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Transforming a National Historic Landmark Into a Green Nanogrid

CROWN HALL COURTESY OF WIKIMEDIA COMMONS/JOE RAWI. ELECTRICITY—iSHUTTERSTOCK/MUTUS

The case of Crown Hall.

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R. CROWN HALL, DEPICTED IN FIGURE 1, LOCATED AT 3360 South State Street, Chicago, Illinois, on the main campus of the Illinois Institute of Technology (IIT), is home to the College of Architecture. Crown Hall is a modern masterpiece that *Time* magazine called, “one of the world’s most influential, inspiring and astonishing structures.” Designed by Ludwig Mies van der Rohe in 1956, Crown Hall cohesively represents his architectural concepts and theories in their most complete and mature form. Crown Hall is a straightforward expression of construction and materiality, allowing the

structure to transcend into art. Its refinement and innovation place Crown Hall among the most distinguished buildings of its age and define its importance in the history of architecture. Crown Hall was granted National Historic Landmark status in 2001 by the National Park Service, U.S. Department of the Interior. Crown Hall was last restored in 2005 by the architects Mark Sexton and Gunny Harboe, who led the multimillion dollar restoration project of this landmark building.

Just as the Crown Hall restoration marvelously preserved the architectural beauty of this National Historic Landmark, the introduction of renewable energy and energy storage technologies to this building have elevated its stature as an energy efficient landmark in the city of Chicago. With the generous support from the U.S. Department of Energy (DOE), the Illinois Clean Energy Community Fund (ICECF), Commonwealth Edison (ComEd), the Center for Smart Grid Applications, Research, and Technology at IIT, and Willdan Energy, the university acquired and installed in 2019 a photovoltaic (PV) system and a battery energy storage system (BESS) in Crown Hall. The PV system and BESS, which converted Crown Hall to a nanogrid (henceforth termed the *Crown Hall nanogrid*), are also used to analyze and demonstrate the benefits of

supplying clean energy that can enhance the economics, reliability, resilience, sustainability, and security of a national landmark. The PV and BESS components at Crown Hall, together with their associated control relays, software, and modifications to the building's electrical distribution system, make the building a stand-alone nanogrid. Crown Hall is part of the campus microgrid at IIT (henceforth termed the *IIT microgrid*). The IIT microgrid encompasses 35 buildings, which are divided into seven high-reliability electrical loops, as depicted in Figure 2. Crown Hall (circled in red) is located in Loop 5.



Figure 1. The Illinois Institute of Technology's (IIT) S.R. Crown Hall (a National Historic Landmark).

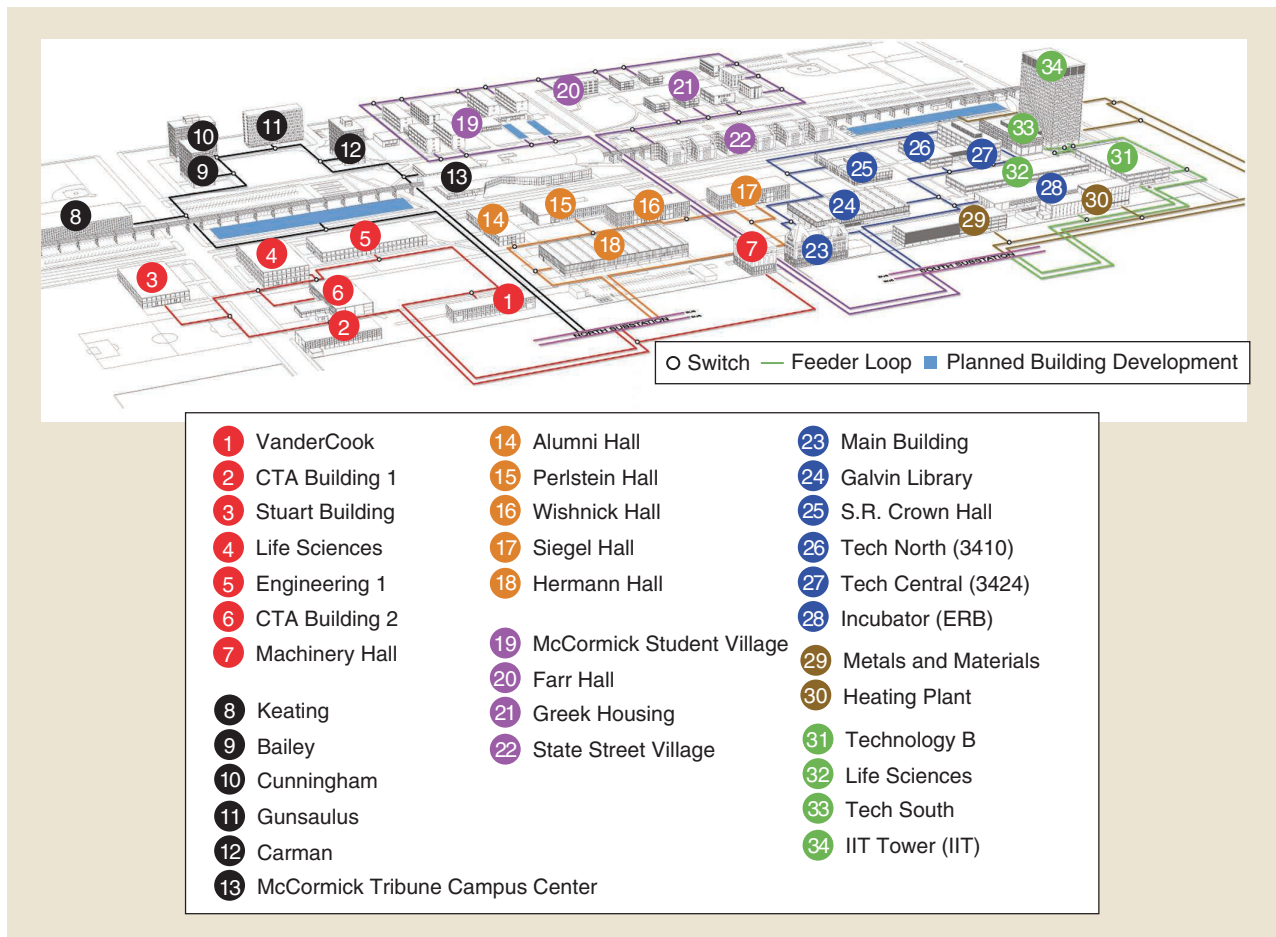


Figure 2. The location of the Crown Hall nanogrid at the IIT microgrid.

The islanding capability can be automatic or manually controlled. The PV panels and BESS located in the Crown Hall Nanogrid are optimally scheduled by a control unit for optimizing the electricity supply to the building. The additional generating units located within the IIT microgrid will supplement the electricity generated at the Crown Hall. In addition, Crown Hall can be disconnected from the campus grid and operated as an islanded nanogrid with greater energy efficiency and reliability. This is the third islandable nanogrid building on the IIT campus, with each building supporting the overall energy distribution schema and the demand of the campus on the utility or campus grid.

The introduction of renewable energy and energy storage technologies to this building have elevated its stature as an energy efficient landmark in the city of Chicago.

a redundant structure enables the Crown Hall nanogrid to be more resilient to power disruptions. The various energy resources are interconnected with ac and dc buses, making the building ac/dc coupled. There are 230 PV panels mounted on the roof of the building. As seen in Figure 3, certain PV modules have dedicated microinverters when connected to the ac bus. The PV array harvests solar energy and converts the solar energy to dc electricity; then, the microinverters connected to certain PV modules convert the dc to ac electricity, which is then inter-

connected to the building ac bus. The ac bus is a four-wire, three-phase, wye with a nominal 208Y/120-voltage alternating current (Vac) configuration. The ac system is interconnected with the dc bus via an ac/dc bidirectional converter (BDC) (i.e., a voltage source that converts ac to dc power and vice versa, and a transformer that converts 480Y/277 Vac to 208Y/120 Vac). The ac system is connected to the rest of the IIT microgrid, allowing the Crown Hall nanogrid to exchange power with the IIT microgrid when there is a power imbalance. The dc bus,

Design and Implementation of the Crown Hall Nanogrid

Design of the Crown Hall Nanogrid

Figure 3 depicts the electrical architecture of the Crown Hall nanogrid. The building loads are fed by the PV system, BESS, IIT microgrid, and the local utility grid. Such

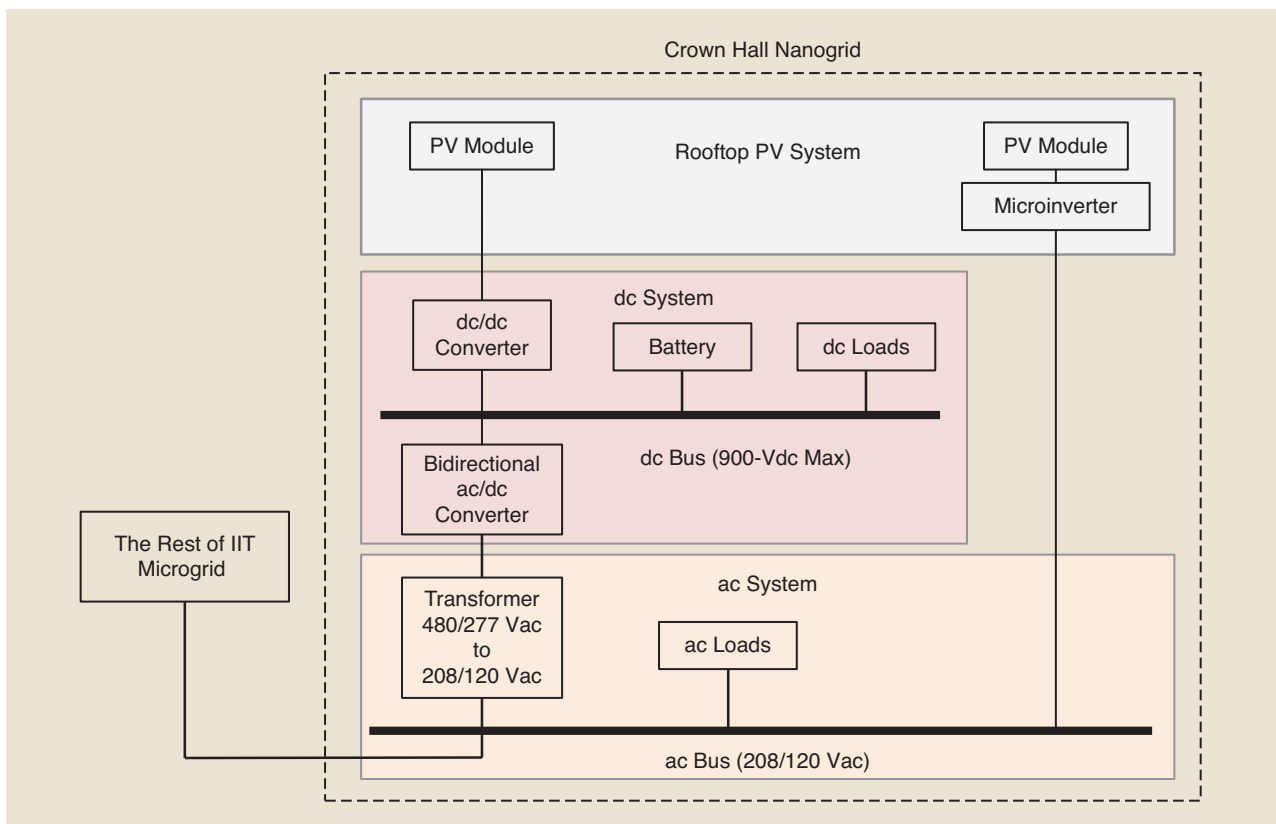


Figure 3. The electrical architecture of the Crown Hall nanogrid.

which is operated at a voltage up to 900 voltage direct current (Vdc), is fed by PV modules through dc/dc converters to feed the battery storage and dc loads. The power converters manipulate the voltages to interface the generation sources, energy storage, and loads to the Crown Hall nanogrid.

The Tesla BESS used in the Crown Hall nanogrid stores energy in multiple lithium-ion battery banks connected to the dc bus, levels off the fluctuations in the PV power output, and allows for building peak load shaving. The excess power on the ac bus is rectified by the BDC to charge the battery storage. When ac power is needed, the BDC inverts dc power from the battery storage to produce ac power that drives the building loads or is pushed out to the campus grid if it is needed elsewhere. The BDC, unlike the PV inverters, can create its own grid and black start the Crown Hall electrical system without any grid interaction. In other words, if the utility grid and the IIT microgrid are experiencing any power outages, the Crown Hall nanogrid can island itself and get started as a stand-alone nanogrid to supply its load. The same black start capability is also embedded into the other two nanogrids at IIT.

Implementation of the Crown Hall Nanogrid Project

The Crown Hall nanogrid was implemented in two phases, as shown in Figure 4. This two-phase process was necessary due to lengthy approvals required for the installation of the PV system and different purchasing timelines for the equipment in the PV system and the BESS.

In Phase 1, a total of 75 kW of polycrystalline PV modules were installed on the roof of Crown Hall. The PV layout, displayed in Figure 5, maximizes the PV capacity and energy production for the shading of the nearby trees, mechanical penthouse, and structural beams on the roof of Crown Hall. As Crown Hall is a National Historic Landmark with unique architecture design, certain limitations were taken into consideration for the nanogrid design, including 1) a review of the proposed plan by the National Historic Landmark program, 2) approval by the Areawide Development Review Committee (ADRC) and the Chicago Landmarks Commission for altering a landmark building, 3) consideration of no line-of-sight exposure from the ground level of the landmark building, 4) a review of the roof installations by the designated roofer for the landmark building, and 5) a specific design for electrical wiring and connections that could not disturb the existing infrastructure within the landmark building.

This is the third islandable nanogrid building on the IIT campus, with each building supporting the overall energy distribution schema.

The north-south beams located on the roof (seen in Figure 1), a distinctive architectural and structural characteristic of this unique building, are extended approximately 7 ft above the roof surface. The beams create a significant shadow to the east and west in the morning and late afternoon, respectively, which result in about 8% energy production loss, along with the shading from the trees and penthouse. The solar PV layout depicted in Figure 5 was designed to secure the ADRC requirements. Having the PV system in three bays holds back some distance from the north and south

roof edge, which satisfied the line-of-sight requirement, as the girders help block the view. An illustrative line-of-sight study is presented in Figure 6, illustrating an elevation rendering a sightline from an observer standing on the ground. The 15-ft setback of the PV modules from the roof edge was designed to result in a long sightline, rendering the PV array invisible from the ground.

In Phase 2, the Tesla Powerpack-2 BESS was constructed and integrated. This phase included the identification and the preparation of the BESS installation site in the vicinity of the Crown Hall Nanogrid, the installation of the Tesla Powerpack2 BESS, the interconnection and

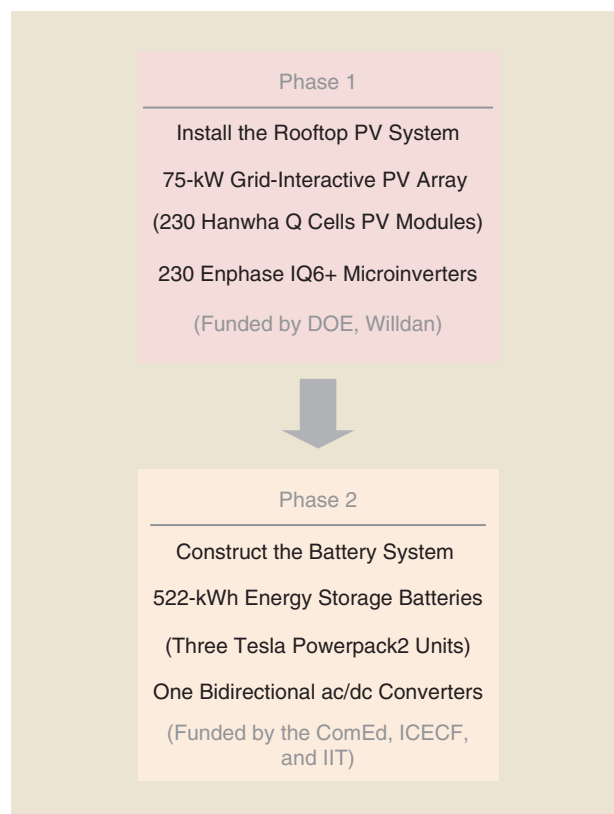


Figure 4. The two phases of implementing the Crown Hall nanogrid.

configuration of islanding capabilities (including the installation of the transformer and islanding relays), and the associated excavation, trenching, fencing, underground penetration of the building wall, and interior conduit runs. Figure 7 shows the battery storage and power electronics devices that were installed in this phase, and Figure 8 details the layout of the electrical room at the Crown Hall nanogrid. Table 1 lists the components that were placed into the Crown Hall nanogrid operation and the corresponding component design specifications. At the end of Phase 2, the Crown Hall nanogrid was capable of islanding itself from the IIT microgrid while serving its load by utilizing on-site resources. The interconnection and configuration of the islanding capabilities required extensive work in the electrical basement. This included stepping down the Tesla BESS voltage to match the

Crown Hall building voltage and the interruption of the building service to install the islanding relays.

Distinctive Components of the Crown Hall Nanogrid

Fully Integrated BESS

Tesla Energy's Powerpack-2 BESS was installed as the backbone of the Crown Hall nanogrid energy operation. The building block of the BESS is a lithium-ion battery pod, where each unit includes 16 battery pods, as illustrated in Figure 9. Each pod has an isolated dc/dc inverter and a thermal control system. Multiple sensors were utilized to monitor the battery storage performance in real time to ensure the optimal and safe operations of the battery storage. The batteries were interconnected to the ac bus via the Powerpack-2 BDC, whose technical

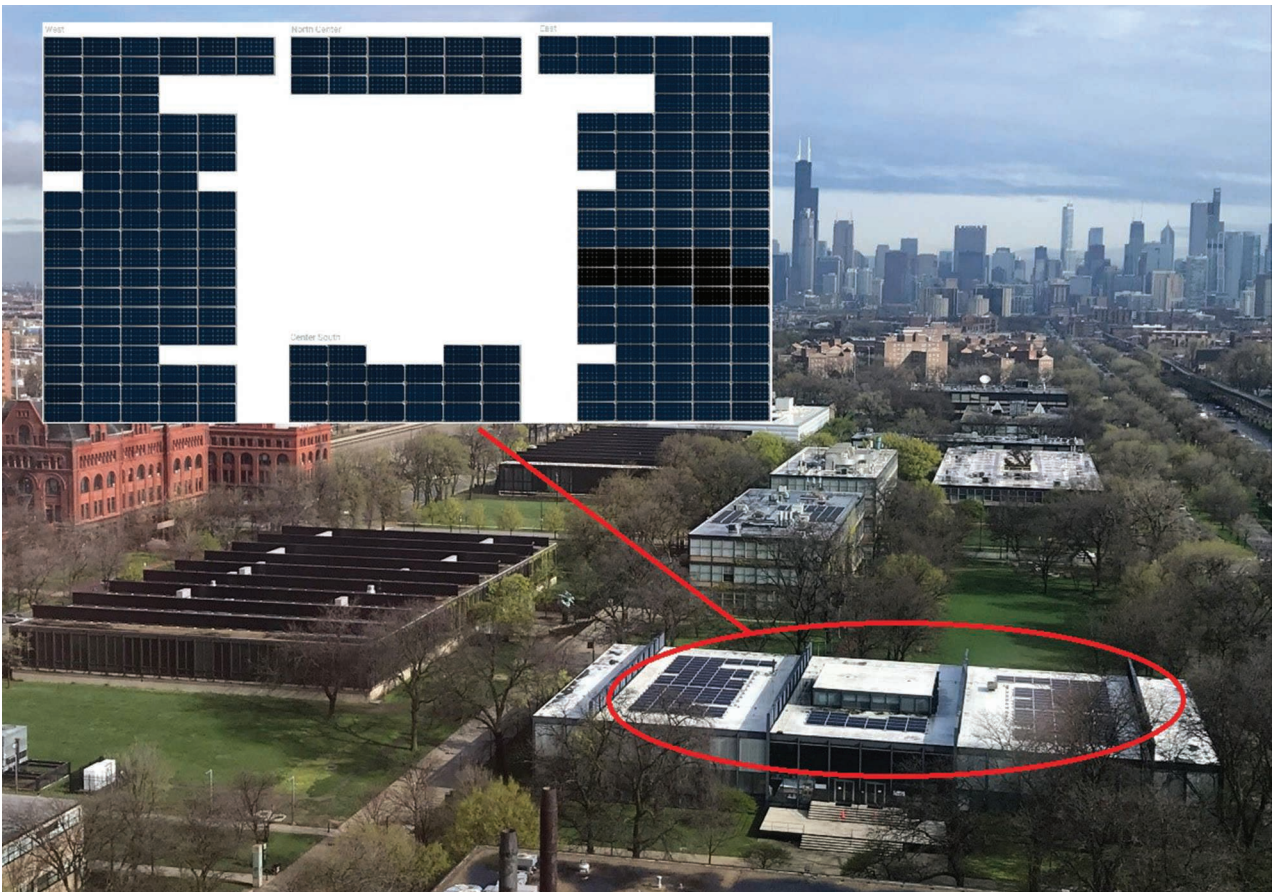


Figure 5. The rooftop PV system layout.

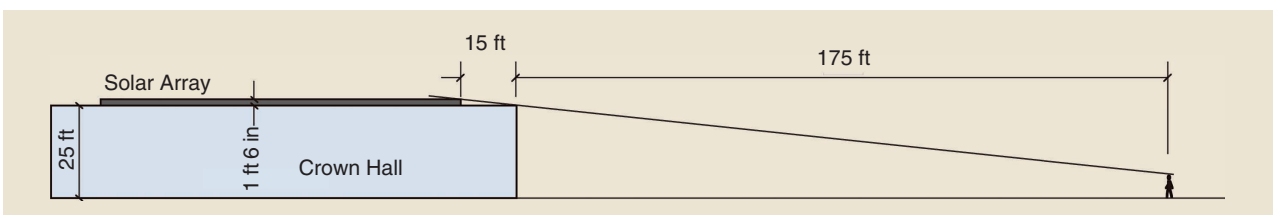


Figure 6. The line-of-sight study for the solar PV system.



Figure 7. The (a) battery storage and (b) power electronics control room.

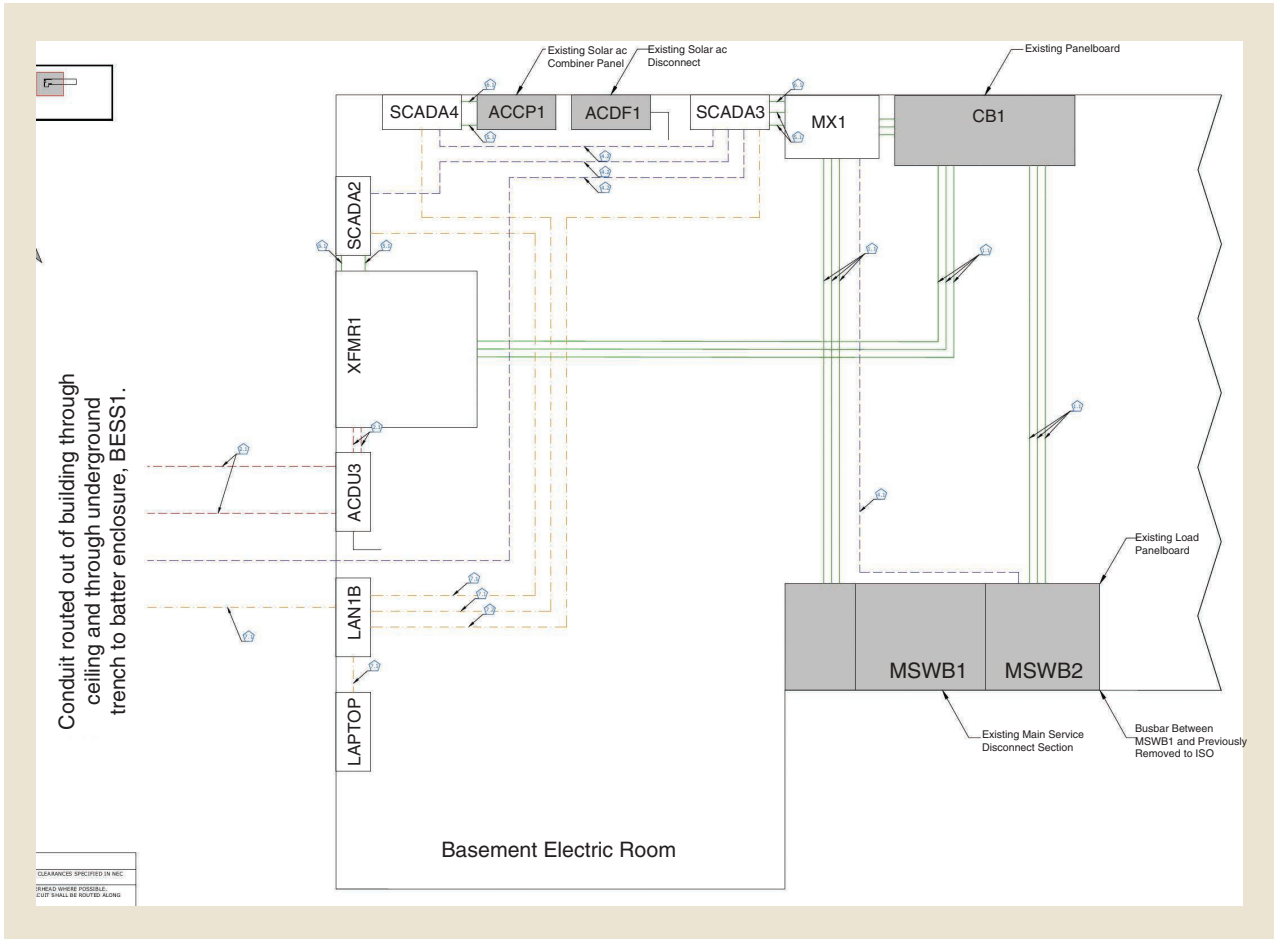


Figure 8. The electrical room equipment installation.

specifications are detailed in Table 2. The BDC is fully automated and managed by the Tesla integrated controller, depicted in Figure 10, which aggregates real-time information from all of the Tesla building blocks, including the battery pods in each Powerpack battery storage unit, the inverter modules in the Powerpack battery inverter, and multiple sensors. The Tesla integrated controller uses commands received from the IIT Microgrid and the Crown Hall nanogrid controllers to optimize the commands sent to the individual Tesla building blocks.

PV Array Utilizing Microinverters at the Crown Hall Nanogrid

The PV array located on the roof of Crown Hall includes 230 PV modules, where each PV module is equipped with a smart grid ready Enphase IQ 6+ Microinverter, as shown in Figure 11. Each microinverter has a maximum power point tracking (MPPT) range of 27–37 Vdc and a maximum output power of 290 volt-amperes. The microinverters

have an interconnected data link between them, where the operation information is aggregated and utilized by an Envoy PV controller. The use of microinverters in the proposed configuration offers multiple advantages. First, it maximizes the individual PV modules for optimizing the PV system's power and energy output in the Crown Hall nanogrid. The multiple PV modules in a conventional configuration would be connected in series to form a PV string, where multiple PV strings are connected in parallel and controlled by a single inverter. Under the sting inverter configuration, if one PV module was affected by shade (for example, a cloud, tree shadow, roof beam, or pent-house shadow), the dc output of that PV module would be dropped significantly, and the operation point of the entire PV string and other strings on the same inverter would be dropped to accommodate the affected PV module. So if a PV string has nine PV modules and four PV strings per inverter, then the shaded module would only be running at the MPPT point, and the remaining 35 modules would be operating at a suboptimal point.

By comparison, the proposed microinverter configuration allows each PV module to use its own microinverter, where the modules are interconnected with the ac bus. Accordingly, each PV module is operated independently at its own MPPT point and will be optimized individually for performance. One shaded PV module is not going to affect the entire system. Figure 12 depicts the PV modules on the roof of Crown Hall running at their independent optimal operation points. The second benefit of the proposed configuration is the enhanced reliability of the nanogrid. In a conventional configuration, a single PV module failure will affect the entire PV string. In the proposed microinverter configuration, all of the PV panels are in parallel at the ac bus, where any single module failure would only affect the module itself. This configuration has enhanced

TABLE 1. A list of the Crown Hall nanogrid components.

Nanogrid Components	Design Specifications
PV module	Hanwha Q Cell Q.Peach L-G4.2 360 M
Battery module	Tesla Powerpack-2 battery module
Bidirectional ac-dc converter	Tesla Powerpack-2 inverter module
dc-dc converter	Schneider Electric Xantrex XW MPPT 80 600
Microinverter	Enphase IQ 6+ microinverter
Islanding relay	Schweitzer Engineering Laboratories SEL-700G
Transformer	Schneider Electric EX300T3H



Figure 9. The individual battery rack with 16 interior battery pods.

TABLE 2. The specifications of the Tesla Powerpack BDC at the Crown Hall nanogrid.

Height, Width, Depth	2,140 mm, 1,254 mm * 1,014 mm
Weight	1,200 kg
Rated output power	300 kW
Nominal ac voltage	480 Vac
Maximum dc input voltage	900 Vdc
Peak efficiency	99%
Total current demand distortion	<3%
Power regulation accuracy	<2%
Total power command response time	<25 ms
Maximum rise time	<8 ms
Ambient operating temperature	-30–50 °C

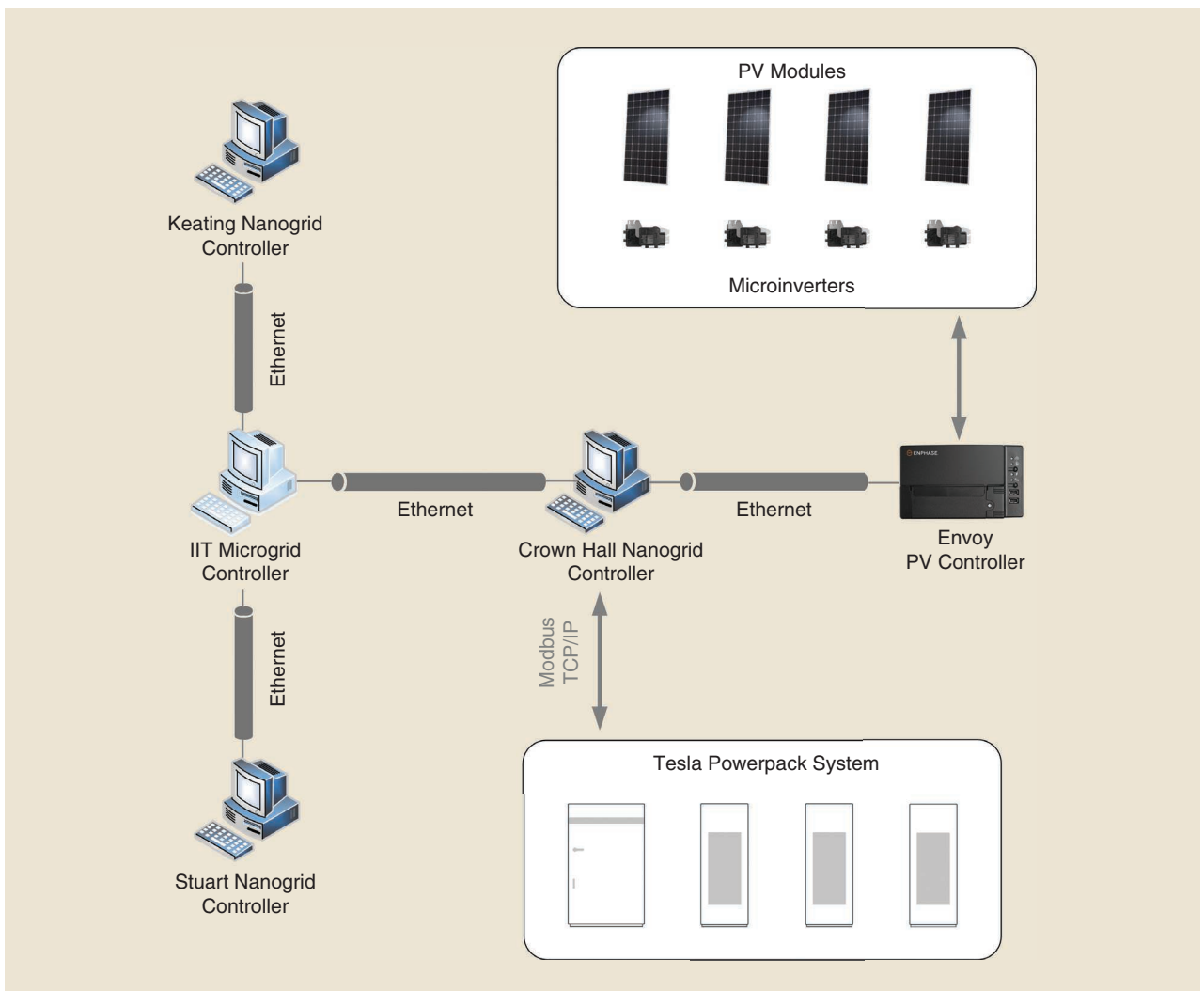


Figure 13. The communication infrastructure in the Crown Hall nanogrid.

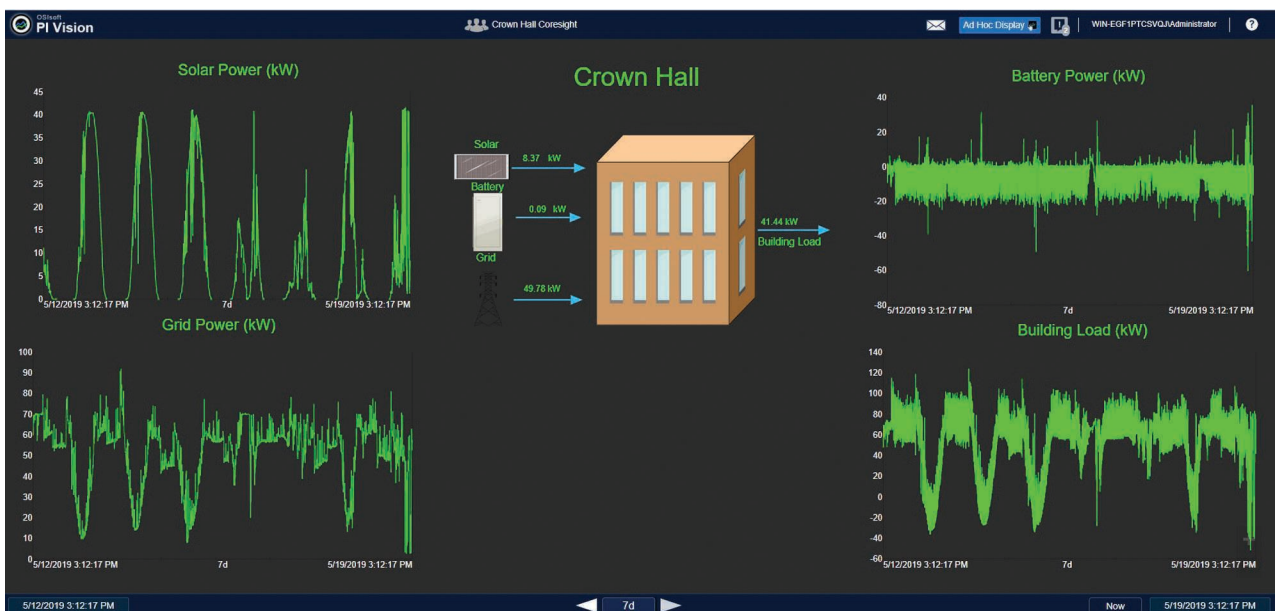


Figure 14. The Crown Hall nanogrid SCADA system based on the OSIsoft PI platform.

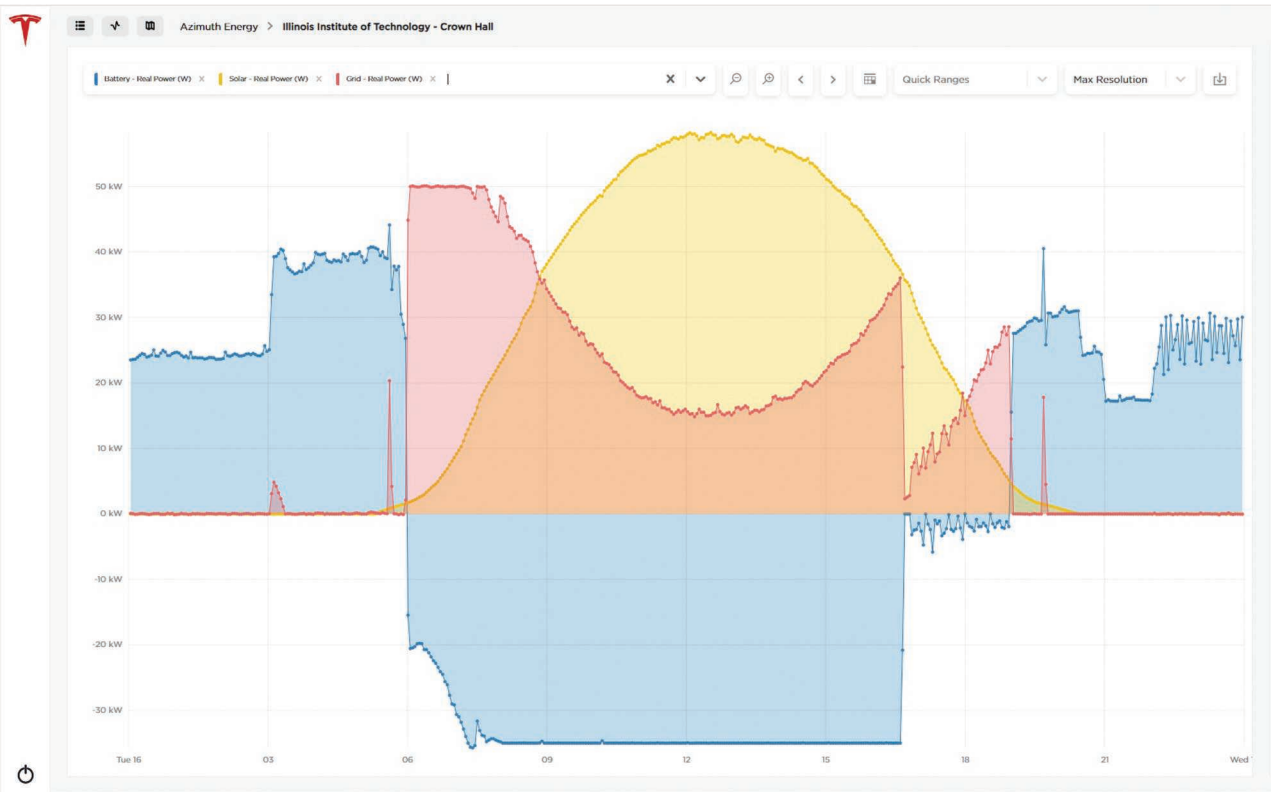


Figure 15. The Crown Hall nanogrid operation.

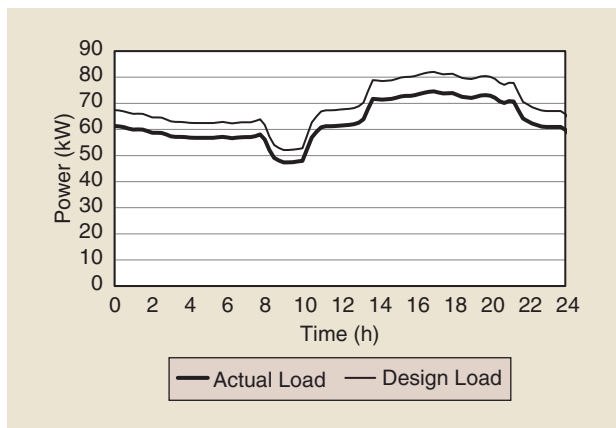


Figure 16. The daily load curve in Crown Hall, actual and 10% growth.

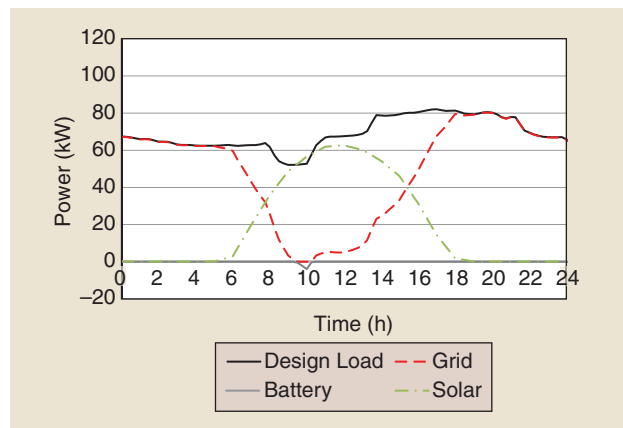


Figure 18. The peak shaving set point at 100 kW.

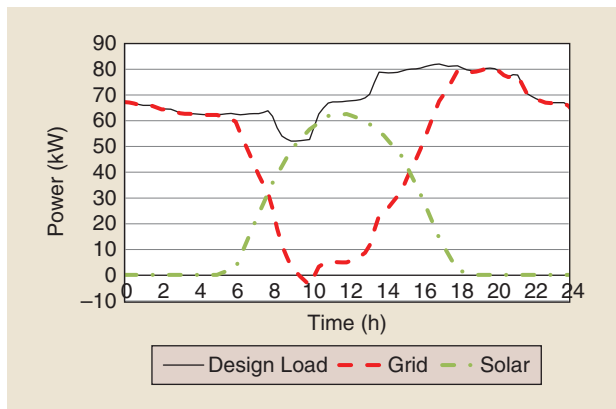


Figure 17. The daily demand curve with the PV system.

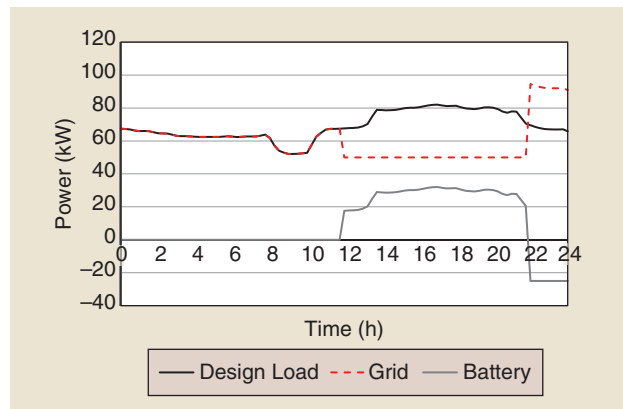


Figure 19. The daily discharge window at a 50-kW maximum demand set point.

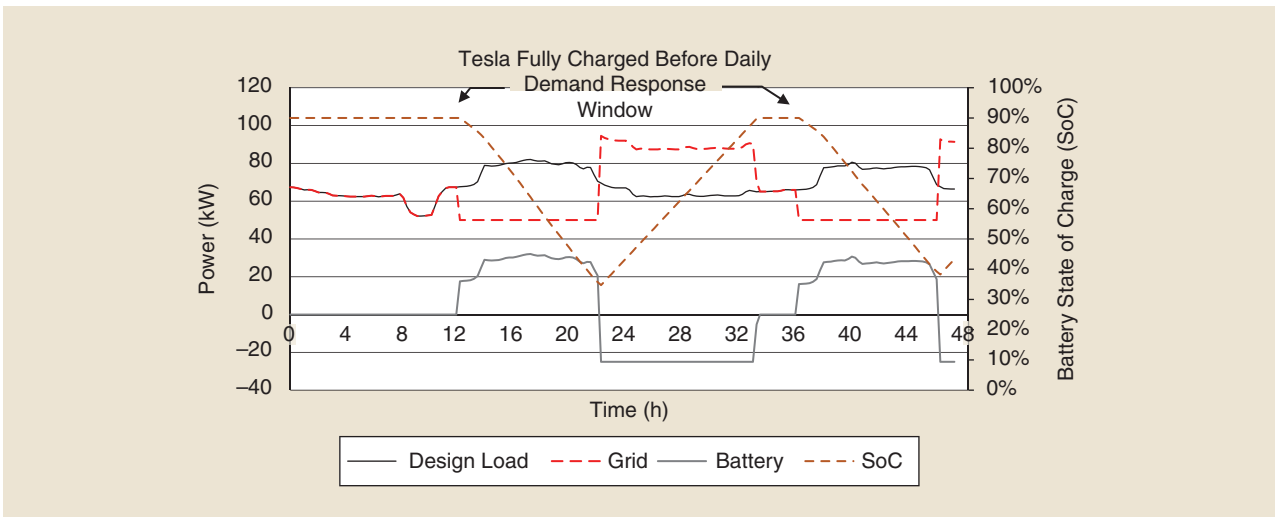


Figure 20. The battery state of charge (SoC), 48 h.

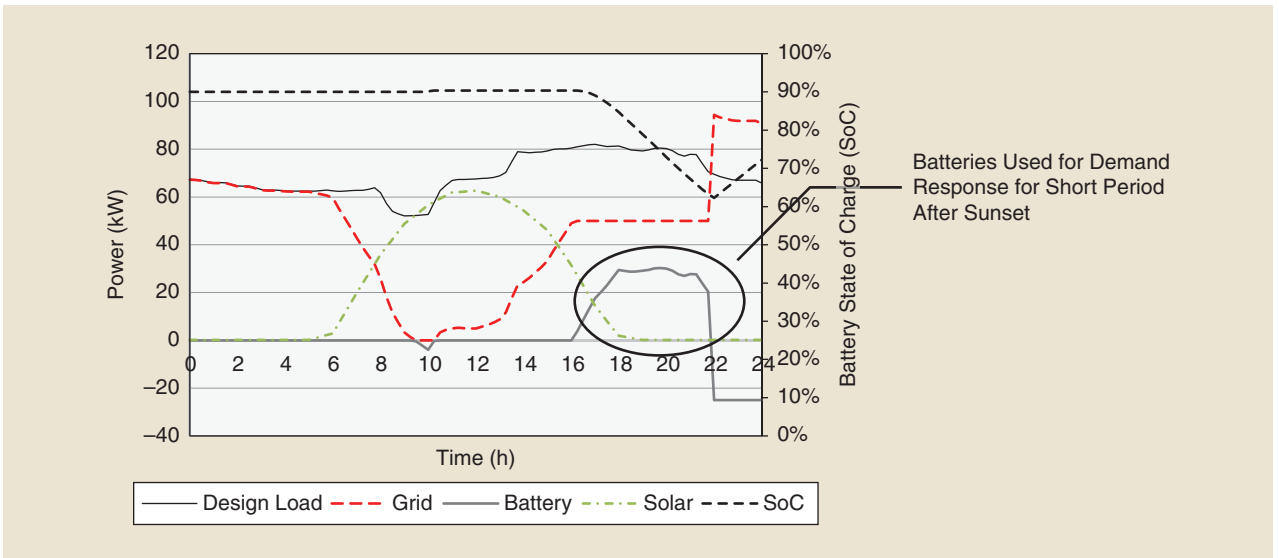


Figure 21. The battery state of charge, with the PV system.

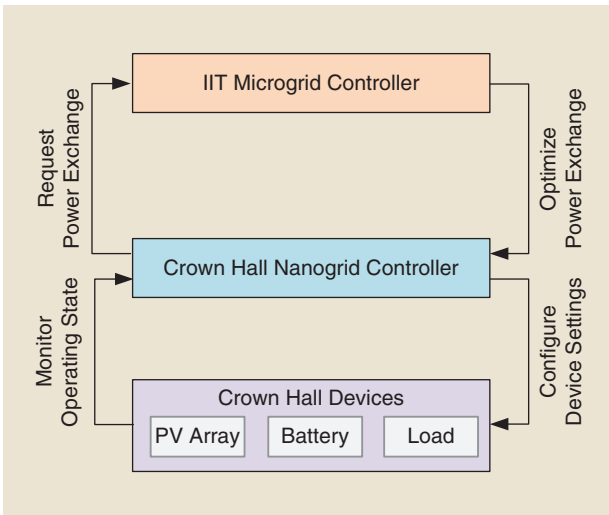


Figure 22. The energy management system at the Crown Hall nanogrid.

building power is interrupted due to unforeseen events, such as a building fire, the PV microinverter instantly stops producing and exporting power. This is a critical safety feature to protect the safety of utility workers who might be fixing the outage outside of the nanogrid. Unlike the Tesla BDC, which is a voltage source converter, the conventional PV inverter is a current source converter that cannot create its own voltage waveform and must sync to the grid voltage. When the grid fails, a conventional PV inverter instantly stops producing potentially deadly voltage and exporting power on its ac side. However, the dc side can still be energized whenever the sun is shining. These energized dc conductors, which may run in conduit from the basement to the roof, might be a potential hazard to firefighters and first responders. In contrast, the microinverters improve this safety situation by shutting off the power to each PV module. Thus, all of the conductors in the PV system and in the building will be de-energized in an emergency.

Operation and Control of the Crown Hall Nanogrid

Communication Infrastructure of the Crown Hall Nanogrid

The Crown Hall Nanogrid, demonstrated as an islandable entity, possesses its own specific frequency

and voltage requirements, and thus efficient and reliable communication is indispensable to its operation. Figure 13 presents the communication infrastructure embedded in the Crown Hall nanogrid, whose controller, serving as the nanogrid communication hub, communicates with the nanogrid field devices via

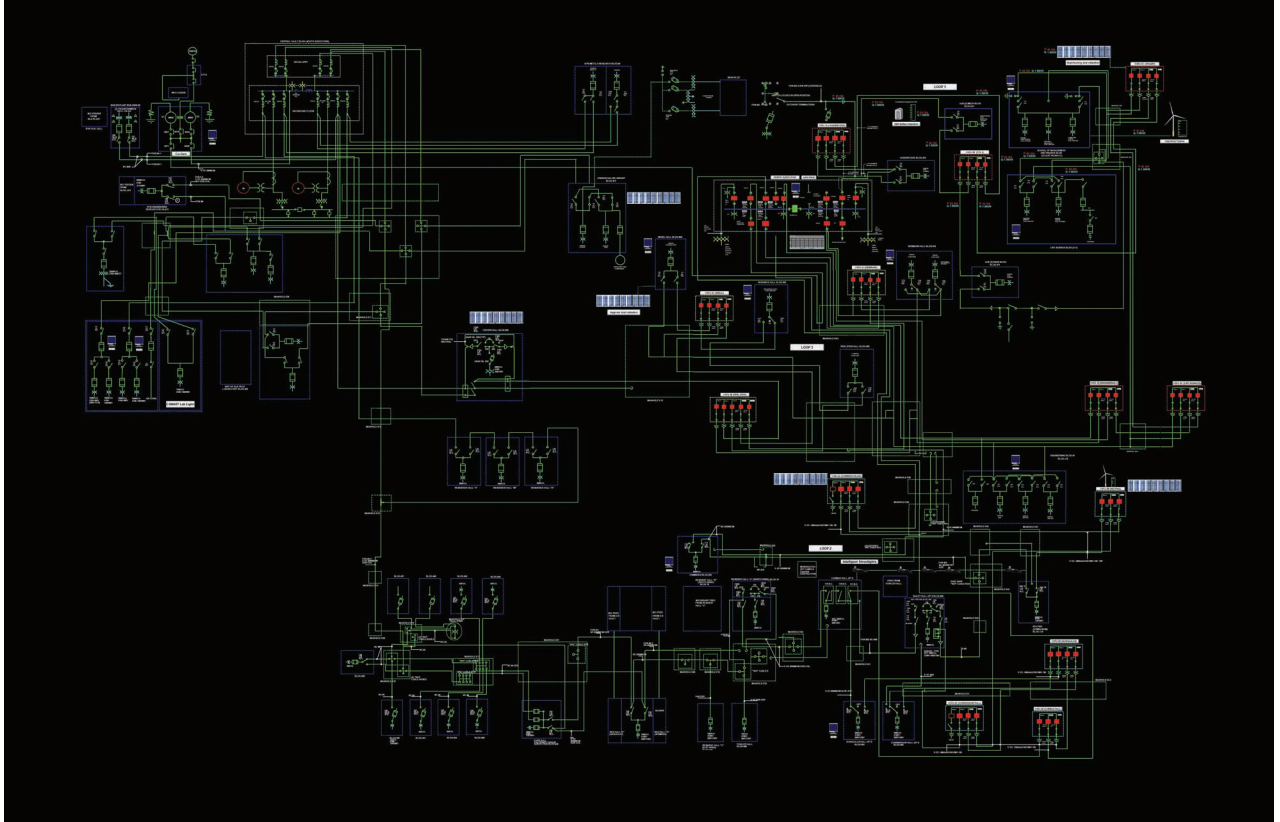


Figure 23. A one-line diagram of the IIT microgrid SCADA system, based on PI OSIsoft Coresight.



Figure 24. The renewable energy sites and nanogrids at the IIT.

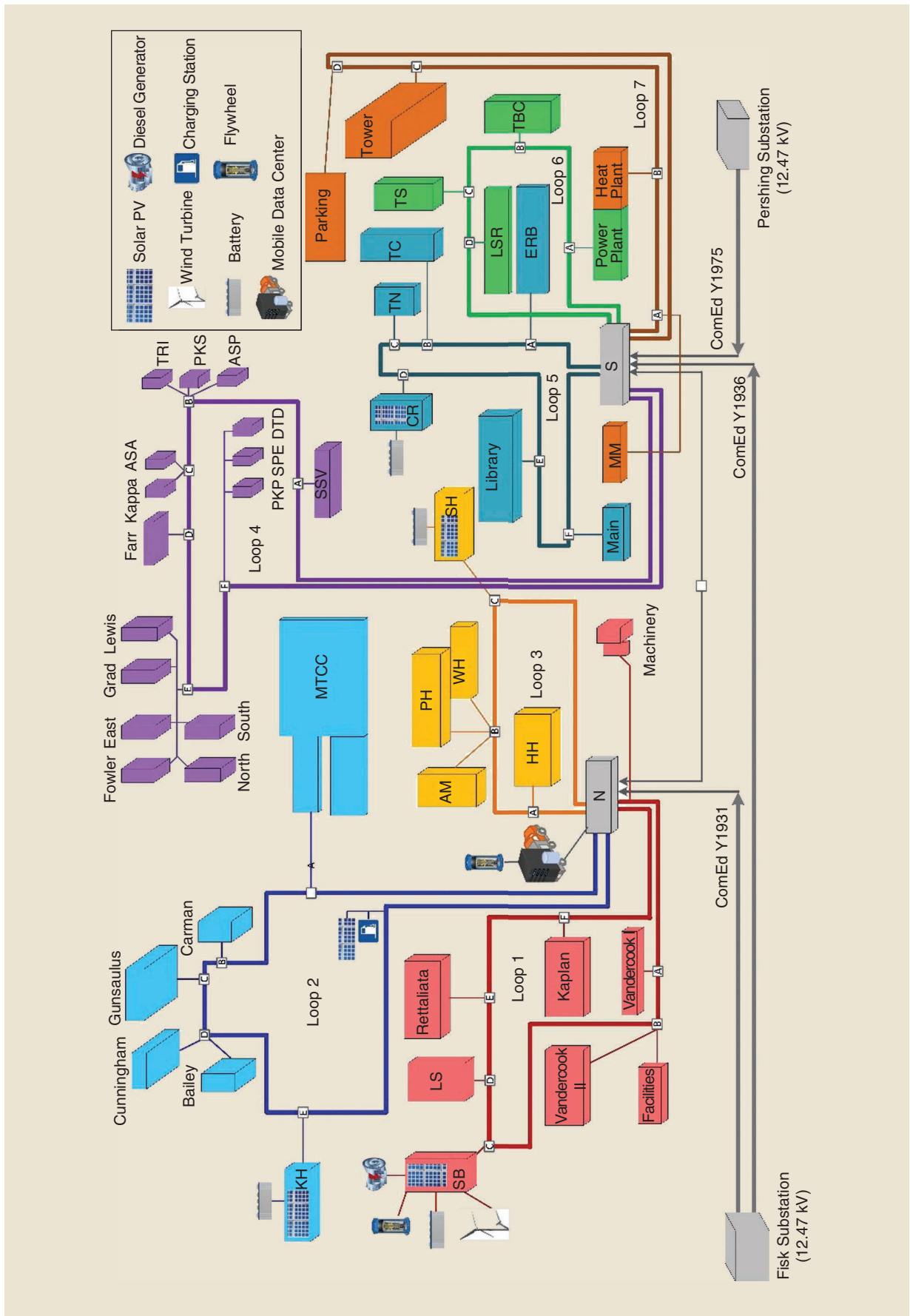


Figure 25. The renewable energy and nanogrid sites at the IIT microgrid.

diverse communication protocols and interacts with the IIT microgrid controller via the Ethernet. The Tesla Powerpack Controller has an integrated battery storage monitoring and control unit that parses, processes, and stores the data collected from the Tesla Powerpack battery units and the Tesla Powerpack BDC modules and performs optimal operations among each of the Tesla Powerpack building blocks. The Tesla Powerpack Controller exchanges monitoring information and control commands with the Crown Hall nanogrid controller via Modbus TCP/IP. The Envoy PV controller monitors and controls all of the microinverters via a power line and exchanges monitoring information and control commands with the Crown Hall nanogrid controller via the Ethernet.

The OSIsoft PI system is employed as the supervisory control and data acquisition (SCADA) system for monitoring and regulating the Crown Hall nanogrid controller. Figure 14 shows the Crown Hall nanogrid SCADA system, developed at IIT, which is based on the OSIsoft PI platform that synchronizes and integrates the data transmitted to and from the Crown Hall nanogrid controller via diverse communication protocols. In particular, the PI Coresight is an intuitive web client visualization tool that offers access to the real-time information in a fast, easy, and secure manner so that a nanogrid operator can gain sufficient

insight into the nanogrid conditions based on data driven analyses.

Figure 15 demonstrates the Crown Hall nanogrid operation using the SCADA system on 16 June 2020. In this case, the Tesla BESS was charged during the day and was carrying the entire building load at night.

Energy Management in the Crown Hall Nanogrid

The 500-kWh Tesla BESS provides the primary functions for the Crown Hall nanogrid, including 1) backup for the building, 2) continuous peak load shaving, 3) time-block demand reduction, and 4) islanding of the building. The control system also allows the building to be intentionally islanded from the IIT microgrid. The Tesla BESS design is based on a typical daily load curve for the Crown Hall nanogrid, depicted in Figure 16. This graph also includes a potential 10% future load growth (for managing the PV variability), which was recorded from the IIT microgrid monitoring system in May 2019. The Crown Hall demand does not decrease at night, as is often the case with commercial buildings. This observation points out that any energy efficiency measures can potentially reduce the overall energy consumption in Crown Hall, which would increase the effective operation of the Tesla BESS and the PV system. The solar PV production reduces the net building demand and often back feeds the power to the BESS and IIT microgrid, as shown in Figure 17.



Figure 26. The IIT Real-Time Digital Simulator.

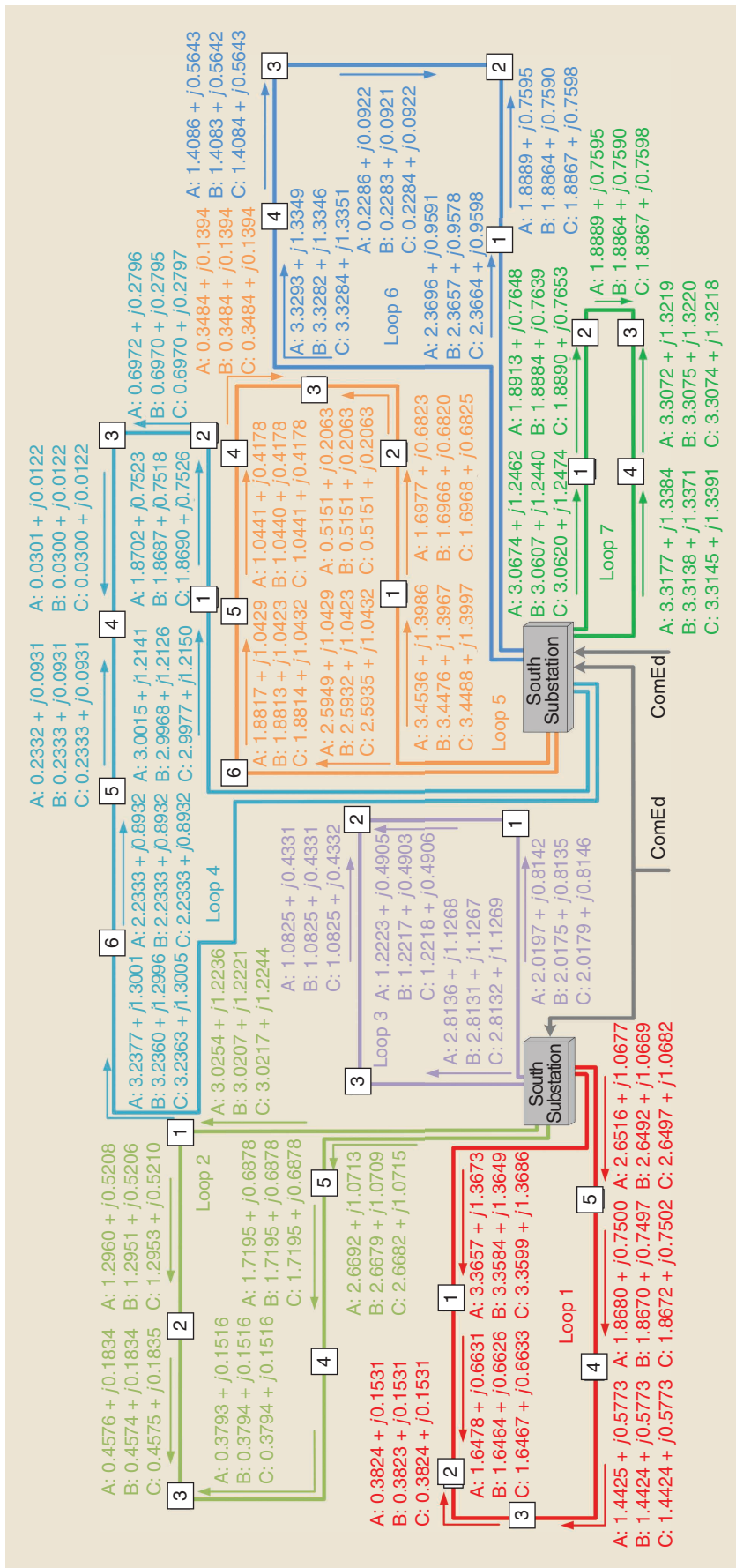


Figure 27. The three-phase power flow of the loop-based IIT microgrid.

Operation Strategy of the Tesla BESS

Peak Shaving

The Tesla BESS is designed to shave the daily peak load and keep the maximum grid power supplied to the nanogrid within one standard deviation of the average load, set at 100 kW, as seen in Figure 18. When the Crown Hall power consumption exceeds 100 kW, the Tesla controller will automatically adjust its output voltage so that the BESS will supply any nanogrid power demand above 100 kW (up to a maximum of 220 kW). Here, the BESS discharges initially to meet the nanogrid peak load, and then it recharges from the IIT microgrid later, when the nanogrid demand drops below 100 kW. When operated in peak shaving mode, the Tesla BESS recharging is limited to 25 kW to avoid increasing the demand charges and reducing the stress on the grid supply.

Demand Response

The Tesla BESS controller is also configured to limit power consumption at the Crown Hall nanogrid and reduce the demand charges from the utility that are based on peak power demand during any 15-min interval on any day in the billing cycle. During the daily time intervals with higher demand rates in the tariff structure, the Tesla BESS will be discharged to the Crown Hall nanogrid to maintain the grid supply below a preset limit. The peak hours at the local utility are from 12 p.m. to 10 p.m. The scenario depicted in Figure 19 portrays this performance with no PV offset (i.e., on a cloudy day).

System Flexibility

The Tesla BESS will charge and discharge on a daily basis. To optimize the utility cost savings, the nanogrid controller

will minimize the grid power while fully recharged prior to the next day demand window. This is done by setting the minimum demand response during off-peak hours to enable a full Tesla BESS recharge. Considering a 48-h period, Figure 20 demonstrates that the Tesla BESS is fully recharged each day prior to the 12 p.m.–10 p.m. discharging window. Note that this scenario considers the worst-case cloudy conditions. The scenario in Figure 21 depicts the same demand-reduction scenario as that in Figure 20, but the PV power production is included. This case considers the worst-case scenario of a high load with no PV production (Figure 16) to ensure that the batteries are never fully depleted. In Figure 21, the PV system allows the Tesla BESS to remain fully charged for most of the day under the design load (i.e., 10% higher than the actual load). Under the actual load, with the PV system in operation (for example, on a sunny day), the Tesla BESS might not be needed for achieving the targeted demand-reduction performance.

Island Operation

When the Crown Hall nanogrid is islanded, the building load is carried by the Tesla BESS in parallel with the rooftop PV system. Should the battery storage become depleted [that is, less than 10% state of charge (SoC)] because the sun is not shining, the Tesla BESS reverts to standby until the grid is restored.

The SCADA System

The control technology embedded in the Crown Hall nanogrid is a collaborative system with the IIT microgrid, which is shown in Figure 22. The SCADA system for the IIT microgrid (Figure 23) is updated every 5 s, which allows the IIT microgrid to control the entire campus system, including the Crown Hall nanogrid, in real time. The SCADA system gathers the real-time data on all building energy consumptions as well as the status of the PV system, wind unit, and battery storage units. The IIT microgrid operator utilizes the real-time data to optimize the delivery of electricity to the Crown Hall nanogrid, as depicted in Figure 22.

The IIT microgrid applies the same SCADA system for the monitoring and control of other renewable energy sites and nanogrids at IIT (see Figure 24). The actual locations of these sites are displayed in Figure 25. The collected SCADA data will be used for the real-time simulation of the campus operation, which is discussed next.

Real-Time Simulation of Power Flow in the Crown Hall Nanogrid

The IIT microgrid controller uses the Real-Time Digital Simulator (RTDS) for the detailed modeling and control of the campus components. RTDS operates in real time,

allowing the controller to interface the physical equipment with the simulated model to test and validate the operation of the microgrid protection and control devices under realistic conditions. The RTDS allows the IIT to simulate in real time the actual behavior of the microgrid operation should a critical situation occur anywhere at the IIT microgrid site. Figure 26 shows the RTDS, located on the left side of the control room, for the monitoring and control of the renewable energy sites and nanogrids at the IIT. Figure 27 displays a sample result of power flows across the IIT cable lines.

Acknowledgment

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For Further Reading

M. Shahidehpour and J. F. Clair, "A Functional microgrid for enhancing reliability, sustainability, and energy efficiency," *Electr. J.*, vol. 25, no. 8, pp. 21–28, 2012. doi: 10.1016/j.tej.2012.09.015.

M. Shahidehpour and M. E. Khodayar, "Cutting campus energy costs with hierarchical control: The economical and reliable operation of a microgrid," *IEEE Electr. Mag.*, vol. 1, no. 1, pp. 40–56, Sept. 2013. doi: 10.1109/MELE.2013.2273994.

"Real-time data and event infrastructure for the enterprise," OSISOFT System, San Leandro, CA, 2017. [Online]. Available: http://www.osisoft.com/software-support/what-is-pi/What_Is_PI.aspx

"Enphase microinverters," Enphase Energy, Fremont, CA, 2018. [Online]. Available: https://enphase.com/sites/default/files/downloads/support/IQ6-IQ6-plus_DS_EN-US.pdf

"Enphase networking," Enphase Energy, Fremont, CA, 2018. [Online]. Available: <https://enphase.com/sites/default/files/downloads/support/IQ-Comm-Envoy-EN-US.pdf>

"Q.ANTUM solar module," Q.Antum, North Sydney, Australia, 2016. [Online]. Available: https://www.solar-electric.com/lib/wind-sun/Data_sheet_QPEAK_L_G4_2_360.pdf

"Tesla microgrid solution," Tesla Motors, Palo Alto, CA, 2017. [Online]. Available: https://www.gemenergy.com.au/wp-content/uploads/2017/11/Powerpack_Microgrid-System-Brochure.pdf

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