteries-introduction/.
26. O'Connor, J. Battery showdown: Lead-acid vs. lithium-ion. Medium.com, 2017, Available at https://medium.com/solar-microgrid/battery-showdown-lead-acid-vs-lithium-ion-1d37a1998287.
27. William A. Wallace, J.W., David Torrey, Nicholas Renna and Jiewei Tan, Guidelines for traffic signal energy back-up systems. NY DOT, NY, 2009. Report No: 09-05, Rensselaer Polytechnic Institute. p. 105.
28. Glenn, V. Traffic operations department installing traffic signal battery backup system. Cocho Valley homepage.com. 2019. Available at https://www.conchovalleyhomepage.com/news/news-connection/traffic-operations-department-installing-traffic-signal-battery-backup-system/1836520485/.
29. Benson, J. Brooklyn hoping to keep traffic signals working during power outages. Cleveland.com, 2018. Available at https://www.cleveland.com/brooklyn/2018/04/brooklyn_hoping_to_keep_traffi.html.
30. Smithson, S. City works to put traffic signal backup batteries at every intersection. kait8.com, 2018. Available at https://www.kait8.com/2018/12/04/city-works-put-traffic-signal-backup-batteries-every-intersection/#:~:text=JONESBORO%2C%20AR%20(KAIT)%20%2D,Jonesboro%20to%20reduce%20those%20problems.&text=The%20battery%20backups%20can%20keep,after%20the%20power%20goes%20out.
31. Tesla Powerwall Technical Specifications. Tesla.com, 2019, Available at https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_northamerica.pdf.
32. Zhao M, Sharma A, Smaglik E, Overman T. Traffic Signal Battery Backup Systems: Use of Event-Based Traffic Controller Logs in Performance-Based Investment Programming. *Transportation Research Record*. 2015;2488(1):53-61. doi:10.3141/2488-06
33. FuelCells.org, Fuel Cell Basic Applications. 2011. Available at http://www.fuelcells.org/basics/apps.html.
34. Agnolucci, P., *Economics and market prospects of portable fuel cells.* International Journal of Hydrogen Energy, 2007. **32**(17): p. 4319-4328.

36. Sturt Usland Energy Initiative. Available from http://www.siei.org/.
37. FuelCells.org, Fuel Cell Basic Benefits. 2007. Available at http://www.fuelcells.org/basics/benefits.html.
38. Schmidt-Rohr, K., *Why Combustions Are Always Exothermic, Yielding About 418 kJ per Mole of O2.* Journal of Chemical Education, 2015. **92**(12): p. 2094-2099.
39. Fuel Cell & Hydrogen Energy Association, Traffic signals, railroads, and public safety. 2018. Available at http://www.fchea.org/in-transition/2018/12/17/traffic-signals-railroads-and-public-safety.
40. Hahn, E. Difference between LPG vs natural gas. 2019. Available at https://www.elgas.com.au/blog/486-comparison-lpg-natural-gas-propane-butane-methane-lng-cng.
41. Naturalgas.org, Natural gas and the environment. 2009. Available at https://www.elgas.com.au/blog/486-comparison-lpg-natural-gas-propane-butane-methane-lng-cng.
42. International Energy Agency, 2014 Key World Energy Statistics. Available at https://web.archive.org/web/20150405035039/http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf.
43. Onder, C. Clean engine vehicle. 2009, Institute for Dynamic Systems and Control, Available at https://web.archive.org/web/20150405035039/http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf.
44. Cunningham, M. What are natural gas generators? How Stuff Works.com. Available at https://auto.howstuffworks.com/fuel-efficiency/fuel-saving-devices/natural-gas-generator.htm.
45. Power Up Systems, PowerUp Traffic System. Available from https://www.poweruppowersystems.com/products/traffic-systems/.
46. Kohler 6VSG Specification Sheet. Available at http://www.kohlerpower.com/home/common/pdf/g4213.pdf.
47. Altergy Freedom Power System – Nacelle. Available at https://www.altergy.com/wp-content/uploads/2017/09/Altergy_Nacelle_Data_sheet_ATP_web.pdf.
48. Paris, W. Portable generators: Backup power at a lower cost. Hoselogic.com. Available at https://www.houselogic.com/finances-taxes/home-insurance/portable-generators-backup-power-at-a-lower-cost/.
49. Lesson, N.T. Weston takes hurricane precautions. *South Florida Sun Sentinel, sun-sentinel.com,* June 28, 2006. Available at https://www.sun-sentinel.com/news/fl-xpm-2006-06-28-0606260135-story.html.
50. Seltzer, A. Lessons from Wilma: How county got key stoplights running after Irma. *Palm Beach Post,* 2017. Available at https://www.palmbeachpost.com/news/local/lessons-from-wilma-how-county-got-key-stoplights-running-after-irma/LEDdbxyiq4xDAjJhUfQVoN/.
51. Masson, G., *Global Market Outlook: For Photovoltaics 2014-2018*, T. Rowe, Editor. 2018, European Photovoltaic Industry Association.
52. Khazaei, J., et al., *Real-time digital simulation-based modeling of a single-phase single-stage PV system.* Electric Power Systems Research, 2015. **123**: p. 85-91.

53. Tazay and Z. Miao, "Control of a Three-Phase Hybrid Converter for a PV Charging Station," in *IEEE Transactions on Energy Conversion*, vol. 33, no. 3, pp. 1002-1014, Sept. 2018, doi: 10.1109/TEC.2018.2812181.
54. ASTM International, Standard test methods for determining mechanical integrity of photovoltaic modules. ASTM E1830–15(2019). 2019, ASTM International.
55. US Department of Energy, Office of Energy Efficiency & Renewable Energy, Solar Photovoltaic Systems in Hurricanes and Other Severe Weather,energy.gov, DOE/GO-102018-5109, April 2018. Available at https://www.energy.gov/sites/default/files/2018/08/f55/pv_severe_weather.pdf.
56. Solar Electric Supply, I. Wholesale Solar Panels, Solar Systems & Supplies. 2019. Available from https://www.solarelectricsupply.com/.
57. Historical Weather Data. 2017-2019. Available from https://www.wunderground.com/.
58. Zientara, B. How much electricity does a solar panel produce? SolarReviews.com, 2018. Availbale at https://www.solarreviews.com/blog/how-much-electricity-does-a-solar-panel-produce.
59. TurbineGenerator.org. Florida Sunlight Hours & Renewable Energy Information. June 2019. Available from https://www.turbinegenerator.org/solar/florida/.
60. Sunmodule Bisun SW 325 XL Duo Data Sheet. 2019.
61. Spakovskis, R. SolaRoad: World's first solar cycle path to open in the Netherlands. phys.org, November, 2014. Available at https://phys.org/news/2014-11-solaroad-world-solar-path-netherlands.html.
62. Ryan, D. Solar panels replaced tarmac on a motorway. Here are the results.phys.org, 2018. Available at https://phys.org/news/2018-09-solar-panels-tarmac-motorwayhere-results.html.
63. John, J.S. Solar roadways prove expensive and inefficient. Greentechmedia.com, September, 2018. Available at https://www.greentechmedia.com/articles/read/solar-roadways-are-expensive-and-inefficient.
64. Graham, N.S. Hurricane Irma outages prompt solar powered light signals in Hillsborough. wusfnews.com, January, 2019. Available at https://wusfnews.wusf.usf.edu/transportation/2019-01-29/hurricane-irma-outages-prompt-solar-powered-light-signals-in-hillsborough.
65. Solar beacons to improve safety when traffic signals go dark. hillsboroughcounty.org, January, 2019. Available at https://www.hillsboroughcounty.org/en/newsroom/2019/01/11/solar-beacons-to-improve-safety-when-traffic-signals-go-dark.
66. Lipscomb, J. After hurricane outages, Miami-Dade could make traffic lights solar-powered. Miaminewtimes.com, November 2017. Available at https://www.miaminewtimes.com/news/after-hurricane-irma-outages-miami-dade-could-make-traffic-lights-solar-powered-9838151.
67. Gilpin, L. After the hurricane, solar kept Florida Homes and a city's traffic lights running. insideclimatenews.org, September 2017. Available at https://insideclimatenews.org/news/15092017/after-hurricane-irma-solar-florida-homes-power-gird-out-city-traffic-lights-running/.
68. Kudou, S. Toyota Industries charges fuel-cell forklifts with solar hydrogen. Material Handling Wholesaler Magazine, May, 2019. Available at

https://www.mhwmag.com/nuts-bolts/toyota-industries-charges-fuel-cell-forklifts-with-solar-hydrogen/
69. Fan, L. and Z. Miao, *Modeling and Analysis of Double Fed Induction Generator Wind Energy Systems*. 2015: Elsevier Press.
70. Fan, L. and Z. Miao, *Wind Energy Conversion Systems*. 2012: Springer.
71. Y. Li, L. Fan and Z. Miao, "Wind in Weak Grids: Low-Frequency Oscillations, Subsynchronous Oscillations, and Torsional Interactions," in *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 109-118, Jan. 2020, doi: 10.1109/TPWRS.2019.2924412.
72. L. Fan, "Modeling Type-4 Wind in Weak Grids," in *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 853-864, April 2019, doi: 10.1109/TSTE.2018.2849849.
73. Y. Li, L. Fan and Z. Miao, "Stability Control for Wind in Weak Grids," in *IEEE Transactions on Sustainable Energy*, vol. 10, no. 4, pp. 2094-2103, Oct. 2019, doi: 10.1109/TSTE.2018.2878745.
74. Evans, A., V. Strezov, and T.J. Evans, *Assessment of sustainability indicators for renewable energy technologies.* Renewable and Sustainable Energy Reviews, 2009. **13**(5): p. 1082-1088.
75. Canadian Wind Energy Association, Small Wind turbine purchasing guide, S.S. Schwartz, Editor. 2013, Canadian Wind Energy Association.
76. Zhao, M., Economic analysis of using a renewable wind power system at a signalized intersection. *Journal of Intelligent Transportation Systems*, **17**(3), 2013.
77. Qiao, W., A. Sharma, and J.L. Hudgins, Roadway *Wind/Solar Hybrid Power Generation and Distribution System: Toward Energy-Plus Roadways*. 2016, University of Nebraska–Lincoln.
78. AlphaGen ® DC Generator System, Alphagen datasheet, Alpha Technologies, Available at https://www.alpha.ca/solutions/products/generators/item/alphagen.

Appendices

Appendix A – Technology Comparison Matrix

Table 28. Comparison and Assessment of Backup Power Systems

Power Type		Solar+Battery		Battery	Hydrogen		Natural Gas (NG)/Liquid Propane (LPG)		
Vendors		First Solar	SunPower	Tesla	Ballard	Altergy	Kohler	Generac	PowerUp Power System
Model Number		Series 6TM	X21-Series	Powerwall 2	FCgen®-H2PM	FPS - 2.5 24/48N	6VSG	G006998-1	PowerUp Traffic System
Performance	Power per unit (kW)	0.45	0.34	5	1.7	2.5	6	6	6
	Voltage per unit (V)	DC 220	DC 57	AC 120/240	DC 48 to 55	DC 24V/48V	DC 24/36/48	AC 240	AC 240
	5 days Capacity Fuel Size	36 kWh Li-ion battery	36 kWh Li-ion battery	13.5 kWh*3	27 m3	40 m3	50m3(NG); 15gal(LPG)	50m3(NG); 15gal(LPG)	50m3(NG)
	Lifespan	10 years	10 years	10 years	7,000 hours	NA	NA	NA	NA
Installation	Ambient Temperature	-40°C to + 85°C	-40°C to + 85°C	–20°C to 50°C	-20°C to + 45°C	-40°C to + 50°C	NA	NA	NA
	Relative Humidity	NA	NA	Up to 100%	NA	5% to 95%	NA	NA	NA
	Location	Outdoor	Outdoor	Outdoor	Indoor or Outdoor	Indoor or Outdoor	Indoor or Outdoor	Indoor or Outdoor	Outdoor
	Per Unit Size (inch)	79 × 49 × 2	61.3 x 41.2 x 1.8	29.7 x 6.1 x 45.3	18 x 25 x 15	16 x 47 x 17	39.7 x 27.8 x 28.5	36 x 27 x 25	48 x 32 x 36
	Cost ($)*	$445	$565	$21,200	Varies	Varies	$5,625	$2,000	Varies
Operation	Blackstart	Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto
	Noise	Low	Low	< 40 dBA	62 dBA	60 dBA	62 dBA	NA	NA
	Clean	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Safety Concern	Less	Less	Less	More	More	Less	Less	Less
	Per kWh Cost ($)*	0	0	0.14	0.95	1.39	0.68(NG); 0.45(LPG)	0.68(NG); 0.45(LPG)	0.68(NG)
Maintenance	Maintenance Cycle	Annually	Annually	Annually	NA	NA	Weekly	every 200 hours or 2 years	NA
	Cost ($)*	NA	NA	NA	NA	NA	NA	NA	NA
	Warranty	10 years	10 years	10 years	NA	NA	5-year, 2000-hour	3 years	3 years

*Note: Approximately calculated numbers are for reference only; accurate prices cannot be evaluated unless with detailed design and installation.

Appendix B – Backup Power System Specifications

The following specifications are adopted from the current uninterrupted power supply (UPS) specifications used by the TERL and modified to cover a backup power system (BPS). As the BPS is a type of UPS, it is advisable to use the UPS specifications as a template. These specifications refer to two types of backup power systems (BPS): Backup system with generator and backup system with battery-solar.

B.1 General

BPS assemblies must be designed for installation in a roadside National Electrical Manufacturers Association (NEMA) 3R enclosure to provide backup functionality for traffic control systems, including traffic signal and intelligent transportation system (ITS) devices. BPS assemblies must include a power source provided by the BPS manufacturer or in accordance with manufacturer's requirements. Generators that are designed to be installed outdoors must be enclosed in similarly rated enclosures.

Loss of utility power, transfer from utility power to backup power, and transfer back to utility power must not interfere with normal operation of connected equipment. In the event of BPS failure or backup power source depletion, connected equipment must be energized automatically upon restoration of utility power or power provided by a renewable source, i.e., solar, or wind power.

Removal and replacement of the BPS must not disrupt the operation of the equipment connected.

All harnesses necessary to connect and operate the system must be included, and all connectors must be keyed and labeled to prevent improper connection.

B.1.1 Generator

The generator must operate in hot standby mode, with power transfer being accomplished in less than 40 milliseconds and without noticeable loss of power to the connected equipment. In case the generator cannot transfer power in such time, a secondary UPS must be used to provide power to the cabinet until the generator can transfer the load.

B.1.2 Battery-Solar System

The battery-solar system must operate in hot standby mode, with power transfer being accomplished in less than 40 milliseconds and without noticeable loss of power to the connected equipment.

B.2 Configuration and Management

A BPS must support local and remote configuration and management, including access to all user-programmable features as well as alarm monitoring, event logging, and diagnostic utilities.

Configuration and management functions must be password-protected.

Alarm function monitoring must include loss of utility power, inverter failure, low fuel (or battery), and temperature out of range.

The BPS must include a method such as an event log that indicates the date and time of events including AC high, AC low, AC frequency error, AC fail/blackout, and over temperature, and the BPS event log must be able to store a minimum of 60 events.

The BPS must include a front panel display and controls that allow programming of configurable parameters, features, and functions without the need for another input device. The BPS must have visual indications for Power-On, Mode of Operation (utility power or inverter), Fuel (or Battery) Status, Alarm Status, Load Levels, and AC Output Voltage.

B.3 Communication Interfaces

An Ethernet port (RJ45) must be provided for local control using a laptop PC and remote control via a network connection.

B.4 Fuels and Batteries

The BPS must be supplied with a wiring or tube harness for connections and allow six feet of separation between the BPS and its fuels tank (or battery bank). Terminals must include a protective covering to prevent accidental spark or shorting.

For other fuels or renewable source management, the BPS must have functions that include monitoring of remaining fuel level, status and rate of charge and discharge, and environment temperature.

B.4.1 Generators

Only the fuel recommended by the manufacturer should be used. Any internal batteries must be sealed and require no maintenance, cause no corrosion, and be capable of maintaining 80% of original capacity and performance for a minimum of 3 years.

B.4.2 Battery-Solar System

Batteries must be sealed and require no maintenance, cause no corrosion, and be capable of maintaining 80% of original capacity and performance for a minimum of 10 years.

A BPS with batteries must include battery management functions that includes active or equalized balancing, monitoring of temperature and voltage as well as amperage of charge and discharge, and temperature-compensated automatic charging to maximize the life of the batteries.

B.5 Electrical

BPS assemblies used to provide backup power in a traffic signal controller cabinet must provide a minimum of 400 watts (at 120 V_{AC}) of continuous power for a minimum of 72 hours unless otherwise shown in the plan. Upstream back feed voltage from the BPS must be less than 1 V_{AC}.

The BPS must be capable of simultaneously producing fully regenerated and regulated, conditioned, True Sine Wave power and hot standby AC output and have a minimum operating efficiency of 90%.

B.5.1 Generators

Frequency must be regulated to 60 Hz, plus or minus 0.5 Hz, while the BPS is supplying power. The BPS must operate on 85 to 140 V_{AC} without transitioning to batteries. If the generator is not able to provide this frequency and acceptable deviation, a power conditioning device may be used to achieve the desired outcome.

B.5.2 Battery-Solar Systems

Frequency must be regulated to 60 Hz, plus or minus 0.5 Hz, while the BPS is supplying power. The BPS must operate on 85 to 140 V_{AC} without requiring generator assistance.

B.6 BPS Cabinet

B.6.1 Generators

All parts of the generator assembly including the fuel tank must be rated for outdoor installation and can be used without additional enclosures.

The fuel tank must be mounted on the ground on a concrete slab with the same specifications as the traffic cabinet. The generator must include a main breaker.

The generator must include an automatic transfer switch to automatically transfer power from utility to generator upon loss of utility power.

B.6.2 Battery-Solar Systems

The battery-solar system must be housed inside a cabinet. BPS assemblies (and cabinets) must be designed to be mounted to the side of a traffic cabinet or base-mounted. Cabinets must meet the requirements of Section 676 and must include shelves and rack rails to house all BPS system components, including the BPS, batteries, harnesses, switches, surge protective device, power terminal block, and a generator hookup with transfer switch. The BPS cabinet must allow a maintenance technician to safely insert power for traffic signal operation while the BPS or associated equipment is being serviced or replaced.

A surge protective device must be installed where the supply circuit enters the cabinet in accordance with Section 620-2.7.1.

The cabinet must include a main breaker and must include an automatic transfer switch unless the transfer switch is part of the BPS.

B.7 Mechanical

All parts of the BPS must be made of corrosion-resistant materials such as plastic, stainless steel, anodized aluminum, brass, or gold-plated metal. All fasteners exposed to the elements must be Type 304 or 316 passivated stainless steel.

B.8 Environmental

Battery-solar BPS assemblies, including batteries, must provide continuous power with specified wattage and must operate properly during and after being subjected to the environmental testing procedures described in NEMA TS 2, Sections 2.2.7, 2.2.8, and 2.2.9.

B.9 Installation

BPS assemblies must be installed in accordance with the manufacturer's recommendations. All equipment used to keep the intersection signalized must be backed up and protected by the BPS.

A BPS operation and maintenance manual that includes cabinet wiring schematics, electrical interconnection drawings, parts layout and parts lists must be included in the cabinet where the BPS is installed.

B.9.1 Installation Requirements

B.9.1.1 Controller Cabinets

The controller cabinet must meet the requirements of Section 676.

B.9.1.2 Field Wiring

Field wiring of the BPS must meet the requirements of Sections 632 and 676.

B.9.1.3 Grounding

Grounding of the BPS must meet the requirements of Sections 620 and 676.

B.9.1.4 Equipment Placement

All equipment in the cabinet must be installed in accordance with the manufacturer's recommendations.

B.10 Testing

A field acceptance test plan must be provided to the Engineer for approval at least 10 days prior to commencement of testing. After approval of the plan, testing of the installed BPS equipment must be conducted, and all equipment, software, and supplies necessary for conducting the test must be furnished.

B.11 Warranty

The BPS must include a manufacturer's warranty covering defects for a minimum of 10 years from the date of final acceptance in accordance with Section 608. The warranty must include provisions for providing a replacement BPS within 10 calendar days of notification for any BPS found to be defective during the warranty period at no cost to FDOT or the maintaining agency.

B.12 Method of Measurement

The contract unit price for each BPS will include furnishing, placement, and testing of all equipment and materials as specified in the Contract Documents and all tools, labor, operational software packages and firmware, supplies, support, documentation (including the field acceptance test plan), and incidentals necessary for a complete and accepted installation.

B.13 Basis of Payment

Price and payment will be full compensation for all work specified in Section XXX*. Payment for each will be made under:

- Item No. XXX*-1 – Backup Power System
- Item No. XXX*-2 – Remote Power Management Unit.

** The final section number for this specification will replace XXX.*

Appendix C – Recommended Test Procedure

Based on the testing procedure the CUTR team followed during Task 3, a generic testing procedure is proposed for testing a BPS, including device preparation, device connections, data monitoring, and data analysis.

C.1 Device Preparation

The vendor should complete all pretest work, including electrical preparation and installation of the system.

C.1.1 Electrical Preparation

The BPS can be tested using an actual traffic signal cabinet or a simulated load to the desired level. The specification requires 400W of continuous power for 72 hours. If the power load used for testing differs (higher or lower) the length of time needs to be adjusted according to data in Section C.3.

C.1.1.1 Traffic System Voltage Identification

The output of the voltage type must be determined for testing. Generally, the voltage level is 120 V for an AC system. If the traffic cabinet system can be powered with DC voltage, additional AC/DC or DC/DC converter might be required.

C.1.1.2 Output Voltage Quality

The output voltage of the BPS should be pre-tested to check the voltage quality. Figure 65 shows an example of measured sine wave voltage from a generator compared with grid utility voltage sine wave, which has little variation in frequency. Per specifications described in Section C.5, the output voltage should be measured and compared with a standard sine wave. Additional equipment such as a voltage filter or conditioner should be used to meet the specifications. For electric requirements, refer to 685-2.2.4, Electrical in *FDOT Standard Specifications for Road and Bridge Construction* manual.

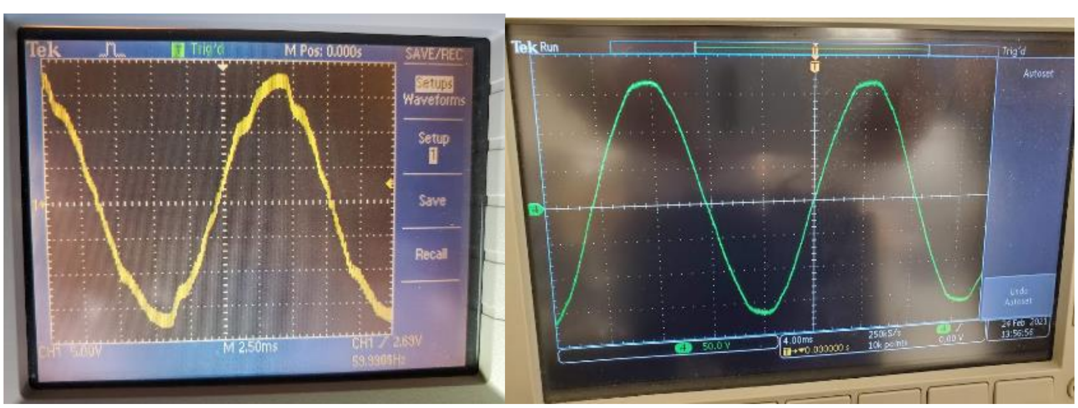


Figure 65. Example of Oscilloscope-measured propane generator output AC voltage (*left*) vs. utility AC voltage (*right*)

C.1.2 Installation

The BPS and all component installation should be based on the manufacturer's certified drawings and instructions.

C.1.2.1 Controller Cabinets

If a cabinet is required for the BPS, the cabinet must meet the requirements of Section 676.

C.1.2.2 Field Wiring

Field wiring of the BPS must meet the requirements of Sections 632 and 676.

C.1.2.3 Grounding

Grounding of the BPS must meet the requirements of Sections 620 and 676.

C.1.2.4 Equipment Placement

All equipment in the cabinet must be installed in accordance with the manufacturer's recommendations.

C.1.2.5 Bursting

Regarding the bursting and flammable fuel storage, the pipeline must be installed in accordance with the manufacturer's written instructions. Bursting should be limited to vitrified clay or concrete cross drain or side drainpipe having no lateral connections or risers and to locations where no part of the host pipe passes within 5 ft of any buried utility or pavement base material.

C.1.2.6 Structure for Solar Panels

The structure that will support the solar panels must meet specifications in the Section and Standard Plans, Index 695-2.4. The panels should be mounted and oriented to the south and angled in accordance with Standard Plans, Index 695-001.

C.2 Device Connection and Data Monitoring

C.2.1 Device Connection

The BPS should be properly connected to the traffic control cabinet or simulated load, including a method to stop utility power from reaching the traffic cabinet so the automatic transfer of power can be observed. All devices supported in the cabinet must be checked for proper operation after the power is transferred to the BPS.

C.2.2 Data Loggers

Data loggers can be used to collect the testing data for analysis. If the BPS does not have an integrated data monitoring system, an additional voltage logger and current logger should be connected to cabinet terminals to collect data during the test. Data loggers should be able to collect at least 4 days of voltage and current magnitude data continuously at a minimum 30 sec sampling interval. Figure 66 gives the AC power meter placement for the 120 VAC system.

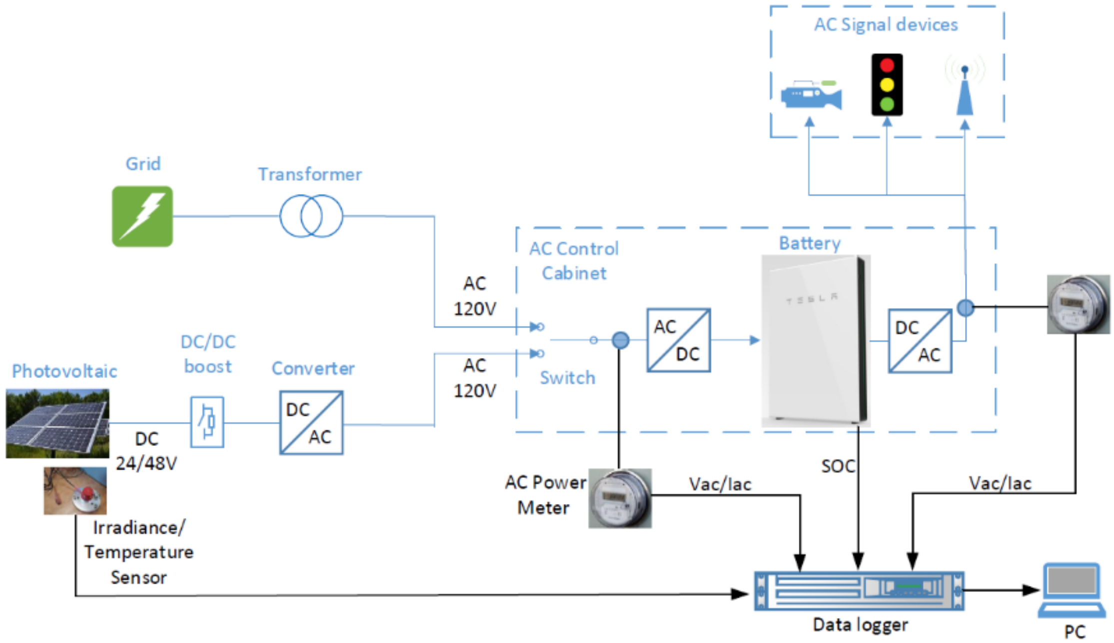


Figure 66. Recommendation of 120 VAC system assembly and data logger connection

C.2.3 Additional Data

Weather data, e.g., sunshine irradiance, should be recorded if solar panels are adopted as the power generation for the BPS. This can be achieved either via a solar irradiance meter or can be accessed via online portals such as https://solcast.com/.

Additionally, temperature and video monitoring are recommended to be recorded. Temperature fluctuations might have influence on BPS performance, and video records can be used to cross-check the intersection signal lights working condition.

C.3 Data Analysis

After the test, the collected data is analyzed to evaluate the BPS performance. The following should be examined.

C.3.1 Power Computation and Plotting

Total traffic system power consumption can be calculated via the voltage and current measurement from data loggers or monitoring system. Figure 68 shows an AC power computing example carried out from voltage and current measurement data in Figure 67.

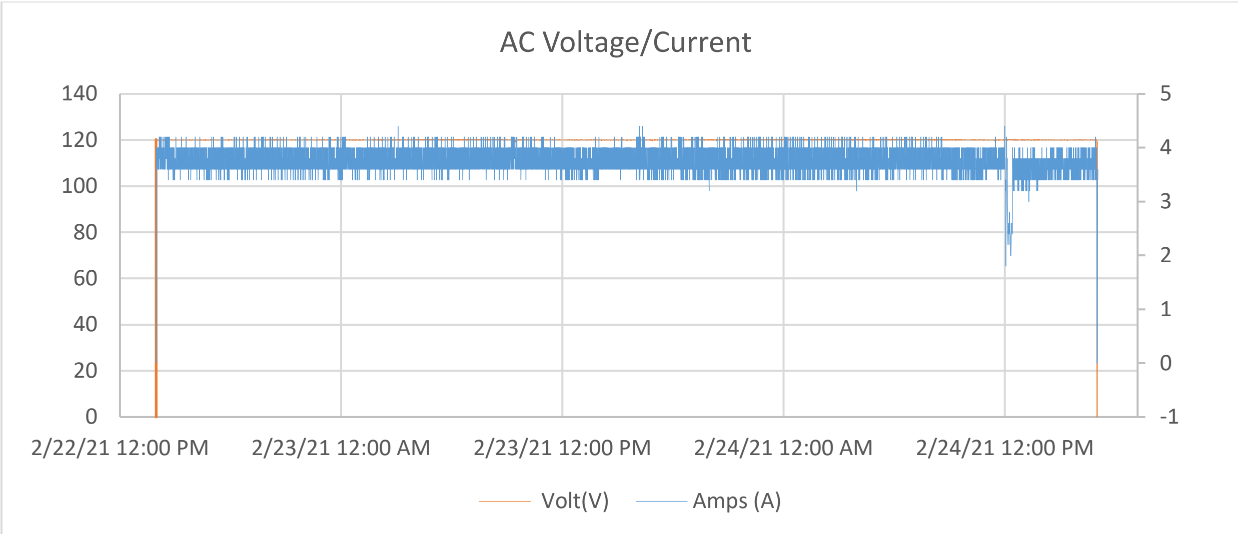


Figure 67. AC voltage/current logger collected data in propane generator test

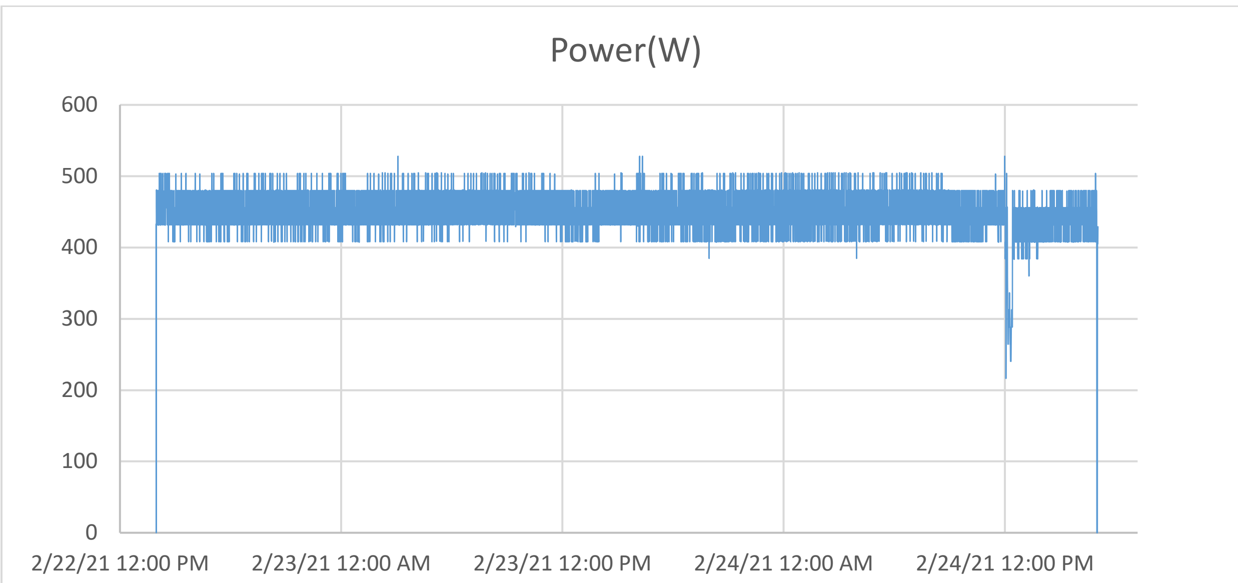


Figure 68. Computed power in propane generator test

With the computed power data, the traffic system working condition can be identified based on the power estimation. Figure 69 shows the operation condition evaluation strategy to identify TERL's test intersection working mode.

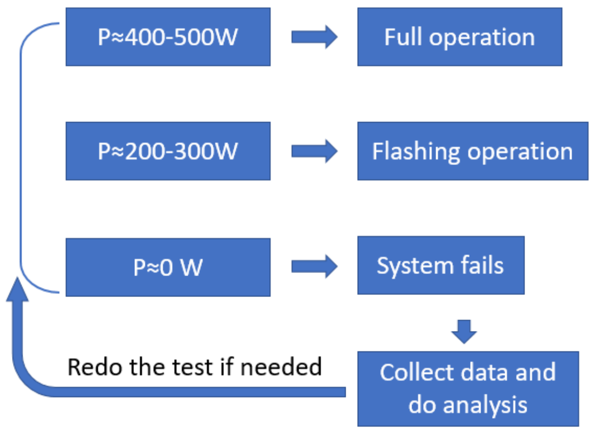


Figure 69. Operation condition evaluation flowchart

C.3.2 Backup System Capacity Analysis

C.3.2.1 Fuel Consumption Rate

The collected data should be able to show the fuel consumption process during the test. This will be compared to the specified consumption from the manufacturer. For example, Figure 70 shows the propane fuel level during the test. The fuel consumption is in a linear relationship with time, and the total generator running time was 51 hours. Thus, the propane generator used 0.87 gal/hr when supporting the traffic signal system.

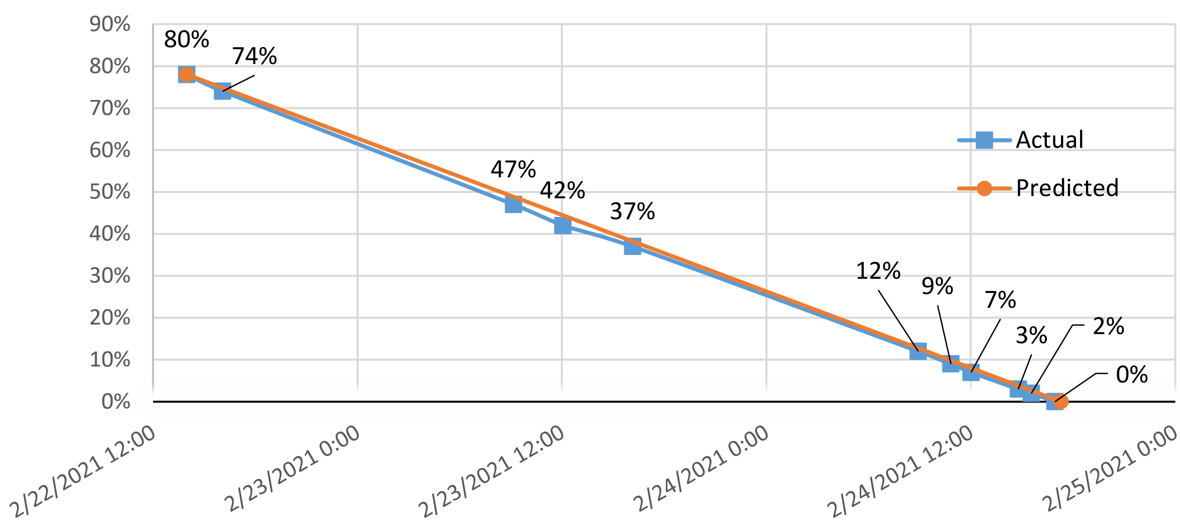


Figure 70. Propane fuel comsumption during test

C.3.2.2 Runtime Estimation

There may be many combinations when selecting the backup system generation and storage equipment. For example, battery + solar system performance depends on the number of solar panels and battery capacity. Therefore, the estimated runtime should be listed under different combinations for the tested backup power system. Table 29 and Table 30 provide an example of combinations of solar panels and battery capacity with runtime. Also, the solar generation power and capacity are estimated using one particular weather condition, but testing needs to confirm a few conditions such as full sun, partly cloudy and rainy conditions.

Table 29. Runtime Regarding Different Batteries and Loads

Battery	0.45 kW load	0.34 kW load	0.22 kW load
10 kWh	20 hrs	24 hrs	36 hrs*
15 kWh	30 hrs*	36 hrs*	44 hrs*
20 kWh	40 hrs*	48 hrs*	72 hrs*

*Estimate

Table 30. Solar Generation Power and Capacity Based on 07/06/2021 Irradiance

Panel Number	Max Solar Power	1-day Generation	% of 10 kWh Battery
PV x 8	3.2 kW	10 kWh	100
PV x 6	2.4 kW*	7.5 kWh*	75*
PV x 4	1.6 kW*	5 kWh*	50*
PV x 2	0.8 kW*	2.5 kWh*	25*

*Estimate

C.4 Summary

The testing procedure for the BPS requires a series of steps outlined in previous sections of this appendix. The system must be installed following the manufacturer's instructions and connected to the traffic cabinet or load to test its efficacy. The system must be able to provide continuous power to the traffic cabinet or load for 72 hrs for normal operation. If the BPS cannot provide the required runtime, it can be tested for flashing operation which requires less power. Ultimately, the system must meet all specifications and runtime/capacity requirements to pass the test.