Chapter 1

Introduction

Consumers expect electrical energy to be available whenever it is required, be it for charging a mobile phone or their electric vehicle, running kitchen appliances or office copiers, or for indoor climate control using individual air-conditioners or huge chilling units. But, rapidly growing energy demand and the dependency on fossil sources to meet the gross as well as peak demand have raised concerns over poor quality of service (occurrences of black-outs, brown-outs and load shedding), depletion of resources and impact on the environment. Even major developed economies, such as the USA, have experienced major power outages over the past decade [Amin (2007)]. The catastrophic blackout that India experienced in August 2012, which left more than 500 million people without electricity and basic amenities for several days, serves as a reminder of the urgency of acting on this challenge.

> Energy management is all about making energy available whenever it is demanded by the consumers in order to maintain certain quality of life and sustain growth to meet the human development goals.
> Energy management requires monitoring, controlling, and optimizing the performance of all the elements of the electric grid in order to provide the required energy of desired quality to the consumers.

Due to our desire to improve and maintain a certain quality of the environment in our homes and offices, not only is the demand for energy by buildings growing rapidly, but also the need for more robust systems for energy generation, transmission and supply to the end-user. Therefore, consumption, predictability of consumption, users' participation in the demand-response control are all going to play a big role in overall energy management. While the consumption in the industry can largely be reduced by improvement in the processes that results in efficient energy usage, current research shows that about 40% of the energy demand comes from buildings and there exists considerable scope for reduction in consumption and peak power demand. Both the overall consumption and the level of peak demand affect the electric grid and its performance — economic as well as electrical. For example, about 20% of the generating capacities exist in a power grid to meet the peak demand, which is used only 5% of the time [Farhangi (2010)]. In practice, quick-responding oil/gas fired based generating sources and hydroelectric plants are brought in to satisfy the peak demand. This is because they can be started within minutes and ramped up or down quickly to meet spikes in demand or sudden changes in the loads. While oil/gas turbine sources are inefficient and costly, the hydro generating sources have their own disadvantages — due to impact on the environment in terms of ill-effects on the land, impact on wild life, causing or aggravating flood situations. Therefore, the demand of the day is making both the grid and the buildings smarter by leveraging the recent developments in information and communication technology (ICT) making the sensors, actuators and the controllers smart.

The transitioning of existing electrical grids to “smart grids” involves a process that requires replacement of aging grid components, integration of renewable energy sources and energy buffering solutions, for example, storing excess energy in batteries, widespread deployment of sensors and actuators, and automating grid management using distributed Information and Communication Technology (ICT) systems [DOE 2012, Smart Grid Policy]. Concurrently, there has been an increasing focus on developing new technologies that will provide for a more sustainable future for our society. Since a significant portion of global energy use (and more specifically electricity use) continues to depend on traditional sources such as coal and natural gas, the use of novel ICT methods for the “greening of energy” has emerged as an important research area.

This is evident from two broad technology trends. First, there is a trend towards making the electric grid smarter, greener and more efficient. What makes a grid smart is the way this balance between demand and generation is maintained, mainly due to the focus on automatic detection of the imbalance between transmission and distribution and taking *preventive* actions rather than taking just *protective* actions against system failures. Whether a grid is smart or conventional, power generation, transmission and consumption must be kept in perfect balance in the system. Any imbalance will cause disruption in the quality of electricity supply in the form of blackouts, brownouts or load shedding.

We begin this chapter with an introduction to energy management we examine the fundamental characteristics of Energy management systems, introduce the basic terms, provide the necessary background and present the concepts related to energy. The need for a data and computation driven approach to energy management is motivated next. We end this chapter with a look at how the rest of this monograph is structured. In the process, we present our motivation behind writing this monograph and how readers can benefit the most from it.

1.1 SMART Systems

There is enormous excitement about synthesizing and benefiting from numerous technologies, including net metering, demand-response (D-R), distributed generation from intermittent sources such as solar and wind, active control of power flows, enhanced storage capabilities, and micro-grids. Additionally, since building energy use represents a significant fraction of total energy expenditures, a second trend is the design of smart residential and office buildings. These have the ability to interface with the smart grid and regulate their energy footprint, reduce peak consumption, incorporate local renewable energy sources and participate in demand-response techniques. The electric grid that results from these steps is said to be `smart`.

Consider a digital temperature sensor (a smart device — more than a simple sensor), senses the temperature of the surrounding atmosphere through its sensor (e.g., thermistor or thermocouple), its ADC (analog-to-digital-converter) circuitry samples (with the help of a processor — usually a microcontroller) the sensor's analog voltage output with some specified frequency and produces a digital value, computes/processes the digital data to find the equivalent temperature value and finally responds either with a display of the temperature on the LCD or sends data over the network. This device can also analyze the digital temperature data and compare it with a set value to generate an alarm if the temperature goes beyond the set limit. Here, we are essentially tracking the temperature and taking some simple actions.

For a more dramatic example, one with a lot of complexity, consider the systematic and fast evacuation of people during an emergency like fire, floods, etc., a significant concern in modern society. With the increased threat of attacks by miscreants, this has become even more important.

The problem has many dimensions. In case of fire and bombs in a building, the need is to quickly move people to the exits. In case of floods and water logging in a city/village due to disasters like Tsunami, people have to be moved to safe zones of the city/village. Since human life depends on the success of evacuation planning, a Smart Building Evacuation Planning System is required, which will help the building managers to evacuate people efficiently and systematically during an emergency such as scare, fires and terrorist attacks. In this case, sensors are deployed in the building to determine if a threat exists (such as a fire alarm). It will also use sensors to estimate the number of people present in the rooms and corridors of the building. We must also take into account the behavior of people during an emergency. Based on such information and the floor plans of the building, the system will suggest the routes that should be followed by building users during evacuations. Routes can be displayed using people's mobile phones, display boards and other notification mechanisms. The system is constantly executing the sense meaningfully–analyze–respond timely cycle until it is known that it has no more work to do, i.e., nobody is known to remain in the building.

In this example, we are sensing the environment carefully to determine whether or where humans may be present in the building, then depending on where people have been spotted we analyze possible solutions to choose the route for each person. We can extend such a building evacuation planning system to evacuate entire regions and cities. Of course, the scale of such an evacuation process will require highly efficient and scalable algorithms, along with low-cost and precise sensor technology.

Thus, a careful examination of the working of smart systems/devices/appliances reveals that they have a certain pattern in their behaviour: a device meaningfully senses the parameter that informs the system about the current state of interest, analyzes the sensed value (often after some processing) to help in decision making and finally produces a timely response, which can be a decision or a value. Let us look at the three phases that embody a smart system.

1.1.1 *Sense, Meaningfully*

Smartness of any control and monitoring system comes from accurate sensing of the environment and timely delivery of sensed data to the analytics subsystem for additional processing, analysis, control and further action. Sensor driven building management is motivated by goals like reducing and optimizing power consumption, monitoring the health of the building appliances, maintaining quality of the atmosphere in the building and tracking occupants in various parts of the building (useful for building safety and emergency evacuation), to name a few. Different sensing and inferencing mechanisms are used to obtain the observations pertaining to different facets of the building.

The accuracy of sensed data and latency of communicating it to applications determine the quality of service (QoS) of a system. The accuracy of sensing may be affected by faulty or biased sensors while timely delivery may be affected by queuing and processing of increased data traffic in the communication and computing infrastructure. Feeding inaccurate data for analytics or exceeding the latency bounds affects the performance of applications and thereby the reliability and responsiveness of the system. In practice, there is a tendency to over-provision sensors under the rationale that the more the data the more informed the decisions will be. Meaningful sensing relates to judicious sensing that ensures correct and timely decisions. Inaccuracy, unnecessary duplication or delays in sensing can make sensed values and hence decisions based on them meaningless.

A network of sensors is usually set up in the building by a BMS to obtain the information of interest. But installing these sensors in different parts of the building can a) be tedious and expensive b) cause inconvenience to the users c) increase the payback period and, d) affect the aesthetics of the building.

The fact that a sensor, suitable for observing a particular parameter, may in turn help to infer other parameters can be exploited to reduce the number of physical sensors deployed in a building. Similarly, inferences that are enabled by exploiting the structure of the building or the formal relationship between parameters, can lead to a better utilization of sensory resources.

1.1.2 *Analyze*

Analysis of the data sensed by the smart system has two major manifestations. One is based on archival or historical data. Another is on data pertaining to the prevailing situation. Given the online nature of decision making, i.e., we decide what is to be done in response to some real-world event, when the event happens, the response time is limited and hence we cannot always expect our choice of solutions to be optimal. Hence, often, to reduce the reaction or response time, the system analyzes the many possible solutions; the system state in which a particular solution will be appropriate will be analyzed and remembered by the system. When a real-time event occurs, the state that prevails then dictates the choice made.

1.1.3 *Respond, Timely*

Response is the action taken by the user or the system itself based on the analysis of the sensed data. Most "situations", unless reacted to in time, will escalate. Hence the response of the system should be timely, many of the situations will have timeliness related requirements (e.g., deadlines) attached to them.

Because of the above characteristics of the sense-analyze-respond cycle, in many scenarios, special purpose hardware is designed for one or more of the three phases.

Sense **M**eaningfully, **A**nalyze and **R**espond **T**imely

Aficionados of the English language will balk at the last part of this phrase. Still, we like to use this acronym given that it is very effective and *a propos*.

A SMART approach results when we have a smart control and monitoring system whose tasks will depend on the dynamics of the environment and whose responses are also situation dependent. Neither can be fully characterized statically (i.e., just a table lookup is insufficient to decide what to do at run time). Clearly, use of data from sensors to obtain situational awareness — state of both the environment as well as the system (resources) — is essential for meeting the challenges of such systems. Another crucial element is the synergy between the physical world and the ICT or cyber world.

What makes a grid smart is the way this balance between demand and generation is maintained, mainly due to the focus on automatic detection of the imbalance between transmission and distribution and taking *preventive* actions rather than taking just *protective* actions against system failures.

1.2 Computational Techniques in Energy Management

Computational Techniques in Smart Energy Management

The important concepts that have been borrowed from the domain of computer science in solving energy management problems and discussed in this monograph include the following.

- Real-time data communication and processing,
- scheduling,
- logic,
- algorithms,
- patterns,
- abstraction,
- optimization and
- machine learning.

It is interesting to note that a number of concepts from computer science inform us about how to solve some of the smart energy management problems. The example of an intrinsic computer science problem that finds its direct application in energy management is the communication and processing of huge amount of electrical grid data (voltage and current phasors and frequencies of the large number of interconnected buses geographically distributed over large distances) in *real-time*. This is essential for assessing the health of (the elements) in the grid and taking corrective actions in real-time (in the event of fault or excessive overload) so that blackouts and possible grid failure can be avoided.

The important concepts that can be borrowed from the domain of computer science in solving energy management problems include, i) Real-time data communication and processing, ii) scheduling, iii) logic, iv) algorithms, v) patterns, vi) abstraction, vii) optimization and viii) machine learning. Glimpses of applications of a few of these concepts follow.

As already mentioned, critical *real-time* grid monitoring applications require high data rate and strict latency. This demands designing of efficient query processing techniques that allow flexible bandwidth sharing among the applications.

Patterns can be observed in the energy consumption in homes/buildings due to appliances like air-conditioners (AC), washing machines and dishwashers. In case of on-off controlled ACs, the peak energy demand can be shaved by *scheduling* the operation of these appliances without compromising the thermal comfort requirement of the consumers. However, this requires *feasibility analysis* — derived from simple physics-based thermal models and *abstractions* of the building spaces with HVAC and *algorithms* for run-time control.

The consumption patterns of the appliances can also be used for non-intrusive load monitoring and finding the prevailing power usage. This information can be used for automatic intervention to achieve more economic use of these appliances by adjusting their time of operation. Inferencing *Logic* can be utilized as *soft sensors*, which can help in minimizing the number of physical or *hard* sensors. For example, from the temperature and RFID data of the occupants, the power consumption owing to ACs can be inferred. In case of deficiency in generation, power can be distributed *optimally* to the consumers using brownouts (rationing the available power to the loads based on their criticality/urgency of requirement for uninterrupted supply) instead of the existing practice of rolling blackouts. *Machine learning* techniques can be used for customizing the schedule-based HVAC control in commercial buildings based on dynamic adaptation of occupancy patterns.

In subsequent parts of this monograph, we illustrate the application of of the computational techniques used for solving problems in energy management.

1.3 Smart Electric Grid

In this section we will take a brief look at the inadequacies of the traditional grid and show how the modern smart grid is being designed to overcome these.

1.3.1 *The Grid of the Last 100 Years*

Historically, the electric grid has served as a common interconnection network connecting power generators with consumers. At any instance of time, all the generated electricity is consumed entirely. In other words, balance is always maintained between the amount of generation and consumption.

Generators are interconnected through a network of power transmission lines so that electricity reaches the consumer with the highest level of availability via these distribution lines. The grid can be viewed as a network of power transmission lines equivalent to links with generators as nodes.

The distribution lines facilitate tapping of electricity at various points on the *infinite bus*, namely, the grid, and make power available to consumers, both industrial and domestic.

The interesting property of the *infinite bus* is that ideally the electrical parameters, the voltage and frequency, of the grid remain unaffected even with changes in the electrical load connected to it. This is a necessity given that the loads are designed for particular voltage and frequency and their performance depends on the stability of these two electrical parameters. But, this does not mean that any amount of load can be connected or disconnected to the grid any time. The grid can accommodate fluctuations in load within its designed capacity. The stability of a grid under load fluctuations is briefly introduced in Chapter 2 and discussed with relevant details in Appendix B. Further, electrical loads consume two kinds of power: *real* and *reactive* (discussed in Appendix A) and therefore grid has to supply both types of power.

1.3.2 *Balancing Generation and Consumption*

Generation, transmission and consumption are to be kept in perfect balance in the electrical grid — smart or conventional. Any imbalance will cause disruption in the quality of electricity supply in the form of blackouts, brownouts or load shedding. The good old grid system is no longer adequate to meet the present requirements — mainly in i) offering support to diverse and large distributed generation, ii) monitoring grid health by handling large volume of data in real-time so that faults can be prevented, rather than mitigated and iii) facilitating consumers' participation in demand-response (D-R) control.

What makes a grid smart is the way this balance between demand and generation is maintained, mainly due to the focus on the automatic detection of transmission and distribution imbalance and taking *preventive* action rather than taking only *protective* action to system faults.

> In the *electric grid* balance between generation and consumption is maintained at all times. An imbalance can cause disruption in the quality of electricity supply resulting in blackouts, brownouts or load shedding. This balance between generation and consumption is a prerequisite for *normal* state of a grid.

1.3.3 *Peak Demand versus Aggregate Demand*

The demand for energy varies widely during the day. During certain hours in the morning and evening, demand is very high; such times are referred to as *peak* demand hours. Demand can become high during certain seasons like summer in tropical countries and winter in cold countries. Further, statistically, there can be sudden rise in demand in a grid with huge consumer base. In order to meet the peak demands, utilities must have provisions for additional generating capacities. Base load is managed by nuclear power plants and large thermal plants. But these cannot be brought in to meet sudden rise in demand, as it can take hours for them to start-up and get ready to be synchronized with the grid.

We have already discussed that quick-responding oil/gas fired generating sources and hydroelectric plants brought in to meet the peak demand are less economical and more hazardous for the environment. Thus most of the utilities penalize the consumers, especially bulk consumers by charging higher tariff during peak hours. Therefore, flattening of peak demand is a need for improving economic efficiency.

Smart Energy Management Tasks

- Providing power to consumers, ensuring quality — with greater availability at a lower cost.
- Enabling energy conservation — to decelerate the depletion of nonrenewable resources.
- Reducing the dependence on unsustainable energy sources — by avoiding unnecessary consumption.
- Increasing the use of sustainable energy sources — by exploiting renewables and finding ways to store excess energy from the sun or wind during periods of low consumption.
- Achieve peak shaving — by staggering loads or by scheduling appliances at the right times.
- Ensuring user convenience or comfort by automating tasks, providing timely feedback, or ensuring a comfortable environment.
- Incentivise users to become more energy efficient and adopt a more sustainable lifestyle.

Smart Energy management tasks require up-to-date information about the power required at a certain point in time, both for satisfying what is needed at that time instant and also for informed planning for the future. Which energy source to use should be decided for each customer or group of customers so that available energy is used optimally at all times, reducing collateral damage to the environment and providing energy of acceptable quality to all consumers. This implies that a "one size fits all" mindset or static decisions based solutions to energy management will not suffice. The disadvantages of the traditional approach to grid operations and energy management are further exacerbated by the inclusion of renewables in the source mix and the blurring of the classical distinctions between energy producers and consumers.

All of these imply the need for decisions based on knowledge about the current state of all the elements of the electric grid: Consumers, producers, and the interactions between them. This knowledge comes from the data made available from sensors embedded throughout the grid.

A smart grid uses the data available, from Phasor Measurement Units (PMU), to detect transmission and distribution imbalance vis-à-vis generation, overload conditions and takes *preventive* actions.

It exploits sensing, embedded processing and digital communications to enable the electricity grid to be

- *observable* (able to be measured and visualised),
- *controllable* (allowing it to be manipulated and optimised),
- *automated* (able to adapt and self-heal) and
- *fully integrated* (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources).

From what we have said thus far, we need up-to-date data to make the grid smart.

For example, QoS requirements for various grid applications demand data dissemination with timeliness guarantees. In addition, we also need all the consumers to be smart, that is, use the energy (made available to them) in a smart manner, and should design the generation decisions so as to be smart.

1.3.4 *Conventional Grid versus Smart Grid*

From the above discussion, it is clear that the scope of smart grids is very wide and therefore a short yet complete definition of smart grids is not easy. This is evident from the following definitions from the Joint Report [Giordano and Bossart (2012)] of European Commission (EC), JRC and US-Department of Energy titled "Assessing Smart Grid Benefits and Impacts: EU and U.S. Initiatives, 2012".

According to EC [EC Task Force for Smart Grids, 2010a],

A Smart Grid is "an electricity network that can intelligently integrate the behaviour and actions of all users connected to it — generators, consumers and those that do both — in order to efficiently ensure sustainable, economic and secure electricity supply".

According to the U.S. Department of Energy:

A smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electrical system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources.

Table 1.1 summarizes the key differences between the conventional grid and a smart grid. We will return to a more elaborate treatment of the smart grid in Chapter 2.

Table 1.1 Comparison between conventional grid and smart grid.

Topic	**Conventional Grid**	**Smart Grid**
Approach to power system faults	Detection and mitigation with a focus on protection of equipment	Focus is on prevention of fault by detecting emerging fault situations rather than responding only to the manifested faults.
System Monitoring and Control	Monitoring of grid health is limited to small number of large power plants and no real-time information for adaptive protection.	WAMS (Wide Area Measurement System) enabled by ICT to convey real-time information for improved monitoring and almost instantaneous stability of supply and demand on the grid.
Integration of renewable generation	Not equipped to support Distributed Energy Resources (DER)	Supports diverse and distributed generations with a focus on renewable resources
Power Quality (PQ)	PQ mostly neglected with focus on minimizing outages	Ability to identify and resolve PQ issues like voltage fluctuations, interruptions, waveform distortions prior to manifestation.
Consumers participation	Uninformed Consumers have no role to play in the power system management	Two way communication and active involvement facilitating deeper Demand-Response penetration

1.4 Smart Buildings

About 40% of total energy demand comes from buildings, commercial and residential, of which the major contributors are appliances for maintaining thermal comfort in buildings. Next to air-conditioners and heaters, the high energy consuming appliances in residential buildings, are washing machines and dishwashers. These appliances are often major sources of wastage of energy due to the absence of state of the art building energy management systems (BEMSs) combined with human negligence in not switching them off when not required.

A smart building refers to the new age building which provides better comfort levels to users, while minimizing energy consumption, handling safety and security issues, providing for maintainability, etc. It has an embedded BEMS in it to track and *control the use of available energy*, environmental parameters (e.g., temperature, humidity), occupancy status and count, etc. It is also able to reduce and optimize power consumption, monitor the status and health of the appliances in the building, profile energy consumption of different areas and identify zones with anomalous power consumption.

A smart BEMS is able to exploit various kinds of information which give deeper insights about the building. The required information comes from numerous sensors installed in smart buildings. Minimization of the number of sensors and use of *soft sensors* by exploiting the facet-sensor relationship (discussed in Chapter 3) is an example of extracting deeper inferable information thereby using fewer sensor data.

A building's energy footprint or its energy bills can be reduced, if wastage is reduced or prevented. Automated intervention by a BEMS can make a building *smart* so that energy can be saved and energy bill can be reduced without affecting the desired quality of life like provide thermal comfort with minimal dependence on human intervention. The main reasons behind wastage of energy in buildings are

- HVAC equipment, lights and fans remaining ON during periods of non-occupancy.
- Wrong placement of temperature feedback sensors, especially in auditoriums and large meeting halls, which can lead to over-cooling, to the extent that people start wearing jackets while inside an auditorium.
- Ad-hoc pre-cooling before the starting of an event like meetings, seminars etc.

- Lack of systematic and automatic health monitoring of equipment until it goes completely out of order.

Therefore, by detecting occupancy and opportunistically disconnecting loads in unoccupied rooms can save energy, a smart BEMS ensures that consumption is reduced and peaks are flattened.

Many electric utilities are moving away from a flat pricing model to a variable or peak usage-based pricing. In peak usage-based pricing, a utility monitors electricity usage over specific periods, such as every hour or every half hour, and bills customers, in part, based on the energy consumed in the peak period. So, a decrease in total and/or peak usage results in a more than linear reduction in the monthly electricity bill.

In sum, reduction in peak energy demand or prevention of energy wastage call for intervention by BEMS.

1.4.1 *Thermal Comfort in Buildings*

Thermal comfort in buildings is essential in order to provide favorable habitability and working environment in homes, offices, classrooms, auditoriums, etc. This requires provisioning of heating, ventilation, and air-conditioning equipment. Buildings are equipped with different kinds of air conditioning equipment like window/split AC, variable refrigerant flow (VRF) AC and large chiller plant depending on the types of spaces and the cooling capacity requirements. All these equipment/plants are energy consuming devices and they constitute 40% additional share of consumption in a building.

However, providing adequate cooling/heating capacity neither guarantees energy efficiency nor provides satisfactory thermal comfort to all the occupants. Complaints of over-cooling and under-cooling are common in offices, auditoria, etc.

Energy is often wasted simply by not following the discipline of switching HVACs, when not used. Preventing wastage is saving of energy. Therefore, automated intervention in operating HVACs based on occupancy becomes a necessity. Wi-Fi based occupancy sensing and schedule driven HVAC control (discussed in Chapter 5), where occupancy is estimated by monitoring and automatically learning the occupancy pattern, are examples of automatic intervention techniques. Another example is real-time chiller sequencing based on varying cooling loads, where historical data is used for prediction of COP (co-efficient of performance) using machine-learning techniques (Chapter 5).

Developing improved models that capture not only physical, i.e., thermodynamic, but also physiological, psychological, cultural and contextual factors, which play significant roles in the thermal perceptions of the individuals, is a challenge. Further, this also demands the model to be adaptive.

Therefore, providing thermal comfort to most of the occupants in an energy-efficient way is still a major challenge. We discuss the challenges and some solutions in Chapters 4 and 5.

1.4.2 *Solar Energy in Buildings*

The potential of integration of renewables like solar power with roof-top solar panels and building integrated photovoltaics (BIPV) is enormous. However, it has its own challenges, especially in the urban set up. The roof spaces are restricted by water tanks, AC outdoor units (ODU), DTH dishes, etc. In addition to space restrictions, the availability of direct sunlight on PV panels throughout the day is affected by these installations. Further, partial shading caused by nearby buildings, poles, overhead tanks and trees poses technological challenges in exploiting the full potential solar generation in buildings. These aspects of solar energy in buildings are discussed in Chapter 6.

1.4.3 *Smart Techniques for Handling Power Deficit*

In most of the developing countries like India, one of the nagging problems is deficiency in power generation to meet the demand. The prevalent approach adopted by the power utilities to deal with this problem is scheduled or rolling blackouts. In this approach, power supply in sub-areas within the distribution zones are disconnected (blacked out) for non-overlapping time intervals. On the other hand, consumers make their own arrangements for power during the blackout intervals. Commercial consumers resort to inhouse diesel generators, which include small portable *gensets* (about 1 KW) used by shopkeepers and stores. Residential consumers use battery-backed inverters for their essential loads like lights and fans and the inverters are charged during the time slots when power is available. This adds up to the original problem of energy deficit as it involves charging and discharging efficiencies of inverter batteries. A brownout technique of managing building loads based on their priority by following the grid (available supply) is discussed in Chapter 7.

Another important area of research related to energy management in building is non-intrusive monitoring of loads, known as NILM. The NILM is attractive to the consumers as this is non-invasive and does not require installation of additional sensors. NILM is primarily aimed at collecting and analyzing data related to energy consumption and their pattern (power usage on different times of the day by different types of appliances) and thereby educate and influence individual consumers concerning the energy conscious utilisation of the appliances. NILM is an open research area and in Chapter 7, we introduce the fundamental techniques behind it, with examples.

1.5 About this Monograph

In this monograph we will focus on Computer Science approaches for addressing the problem of smart energy management. We believe that the so-called "computational thinking" can lead to approaches that are applicable to the topic of energy management. Further, data driven approaches and use of Artificial Intelligence (AI) techniques such as inference and learning also lend themselves to smart energy management. To this end, this monograph is designed to help understand the recent research trends in energy management, focusing specifically on the efforts to increase energy efficiency of buildings, campuses, and cities.

1.5.1 *Why this Monograph?*

Efficient use of energy is an age-old goal. But its importance has become even more apparent with the increased emphasis on human development and the increased use and thirst for more energy that it engenders. This monograph's *raison d'être* is its focus on addressing the energy concerns through the use of information and communication technologies (ICT). This has two implications: (i) Harness today's processing and communication tools to improve the efficiency and responsiveness of existing energy management systems. (ii) Use the ability of modern sensing and IOT (Internet of Things) devices to inform us about the current state of the system and provide a timely and state-appropriate (rather than a broad, imprecise) response, backed up by analysis. This goal will drive us to make use of recent research trends in data driven methods for improving energy-efficiency of buildings, campuses, and cities.

1.5.2 *Topics Covered by this Monograph*

Smart energy management in buildings — by users, and within the electric grid by grid operators, are the key focus areas of this monograph. There is enormous excitement about synthesizing and benefiting from numerous technologies, including real-time monitoring, net metering, demand response, distributed generation from intermittent sources such as solar and wind, active control of power flows, enhanced storage capabilities, and micro-grids. Additionally, since building energy use for maintaining thermal comfort represents a significant fraction of total energy expenditures, a second trend is the design of smart building management systems (BMS), which can maintain thermal comfort with improved energy-efficiency. Incorporation of local renewable energy sources is one of the techniques used to reduce dependence on traditional energy sources like fossil fuels. These obtain their smartness from being able to regulate their energy footprint, reduce peak consumption, and participate in demand-response techniques by cleverly using renewable energy sources.

This monograph is designed to help chronicle the recent research trends in energy management by examining various measures being undertaken for increasing energy efficiency of buildings, campuses, and cities and their connection with the smart electric grid. It examines the key enablers of smart buildings that will interface with the future smart grid. A common theme in our treatment of this broad area is the data-driven nature of the enabling technologies — we seek to analyze requirements, use measurement/monitoring data to drive actuation/control, optimization, and resource management.

Chapter 1 has already provided the motivation for managing electrical energy using smart (computational and data driven) techniques. Specifically, we motivated the need for being SMART from the perspective of deriving the benefit of computational techniques by means of facilitating interaction between physical and computational components.

Chapter 2 focuses on energy management issues within the smart electric grid. To this end, we discuss Phasor Measurement Units (PMUs), the sensors used within the grid, and show how queries over PMU data — required to track, manage and control the grid elements — can be deftly processed using the semantics of the data and the queries. We use examples from the Indian grid to drive home the advantages of this approach to data handling.

Chapter 3 is devoted to the study of buildings, viewed as smart systems. With this goal, we look at the SMART model in the context of buildings and identify the areas that demand attention to make a building smart. These are i) smart sensing, ii) modeling electrical loads, analyzing their pattern of operation and power consumption and iii) offering suitable control action to achieve the objective of reduction in energy consumption, flattening of peak demand and providing thermal comfort to the consumers. The section on smart sensing describes the gamut of sensors that have been and are being developed to obtain the building state with optimal deployment of sensor resources related to occupancy, power consumption, thermal conditioning, status' of appliances, etc., necessary to meet the objectives of smart buildings. Classification, modeling and analysis of electrical loads in buildings are discussed with a view to facilitating higher level energy optimizations such as flattening of peak demand and reduction in consumption. Real-world examples from buildings are provided throughout to exemplify various concepts.

Chapter 4 focuses on achieving thermal comfort for users. Heating and cooling are the dominant contributors to the energy consumption of buildings. Reducing the energy consumed due to heating and cooling while ensuring thermal comfort for building occupants is therefore a key challenge. The chapter discusses the various considerations in providing thermal comfort, factors influencing thermal comfort, the stages involved in providing thermal comfort given the lifetime of a building, undesirable phenomena requiring pro-active and reactive interventions along with a description of the many possible interventions. We also show the benefits of these interventions by creating a formal physics-based model for heat transfer in buildings, a model that is data driven. Case studies on thermal conditioning of different types of spaces conclude this chapter.

Chapter 5 explores the possibilities where thermal comfort can be customized to i) cater to individual preferences and ii) to prevent wastage of energy by occupancy-based control of HVACs, which includes maximizing the efficiency of the chiller plants under varying cooling-load.

Chapter 6 dwells on the potential of solar energy in buildings with a focus on roof-top solar PV and building integrated photovoltaics (BIPV) in urban areas. The associated challenges in mitigating the adverse effects of partial shading are also discussed along with technological solutions.

Chapter 7 discusses two more topics on energy management that involves both consumers and power utilities more directly. The first topic focuses on grid-following brownouts, which aims at offering a better and more acceptable solution than rolling blackouts during the energy deficient periods. The second topic relates to inferring various facets of a building's energy consumption in a non-intrusive manner, which aims at influencing and educating consumers towards energy-conscious use of appliances. It presents how data sensed by a single smart meter can be disaggregated into the constituent loads inside a building, a method known as NILM (Non-intrusive Load Monitoring). We describe various NILM methods that have been developed in the literature.

1.5.3 *What this Monograph is not about?*

This *book* is intended to be more of a "research monograph" rather than a textbook. The field of smart energy management has seen fairly active research in the last few years, but is still in a state of flux and many interesting problems remain. It is mature enough that some products have hit the market, but not stable enough to deter fresh startups from entering the arena. Given this, our hope is that this monograph will serve to spur further research and will help accelerate the cross-fertilization of ideas from multiple disciplines.

Given that the topic is interdisciplinary, our goal is to demystify ICT to people who study this problem from an electrical engineering or energy science and engineering perspective and for the IT and CS researchers and practitioners to be able to approach the energy issues with some comfort. But, clearly, we cannot delve deeply into the basics in these areas in a book of reasonable size, so much of the required background to the topics will be provided on a need basis. To bridge the gap, we will provide copious pointers to other literature and relevant background materials as appendices, which will help those interested in knowing more.

1.5.4 *Who Should Read this Monograph?*

The target audience for this monograph includes Students/ Researchers/ Practitioners interested in getting to know the latest developments in modern energy management using Computer Science tools and techniques driven by constraints imposed by the energy domain. These include the application of advance concepts from computer systems, analytics, hardware, networking, databases, etc., to address energy problems computationally.

Research students should find this monograph useful to come up to speed on what has been accomplished in the area and what problems remain.

Practitioners should find this monograph useful to check out solutions that are ready to be put into practice.

Researchers from other domains, e.g., policy makers and social scientists, who want to contribute to the spread and impact of the solutions being developed, and so want to understand the social angle, should also find the material accessible.

To this end, each chapter will start with a section that gives the necessary background and end with a summary which will bring to the fore the takeaways from that chapter, reiterating the learning and the gaps that exist in the state of the art/practice in that area. The bulk of the chapter will provide details of the developments in the topic covered by that chapter with numerous examples that will provide nuggets that carry the essence of the covered topics.