This work illustrates recent advances by the authors in the field. The main contribution is a novel approach for the definition and assessment of resilience of FPI systems, based on three pillars: 1) a real-time multiscale numerical model of the infrastructure at the system scale level, 2) remote and in situ sensing strategies for the acquisition of relevant data on the state of the FPI, and 3) risk and resilience metrics for the operational management of the systems under normal and extreme conditions. These three will be described in the following sections, highlighting their complementarity and the connection between them, as depicted in Figure 1.

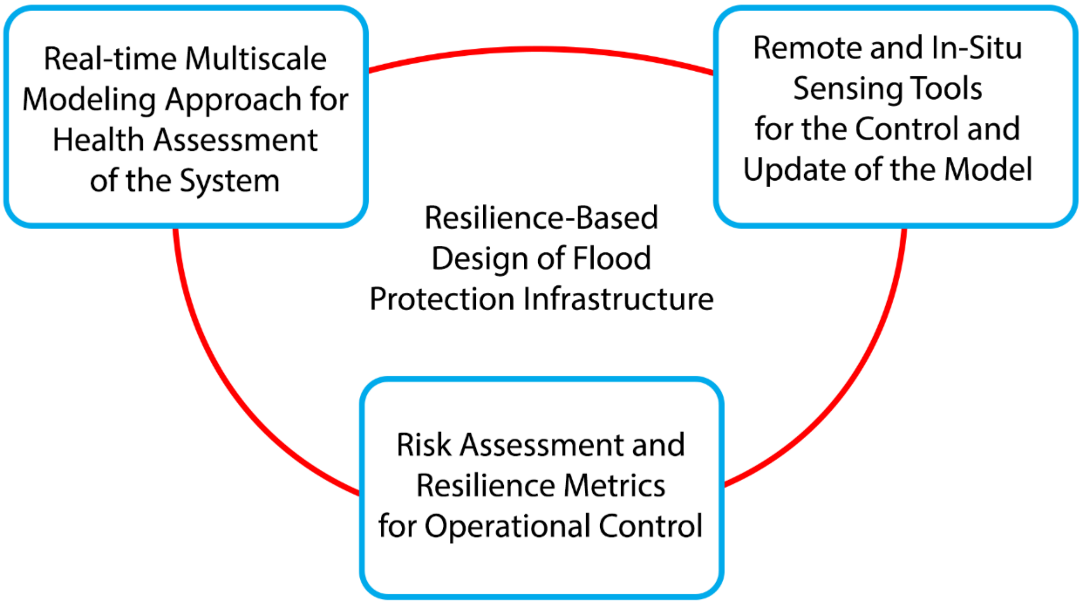

Figure 1 – Proposed resilience-based approach for FPI (Source: author)

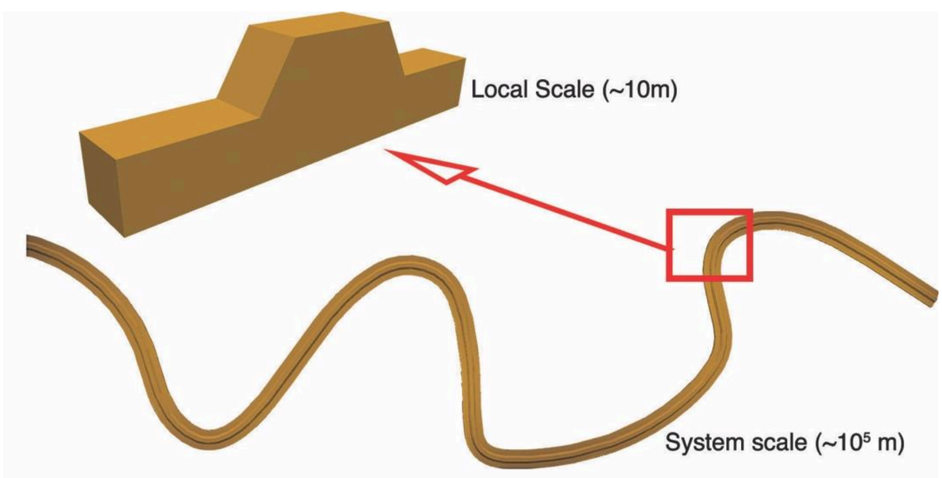

Figure 2 – Multiscale approach for the numerical simulation of FPI (source: author)

MULTISCALE MODELING FOR THE SIMULATION OF REGIONAL-SCALE INFRASTRUCTURE SYSTEM

The physical processes degrading the FPI network are inherently multiscale, as they involve different length and time scales. Internal erosion and localized damage, in fact, happen at the scale of the soil constituents (~10^1 mm scale). On the other end, when assessing infrastructure resilience, it is important to have information on the structural level of the systems (~10^7-10^8 mm scale) to be able to make science-based meaningful decisions (see Figure 2). It is then clear how multiscale techniques assume a predominant role, especially when paired with Machine Learning (ML) approaches for fast and accurate prediction of the state of the infrastructure (Fascetti and Oskay 2019b). Recently developed physics-based models (Fascetti and Oskay 2019a) can describe the progression of degradation mechanisms in the FPI (see Fig. 3). This techniques allow for a deeper understanding of the mechanisms that lead to the loss of stability in the FPI, especially in view of the massive size of the systems that lead to tremendous difficulties in performing full scale experimental tests.

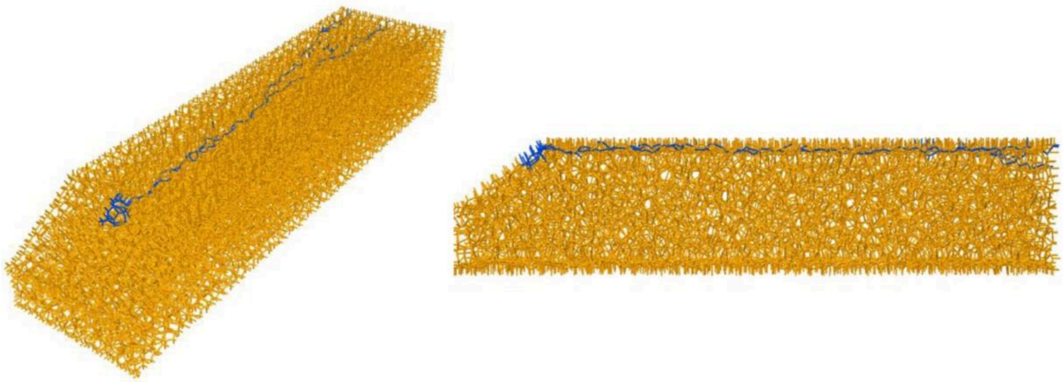

Figure 3 – Local scale physics-based modelling of erosion in FPI (source: author)

These simulations, however, are too computationally expensive to be executed at the system scale, so that properly designed multiscale techniques must be employed to allow for meaningful predictions in a timeframe compatible with decision-making strategies for the systems in exam.

Recent advances in ML algorithms opened up tremendous possibilities for the modeling and simulation of civil engineering structures of massive size. Data-assisted machine learning based simulations allow for real-time solution of the mechanical problem over the entire length of the infrastructure without compromising the accuracy of the results or the rigorous description of the underlying physics. For a full description of this model, the reader can refer to Fascetti and Oskay 2019b.

REMOTE SENSING FOR SYSTEM CHARACTERIZATION

One of the biggest challenges in performing numerical simulations of the FPI is the level of variability of the system across its length. Due to the massive size of the infrastructure, in fact, the level of uncertainties linked to the characterization of the materials and the geometry of the system represents the biggest source of error in the numerical models. Moreover, the need for real-time (or quasi real-time) assessment capabilities is of vital importance, as decision-makers require prompt guidance in the event of natural hazards. Difficulties with both these aspects can be mitigated by the introduction of remote sensing techniques that allow for fast and accurate measurements to complement the information obtained from the numerical models.

Recent advances in Unmanned Aerial Vehicles (UAVs) (Colomina and Molina 2014) and three-dimensional reconstruction of solid objects (Antonarakis et al. 2008) can be exploited to perform accurate sensing of civil systems. The main advantages of using these techniques for the remote sensing of FPI are: 1) the relative easiness in inspecting inaccessible portions of the system (e.g. the upstream side of a river levee), and 2) the lower cost associated with the operations when compared to standard inspections.

The most two common techniques for the UAV digital reconstruction of civil engineering systems are photogrammetry and Lidar-based scans. While the first uses information obtained from a set of sequential oriented images, the second uses information from a rotating laser beam that continuously evaluates distances from the sensor at a 360 degrees angle. Fig. 4 shows the 3-dimensional reconstruction of a portion of the Nashville Metro Levee system performed by the authors. It is worth noticing that in this specific application, there is an additional advantage derived from the usage of LiDAR scans, which lies in the capability of penetrating short vegetation (like the one usually present on the unprotected side of the levees) that allows for a better definition of the geometry of the system (see Figure 4).

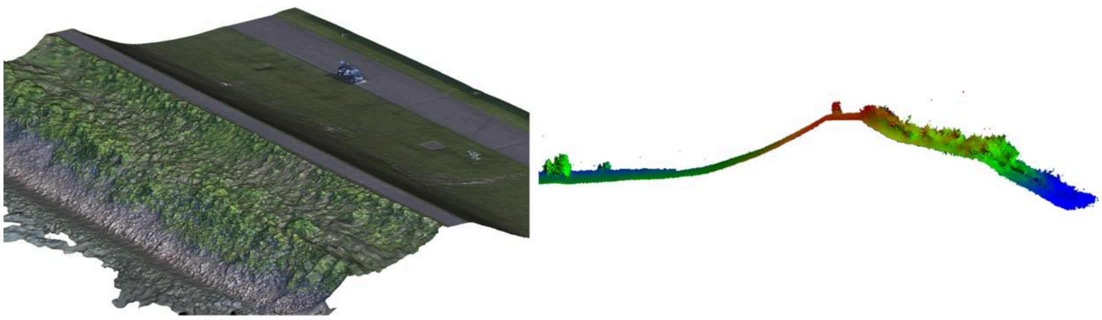

Figure 4 – Digital reconstruction of a portion of the Nashville Metro Levee System by photogrammetry (left) and Lidar (right) (source: author)

RESILIENCE FRAMEWORK

Resilience is defined as the ability of a system or unit to mitigate extreme events, contain the effects of natural hazards and complete recovery activities with minimal disruption of service (Bruneau et al 2003). FPI resilience is achieved by increasing the capability of the system to withstand flooding events, provide safe and accessible emergency response routes and minimize the difficulties linked with the recovery of functionality.

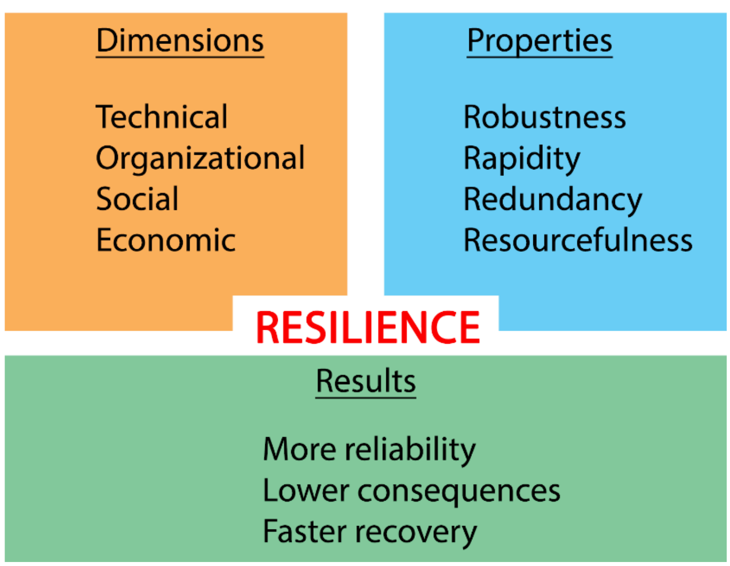

Figure 5 – Graphical interpretation of resilience (source: author)

Resilience is a measurable quantity: given a set of performance measures (e.g. the safety factor against a defined failure mode), the actual or potential performance of the infrastructure can be evaluated as a point in the n-dimensional space of the performance parameters. The change in performance with respect to time can happen gradually (i.e. degradation of the system due to the environmental and aging effects) or abruptly (i.e. in response of an extreme event such as a flooding). Whenever the system's performance falls under a given threshold, resources are needed in order to restore the functionality of the system. Resilience can be defined as the capability of the system to deliver functionality over a given time interval and to recover quickly after a loss of functionality. Figure 5 shows a graphical interpretation of all the factors influencing the resilience of FPI. Different levels of expertise are required in the design and maintenance of the infrastructure (resilience "dimensions"), to guarantee the required characteristics (resilience "properties"). This results in a more reliable system that can absorb damage from extreme events better and allows for faster functionality recover.

CASE STUDY

The proposed framework is demonstrated in a case study regarding the portion of FPI protecting the Nashville Metro area. This infrastructure provides protection to the whole Nashville Metro Area (approximately 2 million people) and is susceptible to failure as testified by the catastrophic flooding event that struck the city in 2010 (Moore et al. 2012, Nashville Metro Water Services 2013, Nashville Area Metropolitan Planning Organization 2015), which resulted in twenty-six fatalities, 10,000 people displaced from their homes and more than $2 billion in private property damage. In view of the susceptibility of the system to flooding events, a window of twelve months was investigated and the response of the system was analysed by the previously described resilience framework. The values of the water height were obtained from the USGS National Water Information System (Goodall et al. 2008).

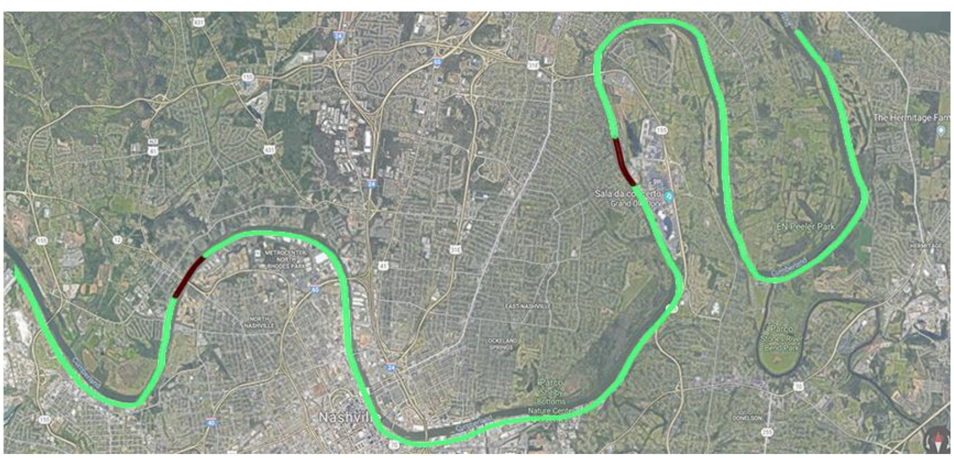

Figure 6 – Result of the proposed resilience assessment for the Nashville Metro Levee System for a fictional scenario (source: author)

The main advantage of using the proposed approach lies in the possibility of testing different scenarios for the system in exam, identifying possible weakness and criticalities in the system, and therefore guiding stakeholders and decision-makers in the design of optimized maintenance schedules.

Figure 6 shows the results for scenario according to which a triggering local damage is discovered in two portion of the levee and consequently the risk associated with the failure of the system in the area is increased.

CONCLUSIONS

A new paradigm in the design and operation of FPI is needed to improve their resilience, operativity and life cycle. Resilience metrics must be incorporated in the definition of these paradigm, together with deeper understanding of the behaviour of the system as a whole. The latter aspect is obtained through a multiscale computational mechanics description of the system, that allows for a level of detail compatible with the assessment of the risk associated to the failure of the infrastructure, while the former cannot prescind from a rigorous evaluation of the risk levels associated with the failure of the systems. A real-life case study is herein presented, where a large portion of the Nashville Metro Levee System was assessed at the structural level and the probability of failure was computed for the whole structure in an accurate and computationally efficient fashion. This information, when coupled with the associated risk, can open up tremendous possibilities for the improvement of current practices in FPI design, operation and maintenance.

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Solar and Energy Storage: Los Angeles Beacon Project Case Study

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ABSTRACT

The next stage of energy infrastructure consists of renewable resources combined with energy storage. With the approval of SB 100, California aims to go carbon free energy generation by 2045 utilizing renewable sources for the majority of its energy demand. Solar and energy storage technologies have emerged in response to that need. Energy storage is necessary to convert the natural variability of solar into a dispatchable resource that mimics conventional fossil generation. The expanding use of energy storage marks a paradigm shift in energy infrastructure and presents a promising transition to a high renewable electric grid. Beacon Solar and Battery Energy Storage Project is the first of its kind for Los Angeles. With 250 megawatts of generation capacity, it is one of the largest solar facilities used by the city. The 20 megawatt storage component is the city's first utility-scale battery system. With new technology also came challenges in integration, operation, and safety. This case study examines the purpose of this joint facility in the context of LA's 100% renewable energy target and alignment with ASCE's policy statements on energy, technology, business, and the environment.

INTRODUCTION

The Beacon Solar and Battery Energy Storage Project (Beacon Solar + BESS) is comprised of a 250 megawatt (MW) solar photovoltaic (PV) system combined with a 20 megawatt – 10 megawatt-hour (MWh) battery energy storage system (BESS). The solar system can power approximately 250,000 homes during peak solar hours while the battery system provides backup power as well as other supporting features for the solar facility. The project is located in Kern County, approximately 105 miles from Downtown Los Angeles. The completed facility went into full commercial operation October 2018. The project represents hundreds of millions of dollars of investment by the Los Angeles Department of Water and Power (LADWP) into clean energy resources.

The project went into development in 2014 in response to the growing Renewable Energy Portfolio Standards (RPS) developed by the state of California (Grid Planning and Development System Studies and Research Group, 2014). The first renewable goal was to reach 20% of retail sales generated by renewable sources by 2013 and 25% by 2016. Beacon Solar, along with its neighboring projects, constitutes upwards of 21% of that target. Studies by LADWP's Integrated Resource Plan and industry experts recommended the utilization of advanced technologies for increased renewable penetration. One such technology was battery energy storage systems. The BESS component of the project was developed in response to a growing need for integration technology to complement the growth of intermittent renewable resources.

Los Angeles strives for high renewable penetration to meet its climate action goals (Mayor's Sustainability Team, 2018). The City is currently examining what investments are required to reach a 100% clean grid, a two-fold challenge to identify large quantities of low cost renewable energy sources while accounting for a growing electricity demand. In 2017, Los Angeles had a peak load of 6,431 MW with a projected growth in average energy consumption of 22,506 MWh per year in 2020 (Integrated Resource Planning, 2017). This demand will result in the need for dozens of renewable energy generation sources and energy storage projects in the coming years.

EXISTING INFRASTRUCTURE

LADWP invested millions of dollars and years of development into the Barren Ridge Corridor which represents its primary "local" renewable hub. The corridor has a combined renewable power capacity of over 700 MW and provides 7.9% of the city's annual energy supply and 21% of its renewable energy portfolio. The corridor comprises the Pine Tree Wind hydropower facility generated by LA's aqueduct system, Pine Tree Solar, Springbok 1&2 Solar, RE Cinco Solar, Beacon Solar, and hundreds more megawatts of planned renewable projects. The system consists of hundreds of miles of transmission assets and substations. All the projects are connected via a 230 kilovolt (kV) transmission line across the Barren Ridge substation and Haskell switching station.

The Beacon Solar + BESS facility is comprised by the Beacon substation, transmission, solar, and BESS systems. The land, nearly 2,300 acres, is owned and managed by the City of Los Angeles. The PV system was constructed and is operated by a third party procured through Power Purchase Agreements (PPAs). The substation and access roads were designed and constructed by LADWP, and the BESS was developed through a public/private partnership.

The Beacon substation receives solar energy from five sub solar facilities at 34.5 kV and steps it up to 230 kV before transmitting it into the grid through the Barren Ridge Haskell transmission line. It also accepts solar from Springbok 1&2 at 230 kV. The substation was constructed according to design criteria found in ASCE 7-10. The transmission lines are held through monopole and A-Frame structures constructed with deep pile foundation. The substation consists of a control house, circuit breakers, switches, transformers, and communication systems.

BEACON SOLAR + BESS

The Beacon Solar Plant spans over 2,300 acres and has five individual solar array sites within the complex. The solar PV systems are comprised of nearly 1 million individual solar panels installed at the sites within the plant, mounted on single axis tracking systems. Each single axis tracker is oriented on a north-south axis, allowing the solar panels, composed of several PV modules strung together into individual electrical circuits, to track the sun from the east to the west during the course of the day.

Solar PV modules are direct current (DC) devices, and as such, the DC circuits must interface into inverters which convert the DC to alternating current (AC). The Beacon Solar Plant utilizes nearly 200 DC-AC inverters and step-up electrical transformers to raise the output voltage of the inverters to the medium voltage (MV) AC feeder circuits feeding into the Beacon substation at 34.5 kV.

The five sites within the Beacon Solar Plant were developed through a Power Purchase Agreement (PPA) and corresponding site Lease Agreement between each developer and LADWP. The solar developers were responsible for the design and installation of the solar power equipment, and LADWP was responsible for site development, design engineering and construction of the civil and electrical infrastructure, 34.5 kV/230kV step-up substation, and the 230kV transmission line necessary to connect the solar plant to LADWP's transmission network. In this public-private partnership, LADWP owns and operates the overall facility, managing and dispatching solar renewable energy, while each of the five individual solar sites are maintained and operated by the solar developers, sPower and Capital Dynamics. Each site ranges from 40 to 56 MW in capacity.

The battery energy storage system (BESS) was also a public-private partnership between LADWP and its BESS contractor, a joint endeavor between KTY Engineering and Doosan Gridtech. The BESS was added to the solar power plant scope in order to better utilize the renewable energy generated by the plant, and to address other electrical, transmission, and power supply issues facing LADWP as a result of natural gas curtailments and the effects of increasing amounts of renewable energy generation capacity in the system during the day.

The Beacon BESS concept was developed in 2016 in response to California Assembly Bill AB 2514 and the need for more energy storage systems to compliment variable renewable energy sources. Traditional generators can modulate their output according the energy demand. Because of how power is transmitted and the 60 Hz requirement on the grid, instantaneous power produced must equal instantaneous power consumed.

Energy storage systems in the past consisted of either large pumped hydro facilities such as LADWP's Castaic Hydro-electric Generating facility or systems that store energy in short periods such as capacitors. Emerging technologies such as batteries presents a middle ground between large scale storage systems of pumped hydro and rapid but short duration capacitors. Batteries function well to firm and shape variable resources such as wind and solar so that they may act more similarly to dispatchable resources such as coal and natural gas thermal generators.

Through years of feasibility development and a comprehensive specification and competitive bid, Doosan and KTY were selected to collaborate with LADWP to install the city's first grid-scale BESS. Like the Beacon Solar Plant, the added BESS work was bifurcated, with LADWP responsible for site development, underground electrical 34.5 kV feeder cable, structural foundations, site drainage and grounding. Doosan and KTY were responsible for the procurement, system integration, logic and controls, auxiliary power and cooling, and warranties and performance guarantees in a turnkey agreement with LADWP. Doosan and KTY designed the packaging of the battery enclosure and the balance of plant system comprising of battery cabinets, air conditioning system, control system, training plan, and initial maintenance and operation. LADWP, Doosan, and KTY collaborated on aspects such as system protection and controls.

The combined Beacon Solar + BESS can be considered an alternating current (AC) Coupled System utilizing lithium ion battery technology. Key aspects of the BESS include a backup diesel generator as backup auxiliary power, harmonic-rated transformers, an alternating current to direct current (AC-DC) bi-directional inverter (Power Control System, or, PCS), a redundant cooling system necessary for maintaining optimal operation of the batteries, and a fire suppression system necessary to protect the battery stacks and the enclosures for safety. The facility is directly controlled by LADWP's Energy Control Center (ECC), monitored for performance guarantees and warranties by Doosan and KTY, and communicates and is controlled on modular energy system architecture (MESA) open standard communication protocol.

The BESS offers many services that complement the operation of the solar facility. These include: load following, frequency control, reactive support, real power support, and voltage support. Two immediate use cases for the battery include saving solar energy during excess generation (periods when there is more solar generation than energy demand) and saving that energy for later in the day when solar resources are down. Another high value use of the BESS is for frequency control where the BESS rapidly injects and absorbs energy to help maintain the grid at 60 Hz frequency. The 60 Hz ensures that all loads connected to the grid is getting proper power quality. Many devices such as clocks and other sensitive equipment cannot function properly if the frequency were to deviate from 60 Hz. Additional use cases include voltage support with reactive power that is discussed in Appendix A.

Figure 1: Beacon Solar and Battery Energy Storage System

ASCE POLICY STATEMENTS

It is important to note that this project falls in line with ASCE's policy statements on energy, resiliency, new technology, and climate change. The projects also present a new way of viewing renewable resources for a resilient and reliable grid, exemplifying what it means to construct sustainable infrastructure. Beacon Solar + BESS aligns with several ASCE policy statements, notably:

Electric Transmission and Generation

The project provides the physical infrastructure for the generation and transmission of electrical energy for public consumption.

Innovation and New Technology

Beacon Solar + BESS utilizes emerging technology, recognizing LA's role as a leader in the energy industry. The battery system is a new technology that the LADWP has invested in for the purpose of integrating renewables. The joint venture serves as a means to learn how to integrate this technology into regular practice. For example, Lithium Ion Batteries pose serious fire risks and LADWP developed new protocols to mitigate and manage this risk, thereby ensuring the safety and proper handling of a new technology.

Public Private Partnership

LADWP utilized public private partnerships to successfully bring the Beacon Solar + BESS system online. Although the land, infrastructure, electrical station, roads, and site improvements