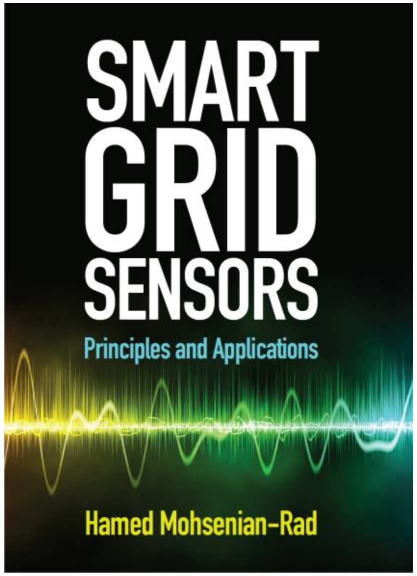
Chapter 7: Other Sensors and Off-Domain Measurements and Their Applications



Smart Grid Sensors: Principles and Applications
Hamed Mohsenian-Rad
Cambridge University Press, 2022
ISBN: 9781108839433

Table of Contents

Overview

- The fundamentals of smart grid sensors and measurement-based applications were covered in Chapters 2–6. However, depending on the application, other sensors or measurements may also be used in this field.

- Some of these sensors and measurements are discussed in this chapter.

- They range from *electrical* to *mechanical* and *chemical* measurements, as well as different types of *images* and *financial data*.

- These additional data and measurements can be used as stand-alone data for one application, or in *cross examination* with some of the measurements from the previous chapters in another application.

Table of Contents

Table of Contents

7.1. Device and Asset Sensors

- Power grids are equipped with millions of transformers, capacitor banks, fuses, relays, switches, regulating devices, etc.

- The proliferation of renewable and distributed energy resources is also adding millions of solar panels, wind turbines, batteries, etc., to the power grid, whether they belong to the utility or to the customers.

- Keeping track of the operation and state of health of these various pieces of equipment and assets is necessary to maintain grid efficiency, identify potential malfunctions, and forecast future issues or failures.

7.1. Device and Asset Sensors

- Many of the grid equipment and assets may have dedicated power system sensors to measure their voltage, current, and power.

- Such measurements can be studied using the same fundamental methods that we discussed in Chapters 2–6.

- Furthermore, some of these equipment and assets may have sensors that are *specific to them and their unique characteristics and issues*.

- In this section, we are particularly concerned with the sensors and measurements that may reveal additional information about certain specific types of grid equipment and assets, beyond what can be achieved by measuring only voltage, current, and power.

7.1. Device and Asset Sensors

7.1.1. Transformers

• Transformers are critical assets in power systems.

• Failure modes for transformers are related to the degradation of components such as the *tap changer*, *bushings*, *windings*, *core*, *tank*, and *dielectric fluid*, or to thermal aging of the *insulating materials* [428].

• Advanced monitoring systems can be installed on transformers to measure voltage and current, *oil temperature*, *ambient temperature*, *hot spot temperature*, *tap changer position*, *moisture*, and the *level of dissolved gas* in the transformer's oil.

• These measurements are often processed on site, and the summary of results are reported to grid operation centers [429].

7.1. Device and Asset Sensors

7.1.1. Transformers

• Dissolved Gas Analysis (DGA) is a common method to monitor the health of a transformer. The levels of dissolved gas contents of the transformer's oil are measured using *chemical sensors*, and if they exceed certain thresholds, then the transformer is flagged for maintenance.

• The dissolved gas levels that are typically monitored include:

- Hydrogen
- Ethylene
- Methane
- Acetylene
- Ethane
- Carbon monoxide.

7.1. Device and Asset Sensors

7.1.1. Transformers

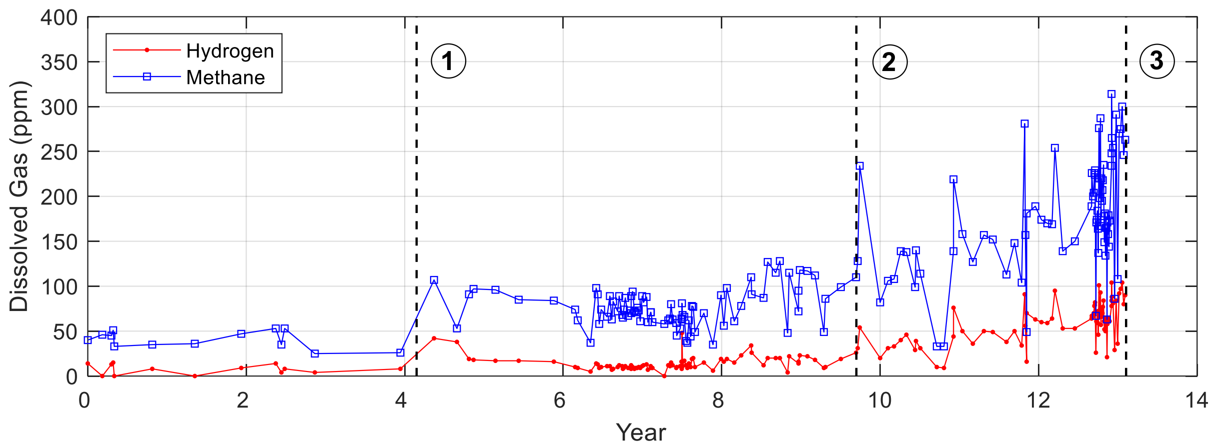
• These chemical measurements can indicate not only the presence of a fault, but also the likely type of the fault [430]:

- If the hydrogen and methane exceed their threshold, then the *likely associated fault* is *arcing*.

- If hydrogen and acetylene exceed their threshold, then the *likely associated fault* is *partial discharge*.

7.1.1. Transformers

• **Example 7.1**: The dissolved gas trends in parts per million (ppm) are shown below for a 700 MVA transformer over several years.



7.1. Device and Asset Sensors

7.1.1. Transformers

- **Example 7.1 (Cont.)**: Three events are marked on the previous Slide.
  - At Event 1, two earth faults occurred relatively close to this transformer. There was a step increase in the gas levels. It was observed that the production of the dissolved gases responded to increases and decreases in the loading. Therefore, the transformer loads were subsequently adjusted to allow it to be kept for operation at stable conditions for several years. Later, at around the point that is marked as 2, the gas levels started to elevate again. This time, the condition progressed quite steadily; which ultimately led to the transformer failure in Event 3; cf. [431].

7.1. Device and Asset Sensors

7.1.1. Transformers

• Traditionally, dissolved gas levels are measured once every few months, and often manually. However, the more advanced transformer monitoring systems provide fast, continuous, and real-time monitoring of the dissolved gas levels and other on-site measurements.

• The DGA results can be reported frequently, such as once every hour. The reporting rates can be set to increase automatically when the gas concentrations exceed their thresholds; cf. [430].

• Such real-time monitoring of dissolved gas levels can help identify incipient issues before they cause catastrophic transformer failures.

7.1. Device and Asset Sensors

7.1.1. Transformers

• The results from DGA can be used together with the power system measurements that we discussed in Chapters 2–5.

• For example, recall from Section 4.3.3 in Chapter 4 that a *zero-current event* that is captured by a waveform sensor may potentially indicate an incipient fault in a transformer tap changer. This issue can be *cross-examined* with the results from DGA in order to draw a more reliable conclusion with respect to the state of the health of the transformer.

7.1. Device and Asset Sensors

7.1.2. Capacitor Banks

• Capacitor banks are used in power systems for reactive power management and voltage support. Most capacitor banks in practice currently do not have dedicated asset sensors; however, it is becoming increasingly common to include built-in monitoring and communications capabilities in the new capacitor bank controller devices.

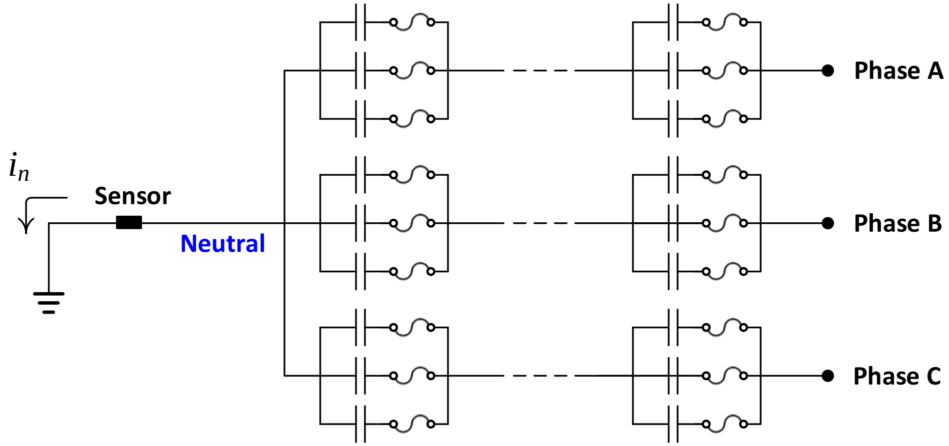
• They measure *voltage*, *current*, *power*, *frequency*, *power factor*, *harmonics*, *temperature*, *daily switching counts*, etc.

• They can trigger alarms in cases such as when the close counter is reached, blown fuses, reaching minimum or maximum voltage limits, reverse power, or when the target power factor is not achieved [432, 433].

7.1. Device and Asset Sensors

7.1.2. Capacitor Banks

• **Example 7.2**: Recall from Section 2.2 that most non-contact overhead line sensors harvest power from the conductor. Suppose a non-contact overhead line sensor is installed externally at a capacitor bank location to measure the neutral current in at the neutral terminal of the capacitor.



7.1.2. Capacitor Banks

- **Example 7.2 (Cont.)**: Initially, and during normal operation, the neutral current is zero (or very small) and the non-contact overhead line sensor is in *sleep mode*. It will remain in sleep mode until a blown fuse or multiple blown fuses cause considerable phase unbalance.

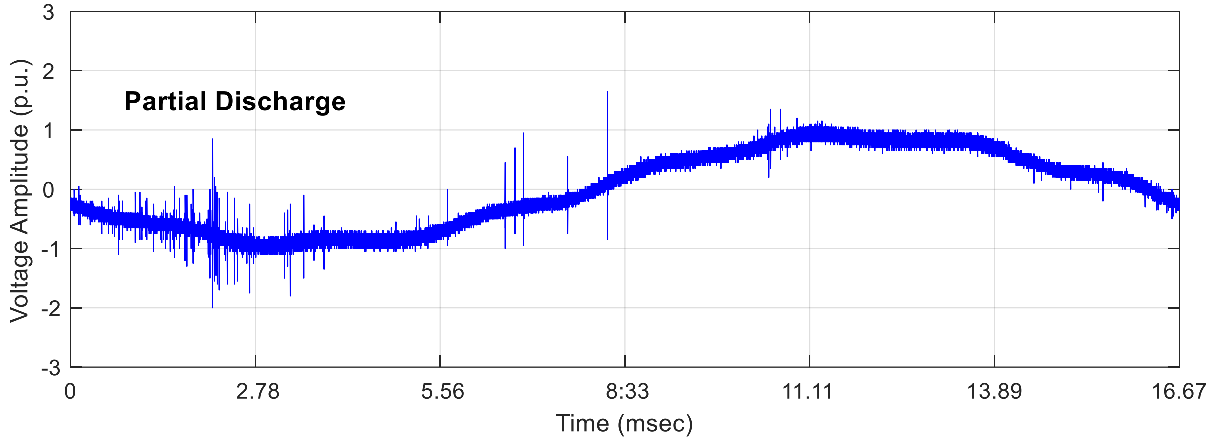
- At that point, the neutral current will start to *harvest power*.

- Shortly after, once the sensor is powered on, the sensor begins to report the RMS neutral current values at a pre-determined time interval. This alerts the utility that there is a recent issue at the capacitor and an *investigation is initiated* [434].

7.1.3. Line Conductors

• Line conductors may also be monitored by dedicated asset sensors.

• For example, dedicated waveform sensors can be used in long transmission lines (installed directly on the conductor) to monitor the health of the conductor and identify partial discharge.



7.1. Device and Asset Sensors

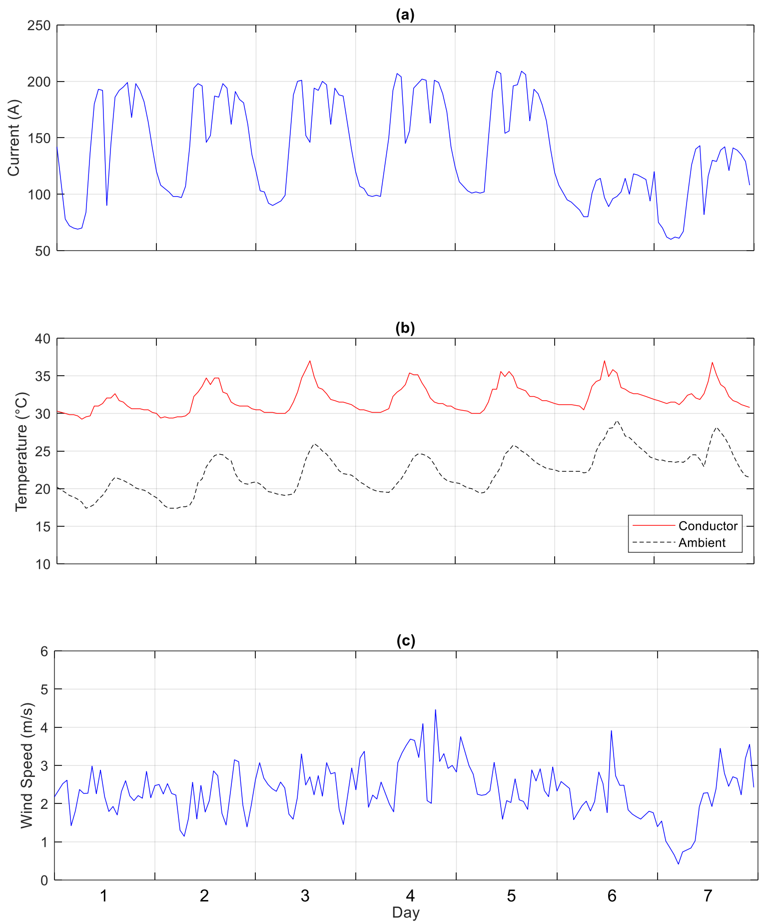
7.1.3. Line Conductors

• **Dynamic Line Rating**: In recent years, overhead line sensors have been equipped to monitor not only voltage and current, but also some mechanical, thermal, and weather parameters such as:

- Conductor temperature,
- Ambient temperature
- Wind speed
- Wind direction
- Solar irradiation
- Line clearance.

7.1.3. Line Conductors

- **Dynamic Line Rating (Cont.)**: An example is shown below:



7.1. Device and Asset Sensors

7.1.3. Line Conductors

• **Dynamic Line Rating (Cont.)**: The additional measurements on the previous slide can be used in dynamic line rating (DLR).

• Power flow on overhead transmission lines must be limited in order to keep the conductor temperature below the power line's Maximum Allowable Conductor Temperature (MACT).

• This is necessary in order to maintain acceptable electrical clearances along the line and avoid excessive aging of the conductor system.

7.1. Device and Asset Sensors

7.1.3. Line Conductors

• **Dynamic Line Rating (Cont.)**: It should be noted that, *static line ratings* (SLRs) equal the maximum line current for which the line conductor temperature is less than the MACT under *conservative weather assumptions*, which often overestimate the conductor temperature.

• For example, according to the International Council on Large Electric Systems (CIGRE), SLRs are calculated based on [436]:

- low-speed wind (e.g., 0.6 m/s); therefore little cooling conditions,
- a seasonally high ambient temperature (e.g., 40◦C)
- and full solar heating (e.g., 1000 W/m2).

7.1. Device and Asset Sensors

7.1.3. Line Conductors

- **Dynamic Line Rating (Cont.)**: DLRs too are equal to the line current for which the conductor temperature is less than the MACT; however, DLRs are calculated based on the *actual weather conditions*.

- Weather conditions vary in time. Thus, DLRs are valid for only a limited time into the future, called the *thermal rating period*, such as the next hour.

- DLRs are calculated by taking into account the actual ambient temperature, the actual wind speed, and the actual solar heating.

- Under most conditions, the DLR is higher than the SLR of the line. Thus, it can result in a *better utilization* of the existing power lines [437].

7.1.4. Wind Turbines

• Condition monitoring and prognostic systems are used in wind turbines to continuously monitor the health of turbine components.

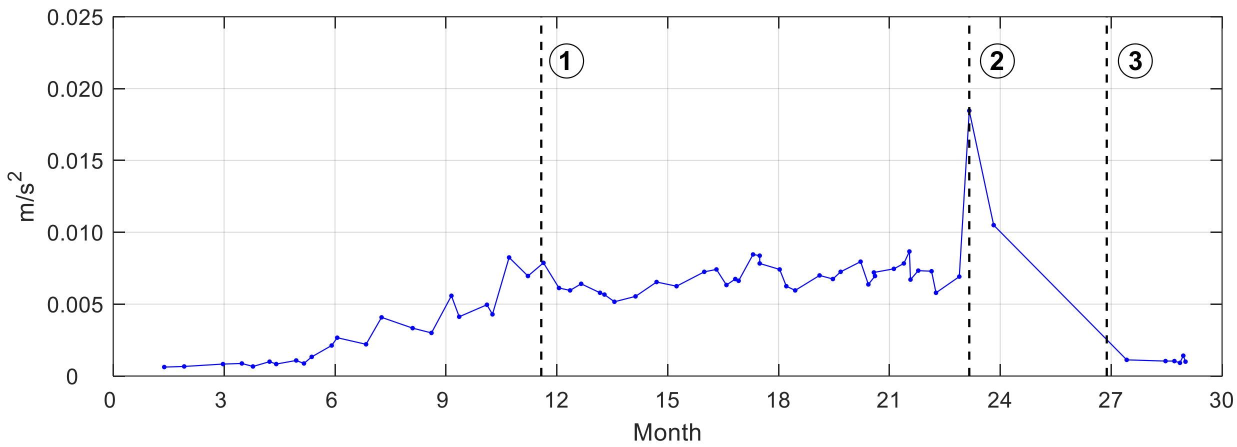
- The objective is to detect faults early so as to minimize downtime and maximize productivity.

• Condition monitoring techniques for wind turbines include [438]:

- Vibration analysis
- Acoustics
- Oil analysis
- Strain measurement
- Thermography.

7.1.4. Wind Turbines

- **Example 7.3**: The vibration measurements at a 2.3 MW wind turbine are shown below during a period of about three years.



- After about six months, the vibration level started to gradually increase, suggesting potential issues with the main bearing.

7.1.4. Wind Turbines

- **Example 7.3 (Cont.)**: About five months later, marked in the figure as ①, a physical inspection was performed and confirmed damage to the bearing, which in this case was a moderate macro-pitting. At this point, the main bearing grease was flushed to extend the bearing's life. After the flushing, the vibration stopped increasing and the bearing continued to run without significant additional deterioration.

- About one year later, at ②, the vibration trend increased rapidly. As a result the operation of the turbine was stopped to avoid catastrophic damage. The main bearing was replaced and the turbine restarted operation after about three months, which is marked in the figure as ③.

- Subsequently, the vibration trends went back to normal [439].

7.1.4. Wind Turbines

- Condition monitoring can help conducting repairs and replacements only when needed in order to avoid unnecessary and costly up-tower jobs at wind turbines.

7.1. Device and Asset Sensors

7.1.5. Solar Panels

• Dust accumulation negatively impacts solar panels output; because it obstructs solar radiation to the surface of the solar panels; thus reducing the overall performance of the solar power generation system [440].

• Most PV systems are cleaned by rain or at scheduled cleaning services.

• Some PV systems are also equipped with an automated cleaning system, which activates the cleaning mechanism, for example, when the output power drops 20% below the average normal production; cf. [441].

• These factors have major impact on the power output of the solar panels.

7.1.5. Solar Panels

• **Example 7.4**: The effect of dust and weather conditions on PV performance was investigated in [442]. The experiments were done in the desert environment in Qatar under the impact of ambient dust.

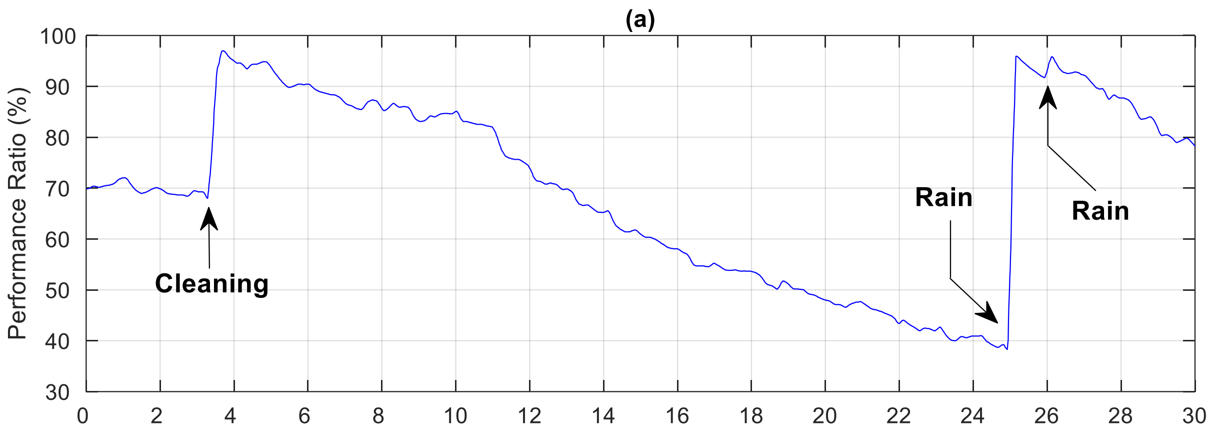
• Three PV arrays were considered with different cleaning frequencies:

- low wash
- medium wash
- high wash.

7.1.5. Solar Panels

- **Example 7.4 (Cont.)**: The performance ratio was measured at the three PV panels over 30 weeks; and the measurements were as follows:

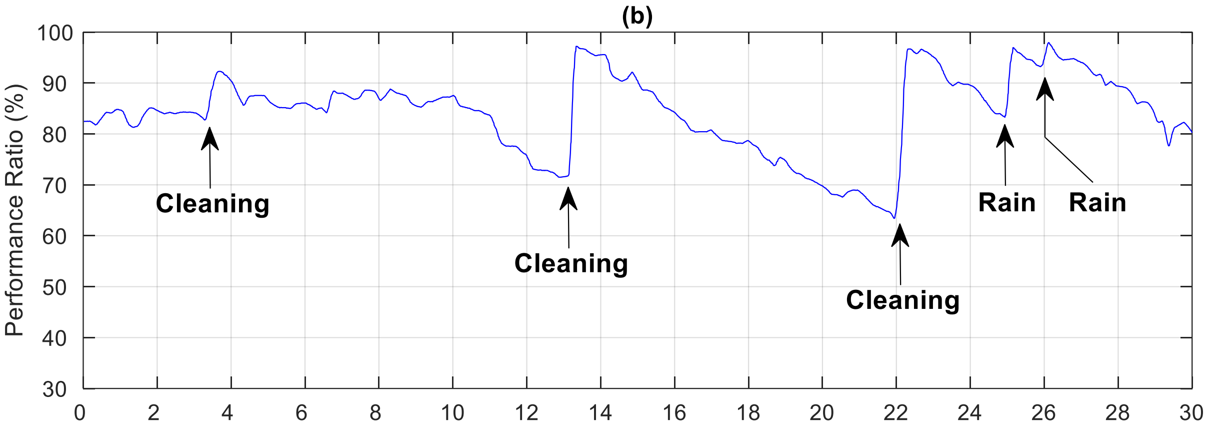
- Low-Wash) The PV array was washed once every six months:



7.1.5. Solar Panels

- **Example 7.4 (Cont.)**:

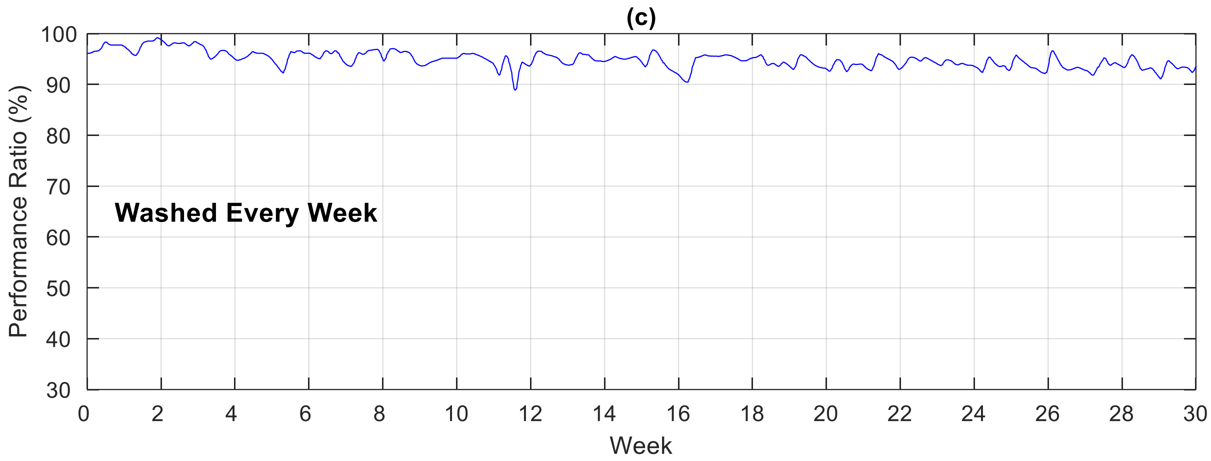
- Medium-Wash) The PV array was washed once every two months:



7.1.5. Solar Panels

- **Example 7.4 (Cont.)**:

- High-Wash) The PV array was washed every week:



7.1. Device and Asset Sensors

7.1.5. Solar Panels

- **Example 7.4 (Cont.)**: We see that the profiles for the performance ratio vary drastically across these three PV arrays. In particular, the power production may drop to as low as only 40% of the normal production rate under low wash conditions; while the power production is almost always close to the normal production rate under high wash conditions.

7.1.5. Solar Panels

• Depending on the size and the penetration rate of the PV units, the impact of dusting and cleaning schedules can be significant on the production output of PV panels and therefore the overall operation of the power system, such as voltage profiles and power quality.

• The measurements on dusting, and the information of cleaning schedules or the details on an automated cleaning system, could all be valuable to the utility operator so as to *better model the PV units* in the power system. Such improved models can be used in various smart grid applications, such as state estimation and solar production forecasting.

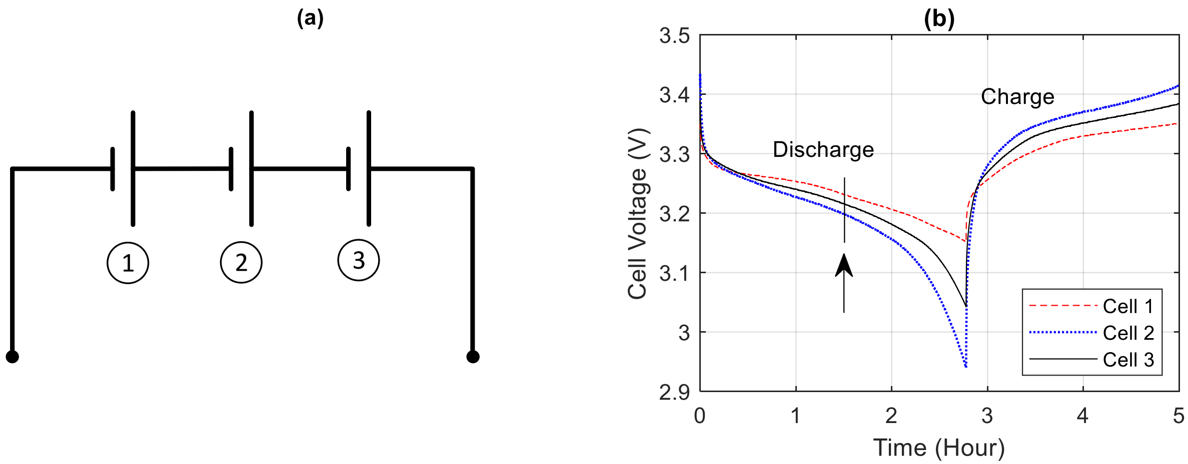
7.1.6. Batteries

- Batteries are DC resources that store and release energy in electrochemical reactions during the charge and discharge cycles.

- Batteries are interconnected to the grid via (charger) inverters, see Section 1.2.9 in Chapter 1. Measurements at the *AC side of inverters* in battery systems can be studied using the various methods that we discussed in Chapters 2 to 5. Measurements at the *DC side of inverters*, they can reveal some interesting information about the battery units.

7.1.6. Batteries

• **Example 7.5**: A battery pack that consists of three battery cells, as shown in Figure (a). The battery cells are connected in series.



• The battery cells are initially charged, and they are balanced. Then they are discharged and subsequently charged. The cell voltages during the discharge and charge cycle are shown in Figure (b).

7.1.6. Batteries

- **Example 7.5 (Cont.)**: The cell voltages are DC. Notice in Figure (b) that the *voltages quickly diverge during discharge*. For example, after about 1.5 hours, which is marked with an upward vertical arrow, the voltages at cells ①, ②, and ③ are measured at 3.231 V, 3.198 V, and 3.215 V.

- At the end of the discharge and charge cycle (i.e., one charge and one discharge), the voltages across the three cells are clearly unbalanced.

- Note: these battery cells are "used". They have aged differently over time. Their effective capacities are different, and they quickly lose balance in their state of charge after only one discharge and charge cycle.

- This condition results in an ineffective use of the battery cells. The battery pack needs to be *reconfigured* to increase its usable capacity [443].

Table of Contents

Table of Contents

7.2. Building Sensors

• Energy usage in buildings currently accounts for about 40% of the total energy usage in the United States [444].

• Electricity is the largest source of energy in buildings, currently accounting for nearly half of the total energy usage in buildings.

• Given the enormous amount of electric power that is consumed in buildings, smart building technologies and building energy management systems play an important role in developing a smart grid.

7.2. Building Sensors

• Recall from Section 5.6.3 that sub-metering can help with monitoring individual appliances or other individual load components in buildings.

• In this section, we will discuss examples of sensors and measurements that are not directly related to power system measurements, but may reveal additional information about different load types in a building, beyond what can be achieved by sub-metering.

•Such additional information may help us better characterize different building loads and also help better control different building loads in order to improve building energy consumption efficiency.

7.2. Building Sensors

7.2.1. Occupancy

• Occupancy sensors are widely used in building energy management, e.g., to control lighting or air conditioning.

• Different occupancy sensors work based on different principles.

• Some sensors detect movement. Some sensors detect heat, i.e., they measure infrared radiation from the human body.

• Other types of occupancy sensors include ultrasonic sensors that send high frequency sound waves into the area and check for their reflected patterns; see the survey in [448].

7.2. Building Sensors

7.2.1. Occupancy

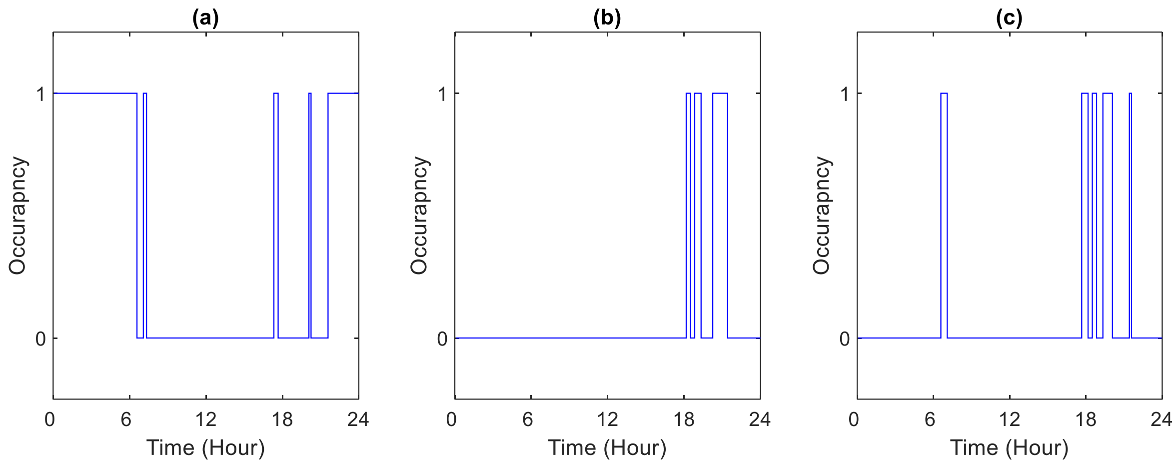
- The basic output of an occupancy sensor is a *binary* number:

  - *One* means occupied
  - *Zero* means not occupied.

- By recording the output of an occupancy sensor during the day, one can obtain the daily occupancy pattern in the area.

7.2.1. Occupancy

- Occupancy measurements in different rooms in a house on a weekday.



- The occupancy patterns are very different across different rooms. (a) The *bedroom* is occupied during the night and in early afternoon. (b) The *living room* is occupied occasionally. (c) The *kitchen* is occupied in the morning for breakfast and also in the evening around dinner time.

7.2. Building Sensors

7.2.1. Occupancy

• Occupancy measurements can be used to *control lighting*.

• The lights may turn on as soon as the room is detected as occupied; and the lights may turn off after a period of time that the room is detected as unoccupied. This simple mechanism can help reduce power consumption without affecting the building's occupants.

7.2. Building Sensors

7.2.1. Occupancy

- Occupancy measurements can be used also to *control air conditioning*.

- For example, in summer, the cooling set point can be set to 76°F (24°C) when the room is occupied and 78°F (25°C) when the room is not occupied. This can reduce power usage without affecting the occupants.

7.2. Building Sensors

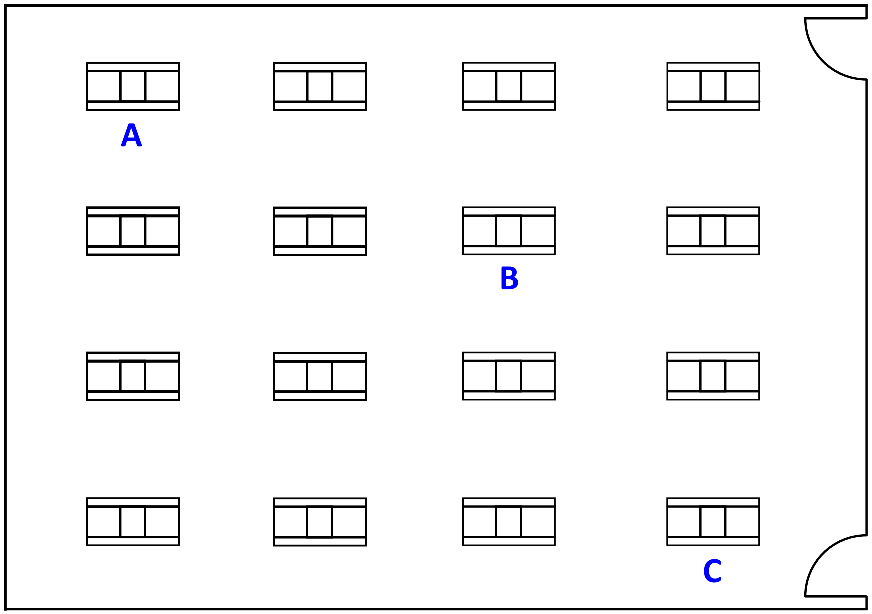
7.2.1. Occupancy

• **Zonal Occupancy Sensors**: A single occupancy sensor might be sufficient for a small room, such as in a single-family house. However, there are advantages to use multiple occupancy sensors in *large rooms*, such as in offices and commercial buildings, including large classrooms, libraries, and warehouses. Using multiple occupancy sensors can help *increase spatial granularity* in sensing occupancy.

• This may help with *fine-tuning zonal control* in a single room; for both lighting and air conditioning. It can also help with understanding zonal occupancy patterns; because *occupancy patterns* may not necessarily be the same across different areas in the same room.

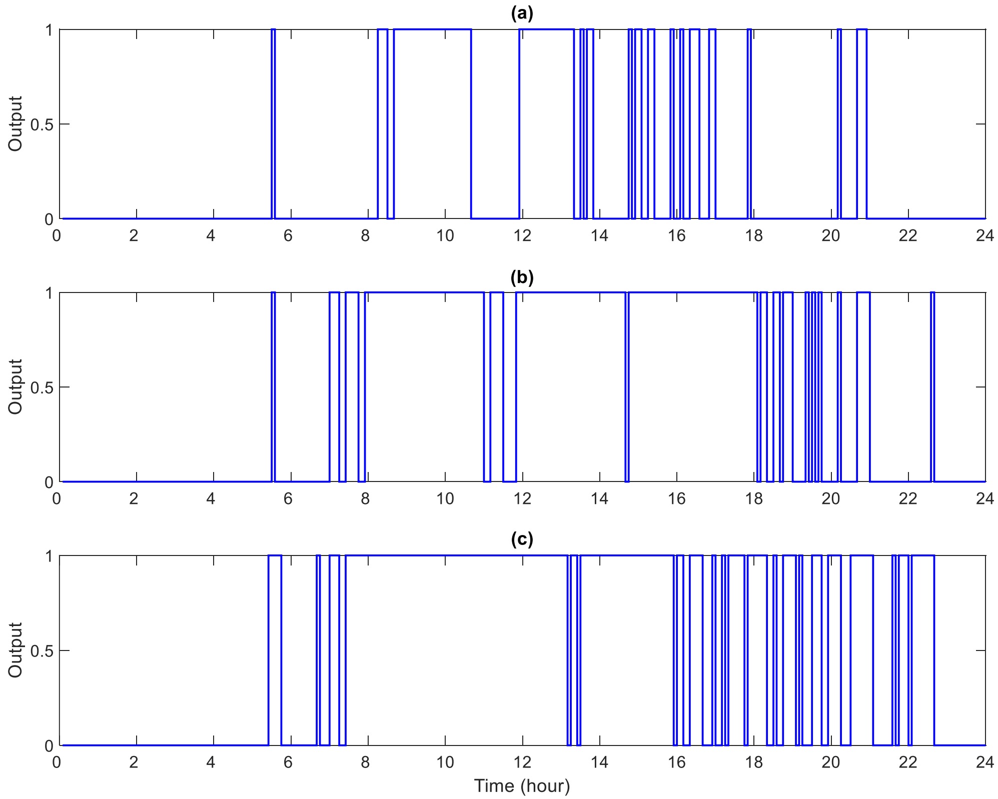
7.2.1. Occupancy

- **Example 7.7**: A classroom with the capacity of 100 college students. A total of 16 light fixtures are installed in this classroom, as shown below.



7.2.1. Occupancy

• **Example 7.7 (Cont.)**: The daily occupancy patterns of three sensors, denoted by A, B, and C, are shown in the figure on the next slide.



7.2. Building Sensors

7.2.1. Occupancy

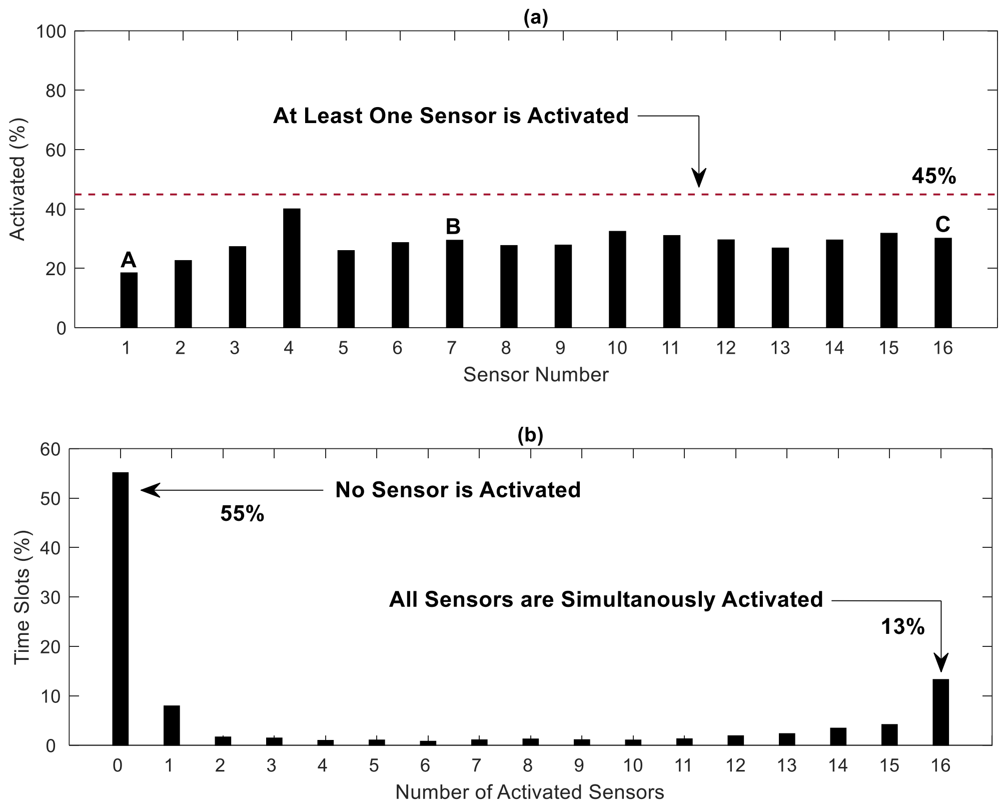
• **Example 7.7 (Cont.)**: Each lighting fixture has a built-in occupancy sensor of the type that is discussed in [449, 450].

• Occupancy is reported once every five minutes.

• We can see that, although the three sensors are in the same room, they detect *considerably different occupancy patterns*.

7.2.1. Occupancy

- Figure below shows a monthly summary of the occupancy measurements in the classroom in Example 7.7.



7.2. Building Sensors

7.2.1. Occupancy

- From Figure (a) on Slide 50, at least one sensor is activated, i.e., it detects occupancy, 45% of the time.

- However, only 13% of the time are all 16 sensors activated simultaneously; see Figure (b) on Slide 50.

- That means, 32% of the time, we need to turn on only a subset of the lights in this classroom.

7.2. Building Sensors

7.2.1. Occupancy

• **Occupancy Counter**: We may also need the *number of occupants* in a room. Such information can be used to model, predict, and minimize energy consumption, such as for air-conditioning systems.

• However, the number of occupants cannot be directly obtained from standard occupancy sensors. In fact, even if there are multiple occupancy sensors in a room, such as in Example 7.7, we still do not know whether there is a single person or multiple persons inside the coverage area of an occupancy sensor when it detects occupancy.

• Furthermore, it is possible that a single person causes multiple sensors in a room to detect occupancy, because *neighboring occupancy sensors may overlap* in their coverage areas.

7.2.1. Occupancy

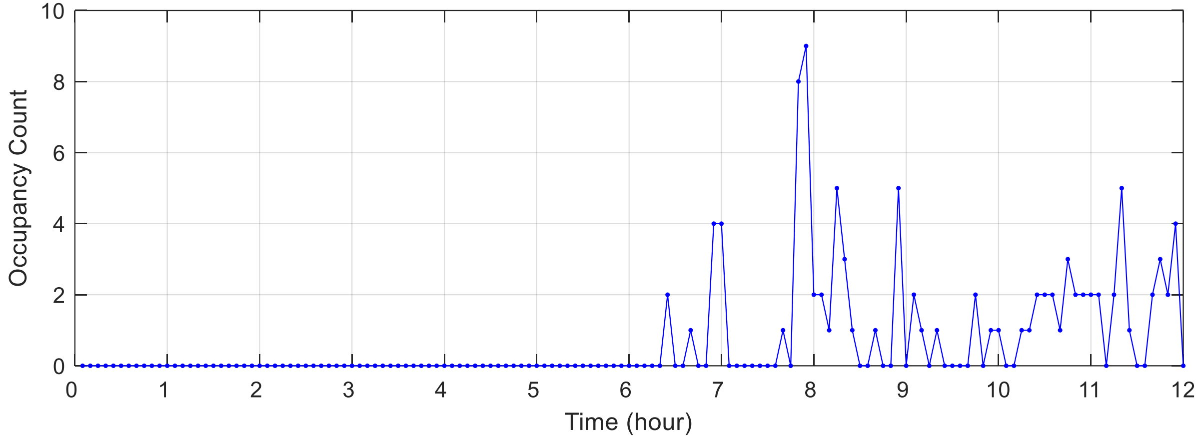
• **Occupancy Counter**: Therefore, in general, the number of occupants in a room is *not* equal to the number of activated occupancy sensors.

• There are sensors, known as occupancy counters, that count the number of occupants in a room; e.g., see the sensor in [451].

  • These sensors are often installed at the entrance and exit locations to keep track of the number of people that enter the room and the number of people that exit the room. The *difference* provides the occupancy count.

7.2.1. Occupancy

- **Example 7.8**: The output of an occupancy counter in a laboratory space in a university over a period of 12 hours, from midnight till noon.



- The output of the sensor is reported once every five minutes.
- The number of occupants fluctuates over time.
- The maximum recorded number of occupants is nine.

7.2. Building Sensors

7.2.1. Occupancy

- While the number of occupants can be counted explicitly using occupancy counters as in Example 7.8, there also exist methods to estimate the number of occupants by using data from the information and communication technology (ICT) systems.

    - Such as based on the number of WiFi connections; see [452].

7.2. Building Sensors

7.2.2. Temperature and Illuminance

• Measuring indoor temperature is widely used in building energy management systems to control heating, ventilation, and air conditioning (HVAC). The common practice is to have one or only a few temperature sensors in each room.

• However, there are new technologies that can support *spot temperate* measurements at *several locations in a room*.

• For example, some lighting fixtures can measure not only spot occupancy (see Section 7.2.1), but also spot temperature [453].

• Spot temperate measurements can be used to achieve *zonal control* in the HVAC system in order to improve building energy efficiency [338].

7.2.2. Temperature and Illuminance

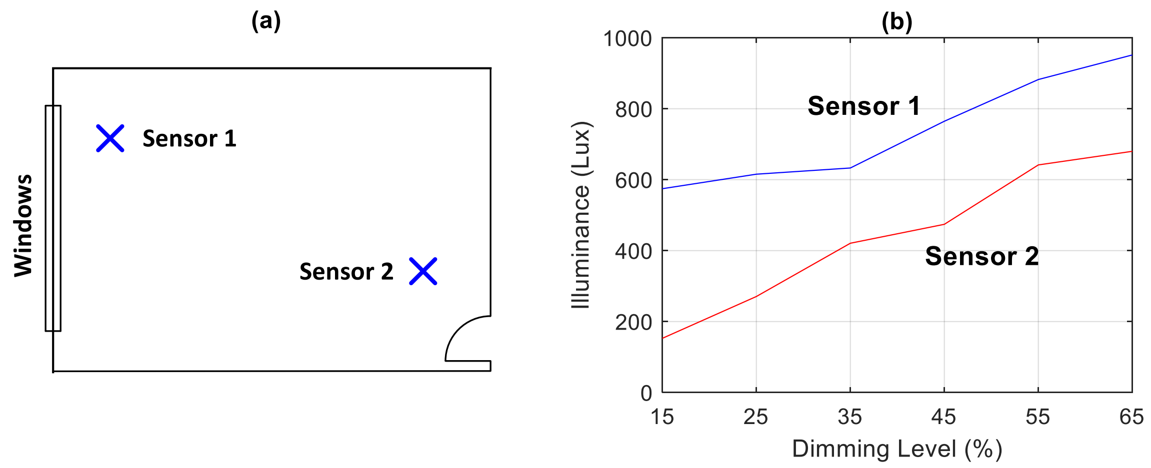
- Illuminance can be measured to improve daylight harvesting in buildings.

- By measuring illuminance at different locations in a room, we can do locational and time-of-day dimming control at different lighting fixtures.

- The lighting fixtures at the locations that are closer to ambient light sources, such as windows and skylights, can be set to reduce their light and reduce their power consumption, as we can see in Example 7.9.

7.2.2. Temperature and Illuminance

• **Example 7.9**: Consider a room as shown in Figure (a). The windows are in the back of the room. The room does not have skylight. Illuminance is measured in two locations, as marked on the figure.



• The illuminance measurements are done under different dimming levels of the ceiling lights in this room, as shown in Figure (b).

7.2.2. Temperature and Illuminance

- **Example 7.9 (Cont.)**: The two locations in the room receive different illuminance flux per unit area, as measured in lux.

- At all dimming levels, the illuminance at Location 1, which is close to the windows, is significantly higher than the illuminance at Location 2, which is far from the windows.

- Therefore, even if the entire room is occupied, one can improve building energy efficiency by lowering the dimming level at the lighting fixtures that are closer to the windows.

7.2. Building Sensors

7.2.3. Electric Vehicles

- Supporting EVs is one of the objectives of developing a smart grid [8, 9].

- On one hand, the growing number of EVs can significantly change the load on power distribution systems. This can require making upgrades in grid equipment and in the way that the power grid is operated [456].

- On the other hand, the energy storage capacity of EVs can support new smart grid concepts such as *vehicle-to-grid* (V2G) and *vehicle-to-building* (V2B); where a parked plugged-in EV is treated as an energy resource.

  - EVs can discharge their battery into the power grid or into a building's electric circuit, respectively [58–60, 457, 458].

7.2.3. Electric Vehicles

- Basic metering of the charge (and discharge) power is necessary in order to support the proper integration of EVs to a smart grid.

- This can be achieved by the sensors that we discussed in Chapter 5.

- However, there are also some measurements that are specific to EVs.

- For example, EV charging stations can record and report:

  - **Plug-in time**: the time when the EV is plugged in to charging station

  - **Plug-out time**: the time when the EV is plugged out, i.e., unplugged.

7.2.3. Electric Vehicles

• **Note**: plug-in time and plug-out time may not be obtained from power metering because an EV is necessarily charged (or discharged) for the entire time that it is parked and plugged in to the charging station.

• Therefore, such information must be specifically provided either by the charging station or the vehicle's charging control system.

7.2.3. Electric Vehicles

- **Example 7.10**: A charging station has four charging ports (1 to 4).

Port	Plug-in Time	Plug-out Time	Energy (kW)
1	7 : 51	9 : 51	7.17
4	7 : 53	9 : 11	8.01
2	8 : 02	8 : 57	5.58
3	8 : 06	10 : 20	7.29
2	8 : 59	11 : 02	12.45
4	9 : 22	11 : 12	11.34
1	9 : 57	12 : 12	6.15
3	10 : 21	11 : 43	4.46
4	11 : 22	13 : 20	12.09
2	11 : 55	16 : 09	13.78
1	12 : 37	14 : 49	2.58
3	12 : 49	16 : 42	9.90
4	14 : 22	16 : 40	6.73
1	14 : 55	17 : 18	3.53
3	17 : 16	19 : 12	6.44

7.2.3. Electric Vehicles

- **Example 7.10 (Cont.)**: The table on the previous slide showed the plug-in time, the plug-out time, and the total charged energy for all the EVs that are plugged into this charging station on a weekday.

- The first EV is plugged in at 7:51 AM.

- The last EV is plugged out at 7:12 PM.

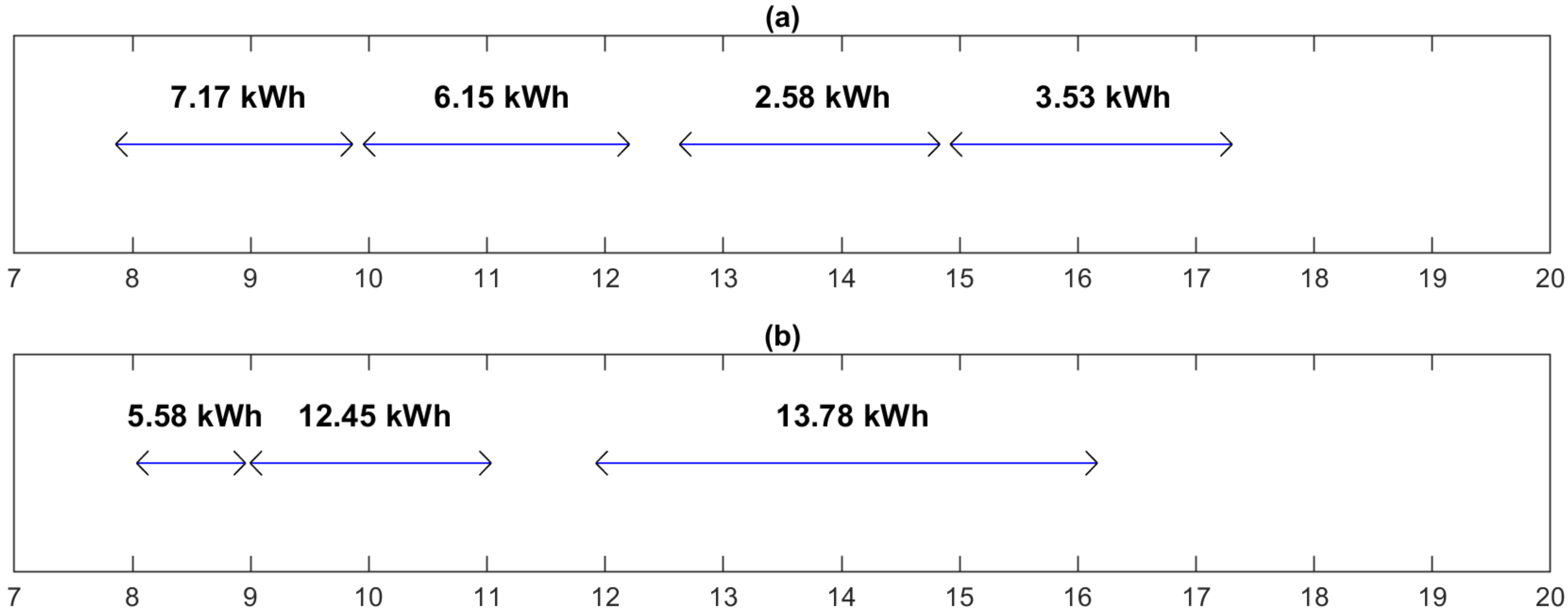
7.2.3. Electric Vehicles

- The measurements in the table in Example 7.10 can be used to *characterize and forecast* the load of the charging station; cf. [459, 460].

- These measurements can be used also to identify which EVs might be able to participate in a demand response (DR) program as a time-shiftable load; also see Section 5.4.1 in Chapter 5.

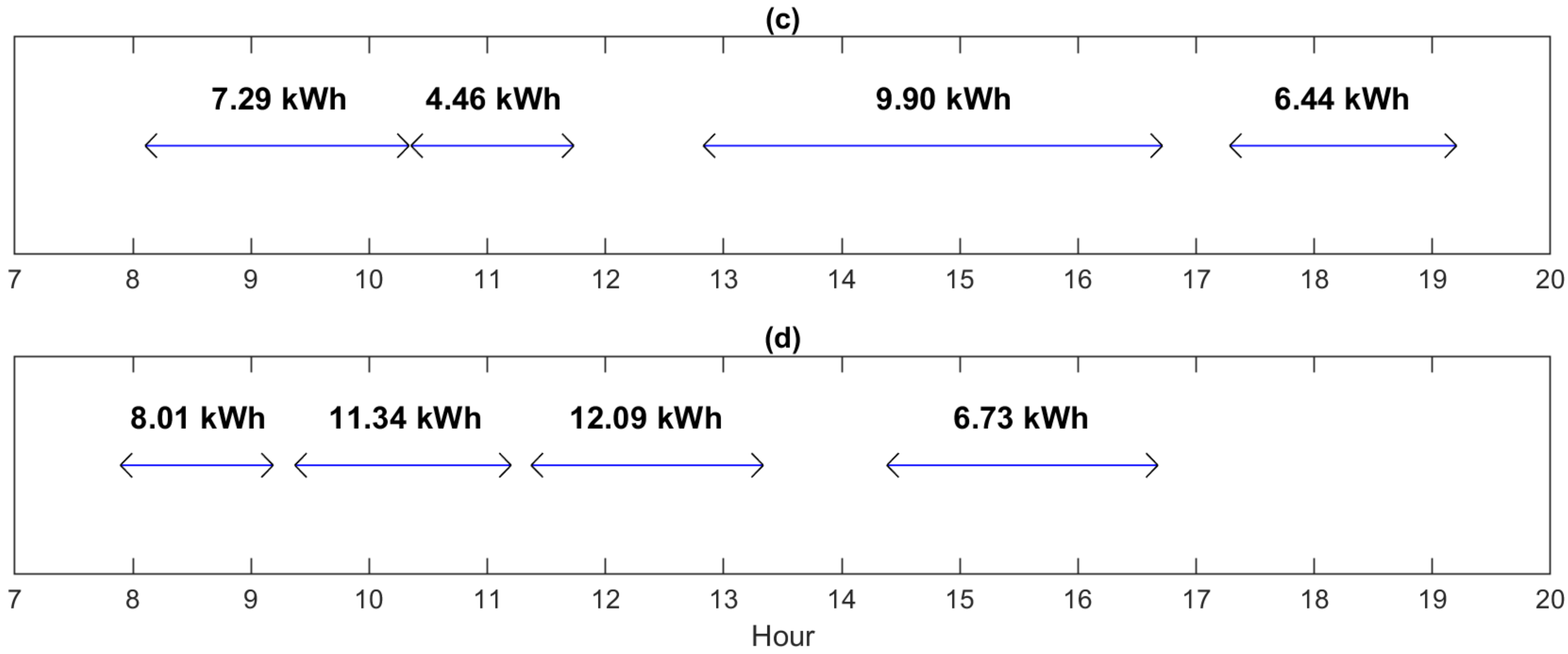
7.2.3. Electric Vehicles

- The measurements in the table on Slide 64 can be visualized as follows:



7.2.3. Electric Vehicles

- The measurements in the table on Slide 64 can be visualized as follows:



7.2.3. Electric Vehicles

- Here, each EV is represented by a two-sided arrow.

- The arrow *starts* at the plug-in time and ends at the plug-out time.

- The number on each arrow is the charged energy.

- Each sub-figure is associated with one of the four charging ports.

7.2.3. Electric Vehicles

• Let us now compare the second arrow in Figure (b) on Slide 67 with the third arrow in Figure (c) on Slide 68.

• The former represents an EV that charges more energy (12.45 kWh) but stays at the charging station for a shorter time (123 minutes).

• The latter represents an EV that charges less energy (9.90 kWh) but stays at the charging station for a longer period of time (233 minutes).

• Accordingly, the latter arrow represents an EV that is *more flexible* in its charging load. Such flexibility can be used in order to shift the actual charging task to the best point in time within the time frame during which the EV is plugged in to the charging station.

7.2. Building Sensors

7.2.3. Electric Vehicles

- **Example 7.11**: At the charging station in Example 7.10, consider the EV that was plugged in to Port 3 from 12:49 till 16:42.

- Suppose this EV is charged at 7.6 kW.

- Therefore, it takes 9.90 kWh / 7.6 kW = 1.3 hours, i.e., 1 hour and 18 minutes, to finish charging for this EV.

- Suppose the rate of electricity is 10.6 ¢/kWh from 10 AM till 3 PM; and 8.83 ¢/kWh from 3 PM till 6 PM.

7.2.3. Electric Vehicles

• **Example 7.11 (Cont.)**: If the EV is charged right after it is plugged in, i.e., from 12:49 till 14:08, then the cost of charging it becomes:

$$9.90 \times 10.6/100 = \$1.05.$$

• However, if the EV shifts its charging load to later in the afternoon, from 15:00 till 16:18, then the cost of charging becomes:

$$9.90 \times 8.83/100 = \$0.87.$$

• Note that, in both cases, the charging of this EV is completed by the time that the EV departs the charging station.

Table of Contents

Table of Contents

7.3. Financial Data

- Operation and planning in a smart grid can be affected not only by technical considerations but also by financial considerations.

- In this section, we overview some of the examples of financial data that can be useful in the field of smart grids.

7.3. Financial Data

7.3.1. Pricing and Billing

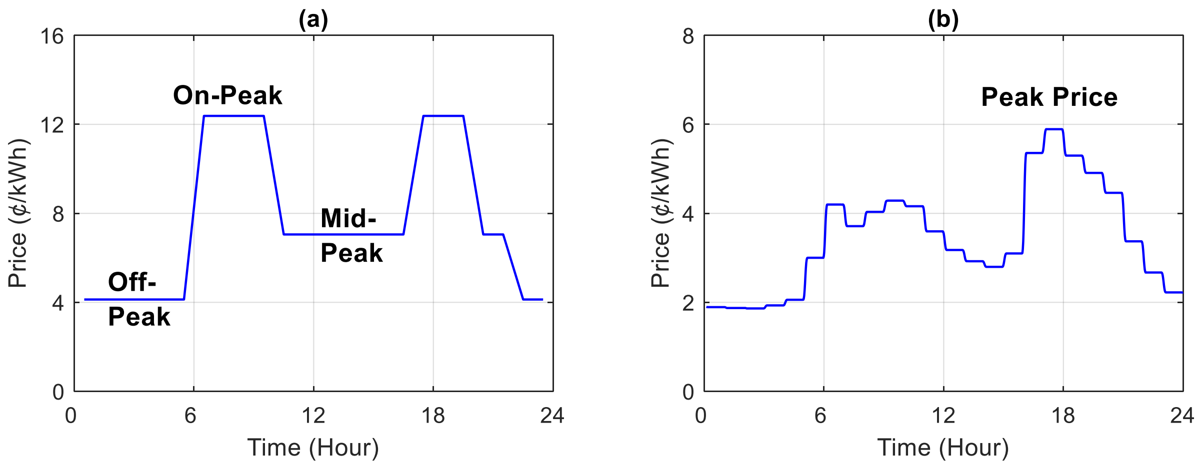
• Pricing data are important for electricity customers so that they can take actions to minimize their electricity cost.

• Moreover, pricing is also a mechanism for utilities to influence the behavior of electricity customers, such as encouraging them to shift some of their major load to off-peak hours.

• A wide range of pricing methods are used in practice. For example, we previously discussed *time-of-use pricing* in Section 5.4.1 in Chapter 5.

7.3.1. Pricing and Billing

• Under ToU pricing, electricity is most expensive during on-peak hours and least expensive during off-peak hours; e.g., see Figure (a) [461].



7.3. Financial Data

7.3.1. Pricing and Billing

- Another example is real-time pricing (RTP).

- Under RTP, price of electricity is more volatile, as it reflects the time-varying cost of generation more directly; see Figure (b) on Slide 77 [281].

  - The electrical prices under RTP are influenced by the prices in the wholesale electricity market (see Section 7.3.2).

7.3. Financial Data

7.3.1. Pricing and Billing

• Other financial data include billing information.

• Traditionally, at each month, the electricity bill shows the customer's electricity usage and the breakdown of the cost of electricity based on the pricing method being used by the utility.

7.3. Financial Data

7.3.1. Pricing and Billing

- **Example 7.12**: The monthly electricity bill for a commercial building:

	On-Peak Hours	Mid-Peak Hours	Off-Peak Hours
Energy (kWh)	5952	13056	25632
Peak Power (kW)	76.8	84.5	73.9

- ToU pricing is used by the utility with pre-determined on-peak hours, mid-peak hours, and off-peak hours. The customer is charged not only for its energy usage in kWh, but also for its peak power usage in kW.

7.3. Financial Data

7.3.1. Pricing and Billing

• In addition to serving the purpose of billing the customer, billing data could be used for power system operation; such as in form of *pseudo-measurements* in distribution system state estimation; cf. [462, 463].

• If smart meters are installed, then they provide even more details about the energy usage of the consumers.

  • See Section 5.4 in Chapter 5 for further discussion.

7.3. Financial Data

7.3.2. Electricity Market

• Many regions in the U.S. and across the world operate competitive wholesale markets for electricity. The markets are often operated by Independent System Operators (ISOs), such as the California ISO [464].

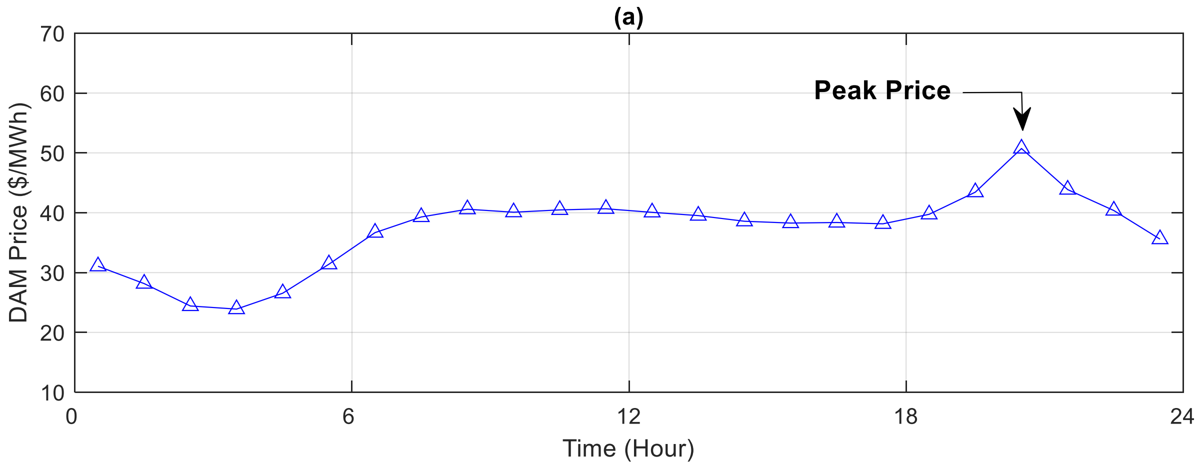
• In a wholesale electricity market, the prices for electricity change periodically, such as once every hour or even once every five minutes, according to factors such as demand, generation cost, and more recently the wind and solar generation levels.

7.3.2. Electricity Market

• Many ISOs manage electricity markets in two settlements, such as a day-ahead market (DAM) and a real-time market (RTM). In each settlement of the market, the ISO processes the demand bids and the supply bids that are submitted by the market participants, such as utilities and power plants, respectively; accordingly, the ISO determines the prices of the electricity. The price of electricity may vary depending on the location and the grid operation conditions.

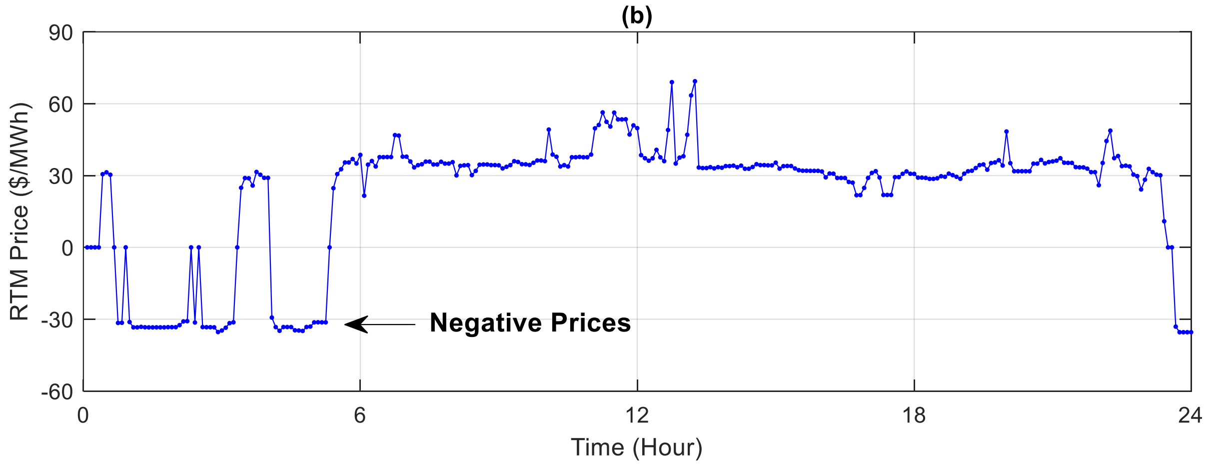
7.3.2. Electricity Market

- **Example 7.13**: The DAM prices are determined once every hour, as shown in Figure (a). The prices are lower after midnight when the demand is low and higher in the evening when the demand is high.



7.3.2. Electricity Market

• **Example 7.13 (Cont.)**: The RTM prices are determined once every five minutes. The RTM prices are much more volatile; since they directly reflect the minutely changes in the load and generation conditions. Occasionally, RTM prices become negative, as marked on the figure.



7.3.2. Electricity Market

• Both DAM prices and RTM prices are often determined by ISOs in the form of locational marginal prices (LMPs), which can be different at different buses across the power transmission system.

• For example, consider the three different buses that are marked on the map of California in Figure (a) on Slide 88, namely Davis in the north, Huron in the center, and Chino in the south. The LMPs in the DAM during a day in July are shown in Figure (b) on Slide 88.

7.3. Financial Data

7.3.2. Electricity Market

- We can see that the prices are similar at night and in early morning; however, they start diverging from each other during the afternoon because of the different conditions in the market at different locations, before they converge again to similar amounts later in the evening.

7.3.2. Electricity Market

- **Example 7.13**: Changes in the price of electricity during a day in early May in the wholesale electricity market that is operated by California ISO:

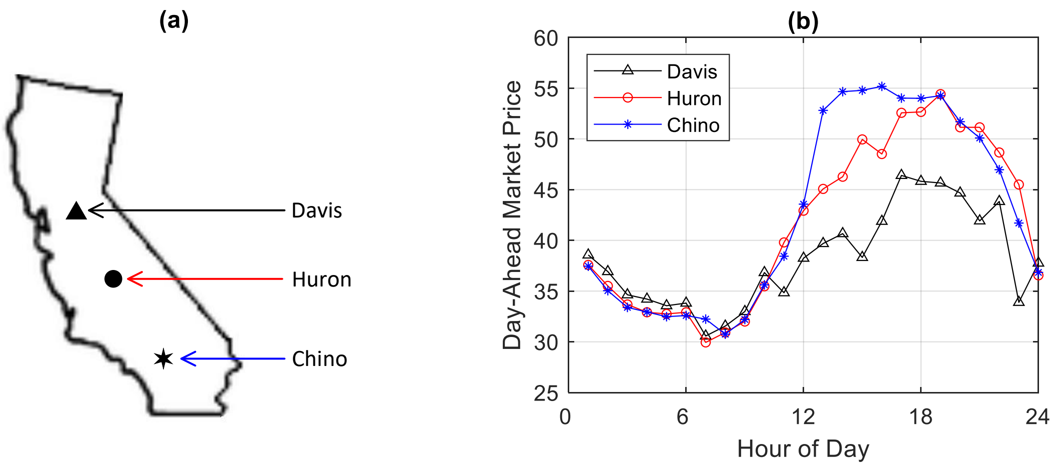


Table of Contents

Table of Contents

7.4. Images, LIDARs, Drones, and Robots

- The field of smart grid sensors is broad and growing rapidly.

- There are sensor technologies that are borrowed from other fields, but they have proved to be useful in the field of smart grids.

- In this section we briefly overview some of these technologies and their existing applications in smart grid monitoring.

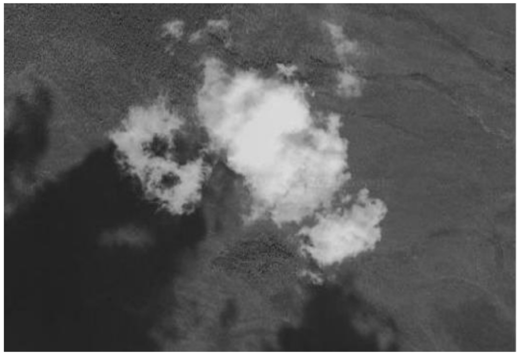
7.4. Images, LIDARs, Drones, and Robots

7.4.1. Images

- Different types of images may have applications in the smart grids.

- For example, satellite images can be used to monitor clouds:

(a)



- Cloud images can be used to enhance solar production forecasting [467].

7.4. Images, LIDARs, Drones, and Robots

7.4.1. Images

- By analyzing cloud movements in cloud images, one can significantly enhance short-term forecasting of the drop in solar production level that is caused at each PV location due to temporary cloud cover.

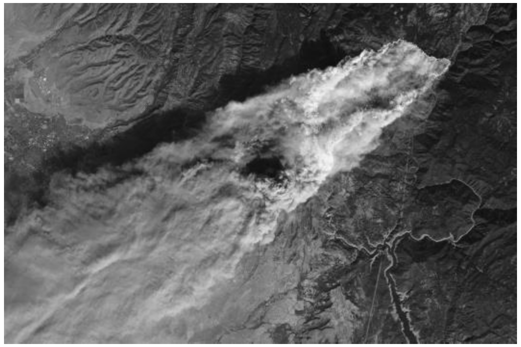
- Such analysis can help the grid operator to cope better with the intermittency in solar power generation.

7.4. Images, LIDARs, Drones, and Robots

7.4.1. Images

• Satellite images can also be used to detect and monitor wildfire:

(b)



•. Recall from Example 4.15 in Chapter 4 that a wildfire near transmission lines and other grid assets can cause major disruptions with cascading impacts across the power system.

7.4. Images, LIDARs, Drones, and Robots

7.4.1. Images

• By analyzing which transmission lines are likely to be impacted by within the next few minutes, the grid operator will have enough time to conduct proper grid reconfiguration, prevent unintended automated protection system triggering, or conduct other remedial actions.

• Even if satellite images are not available, one can still use ground-based images as an alternative in certain applications.

• For example, ground-based sky imaging can also be used to analyze cloud coverage to enhance short-term forecasting at solar PV sites.

• An example for ground-based sky imaging is given in Exercise 7.14.

7.4. Images, LIDARs, Drones, and Robots

7.4.1. Images

- Different types of images may have applications in the smart grids.

- For example, satellite images can be used to monitor clouds, as shown in Figure (a). Cloud images can be used to enhance solar production forecasting [467]. By analyzing cloud movements in cloud images, one can significantly enhance short-term forecasting of the drop in solar production level that is caused at each PV location due to temporary cloud cover. Such analysis can help the grid operator to cope better with the intermittency in solar power generation.

7.4. Images, LIDARs, Drones, and Robots

7.4.1. Images

• Given the low cost of ground-based sky imaging, there have been several recent studies in this area, such as on developing a network of cameras at different locations and facing different directions; see [470].

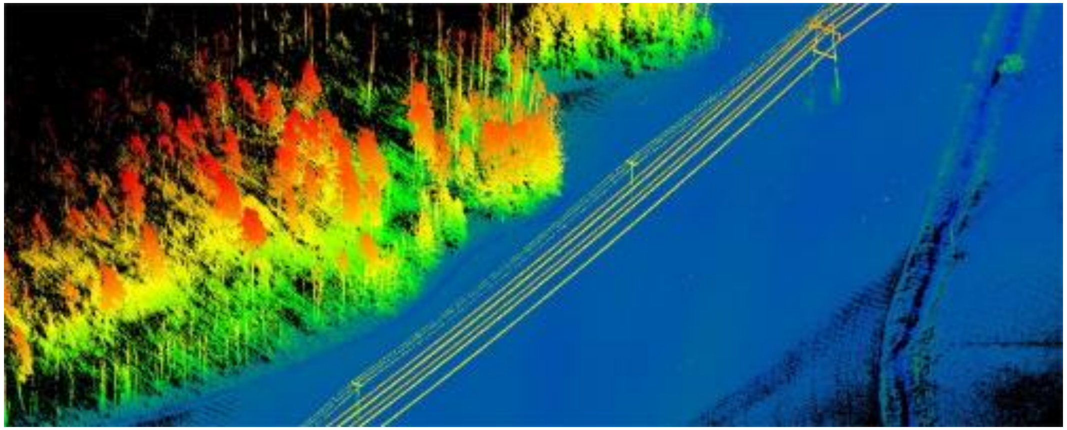
• Other existing applications of images in the field of smart grids include asset health monitoring [471] and physical security monitoring [472].

7.4. Images, LIDARs, Drones, and Robots

7.4.2. LIDARs

• Light Detection and Ranging (LiDAR), or LIDAR, is a remote sensing technology that uses laser beams to measure distance to various objects. LIDAR images can be used to understand the surrounding environment.

• LIDAR-derived imaging is used in recent years to monitor transmission line corridors, to obtain images such as the one shown below.



7.4.2. LIDARs

• LIDAR images can be used to detect different types of damage in poles and towers and line conductors, not only during routine inspections but also particularly after a storm or an earthquake or other natural disasters to quickly identify the damaged components.

7.4. Images, LIDARs, Drones, and Robots

7.4.3. Drones and Robots

- The LIDAR-derived image that we saw on Slide 98 was obtained by an Unmanned Aerial Vehicle (UAV), also known as a drone.

- Drones can be used to monitor electrical infrastructure, such as power lines, by capturing regular aerial images [476], LIDAR-derived images [477], or even infrared thermal images [478].

- While drones are used for *aerial monitoring*, other robotics technologies can be used, for example, to *monitor underground cables*; cf. [479]. Autonomous robotic technologies can also be used for maintenance of power system components [480, 481]. A summary of the recent robotics applications in power systems is available in [482-484].

Table of Contents

Table of Contents

7.5. Other Off-Domain Measurements

- Many smart grid technologies rely on off-domain measurements, i.e., the measurements that are *not primarily intended for the power sector*.

- For instance, *weather data* or data from the National Lightning Detection Network and Geographic Information System (GIS) can enhance power system operations at different levels and time scales; cf. [485, 486].

- Ambient temperature data is a prominent example of weather data that is used for load forecasting, due to its impact on cooling and heating loads.

- Other types of weather data that are commonly used in smart grid applications include wind speed and solar irradiation, which are used for wind power integration and solar power integration, respectively.

7.5. Other Off-Domain Measurements

- *Traffic data* has applications in EV load forecasting or location selection and planning of EV charging stations [488–490].

- Another example of off-domain measurements is data from *social media* to learn customer behavior or identify and engage customers in energy efficiency programs; see some examples in [491, 492].

- There could be other forms of off-domain data that are yet to be explored to identify their relevance and usefulness in smart grid applications.

- There is no limit on the possibilities of the intelligence that can be brought to operation and planning of power systems from all data sources.