

Power Systems

Kostas Siozios
Dimitrios Anagnostos
Dimitrios Soudris
Elias Kosmatopoulos *Editors*

IoT for Smart Grids

Design Challenges and Paradigms

Power Systems

Electrical power has been the technological foundation of industrial societies for many years. Although the systems designed to provide and apply electrical energy have reached a high degree of maturity, unforeseen problems are constantly encountered, necessitating the design of more efficient and reliable systems based on novel technologies. The book series Power Systems is aimed at providing detailed, accurate and sound technical information about these new developments in electrical power engineering. It includes topics on power generation, storage and transmission as well as electrical machines. The monographs and advanced textbooks in this series address researchers, lecturers, industrial engineers and senior students in electrical engineering.

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Springer

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Preface

Recently, the convergence of emerging embedded computing, information technology, and distributed control became a key enabler for future technologies. Among others, a new generation of systems, known as Internet of Things (IoT), with integrated computational and physical capabilities that can interact with humans through many new modalities have been introduced. The impressive recent advances in the IoT domain and its huge potential as “one of the next big concepts to support societal changes and economic growth” motivates the monitoring and management of large networks of “Things” (i.e., equipment, smart devices, actuators, sensors) toward a new generation of applications and platforms for smart environments, business, and services.

Such systems that bridge the cyber world of computing and communications with the physical world are a collection of task-oriented or dedicated subsystems, that pool their resources and capabilities together to create a new, more complex system which offers more functionality and performance than simply the sum of the constituent subsystems. Among others, such a new design paradigm exhibits increased flexibility to interact with, and expand the capabilities of, the physical world through monitoring, computation, communication, coordination, and decision-making mechanisms. Thus, it is expected that such an emerging multi-disciplinary frontier will enable revolutionary changes in the way humans live, while it is also expected to be a key enabler for future technology developments. Furthermore, since the computing and communication capabilities will soon be embedded in all types of objects and structures in the physical environment, the previously mentioned objectives are expected to be widely deployed in the near future. Applications with enormous societal impact and economic benefit will be created by harnessing these capabilities across both space and time domains.

One of the application domains where IoT technology is widely deployed affects the energy systems, which are chaining fundamentally and fast. More precisely, the importance of individual energy sources and options for power generation are changing, as are the ways in which electricity is transmitted and distributed. In addition to that, power generation is becoming more and more decentralized, making grid management increasingly complex and challenging aspect. Thus, it is

upmost important to employ a new information and communication technology (ICT) in order to support the proper orchestration of these systems. IoT platforms promise to deliver this cutting-edge products and services for meeting the previously mentioned challenges by covering the entire energy value chain.

Therefore, the purpose of this book is twofold. Firstly, to be used as an undergraduate- or graduate-level textbook for introduction to topics related to the design and implementation of IoT systems for the smart-grid domain, where the fundamentals as well as details in the many facets of this domain are analyzed. Secondly, it can be used as reference for researchers in the field. For this purpose, the book is organized in two parts.

Part I of the book includes a number of chapters that discuss fundamental components for realizing IoT platforms targeting the smart-grid domain. These chapters can be used as an introductory course in this domain either at the undergraduate or graduate level. Relative information is often summarized here in order to make each chapter as self-contained as possible. At the same time, after the introduction to the fundamentals, the following advances in the area are summarized in a survey manner with appropriate references, so that the student can immediately build upon the fundamentals, while the practising researcher can easily find relative information.

Part II of the book discusses a number of case studies related to the computerized monitor and control of energy systems. More precisely, we highlight how it is possible to employ a number of distributed wireless sensors and actuators in order to control buildings' heating/cooling services with the minimum energy cost. Additionally, at this part we also describe in detail the main features provided by a commercial product in the domain of monitoring large-scale smart grids. Finally, the last chapter in this book provides a survey that summarizes the EU-funded projects in the domain of smart grids. According to this analysis, an interested reader might conclude about the open issues, as well as the research directions in this field.

Finally, the editors would like to thank all the people who helped make this book possible, by contributing and providing reviews and experimental results.

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The editors would like to thank all the contributors who paid a lot of effort in order this book to reflect the current state-of-the-art technology in the domain of IoT systems for smart grid, but at the same time to be a handbook that summarizes open challenges in this field for interested readers and under-/postgraduate students.

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Acronyms

AC	Alternating Current
ALM	Application Logic Module
AMI	Automated Measurement Infrastructure
API	Application Programming Interface
ASIC	Application-Specific Integrated Circuit
BEM	Building Energy Management
BLE	Bluetooth Low Energy
CAM	Communications Adapter Module
CES	Cryogenic Energy Storage
CMMS	Computerized Maintenance Management System
CMS	Central Monitoring System
CoAP	Constrained Application Protocol
CSV	Comma-Separated Value
DDoS	Distributed DoS
DER	Distributed Energy Resources
DMS	Demand Management System
DoS	Denial of Service
DR	Demand Response
DRES	Distributed Renewable Energy Sources
DSM	Demand-Side Management
DSOs	Distribution System Operators
EDC	Energy Distribution Center
EPS	Electrical Power System
ETP	European Technology Platform
EV	Electric Vehicle
FEG	Flexible Energy Grid
FPGA	Field-Programmable Gate Array
GES	Grid Energy Storage
HAS	Home Automation System
HDL	Hardware Description Language

HEMS	Home Energy Management System
HiL	Hardware in the Loop
HVAC	Heating, Ventilation, and Air-Conditioning
HVDC	High-Voltage Direct Current
HW	Hardware
ICT	Information and Communication Technologies
IEM	Internal Energy Market
IMS	Information Management Systems
IoE	Internet of Energy
IoT	Internet of Things
KhW	Kilowatt hour (KhW)
LCOE	Levelized Cost of Electricity
LCP	Load Connection Point
LPWA	Low Power Wide Area
LSS	Large-Scale Systems
LV	Low Voltage
M2M	Machine to Machine
MAS	Multiagent Systems
MiL	Model in the -Loop
MPC	Model Predictive Control
NAN	Neighbor Area Network
NFC	Near Field Communication
NIST	National Institute of Standards and Technology
NSM	Notification Server Module
P2P	Peer to Peer
PCC	Point of Common Coupling
PE	Power Electronic
PID	Proportional–Integral–Derivative
PPC	Power Plant Controller
PPD	Predicted Percentage of Dissatisfied People
PV	Photovoltaic
QoE	Quality of Experience
RES	Renewable Energy Sources
RFID	Radio-Frequency IDentification
RSM	Reporting Server Module
RTL	Register-Transfer Level
RTS	Run-Time Situation
SDL	Specification and Description Language
SESP	Smart Energy Service Provider
SG	Smart Grid
SiL	Software in the Loop
SoC	System on Chip
SW	Software
TCP	Transmission Control Protocol
TLM	Transaction-Level Model

ToU	Time of Use
TRL	Technology Readiness Level
TSO	Transmission System Operator
UML	Unified Modeling Language
VES	Virtual Energy Storage
VSP	Virtual Storage Plants
WSNs	Wireless Sensor Networks

Part I

Fundamental Topics and Technologies

for IoT Systems Targeting Smart-Grid

Domain

Chapter 1

Mastering the Challenges of Changing Energy Systems: *The Smart-Grid Concept*



Kostas Siozios

Abstract The availability of electrical power is a major enabler of social and economic development. During the last decades, electrical consumption continues to steadily rise all over the world and this trend has already changed our life. This in turn impose that fundamental changes in the domain of energy systems will take place. Among others power generation is becoming more and more decentralized making grid management increasingly complex. Additionally, the importance of individual energy sources and options for power generation are changing, as are the ways in which electricity is transmitted and distributed. This chapter provides an overview about the challenges of future energy systems and how these challenges will be addressed with the usage of Information Technology (IT).

1.1 Introduction

During the past decade, there is a mentionable transformation in all segments of the power industry worldwide, from generation to supply. This transformation affects among others domains related to regulatory, technological and market structures. These domains adopted ambitious policy objectives aimed at improving the competitiveness, security and sustainability of energy system. The change of power sector is also guided by the growing penetration of renewable and Distributed Energy Resources (DER), as well as the increasing involvement of electricity consumers in the production and management of electricity, which in turn are expected to radically change the local electricity industry and markets, especially at distribution level, creating opportunities but also posing challenges to the reliability and efficiency of system operation.

The trend is inline to the smart-grid concept, which represents an unprecedented opportunity to move the energy industry into a new era of reliability, availability, and efficiency that will contribute to our economic and environmental health. During the transition period, it is critical to carry out testing, technology improvements,

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consumer education, development of standards and regulations, and information sharing between projects to ensure that the benefits we envision from the smart-grid become a reality. More specifically, the benefits associated with the smart-grid include (but not limited):

- More efficient transmission of electricity;
- Quicker restoration of electricity after power disturbances;
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers;
- Reduced peak demand, which will also help lower electricity rates;
- Increased integration of large-scale renewable energy systems;
- Better integration of customer-owner power generation systems, including renewable energy systems;
- Improved security.

The aforementioned objectives impose that almost all segments of the power industry are affected by this trend. Specifically, smartening of the grid offers opportunities for changing the current energy markets into more efficient and flexible retail markets. By enabling an electricity network to efficiently integrate the behaviour and actions of all users, i.e., energy consumers and producers and those that do both (so called prosumers), connected to it in order to ensure an economically efficient, sustainable power system with low losses, high quality, security of supply and safety (Fig. 1.1).

This trend enables the opportunity for new services to be developed, while the re-arrangement of optimal network management is expecting to introduce new actors

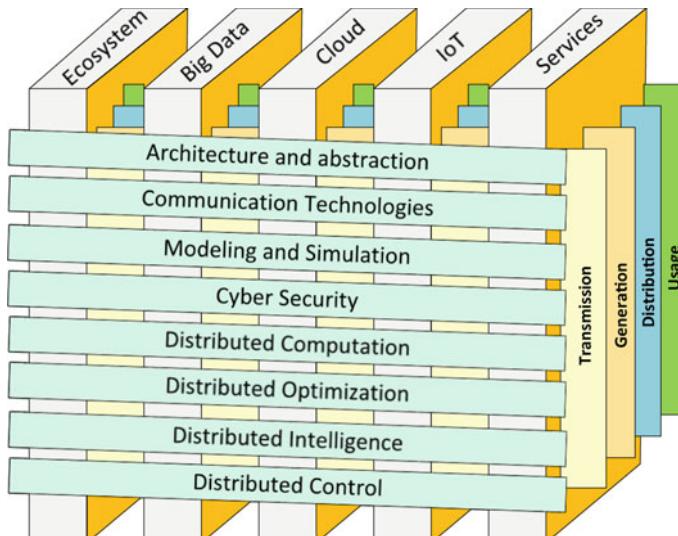


Fig. 1.1 Smart-grid for the IoT view-point

to the energy system, while existing ones will also change in order to take into consideration the new challenges. For example, Distribution System Operators (DSOs), have been put under increasing pressure to adopt a more active role for the development, management and operation of their networks and many of them have started testing smart-grid solutions (in small, medium and large scale) to improve network reliability, efficiency and security. Therefore, energy grids are complemented with Information and Communications Technology (ICT) infrastructure, sensors and actuators such that remote monitoring and control of network components as well as DER are enabled. Compared to the traditional grid operations, new tasks or services can be distinguished in supporting of the DSOs or being provided by the DSOs to other parties.

Furthermore, a number of key players in the energy domain also started showing growing interest for smart-grid solutions, attracted mainly by the opportunities offered by new technologies and emerging business models. Technology manufacturers, service providers and ICT developers for instance, are increasingly eager to develop and test new solutions to gain technology leadership that can be exported globally.

To sum up smart-grids, as shown in Fig. 1.2, are energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand

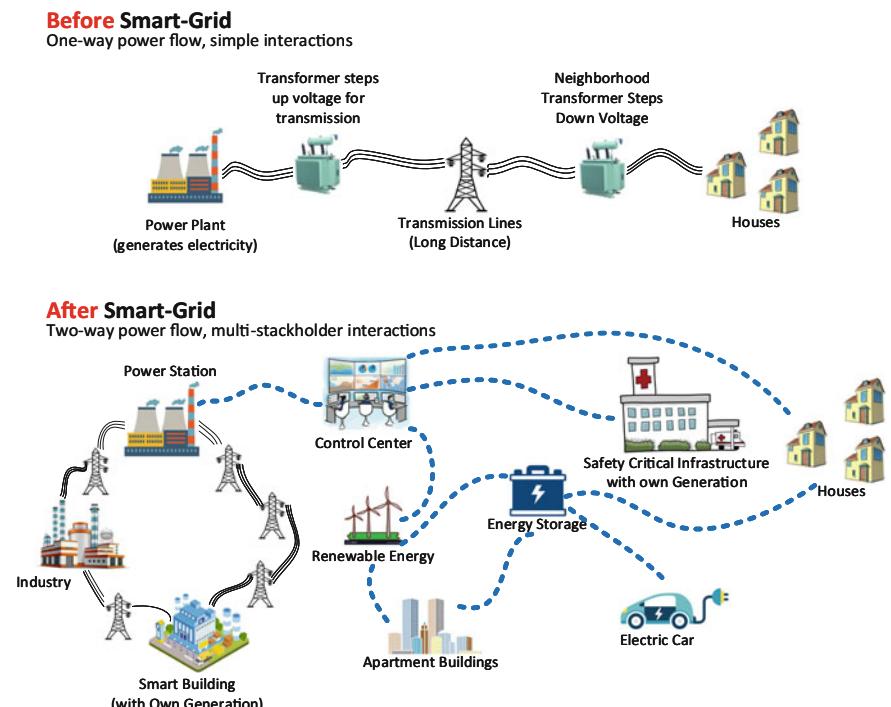


Fig. 1.2 Smart-grid environment within the broader electricity system

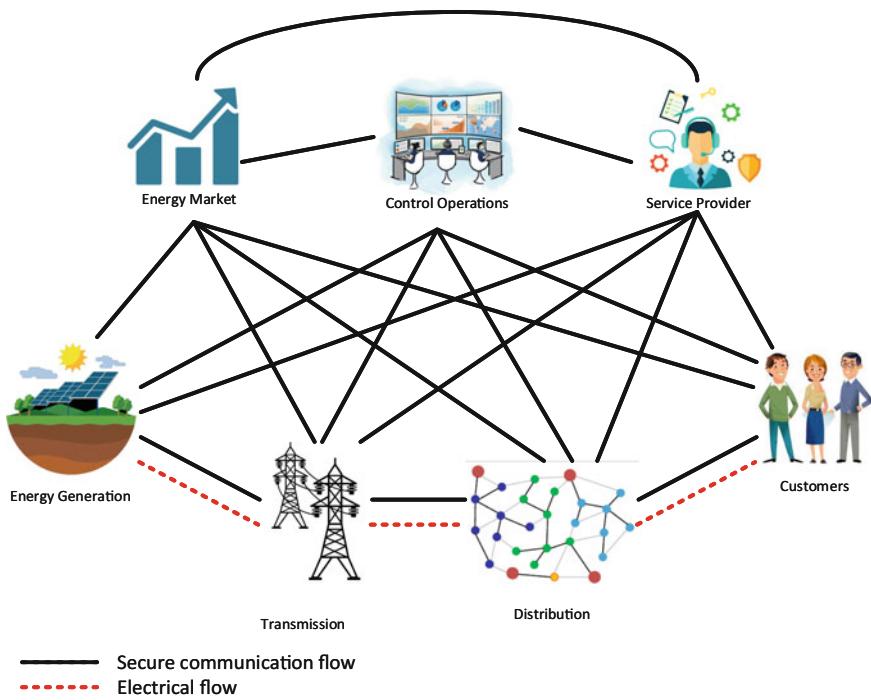


Fig. 1.3 Smart-grid environment within the broader electricity system

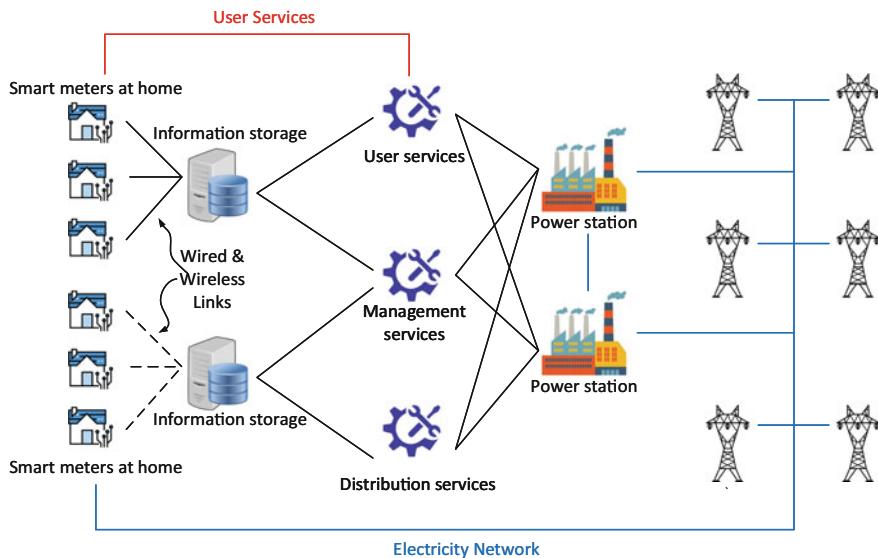


Fig. 1.4 Functional cloud computing service clusters

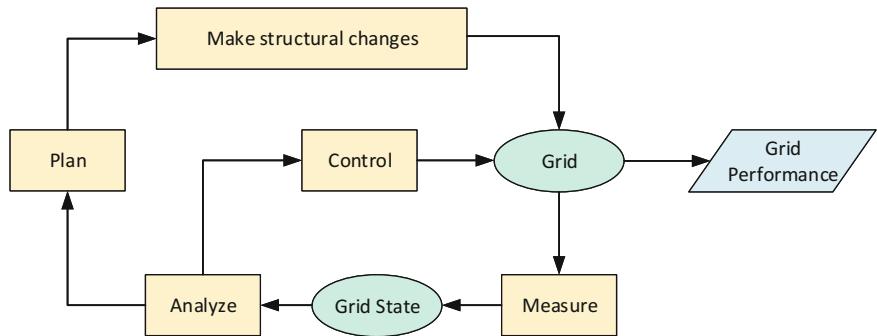


Fig. 1.5 Typical smart-grid data management

(see Fig. 1.3) accordingly. When coupled with smart metering systems, smart-grids reach consumers and suppliers by providing information on real-time consumption (Fig. 1.4). With smart meters, consumers can adapt in time and volume - their energy usage to different energy prices throughout the day, saving money on their energy bills by consuming more energy in lower price periods (Fig. 1.5).

1.2 Actors in the Smart-Grid Environment

The concept of smart-grid impose that a number of different groups and actors might be identified according to their functions and responsibilities, as it is summarized in Table 1.1. Based on this analysis, the transmission and distribution operators together constitute the category of grid operators. All parties physically connected to the grid form the category of grid users, both at the demand and at the supply side, e.g., generator, customer, electrical installer, supplier, retailer, etc. The energy market place is also formed by the actors that are involved in the trading of electricity i.e. traders, suppliers and aggregators as well as the parties that are responsible for imbalance settlement. Next, there is a number of technology providers including the grid equipment providers (hardware and software, services), as well as the providers of equipment connected to the grid at the consumer premises. Finally, there are the influencers that correspond to indirect actors. These impact the operations within and on the smart-grid, while they also include governments and regulators, standardization bodies and the financial sector, as provider of investment funds. Note that each of the previously mentioned actors may have roles within multiple categories.

Table 1.1 Smart-grid actors [1]

Grid operators	<ul style="list-style-type: none"> • Transmission system operator (TSO) • Distribution system operator (DSO)
Grid users	<ul style="list-style-type: none"> • Generator • Customer • Electrical installer • Supplier • Retailer
Energy market place	<ul style="list-style-type: none"> • Balance responsible party • Clearing & Settlement agent • Trader • Supplier • Aggregator
Technology providers	<ul style="list-style-type: none"> • Electric power grid equipment vendor • Ancillary service provider • Metering operator • ICT service provider • Grid communications network provider • Home appliances vendor • Building Energy Management (BEM) system provider • Electric transportation & Vechicle solutions provider
Influencers	<ul style="list-style-type: none"> • Regulator • Standardization bodies • EU and national legislation authorities • Financial sector entities

1.3 Challenges of Smart-Grid

This section summarizes the main challenges found in the smart-grid domain. These challenges affect both technical issues, as well as business aspects.

1.3.1 Technical Challenges

1.3.1.1 Inadequacies in Grid Infra Structure

This is one of the most important challenges in the wide deployment of smart-grid networks. The active networks that constitute many segments of a “smart” distribution system is best served with a more holistic approach rather than focusing on the separate pieces of the generation and distribution process. Since in many countries, the grid infrastructure is still evolving, this makes infrastructure upgrade a major task with significant economic impact for grid operators. The goal for enabling existing

grids to accommodate the upcoming needs of clean energy and distributed generation may throw several challenges in design, erection, operation and maintenance of these networks. Besides focusing on smart-grids, there is also a need to address issues of existing grid infra structure. For instance, in many countries several electrical parts are unevenly connected to national grid in order to optimally evacuate large wind farms or solar parks which otherwise demand for installation of entire infrastructure.

1.3.1.2 Cyber Security

Smart-grid security is crucial to maintain stable and reliable power system operation during the contingency situation due to the failure of any critical power system component. Due to lack of the proper “security measures”, a major blackout may occur which can even lead to a cascading failure. Therefore, to protect this critical power system infrastructure and to ensure a reliable and an uninterrupted power supply to the end users, Smart-grid security issues must be addressed with high priority. More importantly, cyber security emerges to be a critical issue because millions of electronic devices are inter-connected via communication networks (i.e., solutions that rely on Internet of Things technology) throughout critical power facilities, which has an immediate impact on reliability of such a widespread infrastructure.

By appropriately tackling issues related to the security requirements, network vulnerabilities, attack countermeasures, secure communication protocols and architectures in the Smart-grid environment, it is expected to improve considerably the efficiency of the overall system’s safety, security and reliability. In more detail, the cyber security topic in this environment must address both inadvertent compromises of the electric infrastructure, due to equipment failures, user errors, natural disasters, and deliberate attacks, such as from disgruntled employees, industrial espionage, and terrorists. For this purpose, proper mechanism should be incorporated both in software and hardware level. Additionally, due to the importance of this domain, cyber security risk management strategies have also to be deployed both in local, as well as in larger scale, while the promotion of technology transfer of best practices, standards and voluntary guidance, and research in the areas of applied cryptography and cybersecurity for microgrids is also necessary.

1.3.1.3 Storage Concerns

The use of energy from renewable sources requires special attention to grid stability. In view of this, it is clear that energy storage systems will become increasingly important in the near future, since storage units take in surplus electricity that is not needed at a given time and then feed it back into the grid when demand rises. This is also stated at different market analysis. For instance, according to Deutsche Bank, the German market for electrical storage devices is expected to at least double between 2012 and 2025, while by 2040 at the latest, some 40 terawatt-hours (TWh) of electricity will have to be stored on a regular basis, in some cases over a period of

several months. We have to notice that the 40 TWh figure is one thousand times higher than the storage capacity of today's pumped-storage facilities in Germany. This imposes that an associated investment of roughly 30 billion euros will be required in Germany alone over the next 20 years.

In order to fabricate these storage components various technologies are employed. For instance, hydrogen storage devices (their operation relies on electrolysis in order to produce energy-rich hydrogen gas from water) can take in surplus power from wind farms. The produced hydrogen is then temporarily stored in underground caverns that are already used to hold natural gas. Depending on the power demand, the energy-rich hydrogen gas can either drive turbines that then supply electricity to the grid, or it can be converted to methane through a reaction with carbon dioxide; after that the methane can be fed into the natural gas grid. The batteries are also a well-known energy storage system. Lithium-ion cells are currently the best batteries for stabilizing distribution grids because they combine high storage capacity with high charge and discharge rates. If load volatility should occur in the grid, such batteries can take in or dispense power within milliseconds, thus balancing out fluctuations in voltage and frequency. Another way to store energy is also as compressed air. This approach involves pumping air into hollow chambers such as salt domes and then compressing it to a pressure of up to 100 bar. The compressed air is later used to drive a gas turbine.

1.3.1.4 Data Management

Smart-grids ensure efficient connection and exploitation of all means of production, provide automatic and real-time management of the electrical networks. This allows operators to better measure of consumption, optimize the level of reliability and improve the existing services which in turn lead to energy savings and lower costs both for energy producers and consumers. Among others, this concept leads to a very large increase in the volume of data to be processed due to the installation of smart meters and various sensors on the network and the development of customer facilities, etc. Such a data deluge problem becomes far more savage with the wide adoption of Smart-grid concept. In order to depict the importance of this problem, we might employ a commercially available smart meter which sends the consumer energy usage every 15 min, so every million meters can generate 96 million reads per day instead of one meter reading a month in a conventional grid. This prerequisite that a smart-grid apart from efficient energy management have also to take into consideration data management plan in order to deal with high velocity, important storage capacity and advanced data analytics requirements.

Indeed, smart-grids data requires complex analytics, due to their nature, distribution and real-time constraints of certain needs. In other words, big data techniques are becoming necessary for advanced and efficient data management for this kind of applications. Among others, by appropriately analyzing this data, smart-grid producers and operators will be able to do things they never could do before such as bet-

ter understanding the customer behaviour, conservation, consumption and demand, keeping track of downtime and power failures etc.

1.3.1.5 Communication Issues

Although lots of newly-developed information and communication technologies have dramatically affected the other industry sectors, the electric systems generally remain to operate in the same way for decades. However, in recent years there is a continue demand for communication technologies that enable electric generation and distribution systems to incorporate large amounts of distributed energy resources into the grid and to deal with the intermittent nature of renewable energy. Among others, wireless communication plays an extremely important role in realizing all aforementioned goals of smart-grid. More specifically, the advancements in wireless communication technologies have made it possible to implement a smart-grid with its capability to convey various vital information from and to electricity consumers, to achieve a very high utility efficiency. Note that although the wireless concept is not necessary (smart-grid infrastructure can also employ wired links), in general wireless telecommunication infrastructure offer much greater degree of freedoms for information collection, dissemination, and processing than the corresponding wired communication infrastructure. For instance, a typical example is the recent advances in Wireless Sensor Networks (WSNs) have made it attainable to realize embedded electric utility monitoring systems. Apart from this, WSNs can also be employed in order to realize remote system monitoring, equipment fault sensing, wireless automatic meter reading, network distributed resource optimization, and so forth.

To sum up the key consideration for communication infrastructure in the smart-grid environment include among others:

- Ease of deployment;
- Latency;
- Standards;
- Data carrying capacity;
- Secure;
- Network coverage capability.

Finally, Table 1.2 provides technical characteristics regarding a number of wireless and wired communication technologies. At this table, symbols L, M, H denote “Low”, “Medium” and “High”, respectively. According to this overview, a number of conclusions might be derived for the physical implementation of different data transfers within the smart-grid environment.

Table 1.2 Considerations for integrated communication

Technology comparison and risk profile						Regulatory			Standards		Coverage	
Technology	Deploy ability	Cost-Capital	Cost - Ops	Latency	Speed							
Wireless												
Cellular	H	L	H	H	<100 Kbps	L	L	L	L	L	L	
900 MHz	M	L	L	M	<1 Mbps	L	L	L	M	M	M	
WiFi/WiMAX	L	M	L	M	2-30+ Mbps	L	M	M	M	M	M	
Licensed	M	H	M	M	2-30+ Mbps	M	L	L	M	M	M	
Microwave	M	H	L	L	10-500 Mbps	L	L	L	H	H	H	
Wired												
PLC	L	L	L	M	<100 Kbps	L	M	M	M	M	M	
DSL	M	L	M	M	<3 Mbps	L	L	L	M	M	M	
BPL	M	M	L	M	<2-30+ Mbps	M	H	H	M	M	M	
Fixed line	M	L	H	L	2-30+ Mbps	L	L	L	H	H	H	
Fiber	H	H	M	L	>Gbps	L	L	L	H	H	H	

1.3.1.6 Stability Concerns

The engagement of multiple energy producers in smart-grid environment introduce stability concerns. This occurs because the majority of the producers rely on renewable energy sources in order to meet day-to-day load demands. The diverse characteristics of renewable energy-based technologies compared to conventional power plants have led to many technical challenges, including among others operational stability concerns requiring real-time coordinated control strategies for both conventional as well as renewable energy sources. Typical stability problems affect lower voltage stability due to lower power sharing support, low-frequency power oscillations, lower angular stability due to lower overall system inertia, worsening of smart-grid transient profile during micro-grid islanding, and the inability to serve as system reserve.

1.3.1.7 Energy Management and Electric Vehicle

In typical smart-grids, the energy management system is based on pricing. The dynamic pricing is a concept that has immense possibilities for application in the energy sector, since it can be considered as a demand-side management tool that facilitates the offering of different prices at different demand levels, while it also supports producers postpone investment decisions by shifting peak loads from peak to non-peak hours.

In a smart-grid environment the units are categorized into three groups:

- Price-elastic units that can be influenced by prices. Such units are conventional generation units, controllable renewable generation units (e.g., biomass power plants), controllable loads (e.g., electric heaters), etc.
- Price-inelastic units that cannot be influenced by prices. This group include (e.g. mainly the uncontrollable loads and the uncontrollable renewable generation units, such as wind and photovoltaic power plants).
- Electric vehicles which can be influenced by prices but have storage dynamics as well as energy and mobility constraints. These features are desirable to substantially contribute to balancing volatile renewable generation.

1.3.2 Socio-economic Challenges

Socio-economic scenario plays a vital role in implementation and success of any technology. More specifically, a technology becomes irrelevant if it fails to attract the investors or users, leading to failure of pilot projects, rejection of new technology, etc. Sometimes such issues may arise as a result of some economic or technological and some sometimes due to lack of appropriate awareness among stakeholders.

1.3.2.1 High Capital Investment

Global investment in energy storage and smart-grid firms soared during the first three months of the year, according to a new report from consultancy Mercom Capital Group [2] that underlines the growing interest in smart technologies deemed critical to the deep de-carbonisation of power grids. However, we have to notice that although academicians and researchers are exited with the advantages of smart-grid technology, regulators, suppliers and customers have stayed away from the large-scale deployment of this concept. This occurs due to the concerns regarding the potential benefits over the costs of implementation and possible excessive high bill values to customers. Thus, the wide adoption of this scheme raises the question about how participants can benefit from such a competitive energy environment.

Despite this statement, in the near future it is expected that an increased investment in energy storage and smart-grid technologies will take place as energy storage (e.g. battery) costs continue to plummet and grid operators around the world seek to roll out a range of storage and demand management systems designed to help integrate increasing levels of variable renewables on to the grid.

1.3.2.2 Stakeholder's Engagement

At the early stages of smart-grid implementations, stakeholders' negative perceptions can derail even the most beneficial project. This is especially important when the proponents fail to pay close attention to the educational aspects. Advocates need to be able explain and clearly identify the benefits of each component of the smart-grid to the customers that are the potential key to service success. At this point we have to notice that while much of the conversation concerning the smart-grid appears to be taking place between participants identified as "stakeholders", the role of the academy in educating, promoting, and leading needs to be fully appreciated and nurtured.

Towards this direction, new stakeholders (e.g. energy resource aggregators), more flexibility for the consumers (energy market place), and totally new concepts (loading of electric vehicles, usage of these vehicles as flexible power storage, etc) have to be respected. Innovative monitoring and control concepts are required to operate these distributed energy resources in a reliable and safe way, so the communication technologies must support it. Note that all these solutions have to take into consideration the challenges and opportunities provided by the IoT-based solutions, since it is a well-established approach for supporting the implementation of such large-scale solutions.

1.3.2.3 System Operation and Control Aspects

A smart-grid is typically reliable, secure, efficient, economic, environment friendly, and safe to the extreme extent as feasible. By incorporating a number of ICT technolo-

gies to all aspects of the energy transmission and delivery system, the smart-grids provide better monitoring and control, which in turn leads to efficient use of the system. The objectives of smart-grid operation and control include:

- to provide mechanisms that address the challenges that secure and reliable operation of the power grids will face in the future;
- to develop a solid interdisciplinary theoretical foundation in order to enable the development of better tools for different tasks (e.g., planning, operation, and control of power grids interconnected at various voltage levels);
- to innovate in power distribution monitoring and control (e.g. through smart metering devices);
- to enable consumers to react to grid conditions making them active participants in their energy use;
- to leverage conventional generation and emerging technologies when possible including distributed energy resources, demand response, and energy storage, to address the challenges introduced by variable renewable resources.

In order to address the aforementioned challenges, ICT technologies both for the signal processing and the data communication aspects have to be taken into considerations. Internet of Things solutions are suitable for this purpose, as they support also wide deployment without scarifying their quality due to scalability issues.

1.3.2.4 Privacy

The deployment and adoption of smart-grid technologies have opened up several data privacy issues at the consumer end. These concerns affect mostly the collection and use of energy consumption data collected from homes which use smart-grid technology. An overview of these concerns with emphasis on security aspects can be found in [3]. Since the communication infrastructure is a key component of smart-grids, there are also analysis regarding the security threats towards communication networks and evaluation of their impact [4].

Next, we provide a summary of potential privacy impacts from data collected in smart-grid environment [5] (Table 1.3).

1.3.2.5 Fear of Obsolescence

The early adoption of any cutting-edge technology, such as those found in the smart-grid domain, carries with it the risk of incompatibility and limited expansion and upgrade options. This fear is even higher in case the ICT components are proprietary to a specific manufacturer. To effectively address this concern, it is imperative that interoperability standards and backward compatibility of technologies are incorporated into the development of new technologies.

Table 1.3 Potential privacy impacts from data collected in smart-grid environment [5]

Who wants smart meter data?	How could the data be used?
Utilities	To monitor electricity usage/load and to determine bills
Electricity usage advisory companies	To promote energy conservation and awareness
Insurance companies	To determine health care premiums based on unusual behaviors that might indicate illness
Marketers	To profile customers for targeted advertisements
Law enforcers	To identify suspicious or illegal activity
Civil litigators	To identify property boundaries and activities on premises
Landlords	To verify lease compliance
Private investigators	To monitor specific events
The press	To get information about famous people
Creditors	To determine behavior that might indicate creditworthiness
Criminals	To identify the best times for a burglary or to identify high-priced appliances to steal

1.3.2.6 Fear of Electricity Charge Increase

As electricity markets are liberalized, consumers become exposed to higher electricity prices and may decide to modify their demand to reduce their electricity costs. In order to prevent electric power companies to generally monopoly utilities, regulatory agencies approve prices, also referred as electricity rates or tariffs, for electricity to consumers. Recent products in this direction, such as the smart meters, incorporate the advantages provided by ICT technology in order to enable different pricing schemes. For instance, apart from the flat rates and tiered rates, where the energy cost is computed with the same rate and based on a different price depending on blocks of usage (e.g., first 500 kWh vs. next 500 kWh), respectively, the smart-grid environment enables also more advanced pricing schemes (e.g., time-of-use pricing, real-time pricing, variable peak pricing, critical peak pricing, critical peak rebates, etc.).

1.3.2.7 Radio Frequency (RF) Signal and Health Issues

Since the IoT components found in the smart-grid environment, e.g., the smart meters, typically rely on wireless technologies to communicate information, exposure to radio frequency radiation, and possible carcinogenic effect normally attributed to

cell phone usage, has become a serious concern for many customers. This is further exacerbated by the probable eventual incorporation of transmitting devices into all household appliances. During the past years, numerous studies have shown that the levels of radiation emitted by smart-grid transmitting devices are well below that which is considered harmful to mammalian life forms. Yet these perceptions persist and indeed form the mainstay of opposition held by many extremely vociferous consumer groups worldwide.

1.3.3 *Miscellaneous*

Apart from technical and socio-economic challenges, there are also a few more issues that demand concerns from some general perspectives. For instance, policy makers, regulators and legal need to understand the technical as well as social aspects of the technology (Fig. 1.6).

1.3.3.1 Regulation and Policies

Although each country has its own policy and regulatory constellation, while the setups are in many respects quite different, they also hold a number of similarities. For instance, all of them have a centralized body (e.g. the Federal Government in U.S. and the European Commission in Europe) that sets the high-level visions, policies, targets and to some degree regulatory and incentive frameworks. These high-level guidelines are passed to local governments for incorporation and implementation in the respective local jurisdictions. In addition to that, the local governments have a degree of autonomy to exercise their own priorities in implementation. For instance, the concrete policies and derived regulation can depend on the prevailing overall economic, societal and political situations and future outlooks per country. By enabling each government to evaluate the prevailing and project macro environment, it is possible to define their assessments and priorities, while they also establish new policies and pass new regulation aiming toward the high-level objectives of future energy systems. Consequently, and emphasized by electric power being a strategic resource for any and all governments, the faster the pace of change in the macro environment, the more frequent revisions on electric power related policies and regulation can be expected.

1.3.3.2 Power Theft

Electricity theft is a major concern for the utilities and it is estimated to cost billions of dollars per year in many countries. Traditionally, the power theft occurs on the distribution grid (from the substation to the home), as well as at the transmission level. To reduce electricity theft, electric utilities are leveraging data collected by

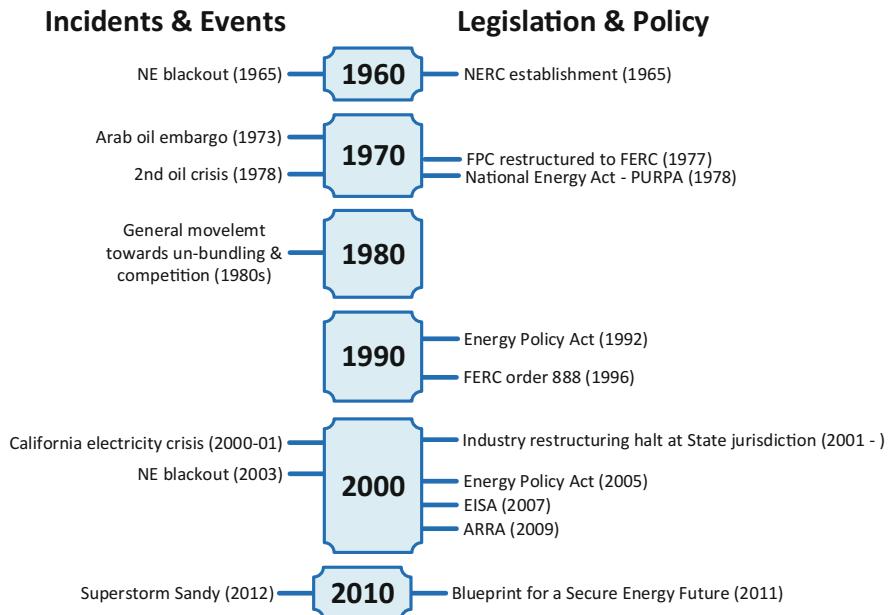


Fig. 1.6 Timeline of selected key incidents and events versus legislative and policy packages [6]

advanced metering infrastructure, such as the smart meters, and using data analytics to identify abnormal consumption trends and possible fraud.

More specifically, smart meters refer to the modernization of the electricity metering system by replacing old mechanical meters by electronic devices that incorporate IoT concepts (e.g. support provide 2-way communications between utilities and consumers). This feature eliminates the need to send personnel to read the meters on site, while they also provide a range of new capabilities, such as, the ability to monitor electricity consumption throughout the network with finer granularity, faster diagnosis of outage, remote disconnect, and the ability to send information such as dynamic pricing or the source of electricity (renewable or not) to consumers, giving consumers more information about their energy use.

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Chapter 2

Edge Computing for Smart Grid: An Overview on Architectures and Solutions



Farzad Samie, Lars Bauer and Jörg Henkel

Abstract Internet of Things (IoT) has made small objects and things to be networked and interconnected, and even connected to the Internet in order to offer advanced control and monitoring services. Smart embedded devices along with intelligent decision-making ability will increase the efficiency of services in different domains including smart grid. Similar to other IoT domain, smart grid consist of a massive number of sensors and data sources which continuously collect high-resolution data. Managing the large volume of data has been identified as one of the major challenges in IoT. To address this issue, Edge Computing envisions to process the data at the edge of the IoT network close to the embedded devices where the data is collected. This chapter aims to investigate the edge computing solutions for the smart grid. An edge computing model for the smart grid information processing, with a focus on smart home, is presented in this chapter. The advantages of this model in terms of self-supporting and privacy are discussed. Moreover, we present a use-case for smart home automation where the operating mode of home appliances are determined dynamically to respect the limited power budget of home while maximizing the user's satisfaction and utility.

2.1 Introduction

Internet of Things (IoT), which has been enabled by recent advancements in wireless, sensing and embedded processing technologies, is a new paradigm that aims at offering advanced efficient monitoring and control services [37]. The IoT is a multi-

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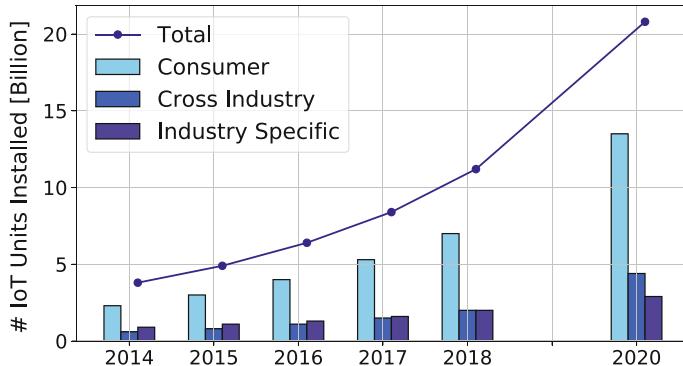


Fig. 2.1 Gartner's estimation on the number of IoT devices in different sectors (the 2019 data is not available) [15]

disciplinary infrastructure in which many of our surrounding objects and *things* will be interconnected. IoT offers a whole new class of applications and services as well as higher efficiency for existing applications and services [18].

Figure 2.1 illustrates the Gartner's estimation on the number of IoT devices by the year 2020 which is more than 20 billion in total [15]. It shows the prediction of IoT devices in different sectors: Consumer sector covers the devices that are purchased and used by the end user (e.g., personal gadgets, fitness bands, health-care devices, etc). The cross-industry sector refers to the *general* devices and items that are deployed and used in industries such as smart home, smart city, etc. And finally, the industry-specific sector refers to the special devices and systems in the factories to increase the efficiency of other sectors. It includes infrastructures to improve the efficiency of production lines, monitoring the quality, etc. The smart grid falls into the cross-industry sector.

2.1.1 IoT Applications, Requirements, and Architecture

IoT covers an ever-increasing range of applications including health-care, smart home, smart building, ambient assisted living, smart city, smart agriculture, smart industry (also known as *Industrie 4.0* in Germany), smart grid, etc [6]. In each domain, applications have specific requirements and characteristics. These requirements and characteristics dictate the design parameters and objectives for different components such as IoT embedded devices, network infrastructure, middleware, management framework, software applications, etc.

The requirements of IoT devices, IoT network, and IoT application include but not limited to the following [19, 20, 26]. Though, it does not mean that each application domain has all the following requirements. But several requirements are common between different domains.

- Devices' Requirements

- *Low Power*: To reduce the cost of deployment or meet the portability requirements, many IoT devices are battery-operated with limited energy budget. Hence, low-power consumption is a major requirement.
- *Small Size*: Being integrated into other systems or being portable, IoT devices require a small form-factor.
- *Low Cost*.
- *Durability*: To reduce the cost of maintenance, the IoT devices must be durable.

- Network Requirements

- *Latency*: Many IoT applications must have a determined and short response time, hence they are latency-sensitive with real-time demands. Therefore, short and deterministic latency is one of the network requirements in IoT.
- *Bandwidth*: Especially in advanced monitoring applications, IoT devices require to transmit a large amount of data. With the increase in the number of IoT devices, the bandwidth of network may become a bottleneck in the IoT systems.
- *Resilience*: With the massive number of IoT devices, the wireless interference will be a challenge for the interconnection network. In addition, the concerns for security attacks such as Denial of Service (Dos) or Distributed DoS (DDoS) call for a network infrastructure that can be resilient against these threats.
- *Scalability*: The ever-increasing number of connected IoT devices necessitates the scalable network infrastructure.

- Application Requirements

- *Security*: Many security concerns must be considered for IoT applications including malicious codes, key management, data integrity, access control, etc.
- *Privacy*: IoT applications will be deeply integrated with our daily lives, and hence, access to our sensitive information.
- *Dependability*: IoT applications will carry out many of our daily operations and required services. The applications must be dependable, available and reliable.
- *Response Time*: Some applications in the smart grid (e.g., self-recovery in renewable distributed energy resources [30]), smart transportation, health-care, etc. require fast response time and have real-time constraints.
- *Service Quality*: It refers to the quality of application's output from user's perspective. The service quality is affected by the input quality (i.e., the resolution and sampling rate of captured data) as well as the data processing algorithm.
- *Fast deployment*.
- *Low Maintenance*: The applications must provide their service constantly over a long period with high availability. Maintenance of remote device's application (e.g., over-the-air firmware) may even open security surfaces.
- *Scalability*: IoT applications must scale up when the number of users, connected devices and service requests increase.

Figure 2.2 depicts the high-level architecture and how IoT embedded devices interact with the physical world through their sensors and actuators. In a cloud-centric IoT

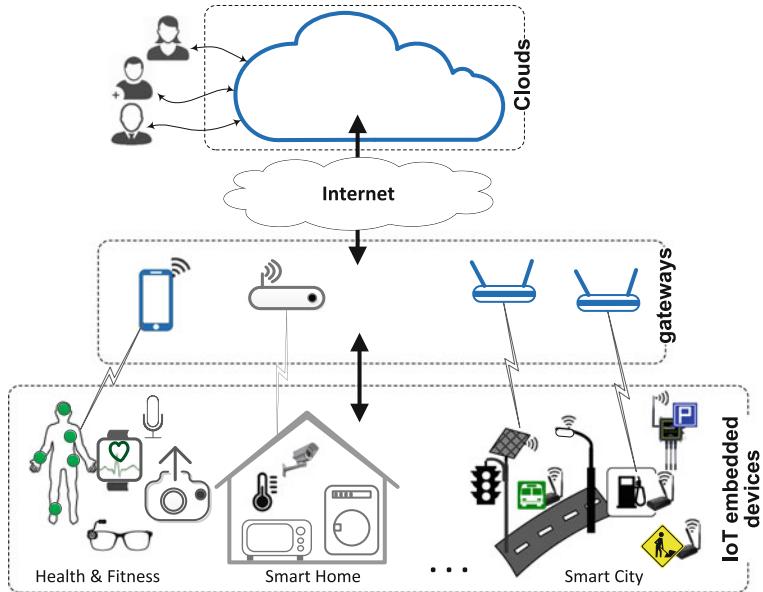


Fig. 2.2 The cloud-centric architecture of IoT systems (adopted from [37])

design, the embedded devices sense the desired parameters from their environment, send the collected data to the cloud. The control decision (if any) will be made in the could, and the result –in form of control command– will be sent back to the IoT device or actuator. In this setup, the gateway's role is limited to seamless integration of low-power wireless networks of IoT devices (utilizing ZigBee, Bluetooth, Thread, Z-Wave, etc.) with other networks (e.g., cellular network, LAN, etc.) to interface the IoT local area networks with the Internet [36]. Hence, the gateway bridges these networks by aggregating the collected data from IoT devices and transmit it to the cloud server. Finally, cloud servers provide data storage, data analysis, and decision-making services.

Figure 2.3 illustrates the main components of the System-on-Chip (SoC) in an IoT embedded device [37] as described in the following:

Analog Interface: Analog front end provides an interface to interact with the off-chip sensors and actuators. It includes Analog-to-Digital Converter (ADC) to read the input data from sensors and digitize it, and also Digital-to-Analog Converter (DAC) to convert the digital values calculated from the controller to the analog output to derive the actuators.

On-chip sensors: To achieve a smaller form-factor, some IoT devices may include several sensors onboard. Accelerometer, gyroscope, temperature, and humidity sensors are among those.

Processing Unit: For many IoT devices, the processing unit only includes low-power microcontroller units. However, some SoCs may provide higher compu-

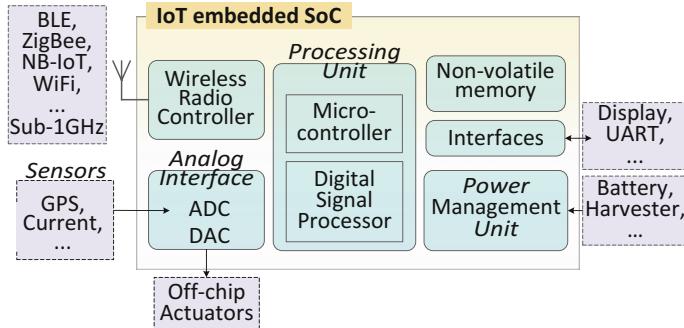


Fig. 2.3 The main components of an IoT embedded SoC (adopted from [37])

tational capability by including hardware accelerators, digital signal processors, etc.

Non-volatile memory: It stores the collected data.

Power Management Unit: Due to the limited power budget, IoT devices require a unit to manage their power. The energy source for IoT devices can be battery, energy harvesters or power line.

Wireless Radio Controller: The communication for sending data and receiving control commands is accomplished through wireless radios on the IoT SoC. Different wireless technologies can be used –depending on the application requirements, design objectives, etc.– which include Bluetooth Low Energy (BLE), ZigBee, Narrow-Band IoT (NB-IoT), Radio-frequency identification (RFID), etc.

The user and application requirements as well as the architecture of other processing layers dictates the design objectives of the IoT SoC for embedded devices. For instance, the required computation capabilities (i.e., processor and memory) depends on onboard processing policy of the system and the workload of the embedded device (e.g., simple control tasks, complex data preprocessing, network protocol stack, etc). Onboard processing may affect the amount of data to be transmitted, and consequently may change the required communication bandwidth.

2.1.2 Smart Grid

Smart grid is one of the main IoT application domains where generation, transportation, delivery and consumption of electricity is improved in terms of efficiency, reliability and safety [9].

The current power grid suffers from several issues such as unpredictable power disturbances and outages, undetectable consumer fraud, inflexible electricity prices, etc [24]. These issues contribute to the cost of utility and ever-rising fossil fuel

demand. For instance, to reduce the risk of an outage, the peak hour demand must be overestimated and more electricity must be generated.

Smart grid envisions to improve the efficiency by seamless integration of renewable energy sources, smart demand management, demand prediction, and constant monitoring of grid's status. The reliability is crucial to ensure that the grid is always available and serves the customers. It can be enhanced using the collected real-time information from energy usage, fault detection, anticipating peak demand, etc [16].

To address the lacking efficiency and reliability in traditional power grid, smart grid exploits the following concepts:

- Dynamic pricing: The main mechanism to manage the electricity demand during the peak hours is dynamic and real-time pricing. A dynamic pricing policy can be established based on the total available power supply, the dynamic demand, and Time of Use (ToU). During the peak hours when the load on power grid is high, the real-time price increases and vice-versa. The pricing policy considers historical demand and real-time demand data to estimate the total demand. It also requires to estimate the supply condition according to the predictive models for renewable energy sources and capacity of conventional power plants.
- Smart Meters: The installation of smart meters enables real-time information exchange between customers and providers. Smart meter can also control the smart appliances in a residential building, schedule their operations, and monitor their energy usage. It may receive the dynamic price information from the utility supplier and send back the information about the energy usage over time.
- Micro-grid: Interconnected subgroups of low-voltage electricity systems are known as micro-grid [3, 12]. Having self-generating and management mechanisms, micro-grid can increase the reliability of local distribution. A micro-grid can be connected to the power grid, but separate itself (go to the island mode) from it when there is a fault, failure, intrusion or other risks for the grid.
- Distributed generation: In the smart grid, consumers can generate power from renewable energy sources such as solar or wind. The excess generated power can be sold to the grid or to other customers within the micro-grid [3, 9]. The share of renewable sources in Germany's electricity is predicted to increase from 35% (in 2017) to more than 80% in 2050.

Figure 2.4 illustrates the main components of smart grid [42]. The generation of electricity is not limited to the conventional power plants (e.g., fossil plants) anymore. The renewable energy sources such as wind and solar are included in the generation phase. To billing, real-time pricing, supply prediction, demand prediction and grid monitoring tasks require management systems. The generated electricity is then transported to the micro-grid for distribution among consumers including smart homes, smart buildings, data centers, factories and industries, electric vehicles, etc. Micro-grids have local management systems and exchange information with other components in the smart grid such as utility suppliers.

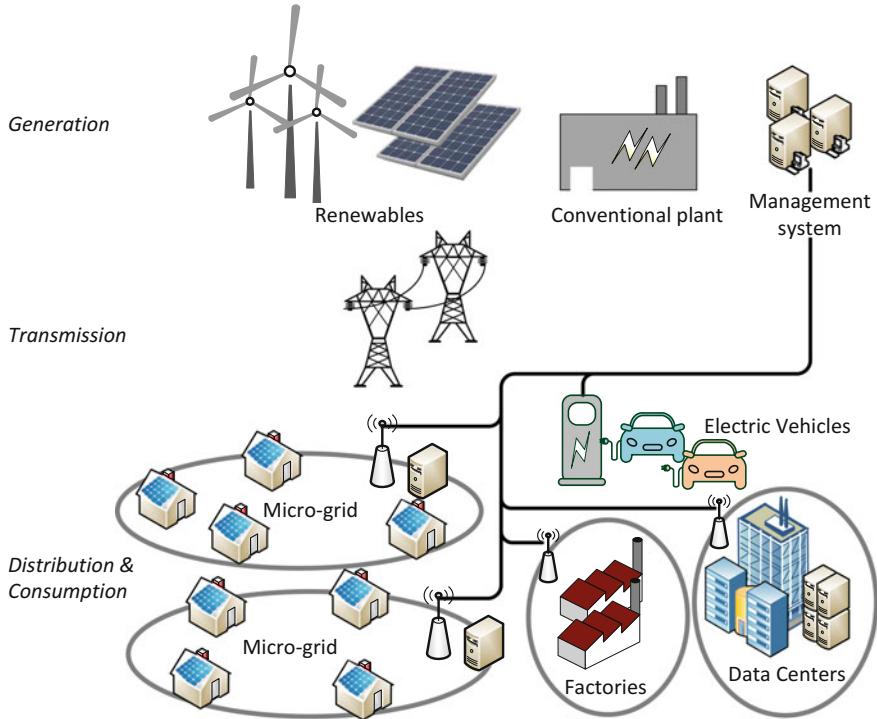


Fig. 2.4 The main components future smart grid

This chapter aims to introduce a hierarchical data processing architecture in the context of edge computing to enable the data processing of smart grid closer to the end user. It considers different components in the smart grid and present an architecture for distributing the computation and management tasks. The main focus of this chapter is on the smart home as one of the most prominent consumers in the smart grid.

The rest of this chapter is organized as follows. Section 2.2 presents the information processing flow in the smart grid considering the utility suppliers, customers, and third-party cloud service providers. Section 2.3 provides an overview of the edge computing role in the IoT era. It describes the shortcomings of a cloud-centric approach and illustrates the ability of the edge computing paradigm to address the foreseen issues. In Sect. 2.4, an edge computing model is presented for the smart home and smart grid by introducing an architecture that distributes computation and enables the edge devices to contribute to data processing. Then we overview the current art in edge computing for smart grid in Sect. 2.5. A use-case for edge computing in smart grid is presented in Sect. 2.6. Finally, Sect. 2.7 concludes this chapter.

2.2 Information Processing in Smart Grid

The core idea of the smart grid is to use advanced communication technologies to collect the power grid data and extract the necessary information to improve the efficiency and reliability of the grid. The collected data includes the energy usage of customers which is usually received from smart meters and transmitted to the utility suppliers. Different entities in the smart grid must act upon the extract information: utility suppliers, and customers.

Utility Suppliers The utility suppliers monitor the status of the grid, predict the accumulated demand from the customers, estimate the energy from renewable sources and generate the required electricity using conventional power plants. The suppliers must update the dynamic and real-time price according to the supply and demand. In addition, suppliers perform accounting and billings based on the dynamic price and energy usage of customers over time. The information management systems (IMS), as well as other services from the utility suppliers, can be hosted on private clouds.

Customers The customers include smart homes, smart building, smart factories, smart cities, etc. In this chapter, our focus is limited to the smart homes and smart buildings. In the smart grid realm where the price of electricity is dynamic, the customers have to manage their demand accordingly to respond to the power grid status and dynamic price to minimize their bill. Scheduling the home appliances, load shifting during the peak hours, and exchanging energy with other customers (i.e., when one customer has surplus power generated from renewables) are among the decision of a home energy management system (HEMS). A home automation system (HAS) can incorporate the dynamic pricing, user's preferences and HEMS to minimize the electricity bill while maintaining the main functionalities of home appliances.

Cloud service providers In a cloud-centric design, customers rely on cloud service providers for their management systems including HEMS, HAS, and Demand Management system (DMS). In addition, customers may supply some portion of their own demand from renewable energy sources such as solar panels in a smart home. Therefore, intelligent supply prediction systems can create customized and dedicated models to predict the available renewable energy based on the historical and weather-related data.

Figure 2.5 shows the relationship between three entities in the smart grid: customers, utility suppliers, and cloud service providers, and the information flow between them. This architecture heavily relies on the cloud computing and information management services from third-parties. However, there will be several issues and concerns regarding this architecture, which are discussed in the following sections.

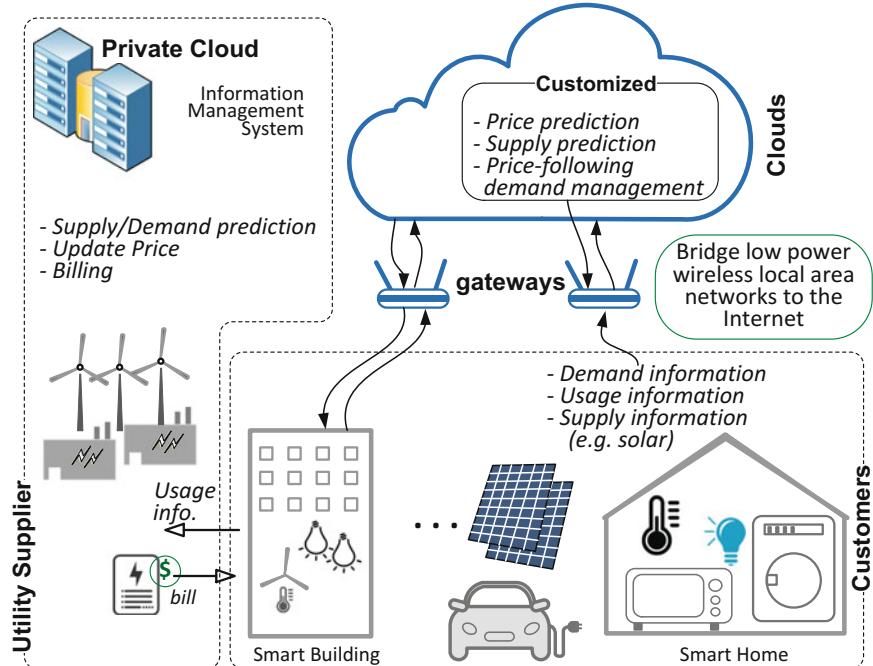


Fig. 2.5 The information flow between customers (e.g., smart home, smart building) and utility supplier as well as cloud service provider, in a cloud-centric design

2.3 Edge Computing in Internet of Things

This section discusses the challenges and issues in cloud-centric IoT design. First, we describe the limitations of cloud computing paradigm to address the diverse requirements of IoT. These limitations stem either from the underlying technologies or from the exploited system architecture. Then we discuss the potentials of new design approaches (i.e., based on Edge Computing paradigm) to address the foreseen issues in IoT.

The massive number of connected IoT devices and their continuous data collection lead to a hard-to-manage amount of data. Traditional cloud computing does not fulfill the requirements of IoT data processing due to the following reasons:

- Cloud servers are geographically distant which requires multi-hop communication. The imposed communication delay is not tolerable for some real-time applications.
- Raw data transmission from embedded IoT devices to the cloud introduces a huge load on the communication network. Hence, the latency and response time becomes unreliable.

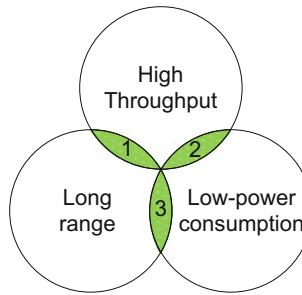


Fig. 2.6 Three main aspects of wireless technologies in IoT. A wireless technology can only achieve up to two out of three

Table 2.1 IoT wireless technologies and their properties [25, 27, 37, 43]

Wireless Technology	Range	Date rate (Kbps)	Throughput (Kbps)
ZigBee	Short (<100 m)	Medium (250)	120
Bluetooth Low Energy	Short (100 m)	Medium (1 Mbps)	300
HaLow	Medium (<1 Km)	Low (150)	100
NB-IoT	Long (1–10 Km)	Low (250)	200
LoRa	Long (5–20 Km)	Low (<50)	<5
SigFox	Very long (10–40 Km)	Very low (0.1)	

- The collected IoT data usually contains sensitive or private information about the user. Sending the raw data to a public cloud where third-party can access them will arise privacy and security concerns.

Limited Network Capacity in IoT Most of the IoT devices are inter-connected using wireless transceivers. Wireless communication in IoT has three major aspects: (1) throughput (or data rate), (2) coverage range and (3) power consumption. The designer of IoT device prefers a wireless transceiver with high throughput, long range, and low power consumption. However, these three metrics cannot be optimized simultaneously. A wireless technology can only achieve up to two out of three aspects. Optimizing one aspect costs degradation in others, as illustrated in Fig. 2.6.

Many IoT devices are battery operated with limited energy budget, and consequently, low power consumption is a critical objective in their design. Hence, the throughput is compromised to gain the required coverage range or vice versa [36]. Table 2.1 summarizes the properties of several low-power wireless technologies in IoT domain which can be exploited in the smart grid. The long-range wireless technologies have a very limited throughput. This, again, underscores the importance of edge computing where the partially-processed or final results are transmitted instead of the raw data.

Privacy Issues in Smart Grid IoT devices are increasingly integrated into our everyday lives. Consequently, a great amount of private information is collected,

transmitted and stored using our surrounding devices and objects. The gathered information carry a significant potential of privacy risks regarding the use of data and its access [46] throughout this chain (from embedded IoT devices, network infrastructure, cloud computing servers, and data centers).

Studies have shown that monitoring electricity usage of home appliances enables recognition of daily activities in a residential environment [2, 23]. The required information for this purpose is available through smart meters, smart plugs, etc. Even though the primary purpose of these researches is to recognize activity for the ambient assisted living applications (helping elderly or impaired people), they will open a door for privacy violation if the raw data is accessible to the third-party on the cloud. The customer's habits, behaviors, physical activities are subjects to be exposed to unauthorized third-parties for commercial purposes (e.g., marketing) or other privacy abuses [24].

Greveler et al., [14] demonstrate that by intercepting data from the smart meter, one can reveal what TV show was displaying. According to their experiments, a 5-min consecutive data is sufficient to determine the displaying content (when there is no major interference from other home appliances).

Even though encryption can protect the content of data that is generated by IoT devices and transmitted over the network, but it is proven to be insufficient to protect customer privacy in some applications. Side channel information such as the volume of network traffic and its pattern can reveal privacy-sensitive information. Internet service provider (ISP) and other network observers such as wireless eavesdroppers can access side channel information. A study has demonstrated that sensitive information about user behaviors and in-home activities can be inferred from network traffic even when the data is encrypted [1].

Another study has shown that machine learning classifiers are able to detect the home appliances such as TV, Kettle, Microwave oven, etc. from the aggregate power usage [17].

In summary, smart devices –such as smart meters and appliances in a smart home– can potentially become surveillance means that invade customers privacy by monitoring their behavior, especially when collecting and transmitting high-resolution data over the Internet.

Edge Computing As A Solution To address the aforementioned issues, EC pushes the data processing task to the edge of the IoT system, close to where the data is collected [41]. A report by International Data Corporation Futurescape estimated that more than 40% of IoT-created data will be processed, stored, and acted upon close to the edge of the network [33]. EC not only reduces the network load by reducing the data transmission volume, it can reduce the latency for real-time applications.

Figure 2.7 shows the hierarchical processing layers in the continuum from cloud to embedded IoT devices [36].

In the envisioned EC for IoT (Fig. 2.7), some of the cloud's tasks are distributed between other processing layers. More specifically, the processing is only offloaded to the higher layers when it is infeasible or inefficient at a layer. For instance, IoT embedded devices can perform pre-processing on the data, e.g., filtering noise, remove

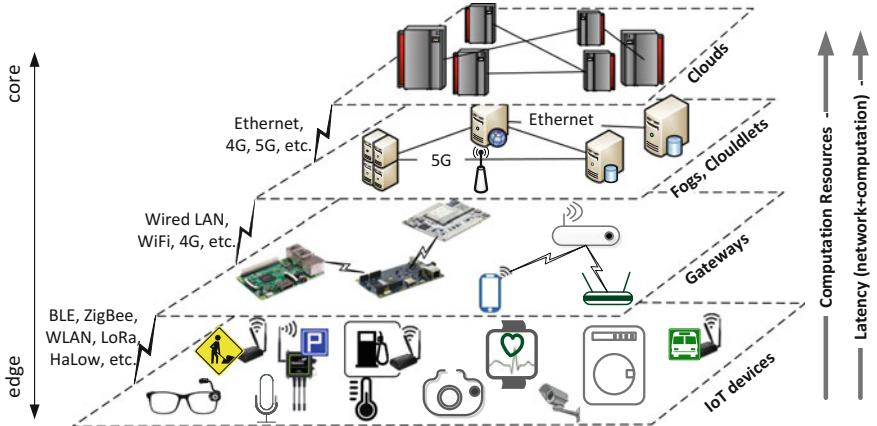


Fig. 2.7 The hierarchical architecture of IoT system with multiple processing layers [36]

redundant information, etc. Due to their limited computation capability and memory, IoT devices are not able to fully process the data in some applications. Hence, they can offload the rest of computation to more powerful layers including gateways [5, 13]. In EC paradigm, gateways provide local computation service at the edge of the IoT network besides their conventional service (i.e., bridge the networks) [36]. Gateways are usually located in the vicinity of IoT embedded devices due to the short-range communication ability of some IoT wireless transceivers (e.g., ZigBee, Bluetooth, etc.).

Fogs are virtualized computation and storage platforms that are geographically distributed to enable low-latency applications and services [4, 19].

EC paradigm does not imply that the cloud computing will be out of the picture. In contrary, the cloud still remains as a key element in the hierarchical architecture of IoT. The final results or partially-processed data can be stored on the cloud in order to provide long-term and demographic analysis. To name a few, analysis of long-term data, study the trends in data over time, building prediction models based on the past data, etc. take place on the cloud.

2.4 Edge Computing Model for Smart Grid

This section provides a model based on EC for the smart homes in the smart grid era. Figure 2.8 illustrates the envisioned model on EC in the smart home. Most of the information processing that is required for managing the demand, home automation, supply prediction, etc. is performed within the home network. In addition, some of the management tasks of utility suppliers are distributed to the micro-grids. Each micro-grid integrates a management system for local supply management, local demand prediction, and local electricity market.

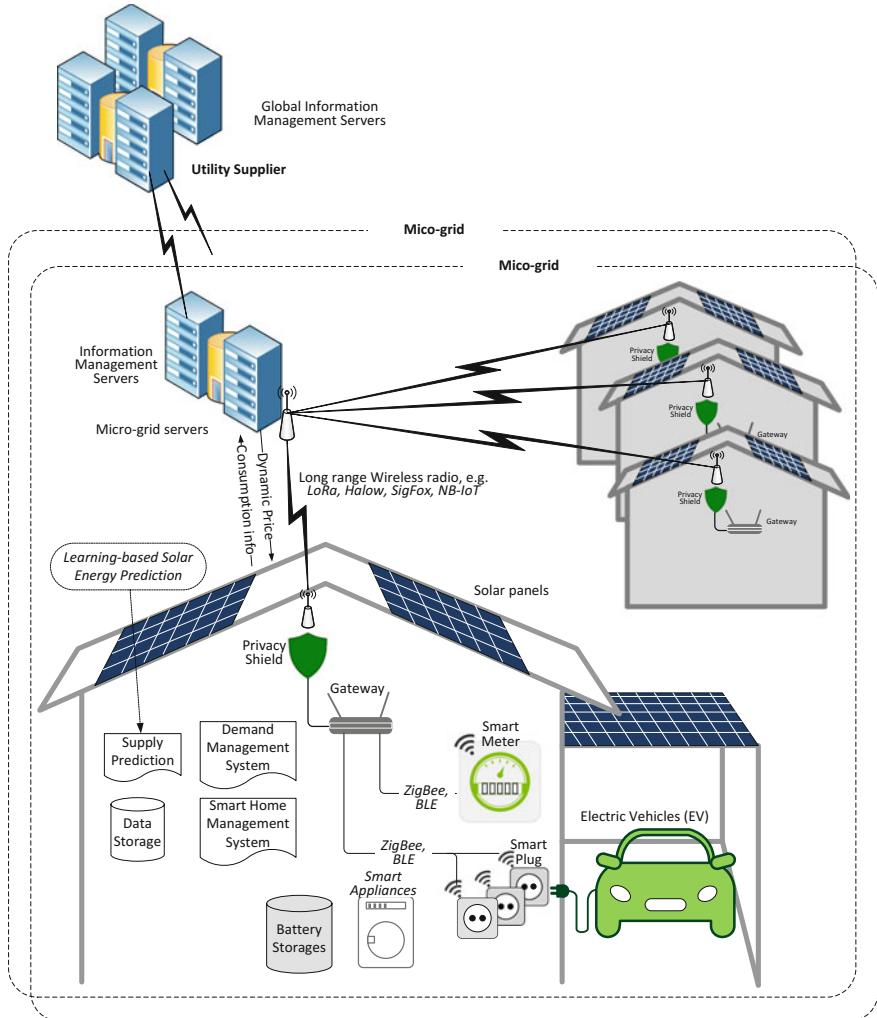


Fig. 2.8 Smart grid integration with smart home

To bring the intelligence close to the consumer (e.g., smart home), the home energy management system, demand management system, and supply prediction are implemented within the home network. The required computation capability to support these systems is available in personal desktop computers and gateways. The real-time usage information of each appliance is transmitted via short-range wireless radio over Bluetooth low energy, ZigBee, etc. to the local gateway.

Intelligence at the Edge Smart home management systems often can boost their efficiency by analyzing the historical data and learning from them. This may include

learning the preferences of consumers (e.g., comfortable lighting of home) as well as learning to predict the user demand and renewable supply.

Machine learning is a powerful and popular tool for data mining and information processing. It aims at capturing the relationship between the dependent variables (i.e., input parameters) and the output and creating models based on past observations. It then uses the created model to predict upcoming output or to discover hidden patterns. The main usages of machine learning models are as follows:

Regression: The output of a regression model is a continuous variable. For instance, a regression model can predict the amount of renewable energy from solar panels according to the weather condition, seasonal information and historical data. Other parameters that can be predicted using regression models include day-ahead or hourly energy demand.

Classification: In classification, the output of machine learning model is among a finite pre-defined set of labels. For instance, using energy usage information to determine which home appliance is operating, falls into the classification problem.

Clustering: The task of clustering is to divide the data into subgroups or *clusters* such that the data points in each cluster are similar to each other and dissimilar to the data points of other clusters [39].

Reinforcement decision making: Reinforcement learning is mainly used for decision making. It is based on trial and error. Each time, the decision is evaluated by a reward or penalty which shows how good or bad the decision was. This reward is handled as a feedback to learn how to make better decisions next times. Reinforcement learning is a suitable approach for autonomous decision-making in smart home management system [8, 22, 29].

The first two models (i.e., regression and classification) belong to the *supervised learning*. They require training datasets which consist of past observations with the input-output pairs. The models are created offline at design time and used at runtime. The last two models (i.e., clustering and reinforcement learning) belong to the *unsupervised learning* which does not rely on the given input-output pairs at design time.

Classification and clustering models are more widely used for the big data processing. Therefore, they have more application for the utility suppliers and cloud service providers. For instance, the supplier can divide the consumers into subgroups and clusters according to their usage patterns, and then create predictive models for each subgroup's demand.

One of the keys to enable edge computing in smart grid is to enable efficient machine learning models on edge devices. In Sect. 2.5, we review the current state-of-the-art and attempts.

Smart Grid Market In micro-grid, the excess of generated power from customer (e.g., solar panels, stored energy in batteries, etc.) can be sold back to other customers. This creates a an energy market where the autonomous agents –representing customers– trade power in auctions to maximize their profit [32].

Edge computing brings other items and services to the market for trade and exchange. For instance, one important service with high demand will be the ‘renewable energy prediction model’. The prediction models for renewable energy sources are based on the local environment parameters such as weather and Geo-location parameters. Highly accurate models usually require high processing power to be trained and built. Some customers might prefer to buy the model or prediction service from neighbor customers instead of spending processing and computation power to build their own model.

2.5 Current Art in Edge Computing and Smart Grid

There have been many recent attempts in distributing the computation of smart grid and bring it to the edge. These attempts include architecture design to integrate the edge devices in data processing flow, algorithm and software design, computation offloading techniques, etc.

Thapa et al., [45] use a learning approach based on the reinforcement principles to schedule the shiftable loads in a micro-grid with rigid power budget. They formulated the problem as a distributed scheduling game where the consumers in the micro-grid negotiate with each other to make the decision whether they want to be supplied in the current time slot or not.

O’Neill et al., [28] present an algorithm, based on reinforcement learning, to estimate the future energy price and schedule the home appliances such that the energy cost is reduced. Feng et al., [11] consider a micro-grid in island mode where multiple renewable energy sources are available. The customer must decide which energy source should be used to maximize the profit. They propose distributed algorithms to discover the all the available energy sources within the micro-grid and to choose the best energy source. The proposed algorithms are inspired by the online machine learning.

Fan [10] presents a distributed demand response for electric vehicles in the smart grid. Each user adapts its demand (i.e., charging rate of the electric vehicle) according to the current prices to maximize its profit. The paper takes the concept of congestion pricing in Internet traffic control and applies it to the demand response problem in the smart grid. Tan et al., [44], too, consider the electric vehicles in their demand response problem. The excess of generated energy from renewable sources as well as the stored energy in the batteries of electric vehicles can be sold back to the grid when it is advantageous. A distributed and parallel optimization problem is formulated to reduce the electricity bill of individual users.

Logenthiran et al., [21] present a demand-side management strategy based on load shifting using a heuristic evolutionary algorithm. The algorithm aims at reducing the peak load demand and energy cost in the smart grid.

Sharma et al., [40] tackle the problem of solar power prediction in micro-grids and smart homes. They analyze historical data from weather stations and forecasts to find the correlation between weather parameters and solar intensity. Then, they

apply machine learning regression techniques to build prediction models for solar intensity using the weather forecast parameters as inputs. Each micro-grid or smart home can train the prediction model based on the parameter values in its location.

As mentioned in previous sections, the customers can buy electricity from local power generators in the micro-grid. Reddy et al., [34, 35] consider a local smart grid market where autonomous *agents* buy and sell electrical power from producer and to consumer, respectively. Each agent represents a customer. Using the reinforcement learning, an agent can learn its pricing strategies in tariff market to earn profits.

Even though there are several research attempts in different directions to bring the intelligence and processing to the edge devices and distribute the computation among local entities in the micro-grid, there are still many open challenges and research problems to be addressed.

2.6 A Use-Case for Home Appliance Management

This section presents a use-case in which the home appliances are managed in a smart home environment to respect the rigid power budget. The problem is formulated as an optimization problem and then a light-weight algorithm is presented to solve the optimization on the edge devices.

In load shifting solutions, some home appliances such as washing machine are not used in peak hours and instead their usage is postponed to the off-peak hours. This model can be extended to support more than two states (i.e., off and on) for home appliances. Even though some home appliances such as washing machine, dishwasher, etc. only support these two states, other appliances can operate in intermediate modes in which a percentage of their full potential is delivered. For instance, an air conditioning system may operate at different configurable levels. These operating modes offer different comfort level or satisfaction to the user, and have different power consumption. Therefore, the home automation systems requires algorithms to determine and enforce the operating mode of each appliance dynamically.

2.6.1 Problem Formulation and System Model

Let us consider N appliances in a smart home each of which is uniquely identified with an integer value $i \in \{1, \dots, N\}$. Each appliance has multiple operating modes: *off*, *fully on*, and some intermediate modes. For instance, a washing machine has only two modes namely off and on. But other appliances such as air conditioning or lights can have multiple discrete modes where they use a portion of their capability (e.g., 30, 50, 70%, etc). Indeed, each operating mode offers a different comfort level or *utility* to the user, and consumes different amount of power.

Each appliance is described with the following parameters:

- M_i denotes the number of operating modes for appliance i . Moreover, m_{ij} describes the j th mode of appliance i where $j \in \{1, \dots, M_i\}$ and $i \in \{1, \dots, N\}$.
- p_{ij} is the power consumption of appliance i when operating in the mode j .
- u_{ij} represents the utility or satisfaction of user when appliance i operates in the mode j .

We assume that there is a rigid power budget (i.e., P) for the smart home which should not be exceeded. This threshold is determined either by the power source [45] or by the customer (to limit its costs).

The main objective is to determine the operating mode of each home appliance dynamically such that the overall utility of user is maximized and the power budget constraint is met. The problem can be formulated as follows:

$$\text{Maximize} \sum_i \sum_j (u_{ij} * w_{ij}) \quad (2.1)$$

$$\sum_i \sum_j (p_{ij} * w_{ij}) \leq P \quad (2.2)$$

$$\forall i : \quad \sum_j w_{ij} = 1 \quad (2.3)$$

where

$$w_{ij} = \begin{cases} 1 & \text{if } j\text{th mode of appliance } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases} \quad (2.4)$$

This formulation is an Integer Linear Program. The value of w_{ij} must be determined such that constraints in Eqs. (2.2) and (2.3) are fulfilled, and the optimization goal in Eq. (2.1) is maximized.

2.6.2 Dynamic Programming Solution

The formulated problem can be solved by heuristic algorithms to obtain sub-optimal solutions, however, we present a dynamic programming algorithm similar to [38] that calculates the optimal solution.

2.6.2.1 Algorithm and Example

Let $G(i, P)$ denote the maximum overall utility of user from the first i home appliances while the power budget is P .

Equation (2.5) formulated the recurrence relation to calculate $G(d, P)$:

$$G(i, P) = \max_{1 \leq j \leq M_{ij}} \left\{ G(i-1, P - p_{ij}) + u_{ij} \right\} \quad (2.5)$$

The equation has two boundary conditions:

$$G(i, P) = \begin{cases} -\infty & \text{if } P < 0 \\ -\infty & \text{if } i = 0 \end{cases} \quad (2.6)$$

The first condition in Eq. (2.6) assures that the total power budget constraint is not violated. The second one stops the recursion when there is no more home appliance left. To find the solution of Eqs. (2.1)–(2.3), one must call function $G(N, P)$.

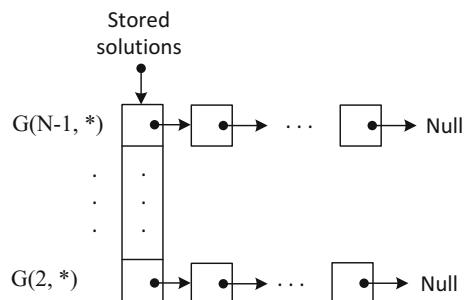
Starting from i th device, we must choose one of its operating modes. Considering the j th operating mode of appliance i , the power consumption and utility values are p_{ij} and u_{ij} , respectively.

We investigate all the operating modes of appliance i . For the j th operating mode in Eq. 2.5, we first find the overall utility of a solution with $i-1$ appliances with the power budge of $P - p_{ji}$. Then, we add it to u_{ij} , the provided utility by j th operation mode itself. This algorithm is proven to have the global optimum solution.

2.6.2.2 Memoization

The advantage of dynamic programming approach stems from the *memoization* where the solutions to the sub-problems are stored. Once the same sub-problem occurs again, the solution can be retrieved from the memory instead of being re-computed. The recursive relation in Eq. (2.5) allows a top-down dynamic programming implementation. The solutions to sub-problems are stored in a linked-list after being called. Figure 2.9 shows the structure of linked-list and how the sub-problems are stored. For each level of recursion, we use a different linked-list and store the address of each in an array with the length of $N - 2$ (i.e., from $N - 1$ down to 2). The advantage of this structure over one linked-list is that it helps to reduce the length of the list that should be searched to retrieve the solution. Consequently, it reduces the execution time of retrieval.

Fig. 2.9 The linked-list structure to store the sub-problems



We also consider the leftover power for each sub-problem in order to cover a range of sub-problems, similar to [36].

2.6.3 Evaluation

Experimental Setup We use a Raspberry Pi 3 Model B to implement the proposed algorithm for home appliance mode selection. It features a quad-core 64-bit Broadcom processor which operates at 1.2 GHz frequency and has 1 GB RAM. The operating system is Raspbian Jessie Linux version 8. Raspberry Pi has been employed in several home automation studies [7, 31].

Results The proposed home management algorithm is compared with a baseline in which no memoization is used. Figure 2.10 shows the execution time of the proposed algorithm compared to the baseline for different number of home appliances. The execution time of baseline algorithm grows exponentially when the number of appliances increases. The proposed algorithm achieves more than 11x speed-up.

The gained speed-up in the proposed approaches stems from memoization (i.e., storing the solution of sub-problems to avoid re-computation). In Fig. 2.11, the number of sub-problems that are stored at runtime as well as the number of memory hits are reported. As the number of home appliances increases, the number of stored sub-problems and number of hits increase, however, the hit ratio remains almost the same.

2.7 Conclusion

Smart grid, similar to other IoT application domains, consists of a massive number of sensors and data sources which continuously collect high-resolution data. Managing this large amount of data is identified as one of the major challenges in IoT, especially when real-time and latency-sensitive services are present. While cloud-centric designs fail to address this issue, Edge Computing envisions to process the

Fig. 2.10 The execution time of the proposed algorithm compared to baseline (i.e., no memoization) for different number of home appliances

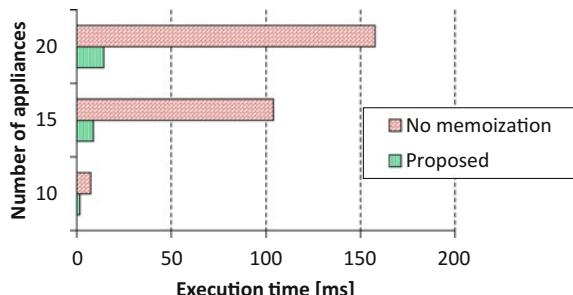
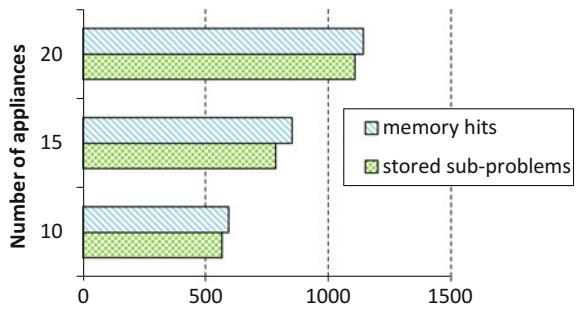


Fig. 2.11 The number of sub-problems being stored and hit in the proposed approach for different number of home appliances



data at the edge of IoT network close to where the data is collected. Edge computing not only reduces the computation and communication load on the IoT network and cloud servers, it also provides opportunities to preserve privacy by transmitting the minimum required information instead of raw data.

This chapter investigates the edge computing potentials in the smart grid domain. It introduces an edge computing model for the smart grid information processing, with a focus on smart home. The advantages of this model in terms of self-supporting and privacy are discussed. Moreover, we present a use-case for smart home automation where the operating mode of home appliances are determined dynamically to respect the limited power budget of home while maximizing the user's satisfaction and utility.

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Chapter 3

Smart-Grid Modelling and Simulation



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and Minas Dasygenis

Abstract This chapter discusses a modeling and simulation algorithm for system behavior analysis and energy consumption in smart-grid environment. Since system behavior and energy consumption constitute very important information for designing an algorithm, the discussed solution models various smart-grids scenarios in an efficient and realistic way.

3.1 Introduction

Modelling smart grids is an active area of research [22]. There are various proposals and techniques, which are based on various data, such as the type of the energy production, the power distribution network, the energy storage devices, the power consumption, the learning algorithm for energy costs reduction, the energy usage etc. Furthermore, each method presents a different objective. Examples include Distributed Online Algorithm for Optimal Energy [12, 21], Metering and optimal energy distribution [22], Optimal Storage management and Dimensioning [19], Learning algorithms for energy costs reduction and energy usage [18] and other. Here, we present some contributions to this field, based on an extensive survey of the literature. Specifically, we demonstrate an algorithm that accepts as input multiple types of energy production, such as solar, water and wind energy, as it occurs in a typical country, and we focus on modeling a distribution energy algorithm for simulation purposes. Therefore, we use a case for the energy distribution network and design a

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Smart Grid with GNU OCTAVE¹ approach. Furthermore, using figures we explain in detail the way the Octave programme is used to design the algorithm and visualize the results. GNU Octave is a free software, which runs on GNU/Linux, macOS, BSD, and Windows platforms and has a powerful mathematics-oriented syntax with built-in plotting and visualization tools. In addition, it is compatible with many Matlab scripts. Using Octave, we explain the way it works, the dashboard, basic functions etc. We analyze every step, starting from the way we analyze and describe the problem, or how we find an efficient solution, up to how we solve the problem. We believe this will help the reader to clearly understand how our model operates.

The main contributions of this chapter are: (*i*) the basic modeling of a typical smart grid (solar, wind and water renewable energy) (*ii*) utilizing the toolbox MAT-POWER² on GNU OCTAVE and (*iii*) presenting a simulation example using octave code on smart grid.

3.2 Modelling of Smart-Grid Infrastructure

As it is evident from previous chapters, the traditional power grid is strictly one-way hierarchical, which means that the energy can only be distributed from the main power plant using traditional infrastructure; in contrast, the smart grid is characterized by the two-way flows of energy and real-time information, which offers tremendous benefits and flexibility to both users and energy providers. There are significant differences between them. The traditional power grid is centralized, which means all power must be generated from a central location, eliminating the possibility of easily incorporating alternative energy sources into the grid. The infrastructure is not equipped to handle many sensors on the power lines, so it makes it difficult to pinpoint the location of a problem, resulting in longer downtimes, manual monitoring of energy distribution, and labor controlling manually and in place the energy. The smart grid has many benefits. First of all, the smart grid employs digital technology, allowing for increased communication between devices, and facilitating remote control and self-regulation. Also, power can be distributed from multiple power plants and substations, to aid in balancing the load, decreasing the peak time strains and limiting the number of power outages. Moreover, there are multiple sensors placed on the lines. This helps to pinpoint the location of a problem and can help reroute power to areas needed, while limiting the areas affected by the downtime. The smart grid can monitor itself by using digital technology. This allows to balance power loads, troubleshoot outages, and manage distribution, eliminating the need for direct intervention from a technician. Last but not least, using smart technologies, infrastructure can be shared. This helps more companies and types of alternative energy to connect to the grid, allowing consumers to choose their energy provider.

¹<https://www.gnu.org/software/octave/>.

²<http://www.pserc.cornell.edu/matpower/>.

The renewable energy sources provide infinite energy, offering us the chance to use them continuously without polluting the environment, in contrast to non-renewable energy sources. It seems that renewable energy sources can easily replace the fossil energy sources, but it is not that easy, due to their influence from natural conditions [3, 11, 17]. For example, water, wind and solar energy depend on the weather; that's why the producers and consumers have to act in a more flexible way to meet the energy needs. Also, the generation cost of renewable power is high [2, 5] and for that the scientists are seeking new and more profitable methods. It is clear that the fluctuation in availability of using the renewable energy sources is depending on the weather and the cost, which are the main problems. From one hand we don't know the exact distribution power and it is also very difficult to predict the power consumption, because the consumers can change their needs at any time. To solve this issue between generation and consumption energy, suppliers may create a special offer, a motive model, such as offering energy at a reduced price during sunny days. The consumers will benefit from this offer and for example will recharge their cars, use the washing machine etc. But this may lead to another problem: plenty of the consumers will react to the same time to benefit from the offer and there will be a spike on the demand. This may cause a blackout to the whole system. The only way to use the time variant prices is to use an energy management system.

It is widely understood that it is very complicated to keep the balance between the produced energy and the consumption. There are several approaches that depend on the perspective the researchers use to resolve the issues. The algorithms have different approaches. In [13] smart homes optimize the consumption of their own devices and share information about their consumption. Another approach is to control an entire power grid [12]. Besides the different approaches, there are also different goals that the algorithms try to reach, e.g. balance of supply and demand [12, 14], reduction of peak loads and energy losses, smoothing of power consumption through load shifting [3] or minimization of micro grid costs [21].

In this chapter, we propose a general real-time algorithm model, which can be used in a variety of smart grids. As we have stated, the smart grid is characterized by the two-way flows of electricity and real-time information, which offers notable benefits and gives the flexibility both to consumers and the energy providers. For example, in order to balance the supply and demand, the energy storage systems can cooperate with distributed renewable energy resources and the consumers can adapt their demand for energy according to the market price fluctuations [8]. There are no limits on the energy provider, which can sell their energy to the smart grid. Any consumer entity, whether it is a private (home) or a company, must install a smart meter, which will collect the information needed. The base of our model will be the Energy Distribution Center (EDC), which collects real-time information from the (*i*) consumers, (*ii*) the smart grid and (*iii*) the energy provider and makes decisions about the optimized energy management. The proposed algorithm uses three sources of energy: solar, wind and water.

The smart grid has to be dynamic and have constant two-way communication. The Fig. 3.1 showcases an example, where the energy distributed by the Photo-voltaic panels, the Micro Wind Turbine and the Hydroelectric Plants, provide the power to

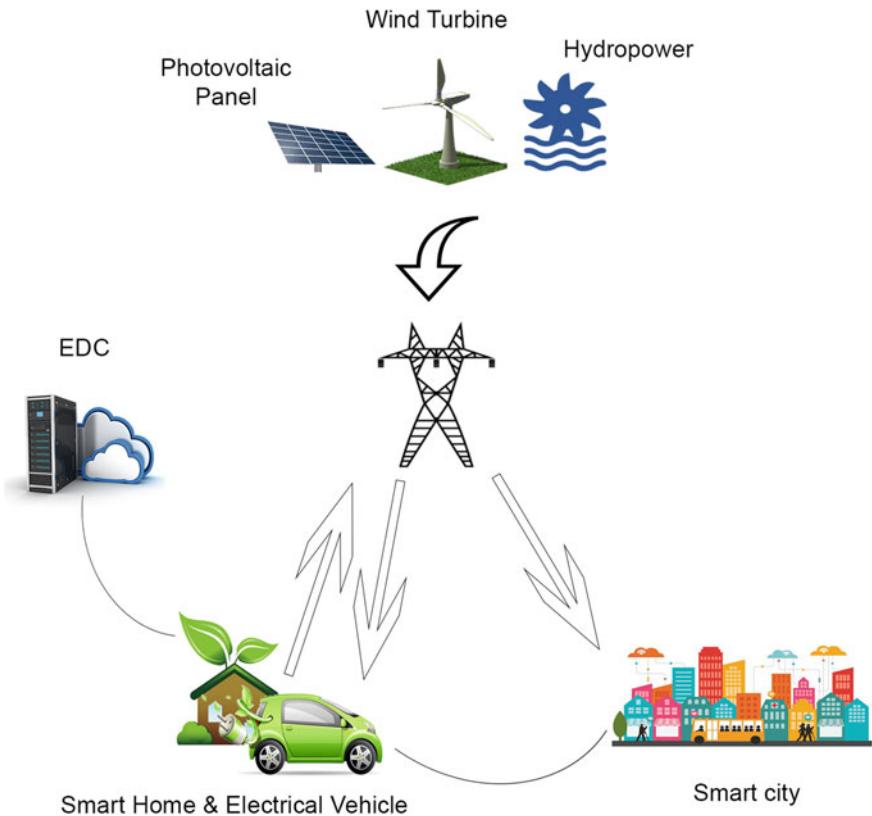


Fig. 3.1 General layout of the smart grid

the smart grid. Also, the houses who have Photo-voltaic panels on the roof, consume and store the energy, which they produce and may consume extra power from the smart grid, if it is necessary. Our EDC manages in an optimum way, the whole process to save energy and increase reliability. The modeling and design must be analyzed separately.

3.2.1 *The Photovoltaic Module*

The general mathematical model for the solar cell has been studied extensively over the last years [13]. The circuit of the solar cell model, which consists of a photocurrent, diode, parallel resistor (leakage current) and a series resistor. According to the PV cell circuit shown in Fig. 3.2 and Kirchhoff's circuit laws, the photovoltaic current can be presented as follows [21]:



Fig. 3.2 The photovoltaic module

According to M.G. Villalva et al. [20] the photovoltaic current can be presented as shown on Eq. 3.1.

$$I_{pv} = I_{gc} - I_o \left[\exp^{\frac{eV_{oc}}{kFT_c}} - 1 \right] - \frac{V_d}{R_p} \quad (3.1)$$

where:

I_{gc} : is the light generated current

I_o : is the dark saturation current

e : electric charge = $1.6 \times 10^{-19} \text{ C}$,

v_d : is the diode voltage,

K : is Boltzmann's constant = $1.38 \times 10^{-23} \text{ J/K}$,

F : is the cell idealizing factor,

T_c : is the cell's absolute temperature and

R_p : is the parallel resistance.

The photocurrent (I_{gc}) and the the cell's saturation current (I_o) are described in Eq. 3.2 and 3.3 [20], respectively.

$$I_{gc} = [\mu_{sc}(T_c - T_r) + I_{sc}]G \quad (3.2)$$

where:

μ_{sc} : is the temperature coefficient of the cell's short circuit current,

T_c : is the cell's absolute temperature,

T_r : is the cell's reference temperature,

I_{sc} : is the cell's short circuit current at a 25°C and 1 kW/m^2 , and

G : is the solar irradiation in kW/m^2 .

$$I_o = I_{oa} \left(\frac{T_c}{T_r} \right)^3 \exp^{\left[\frac{ev_g}{kF} \left(\frac{1}{T_r} - \frac{1}{T_c} \right) \right]} \quad (3.3)$$

where:

I_{oa} : is the cell's reverse saturation current at a solar radiation and reference temperature described on Eq. 3.4,

v_g : is the band-gap energy of the semiconductor used in the cell,

$$I_{oa} = \frac{I_{sc}}{\exp^{\frac{eV_{oc}}{KFT_c}}} \quad (3.4)$$

where:

I_{sc} : is the cell's short circuit current at a 25 °C and 1 kW/m², and
 V_{oc} : is the cell's open circuit voltage.

3.2.2 The Wind Turbine Module

There have been many studies about Wind Turbines and different approaches. In this study we choose a basic model for the renewable energy by the wind which is [4, 7, 10]:

$$P = \frac{1}{2} p A v^3 \quad (3.5)$$

where:

P : is the power in watts

p : the air density

A : the swept area of the turbine blades

v : the wind speed

To understand better this type, we have to mention that for a vertical-axis wind turbines (VAWT) with 40 tall wings and a 30 diameter arc, the swept area is $A = 1.1 \text{ m}^2$ and if the wind speed doubles to 13.4 m/s notice that the power increases more than 8 times.

We can see the operating of the Wind Turbine Module on the Fig. 3.3.

3.2.3 Hydropower Module

The water energy is available from falling water and can be calculated from the flow rate and density of water, the height of fall and the local acceleration due to gravity. We use the basic formula [4, 7], shown in Eq. 3.6.

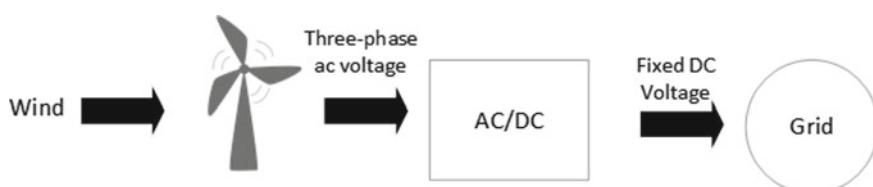


Fig. 3.3 The wind turbine module

$$P = npQgh \quad (3.6)$$

where:

P : is the power in watts

n : is the dimensionless efficiency of the turbine

p : is the density of water in kilograms per cubic meter

Q : is the flow in cubic meters per second

g : is the acceleration due to gravity, and

h : is the height difference between inlet and outlet

An example: If the power of a water turbine is calculated at 85% efficient, with water at 998 kg/cubic meter and a flow rate of $79.3 \text{ m}^3/\text{s}$, gravity of 9.80 m/s^2 and with a net head of 146.3 m, after the calculation using this formula we have Power = 96.4 MW

3.3 Simulation

To understand fully how our algorithm functions, we executed some scenarios. For this purpose we use the software GNU Octave, because it is an open source software which runs on GNU/Linux, macOS, BSD, Windows and it is drop-in compatible with many Matlab scripts. We also use the MATPOWER package, which is another open-source Electric Power System Simulation and Optimization Tool for MATLAB and Octave. This package is an open-source Matlab-language m-files for solving steady-state power system simulation and optimization problems such as power flow (PF), continuation power flow (CPF), extensible optimal power flow (OPF), unit commitment (UC) and stochastic, secure multi-interval OPF/UC. To add the load path of the MATPOWER package we have to type `addpath(genpath('matpower6.0'))`; on the command window of GNU Octave software, for example: if the matpower6.0 zip file have been extracted into the folder C:\Users\Downloads we have to type on the command window `addpath(genpath('C:\Users\Downloads\matpower6.0'))`.

MATPOWER has many sets of matrices packages of MATLAB structure (m format) known as MATPOWER cases. It is very easy to use those algorithms or to edit them with any text editor. We can use one of them to understand how a scenario works. For instance, we will use the ‘case4gs’, which has power flow data for 4 buses and 2 generators.

The first step is to load the algorithm on Octave. Firstly we will quote the algorithm:

```
function mpc = case4gs
%CASE4GS  Power flow data for 4 bus, 2 gen case.
% Please see CASEFORMAT for details on the case file format.
%
% This is the 4 bus example from pp. 337-338
% of "Power System Analysis".
```

```

% by John Grainger, Jr., William Stevenson, McGraw-Hill, 1994.

% MATPOWER

%% MATPOWER Case Format : Version 2
mpc.version = '2';

%%%% Power Flow Data -----
%% system MVA base
mpc.baseMVA = 100;

%% bus data
% bus_i type Pd Qd Gs Bs area Vm Va baseKV zone Vmax Vmin
mpc.bus = [
1 3 50 30.99 0 0 1 1 0 230 1 1.1 0.9;
2 1 170 105.35 0 0 1 1 0 230 1 1.1 0.9;
3 1 200 123.94 0 0 1 1 0 230 1 1.1 0.9;
4 2 80 49.58 0 0 1 1 0 230 1 1.1 0.9;
];

%% generator data
% bus Pg Qg Qmax Qmin Vg mBase status Pmax Pmin Pcl Pc2
% => Qclmin Qclmax Qc2min Qc2max ramp_agc ramp_10 ramp_30 ramp_q apf
mpc.gen = [
4 318 0 100 -100 1.02 100 1 318 0 0 0 0 0 0 0 0 0 0 0 0 0;
1 0 0 100 -100 1 100 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
];

%% branch data
% fbus tbus r x b rateA rateB rateC ratio angle status angmin angmax
mpc.branch = [
1 2 0.01008 0.0504 0.1025 250 250 250 0 0 1 -360 360;
1 3 0.00744 0.0372 0.0775 250 250 250 0 0 1 -360 360;
2 4 0.00744 0.0372 0.0775 250 250 250 0 0 1 -360 360;
3 4 0.01272 0.0636 0.1275 250 250 250 0 0 1 -360 360;
];

```

In the second step, the load flow solving is called by the main simulation function; for example we execute the power flow (runpf). In our example, this is calculated by Newton-Raphson method. The syntax of ‘runpf’ is divided on inputs and outputs options. On the Input options, we can use:

- CASEDATA: either a MATPOWER case struct or a string containing the name of the file with the case data (for our example is ‘case4gs’)
- MPOPT: MATPOWER options struct to override default options can be used to specify the solution algorithm, output options termination tolerances, and more.
- FNAME: name of a file to which the pretty-printed output will be appended
- SOLVEDCASE: name of file to which the solved case will be saved in MATPOWER case format (M-file will be assumed unless the specified name ends with ‘.mat’).

The output options can be:

- RESULTS: results struct, with the following fields: (all fields from the input MATPOWER case, i.e. bus, branch, gen, etc., but with solved voltages, power flows, etc.), order - info used in external < – > internal data conversion, et - elapsed time in seconds, success - success flag, 1 = succeeded, 0 = failed

```
MATPOWER Version 6.0, 16-Dec-2016 -- AC Power Flow (Newton)
```

Newton's method power flow converged in 3 iterations.

Converged in 0.05 seconds

| System Summary |

How many?	How much?	P (MW)	Q (MVAr)
Buses	4	Total Gen Capacity	318.0 -200.0 to 200.0
Generators	2	On-line Capacity	318.0 -200.0 to 200.0
Committed Gens	2	Generation (actual)	504.8 295.9
Loads	4	Load	500.0 309.9
Fixed	4	Fixed	500.0 309.9
Dispatchable	0	Dispatchable	-0.0 of -0.0 -0.0
Shunts	0	Shunt (inj)	-0.0 0.0
Branches	4	Losses ($I^2 * Z$)	4.81 24.05
Transformers	0	Branch Charging (inj)	- 38.0
Inter-ties	0	Total Inter-tie Flow	0.0 0.0
Areas	1		
		Minimum	Maximum
Voltage Magnitude	0.969 p.u. @ bus 3	1.020 p.u. @ bus 4	
Voltage Angle	-1.87 deg @ bus 3	1.52 deg @ bus 4	
P Losses ($I^2 * R$)	-	1.84 MW @ line 3-4	
Q Losses ($I^2 * X$)	-	9.18 MVAr @ line 3-4	

Fig. 3.4 System summary for the case4gs

- SUCCESS: the success flag can additionally be returned as a second output argument

To run this with the default options of the case4gs we type at the Octave's prompt window:

```
>>rmpf('case4gs');
```

When we executed it, we took the system summary result shown as in Fig. 3.4. At the first column we can see that we have 4 buses, 2 Generators (both committed) and 4 Branches. To the second column we see the capacity, to the third, the Power in MW and finally the reactive power Q in MVAr. At the bottom of the table, we see the Minimum and Maximum values of the Voltage Magnitude and Angle, the Power (P) and Reactive Power (Q) Losses. As we see, at the Voltage Magnitude the minimum value is 0.969 per-unit (p.u.) at bus 3 and the maximum is 1.020 per-unit (p.u.) at bus 4. Similarly, the Voltage Angle is -1.87° (deg) at bus 3 and the maximum 1.52° (deg) at bus 4. Finally, for lines 3 and 4 the P losses is maximum 1.84 MW and the Q losses 9.18 MVar.

Bus Data						
Bus #	Voltage		Generation		Load	
	Mag(pu)	Ang(deg)	P (MW)	Q (MVar)	P (MW)	Q (MVar)
1	1.000	0.000*	186.81	114.50	50.00	30.99
2	0.982	-0.976	-	-	170.00	105.35
3	0.969	-1.872	-	-	200.00	123.94
4	1.020	1.523	318.00	181.43	80.00	49.58
		Total:	504.81	295.93	500.00	309.86

Fig. 3.5 Bus data summary for the case4gs

Branch Data								
Brnch #	From Bus	To Bus	From Bus P (MW)	Injection Q (MVar)	To Bus P (MW)	Injection Q (MVar)	Loss (I^2 * Z)	
							P (MW)	Q (MVar)
1	1	2	38.69	22.30	-38.46	-31.24	0.227	1.13
2	1	3	98.12	61.21	-97.09	-63.57	1.031	5.16
3	2	4	-131.54	-74.11	133.25	74.92	1.715	8.58
4	3	4	-102.91	-60.37	104.75	56.93	1.835	9.18
		Total:					4.809	24.05

Fig. 3.6 Branch data summary for the case4gs

```
mpc=loadcase('case4gs'); %read the load flow input data
mpc.bus(1,PD)=200; %increase the real power demand at bus 4 to 200MW
runpf(mpc); %run AC power flow
```

Fig. 3.7 Increasing the demand of real power to 200MW on the case4gs

Figure 3.5 demonstrates the Bus Data Summary of the case4gs, having mainly four columns: bus, voltage (magnitude and angle), generation and the load.

On the Fig. 3.6, it is shown the Branch Data Summary for the ‘case4gs’, where for every branch we receive the simulation output about the Power (P) in MW and reactive power (Q) in MVar, from bus injection to bus injection and the loss.

Finally, we can solve this case with different options such as to increase its real power demand to 200 MW and run AC power flow. To do this we have to type the commands as shown on Fig. 3.7.

Until now, we presented modelling and simulation processes for the distributors, but it is also necessary to refer to the consumers. The consumers on smart grid are the demand-side management (DSM), which includes demand response (DR), an active research area that aims to reduce or smoothen energy consumption. DR mechanisms involve behavioral changes in energy consumption as a response to certain signals to the consumers. There are plenty of researches which try to solve this issue and all the solutions are based on the game theory [9]. A short definition of game theory is

the study of strategic decision making, using mathematical models of conflict and cooperation between intelligent rational decision makers. We can divide the game theory into two categories: (*i*) non cooperative and (*ii*) cooperative games.

Hatzi [6] proposed an end-consumer model based on the serious games design which does not employ direct monetary incentives for the consumers and a generic game-theoretic mathematical framework for the optimization of the parameters of the serious game. Byron Reeves et al. [15] peasants a prototyped game, named Power House, which simulates the real world with this online multiplayer game with purpose to improve home energy behavior. In this game, the researchers input real world home energy data such information that may be transformed into a more palatable and relevant form of feedback. Moreover, by tying energy-friendly real-world behaviors to in-game rewards, users may be incentivized to complete them. Other researchers for a small grid environment, is S. Sofana Reka and V.Ramesh [16], who proposed a demand response modelling for residential consumers using game theory based energy scheduling algorithm, and Saba Al-Rubaye and Bong Jun Choi [1], who introduced an energy demand scheduling using integer linear programming (ILP) to optimize energy for residential consumers.

3.3.1 Conclusion

The modelling and simulation of the smart grid has many different factors, resulting into different points of interest. In addition, the tools which can be used are plenty and the researchers can choose on the basis of the advantages and disadvantages that each tool offers. The proposed methods here, are based on the general principles of the renewable energy. Finally, in this study we selected as an example one model to explain from the literature, which we analyzed it with different data, factors and methods.

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Chapter 4

Communication Protocols for the IoT-Based Smart Grid



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Abstract The Internet of Things (IoT) is the communications paradigm that can provide the potential of ultimate communication. The IoT paradigm describes communication not only human to human (H2H) but also machine to machine (M2M) without the need of human interference. The Smart Grid (SG) is the new paradigm that enables highly efficient energy production, transport, and consumption along the whole chain, from the source to the user. SG is the combination of the classical power grid with emerging communication and information technologies. IoT based smart grid will be one of the largest instantiation of the IoT in the next future. In this chapter, we examine, review and present the current IoT enabler technologies for smart grid applications, starting from the physical layer to the application and data layer.

4.1 Introduction

Internet of Things (IoT) is the new communications paradigm that will expand the current Internet and enable communication through machine to machine (M2M). Until recently, the Internet connected devices were directly controlled by humans and they were mostly computers, tablets and mobile phones. The IoT will enable to

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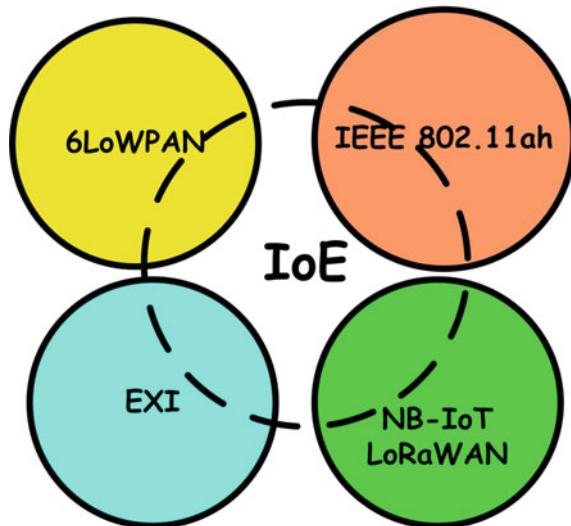
connect to the Internet every kind of device, including sensors and smart tags. This new era of ubiquity means that any device is connected to the network, anytime, anywhere, for anybody [47, 75].

There are several drawbacks in the existing power grid such as lack of efficient monitoring, fault diagnostic, and automation techniques. Moreover, the current power grid is inflexible in adding new energy like that coming from renewable sources. Thus, a more flexible and intelligent power grid is a challenging requirement. This gap is filled by the Smart Grid (SG) paradigm [78]. SG integrates into the current power grid new information and communication networks and technologies. The integration of IoT and SG is referred to as the Internet of Energy (IoE) [16, 43]. The IoE uses the bidirectional flow of energy and information within the smart grid to get information about power usage and that way may predict future actions to increase energy efficiency and low overall cost.

There are several IoT technologies that are key enablers for SG. These technologies cover the whole protocol stack starting from the physical layer to the application layer. Additionally, new IoT designed data layers emerged. In this chapter, we try first to give a brief overview of all these technologies. For short range applications these among others include Radiofrequency identification (RFID) [80], Bluetooth Low-Energy (BLE) [28], Near Field Communication (NFC) [81], fourth generation of cellular systems (4G), IEEE 802.15.4 [40], and the recent IEEE 802.11ah [8]. For long range applications namely the Low Power Wide Area (LPWA) technologies include the LoRaWAN protocol [51] and the future cellular IoT.

Figure 4.1 shows the integration of current and future representative enabling technologies with IoE. These include the NB-IoT [3] and the LoRaWAN protocol as

Fig. 4.1 Enabling representative communications technologies for SG and IoT integration



suitable long range technologies, the IEEE 802.11ah as state-of-the-art MAC layer protocol, the 6LoWPAN (Low power Wireless Personal Area Networks) protocol as key network protocol, and the Efficient XML Interchange (EXI) [45] at the data layer.

4.2 IoT Applications Types

According to [23] the IoT applications can be classified in two categories the Massive IoT and the Critical IoT .

4.2.1 *Massive IoT*

Massive IoT refers to services that typically span over a very large number of devices, usually sensors and actuators. Sensors are extremely low cost and consume very low amounts of energy in order to sustain long battery life. Clearly, the amount of data generated by each sensor is normally very small, and very low latency is not a critical requirement. While actuators are similarly limited in cost, they will likely have varying energy footprints ranging from very low to moderate energy consumption (Table 4.1).

Sometimes, the mobile network may be used to bridge connectivity to the device by means of capillary networks. Here, local connectivity is provided by means of a short-range radio access technology, for example Wi-Fi, Bluetooth or 802.15.4/6LoWPAN. Wireless connectivity beyond the local area is then provided by the mobile network via a gateway node.

Table 4.1 Vertical markets for massive IoT technology [23]

Massive IoT

Transport and Logistics (Fleet management and Goods tracking)
Agriculture (Climate/agriculture monitoring, Livestock tracking)
Environment (Flood monitoring/alerts, Environmental monitoring)
Industrial (Process monitoring and control, Maintenance monitoring)
Consumers(Wearables kids/senior tracker, Medical monitoring)
Utilities (Smart metering, Smart grid management)
Smart cities (Parking sensors, Smart bicycles, Waste management, Smart lightning)
Smart buildings (Smoke detectors, Alarm systems, Home automation)

Table 4.2 Vertical markets for critical IoT technology [23]

Critical IoT
Automotive (V2I, V2V, V2P, V2C, Car entertainment)
Industrial (Remote control, Automated fabrication, Collaborative robots)
Medical (E-Health, Remote surgery, Biomedical sensors)
Public sector (Smart grid, Video surveillance)

4.2.2 Critical IoT

Critical IoT refers to applications such as traffic safety/control, control of critical infrastructure and wireless connectivity for industrial processes. Such applications require very high reliability and availability in terms of wireless connectivity, as well as very low latency. On the other hand, Low Device cost and energy consumption is not as critical as for Massive IoT applications. While the average volume of data transported to and from devices may not be large, wide instantaneous bandwidths are useful in being able to meet capacity and latency requirements (Table 4.2).

There is much to gain from a network being able to handle as many different applications as possible, including mobile broadband, media delivery and a wide range of IoT applications by means of the same basic wireless-access technology and within the same spectrum. This avoids spectrum fragmentation and allows operators to offer support for new IoT services for which the business potential is inherently uncertain, without having to deploy a separate network and reassign spectrum specifically for these applications. From the tables above it is obvious that there smart grid applications like smart meters that can be classified as massive IoT applications while the smart grid based infrastructure may be classified as critical IoT application.

4.3 IoT Based Smart Grid Overview

The SG consists of several groups of applications. These can classified according to [43] into the following application groups or domains.

- *Smart home applications* allow the use of sensors and actuators in devices and appliances. These devices may include smart TVs, smart refrigerators, temperature monitoring, lighting control, and home security systems. That group of devices together forms a Neighbor Area Network (NAN).
- The *online monitoring of power lines* is another useful application of SG. The IoT based smart grid will be able to improve the reliability of power lines by continuous status monitoring. Reports about faults will be send directly to the control units in order to resolve them in an instant way.

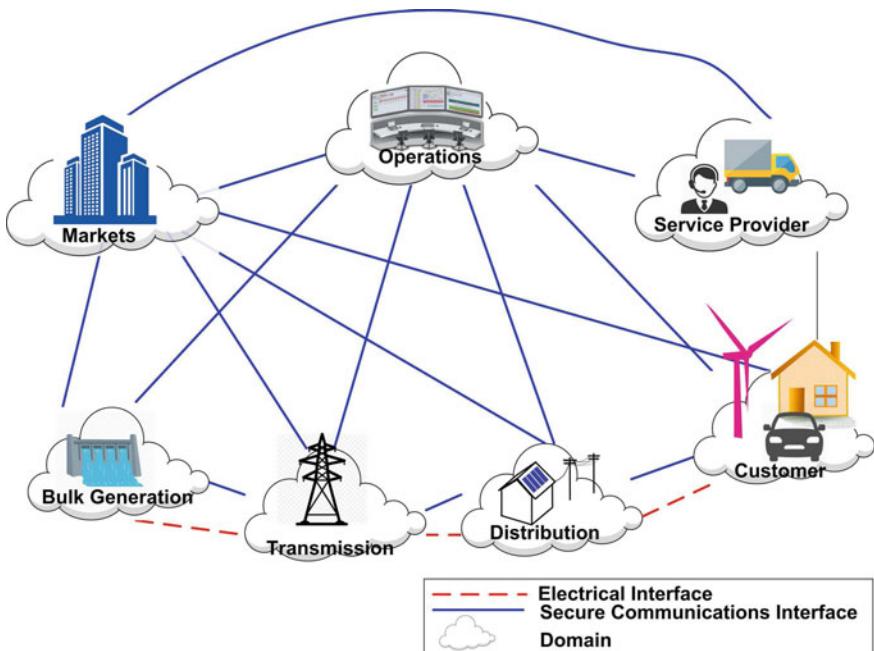


Fig. 4.2 Interaction of Actors in different Smart Grid Domains according to NIST [1]

- The *Demand-side energy management* (DSM) is another critical point where the SG plays an important role. The user energy consumption profile is collected by IoT-nodes and then sent to smart meters. Thus, the demand-response can be regulated in order to minimize the electrical consumption and the operation cost of the smart grid.
- The *integration of distributed energy sources* and especially renewable energy sources is another major issue. IoT nodes can collect data for the weather and therefore predictions about the availability of the renewable energy sources can be made.
- The *integration of electric vehicles* to the power grid is another application domain. The IoT technology helps in this way to collect information about the vehicles battery state and location in order to improve the charging and discharging scheduling algorithms.

NIST has released a conceptual reference model about SG (see Fig. 4.2) [1]. This model is composed of seven different domains. Each domain includes *actors* and *applications*. The *actors* are the devices and systems that make decisions and exchange information like smart meters, solar generators and wind turbines. By the word *applications* NIST models the tasks performed by one or more *actors* in a domain. For example some representative applications could be home automation, energy storage, solar energy generation, and energy management.

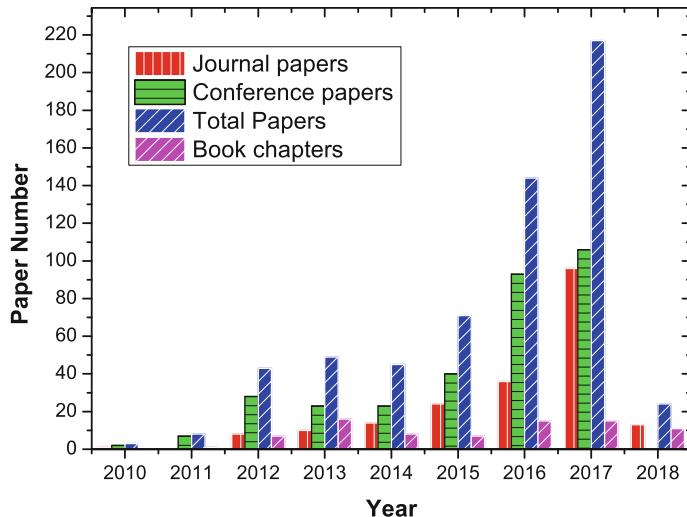


Fig. 4.3 Number of papers for SG and IoT

The integration of smart grid with IoT is a topic of growing interest in the literature. A search in the scopus database reveals that there currently about 604 total papers regarding IoT and SG. Figure 4.3 depicts the number of papers found in the scopus database for different categories from 2010 to early 2018. There are 202 total journal papers, 322 conference papers and 80 book chapters. The current trend shows an almost exponential increase in the number of IoT-based smart grid papers.

4.4 Current IoT Based Smart Grid Technology Enablers

In this section we provide a brief description of the key technologies and elements for IoT-based Smart Grid. There several technologies that may be considered as enablers for SG. A sample protocol stack for servers and IoT nodes is depicted in Fig. 4.4.

We notice that the IoT stack is different from the common host stack in Internet. The protocol stack for IoT nodes consists of constrained or compressed versions of common protocols. There are several options for the physical layer, while for MAC layer the most common option is IEEE 802.15.4. The network layer requires the use of an adaptation protocol like 6LoWPAN in order to compress and fragment the IPv6 headers. In the transport layer UDP is used, while in the application layer a constrained version of HTTP Constrained Application Protocol (CoAP) is utilized. The data layer uses the compressed XML format the Efficient XML Interchange (EXI) protocol.

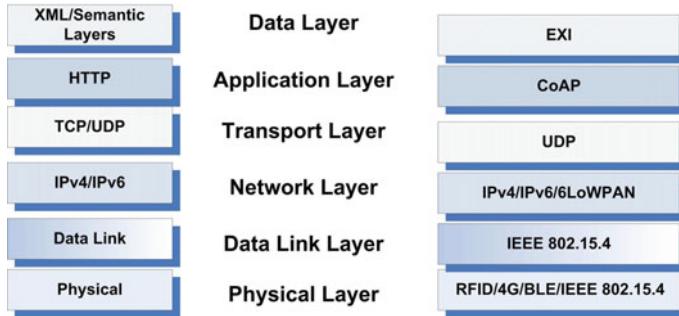


Fig. 4.4 Protocol stacks for hosts (left) and (right) for IoT nodes

4.4.1 *Physical and Data Link Layer Technologies*

Among others the physical layer technologies used in IoT nodes include Radio-frequency identification (RFID), Bluetooth Low-Energy (BLE), IEEE 802.15.4, IEEE 802.11ah, Near Field Communication (NFC), and will include the future fifth generation (5G) of mobile communications. RFID [80] has gained considerable growth in the last decade and remains in the front end of the general research and development sector concerning the remotely receiving and transmitting data using RF waves. The information stored in the RFID tag is unique identification number called Electronic Product Code (EPC). EPCs can be 96-bit or 64-bit long. A performance analysis of the current EPCglobal Gen 2 RFID protocol versus a CDMA approach can be found in [79].

Nowadays the RFID technology providing automated wireless identification and tracking capability and being more robust than the barcode system, has shown a commercial worldwide deployment following frequency allocation in the UHF band, ranging from 860 MHz to 950 MHz [65]. An ordinary RFID system comprises of at least, a reader (Interrogator) with a reader antenna, tags (transponders) which are microchips combined with an antenna in a compact package, a host computer and middleware including software and data base. An overview of criteria for RFID tag antenna design and an analysis of practical application aspects can be found in [27, 65].

NFC is a set of short-range wireless protocols, that work at close range of about 10 cm or less [81]. The operating frequency for NFC is 13.56 MHz and the data rates are small ranging from 106 kbit/s to 424 kbit/s. NFC defines two entities an initiator and a target; the initiator actively generates an Electromagnetic field that be used for powering the passive target. Thus, NFC targets can be very simple devices like unpowered tags, stickers, or cards. Moreover, NFC permits peer-to-peer communication, however, in that case both devices should be powered.

Bluetooth low energy (BLE) [28] is a new wireless personal area network technology designed by the Bluetooth Special Interest Group. BLE provides considerably reduced power consumption and cost while maintaining a similar communication range. BLE provides also high-speed and IP connectivity, which makes it suitable for IoT nodes [6, 47].

The IEEE 802.15.4 5 defines the operation for both physical and data-link (media access control) layers for low-rate wireless personal area networks. (LR-WPANs). products. IEEE 802.15.4 provides low-cost and low-power wireless connectivity within short ranges of up to 20 m. Thus, it is suitable for use in WSNs, M2M and IoT. Another IEEE 802.15.4 advantage is the fact that it supports a large node number (about 65000). However, it lacks support for QoS.

4.4.1.1 IEEE 802.11ah

A standard which is a competitor of IEEE 802.15.4 is IEEE 802.11ah [8], which is a new WiFi standard targeting at IoT nodes using a low power consumption and larger range. A complete IEEE 802.11ah survey for IoT applications can be found in [9, 48]. In order to fulfil the IoT requirement for long coverage range, which can be more than 1 km , the IEEE 802.11ah uses lower frequency bands (below 1 GHz) that provide better propagation characteristics and fewer path loss values than legacy WLANs. Moreover, IEEE 802.11ah utilizes a new modulation and coding scheme and also supports Multiple-Input Multiple Output (MIMO) with spatial diversity. The IEEE 802.11ah bandwidth ranges from 1 to 2, 4, 8 and 16 MHz compared with the 20 MHz of the current WLANs. Thus, narrower bandwidth means longer symbol and guard intervals duration, which makes IEEE 802.11ah less sensitive to inter-symbol interference. The coverage is also extended using multi-hop operation with relays or mesh networking.

In an IoT smart grid environment hundreds of thousands of devices should co-exist. In case of legacy WLANs, this could cause serious interference problems. However, in the case of the IEEE 802.11ah the lower operating frequency also results to less interference. The support of a large number of IoT nodes which can be from hundreds to few thousands is another requirement of IoT-based SG. The IEEE 802.11ah can support the large number of IoT nodes. For example one IEEE 802.11ah access point (AP) may support up to 6000 IoT devices with a capacity of 100 kbps each [48]. This feature makes IEEE 802.11ah suitable for SG-applications. Another crucial aspect for IoT devices is the low power consumption, since most of them might operate using batteries. Legacy IEEE 802.11 devices may remain idle for the maximum period of about 18h, while the IEEE 802.11ah standard defines different periods of inactivity for different applications. As a result IEEE 802.11ah devices achieve more energy savings than legacy devices.

An example use case of IEEE 802.11ah in smart grid is shown in Fig. 4.5. In this case a singe AP covers hundreds or more smart meters that transmit short packets in periodic way.

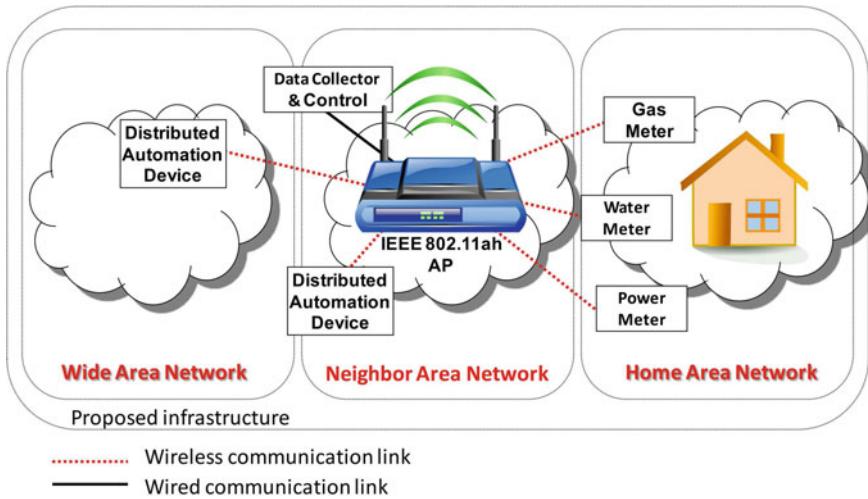


Fig. 4.5 IEEE 802.11ah Smart Grid use case

A feasibility study of IEEE 802.11ah radio technology for IoT and M2M use cases can be found in [34]. The authors in [61] compare performance of IEEE 802.15.4 and IEEE 802.11ah. They conclude that IEEE 802.11ah performs better in cases of congested networks; however 802.15.4 outperforms the IEEE 802.11ah in terms of energy consumption.

4.4.2 Network Layer Technologies

The Internet Protocol version 4 (IPv4) is the main technology at network level that Internet hosts support. The IPv4 addressing principle requires a global unique IP address for every interface connected to the Internet. The IP address space is managed by the Internet Assigned Numbers Authority (IANA) globally. IANA has recently announced the exhaustion of IPv4 address blocks. This is one of the reasons for the deployment of an IPv4 successor protocol the IPv6. The IPv6 standard [86] uses 128-bit IP addresses, therefore it is possible to assign a unique IPv6 address to any possible node in the IoT network.

However, IPv6 header introduces overheads that could be a problem in small data rate capabilities of IoT nodes. IPv6 datagrams require a minimum MTU of 1280 bytes. This size is impossible to handle over a IEEE 802.15.4 MAC with maximum frame size of 127 bytes. Therefore, an additional adaptation layer is required to fit IPv6 packets into shorter IEEE 802.15.4 frames.

A solution to this problem comes with the introduction of 6LoWPAN (Low power Wireless Personal Area Networks). 6LoWPAN works at network level and it is an

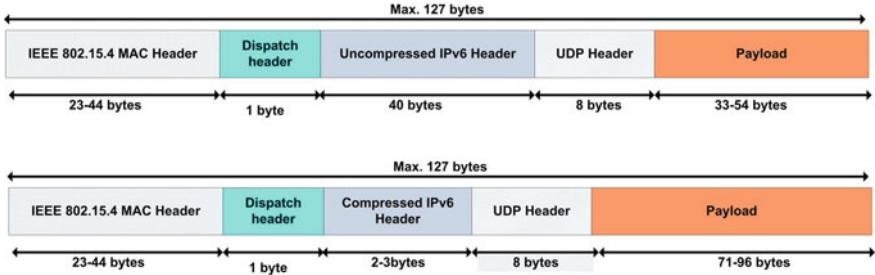


Fig. 4.6 6LoWPAN frames without and with IPv6 header compression

adaptation layer that fits IPv6 packets into smaller IEEE 802.15.4 frames [39, 62]. This is accomplished by compressing the IPv6 header. 6LoWPAN compresses the IPv6 header by removing the not needed fields, by removing fields that have always the same content and by compressing the IPv6 addresses by inferring them from link layer addresses.

An example of 6LoWPAN operation is depicted in Fig. 4.6. One may notice that without IPv6 header compression there only 33–54 maximum bytes left for payload. The smaller number corresponds to IEEE 802.15.3 security options. Using 6LoWPAN the 40-bytes IPv6 header is compressed to 2–3 bytes, thus leaving 71–92 bytes for payload. Additionally, 6LoWPAN defines a header encoding scheme to support fragmentation for large IPv6 datagrams. In case of fragmentation, the 6LoWPAN header size is 4–5 bytes and it consists of the fields datagram size (11 bits that hold the size of the datagram being fragmented), the datagram tag (16 bits that is the number of the fragment), and datagram offset (8 bits that show the offset within the original datagram).

Thus, 6LoWPAN standard uses header compression in order to reduce the transmission overhead, fragments the IPv6 packets to meet the IPv6 Maximum Transmission Unit (MTU) requirement, and forwards packets to data link-layer to support multi-hop delivery [49, 56]. A possible implementation of 6LoWPAN in a smart city could involve the use of a border router like in [84]. The border router is directly connected to the 6LoWPAN network and transparently performs the conversion between the IPv6 and 6LoWPAN networks. Therefore, it translates any IPv6 packet intended for a node in the 6LoWPAN network into a packet with 6LoWPAN header compression format, and operates the inverse translation in the opposite direction.

4.4.3 Transport and Application Layer Technologies

Transmission Control Protocol (TCP) is the most commonly used transport layer protocol in the Internet today. TCP is connection-oriented and uses flow control and congestion control mechanisms. The above requires additional header overhead,

thus making it not well suited for IoT nodes. An alternative solution to TCP is User Datagram Protocol (UDP), which uses a minimum header overhead and it is connectionless. Therefore, UDP is the common solution for transport layer protocol in IoT nodes.

HTTP is one of the most commonly used application layers. However, HTTP is quite complex and verbose, thus it is not suitable for use on IoT nodes. Additionally, HTTP lies above TCP so the combination is very resource consuming for IoT nodes. The solution to overcome this problem is the use of the Constrained Application Protocol (CoAP) on IoT nodes [14, 72]. CoAP is an HTTP equivalent protocol for low power devices over UDP.

The CoAP defines a web transfer protocol based on REpresentational State Transfer (REST) on top of HTTP functionalities. REST represents a simpler way to exchange data between clients and servers over HTTP. The CoAP interaction model is client/server similar to HTTP. CoAP proposes a binary format over UDP and handles only the re-transmissions strictly required to provide a reliable service. The main CoAP header is four bytes long. Additionally, the total header size followed by options is 10 to 20 bytes long. CoAP uses the well-known from HTTP methods like GET, PUT, POST, and DELETE. The CoAP response codes are encoded in a single byte e.g. the “404 page not found” response becomes 4.04 in CoAP. The CoAP uses two layers the Message layer and the Request/Response layer as it is depicted in Fig. 4.7. The bottom Message layer works with UDP. The Message layer

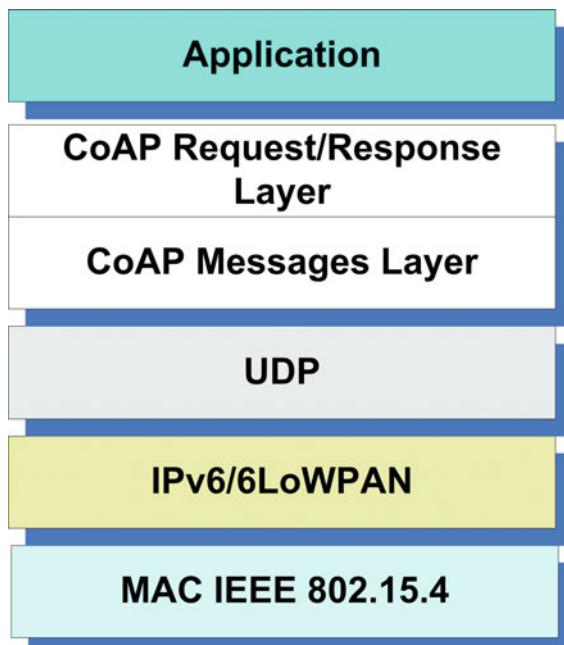


Fig. 4.7 CoAP Protocol stack

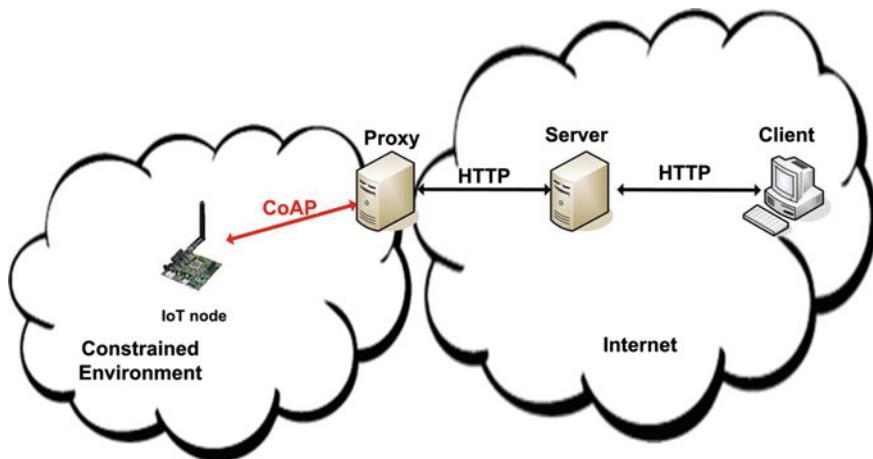


Fig. 4.8 CoAP and HTTP Web architecture

provides reliability over UDP by marking a message as Confirmable (CON). The Request/Response layer deals with communication between client and server using Request/Response messages, which include either a Method Code or a Response Code, respectively.

Moreover, CoAP can interoperate with HTTP. The communication between IoT nodes and the rest of the Internet hosts can be accomplished with the use of a so called cross proxy that translates HTTP to CoAP and vice versa. That way the communication between IoT devices and the rest of the Internet hosts is transparent and straightforward. Figure 4.8 shows an example of such a web architecture.

The next evolution of IoT is the Web of Things (WoT) [33]. WoT evolves the IoT with a common stack based on web services.

4.4.4 Data Layer Technologies

Efficient XML Interchange (EXI) is a binary XML format for exchange of data defined by the World Wide Web consortium (W3C) [45]. EXI is significant because it is designed to optimize XML applications for resource-constrained environments. The main task of EXI is to encode XML documents in a binary data format, rather than plain text. Therefore, EXI reduces the verbosity of XML documents and it is suitable for low power devices and limited bandwidth environments. Additionally, EXI minimizes the required storage size.



Fig. 4.9 EXI Stream

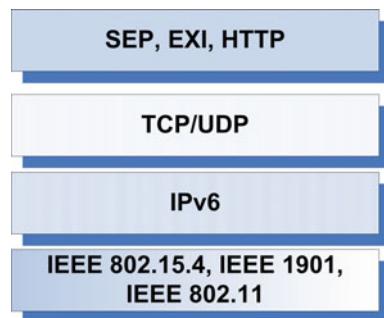


Fig. 4.10 EXI Dataflow

W3C developed EXI around five key design principles. The EXI format had to be general, minimal, efficient, flexible, and interoperable. The first two features general and minimal resolve to the non-invasiveness of EXI. Efficiency is provided by several components such as the compact nature of EXI streams and the fact that EXI uses information from the XML schema to improve compactness and processing efficiency. EXI provides flexibility by handling documents that contain arbitrary schema extensions or deviate from their schema. EXI is interoperable by integrating well with existing XML technologies, thus minimizing the changes required to those technologies. Moreover, EXI is compatible with the XML Information Set. EXI represents the contents of an XML document as an EXI stream. The EXI streams consist of an EXI header and a EXI Body. Figure 4.9 depicts the format of an EXI stream. The EXI header contains the encoding properties that are needed to decode the EXI body. A minimal EXI header can be have the size of a single byte. The EXI body consists of a sequence of EXI events. The XML items are encoded into one or more EXI events.

An EXI Processor performs the EXI compression at the highest level. This processor could have the role of either an EXI Encoder or an EXI Decoder. A typical EXI data processing workflow of an XML document is shown in Fig. 4.10. EXI has the capability to compress XML documents into a structured sequence of bytes without the verbose tagged structure. The compression ratio could vary from 1.4:1 to 100:1 for typical XML documents. EXI is a knowledge based encoding that uses a set of grammars to determine which events are most likely to occur at any given point in an EXI stream and encodes the most likely alternatives in fewer bits. EXI defines two encoding types; schema-less and schema-informed. In the first type when no XML schema information is available, EXI uses a set of built-in grammars to encode XML documents and XML fragments. In case of known schema information (i.e. known

Fig. 4.11 IEEE 2030.5 protocol stack



XML Schema Definition (XSD)), then the EXI grammars can be further improved. All the above-mentioned reasons make EXI suitable for data exchange from IoT nodes.

4.4.5 IEEE 2030.5 (*Smart Energy Profile 2.0*)

IEEE 2030.5 [41] is a newly introduced standard for communications between the smart grid and consumers. The IEEE 2030.5 uses IoT concepts and gives consumers a variety of means to manage their energy usage and generation. Different types of information can be exchanged using this standard, which among other include pricing, demand response, and energy usage. Thus, IEEE 2030.5 enables the integration of devices such as smart thermostats, meters, plug-in electric vehicles, smart inverters, and smart appliances.

Moreover, IEEE 2030.5 defines a framework to support these applications to enable a secure, interoperable, and plug-and-play ecosystem of smart grid consumer devices. IEEE 2030.5 has been recommended as the default protocol for smart inverter communications for California's Rule 21. Additionally, IEEE 2030.5 allows the integration of distributed energy resources to the power grid.

The IEEE 2030.5 standard uses the IoT protocol stack as it is depicted in Fig. 4.11. The physical and data-link layer can be any of several common like IEEE 802.15.), IEEE 802.11, or IEEE 1901, which is a standard for high speed communication devices via electric power lines, often called broadband over power lines (BPL). Generally, lower layer protocols are not discussed in this standard except where there is a direct interaction with the application protocol. The network layer is IPv6, while the transport layer protocol can be TCP or UDP. The IEEE 2030.5 defines the mechanisms for exchanging application messages, the exact messages exchanged including error messages, and the security features used to protect the application messages. The application layer uses HTTP, and EXI for Smart Energy Profile (SEP) messages exchange.

4.5 Future and Enabling Technologies for IoT Based Smart Grid

This section describes future enabling technologies that will play an important role in IoT based smart grid deployment. Among others, we will present the future cellular IoT technologies and the use of semantic web in IoT based SG. Low Power Wide Area (LPWA) is a term that includes devices that have common features like

- Low power
- Long battery life (more than 10 years in some cases)
- Low data requirements (100 kbps or less)
- Wide area connectivity characteristics
- Long range operation devices (in km)
- Low cost devices in terms of both chipsets and networking equipment

These LPWA technologies include a proprietary solution from LoRa Alliance LoRaWAN [51], and the current and future cellular technologies.

4.5.1 LoRaWAN for IoT

LoRaWAN defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link. LoRaWAN operates at unlicensed frequency bands below 1 GHz, which are different for each world region. In Europe the LoRa Alliance defines operation at 867–869 MHz, the uplink and the downlink bandwidth is 250 and 125 KHz respectively.

Figure 4.12 shows the LoRaWAN protocol stack. In the physical layer LoRa uses unlicensed radio spectrum in the Industrial, Scientific and Medical (ISM) bands to enable low power, wide area communication between remote sensors and gateways connected to the network. In the MAC layer LoRaWAN defines three different device types. These devices represent different application profiles.

In LoRaWAN terminology these device types are referred to as device classes. The device classes trade off network downlink communication latency versus battery lifetime. Figure 4.13 depicts these device types. Class A devices are bi-directional end devices that each end-devices uplink transmission is followed by two short downlink receive windows. Class A devices use an ALOHA-type of protocol for transmission. The Class A operation is the lowest power end-device system. Class B devices are also bi-directional, which in addition to the Class A random receive windows, Class B devices open extra receive windows at scheduled times. Class C devices are bi-directional end-devices with maximal receive slots, these devices have almost continuously open receive windows, which are closed only when transmitting.

In a mesh network, the individual end-nodes forward the information of other nodes to increase the communication range and cell size of the network. While this increases the range, it also adds complexity, reduces network capacity, and reduces

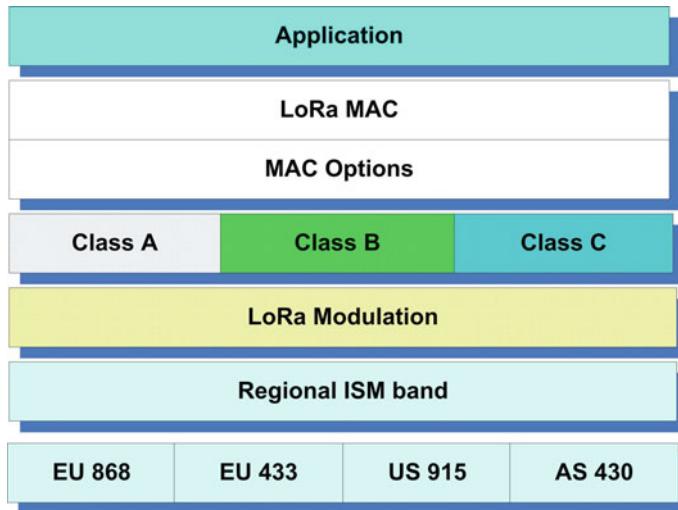


Fig. 4.12 LoRa protocol stack

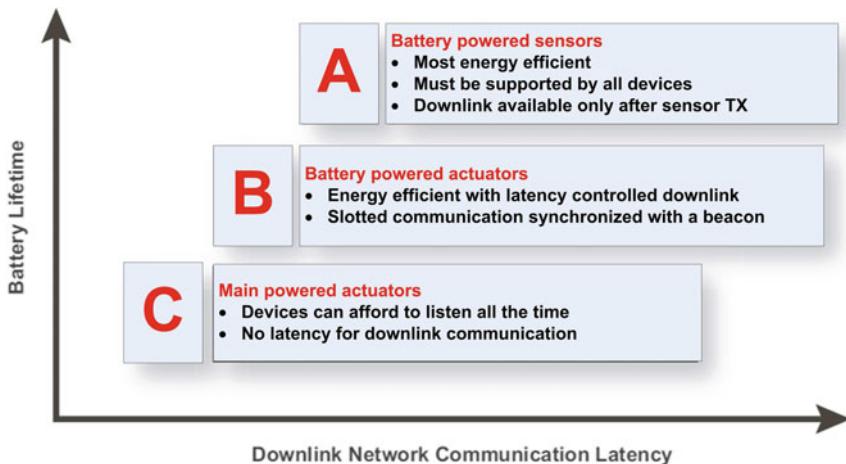


Fig. 4.13 LoRa device classes

battery lifetime. There are several existing deployed IoT networks that utilize a mesh network architecture. In this case the individual end-nodes forward the information of other nodes to increase the range of the network. However, this network architecture increases complexity, reduces network capacity, and reduces battery lifetime because the nodes exchange information with each other. LoRaWAN networks use a star architecture that is more suitable for preserving battery lifetime when long-range connectivity can be achieved.

Thus, LoRaWAN standards-based approach to building a LPWAN, has the benefit of a quick set up of public or private IoT networks anywhere using hardware and software that is bi-directionally secure, interoperable and mobile.

LoRaWAN technology is quite recent so we havent been able to find a large number of papers dealing with it in the literature. We have found a total of 16 papers in the scopus database ranging from 2015 to 2017. Most of them are conference papers. The authors in [55] analyze the LoRa protocols in Europe frequency bands by obtaining uplink throughput and data transmission time for a single LoRaWAN node. They have shown that the capacity of the uplink channel available to a LoRaWAN node strongly depends on the distance from the base station and does not exceed 2 kbit/s. Moreover, the LoRa performance and scalability is the subject of another recent paper [13] where the authors study the capacity limits of LoRa networks. They have developed models that describe LoRa communication behavior and use these models in a simulation to study scalability. Additionally, in [77] the authors study the MAC layer of the LoRaWAN protocol, and more specifically the on-the-air activation procedure. In [64] the authors evaluate the LoRa performance using measurements. They used commercially available equipment that operated at 868 MHz and they had measured the packet success delivery ratio to be 96.7%.

4.5.2 Cellular IoT

Fourth generation (4G) technology includes the Long Term Evolution-Advanced (LTE-A) standard [31]. LTE Advanced is a major enhancement of the Long Term Evolution (LTE) standard. LTE-A added support for bandwidth extension up to 100 MHz, support for downlink and uplink spatial multiplexing using MIMO, and obtains higher throughput and lower latencies compared to LTE. A search in scopus database reveals 178 total papers regarding LTE and IoT. Figure 4.14 depicts the paper numbers over the recent years since 2010. We notice that the number of LTE and IoT related papers rises almost exponentially.

Recently in June 2016, 3 GPP released the first version of the NarrowBand-IoT (NB-IoT)[2, 4]. NB-IoT is an emerging new wireless access technology, which will exist together with the other existing cellular networks like GSM, UMTS and LTE. The main concept from 3 GPP standards is the integration of NB-IoT to current LTE networks. NB-IoT devices will be low cost, that will allow massive deployments and reduced data rates [85]. The carrier bandwidth will be 180 KHz in case of co-existence with current LTE networks. Ericsson predicts that the number of IoT connected devices will reach 1.5 billions by 2022 [24].

LTE-A has been utilized in [19] for convergence between a LTE-A network and a wireless sensor network (WSN). The main objective of the authors was to build a machine-to-machine (M2M) network capable of meeting Quality of service (QoS) issues. Moreover, the authors in [50] optimize the discontinuous reception/transmission (DRX/DTX) mechanism of LTE-A that allows devices to turn off

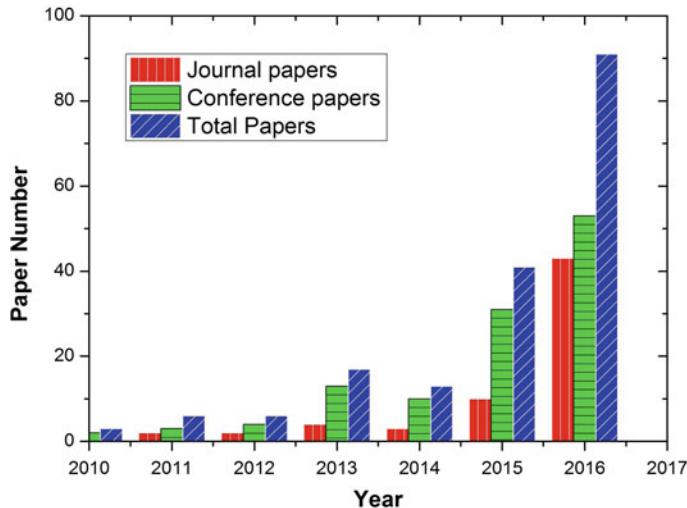


Fig. 4.14 Number of Papers for LTE and IoT

their radio interfaces and go to sleep. The optimization is performed in terms of energy cost.

However, current LTE-A devices are not specifically made to meet the requirements to support the IoT nodes. As a result, 3GPP focuses on standardization efforts for IoT capable cellular devices. The main requirements for such devices as it is reported in a recent white paper from Nokia [60] are long battery life, low device cost, low deployment cost, extended coverage, and support for a massive number of devices. The two main new technologies that will lead to new standards are eMTC (enhanced Machine Type Communication, often referred to as LTE-M) and NB-IoT (NarrowBand-Internet of Things) [22, 32, 66–69, 76]. LTE-M or LTEM2M was released in LTE Advance Pro Release 12 in 2014, while additional specifications are included In rel 13 [22, 60, 67, 69, 76]. LTE Release 12 introduced a new user equipment type called (UE) Category 0. That UE includes features like reduced peak data rate, half duplex operation with relaxed RF requirements, and a single receive antenna [69]. Additionally, eMTC introduced a set of physical layer features with the objective reduce the cost and power consumption. These features include narrowband operation, low cost, simplified operation, transmission of downlink control information, extended coverage, and frequency diversity by RF retuning [69].

An overview of the additional features in the latest LTE release 13 is given in [69]. The authors in [37] present a brief look into the future LTE Release 14. The main new features according to the authors will be including latency reductions, enhancements for machine-type communication, operation in unlicensed spectrum, massive multi-antenna systems, broadcasting, positioning, and support for intelligent transportation systems. Moreover, the authors in [7] provide a comprehensive review



Fig. 4.15 NB-IoT different deployment cases [60]

of the most prominent existing and novel M2M technologies, and discuss about the first real-world deployment experiences.

The M2M technologies in LTE-A is the subject of another review paper [54], where the authors present network architectures and reference models for M2M communication and also give an overview of the future M2M services that are expected in 5G networks. Additionally, the authors in [35] propose a traffic-aware Access Class Barring (ACB) scheme to improve the scalability of M2M networks. Their simulations results show that the proposed scheme outperforms the traditional ACB scheme. The introduction of a new connection-less communication protocol for IoT systems over LTE mobile networks is given in [44], where the authors present simulation results to prove its effectiveness. The problem of uplink resource and power allocation problem for energy conservation in LTE-A networks is addressed in [17]. The authors minimize the total energy consumption subject to QoS constraints.

NB-IoT is expected to be the main IoT over LTE technology in the next years. The bandwidth in NB-IoT is decreased to 180 kHz compared to eMTC. However, as a result of the bandwidth reduction the device complexity is also reduced and the peak data rate is also further reduced (around 50 kb/s for uplink and 30 kb/s for downlink). Additionally, NB-IoT UEs can only support limited mobility procedure and low data rates. On the other hand, eMTC supports applications with higher data rate and mobility requirements. NB-IoT [68] can be deployed in three different operation modes. These are stand-alone as a dedicated carrier, in-band within the occupied bandwidth of a wideband LTE carrier, and within the guardband of an existing LTE carrier (Fig. 4.15). NB-IoT uses a bandwidth of 200 kHz in stand-alone operation mode (GSM channel), while in the two other operating modes NB-IoT it will operate on a one physical resource block of LTE with a bandwidth of 180 kHz. NB-IoT latest specification was in Rel. 13 in June 2016. Initially, the NB-IoT was firstly introduced in Rel. 13, June 2016 while in the Rel. 14 (June 2017) the NB-IoT specification was finalized. This date fully coincides with the first commercially available products (Figs. 4.16 and 4.17).

Additionally, a new standard supporting older 2G GSM networks has emerged. EC-GSM-IoT (Extended Coverage GSM for IoT) is based on eGPRS and designed as a high capacity, long range, low energy and low complexity technology. EC-GSM-IoT networks will co-exist with current mobile networks. The pilot trials for this new protocol have begun, while the first commercial products will be launched in 2017.

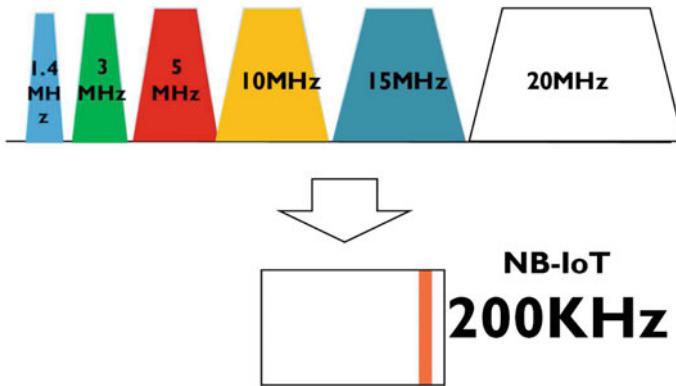


Fig. 4.16 LTE bandwidth options with NB-IoT bandwidth

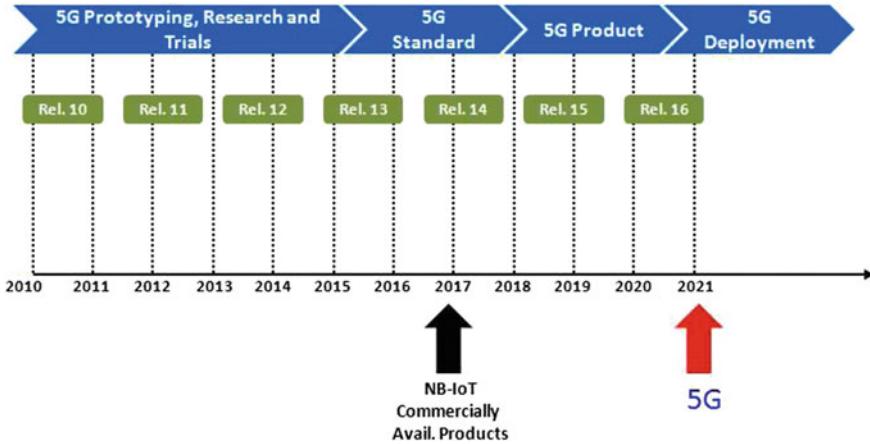


Fig. 4.17 3GPP Roadmap and NB-IoT time relation (estimation) [3]

4.5.3 LPWA Technology for Smart Grid Applications

The requirements of smart electric metering system are high data rates, frequent communication, and low latency. Moreover, since electric meters have a power source available, they do not require ultra-low power and long battery lifetime. The electric companies need real-time monitoring of the grid so they can make immediate decisions based on load, outages and other interruptions. Smart grid electric meters could be implemented using LoRaWAN class C devices in order to have low latency. However, due to the desired higher data rates and frequent communication, NB-IoT is more suitable technology for this application. Additionally, electric meters are placed in stationary locations in mostly densely populated areas so it would be easier for the cellular companies to provide coverage using NB-IoT (Tables 4.3 and 4.4).

Table 4.3 A comparison of current and future long range technologies for IoT [60]

	LoRa	GSM (Rel.8)	EC-GSM-IoT(Rel.13)	LTE (Rel.8)	eMTC (Rel.13)	NB-IoT (Rel.13)
LTE user equipment category	N/A	N/A	N/A	Cat.1	Cat.M1	Cat.NB1
Range	<15 km	<35 km	<35 km	<100 km	<100 km	<35 km
Spectrum	Unlicensed <1 GHz	Licensed GSM bands	Licensed GSM bands	Licensed LTE bands In-band	Licensed LTE bands in-band	Licensed LTE in-band guard-band stand-alone
Bandwidth	<500 kHz	200 kHz	200 kHz	LTE carrier (1.4–20 MHz)	1.08 MHz (1.4 MHz carrier bandwidth)	180 kHz (200 kHz carrier bandwidth)
Max. data rate	<50 kbps (DL/UL)	<500 kbps (DL/UL)	<140 kbps (DL/UL)	<10 Mbps(DL) <5 Mbps(UL)	<1 Mbps (DL/UL)	<170 kbps(DL) <250 kbps (UL)

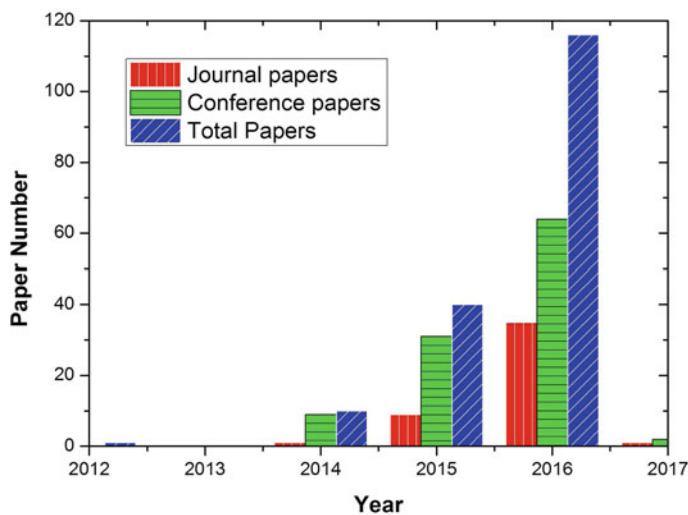
4.5.4 5G and IoT

The next fifth generation (5G) Radio Access technology will be a key component of the Networked Society. 5G will support massive numbers of connected devices and meet the real-time, high reliability communication needs of mission-critical applications. 5G will provide wireless connectivity for a wide range of new applications and use cases, including wearables, smart homes, traffic safety/control, critical infrastructure, industry processes and very-high-speed media delivery. As a result, it will also accelerate the development of the IoT. The 5G technology will become a key driver for global IoT. The main features of the new 5G technology are reviewed and presented in [5, 30, 59, 74]. These new features include very high data rates (typically of Gbps order), extremely low latency, a huge increase in base station capacity, and significant improvement in users' perceived quality of service (QoS). We have searched the Scopus database and found a total of 167 papers about 5G and IoT from 2012 to 2017. The paper number is increasing over the recent years. Figure 4.18 shows the paper number for 5G and IoT papers.

The authors in a recent paper,[63], analyze in detail the potential of 5G technologies for the IoT, by considering both the technological and standardization aspects. Additionally, they present the new massive business shifts that a tight link between IoT and 5G may cause in the operator and vendors ecosystem. Moreover, in [83] the key findings of the European research project 5GNOW are presented, which include new proposed physical layer technologies. The integration of 5G and IoT is also the subject of several recent papers, [18, 26]. In [73] the authors propose a four layer model that is applicable to a smart city or smart home infrastructure and connects the elements using technologies like 5G, internet of things, cloud of things, and distributed artificial intelligence. The end to end (E2E) platform of the

Table 4.4 A comparison of features for different LTE UE [60]

UE category	Category 4	Category 1	Category M1 (eMTC)	Category NB1 (NB-IoT)
Downlink peak rate	150 Mbps	10 Mbps	1 Mbps	170 kbps
Uplink peak rate	50 Mbps	5 Mbps	1 Mbps	250 kbps
Number of antennas	2	2	1	1
Duplex mode	Full duplex	Full duplex	Full/Half duplex	Half duplex
UE receive bandwidth	1.08–18 MHz	1.08–18MHz	1.08 MHz	180 kHz
UE transmit power	23 dBm	23 dBm	20/23 dBm	20/23 dBm
Multiplexed within LTE	Yes	Yes	Yes	Yes/No
Modem complexity	100.00%	80.00%	20.00%	15.00%

**Fig. 4.18** Number of papers for 5G and IoT

Centre Tecnologic de Telecomunicacions de Catalunya (CTTC) that integrates 5G technologies with distributed cloud resources and IoT is presented in [58]. Moreover, the authors in [20] present the mobile access system technology developed to counter increasing data traffic and describe the centralized base band unit supporting LTE-Advanced and indoor femtocell base stations developed by Fujitsu. They also discuss the technological trends for 5G and describe activities to realize such technology.

The authors in [46] deal with the problem of handling different traffic types in future 5G networks. They introduce a random access within the standard acquisition procedures to support sporadic traffic and thus enabling IoT devices.

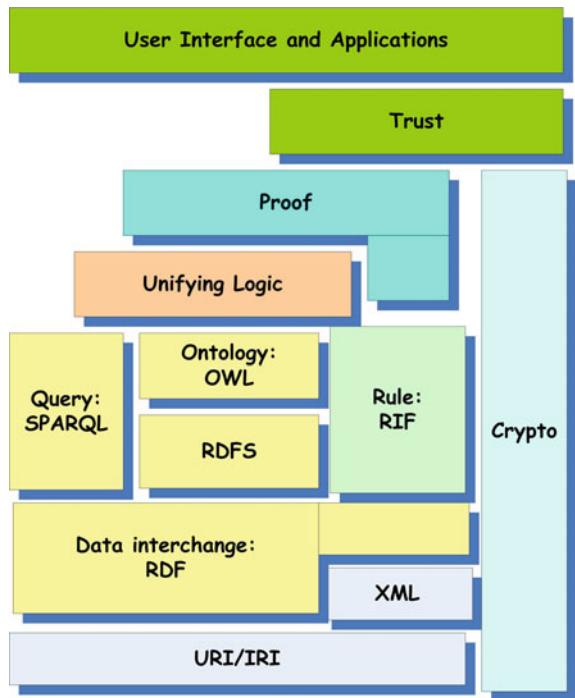
4.5.5 Semantic Web and IoT

The use of Semantic Web, [11], and Semantic Web Services, [25], technologies to enable the interoperability of systems and applications is gaining momentum worldwide. The state-of-the art technology in a web environment is adding semantic meaning to web resources. Currently these resources are usually only human understandable: the hypertext mark-up language (HTML) only provides information for textual and graphical information intended for human consumption. Semantic Web aims for machine understandable information that can be processed and shared by both computers and humans. Tim Berners-Lee (2001) provides the definition of the Semantic Web as “an extension of the current one [Web], in which information is given well-defined meaning, better enabling computers and people to work in cooperation.”

Data representation in a semantic web environment is given in layers as shown in Fig. 4.19 [53]. These layers include XML [15], RDF (Resource Description Framework) [52], Ontology (OWL) [21], and Logic. OWL is an ontology language for the Semantic Web, developed by the World Wide Web Consortium (W3C) Web Ontology Working Group [71]. In OWL, an ontology is a set of definitions of classes and properties. OWL has the ability of applying constraints on the way those classes and properties can be employed. OWL DL (Description Logic) is an OWL sublanguage that supports those users who want the maximum expressiveness while retaining computational completeness.

Semantic technologies use machine-interpretable representations that describe objects, share and integrate information, and infer knowledge. Thus, it would be beneficial to apply such technologies to IoT applications that could deal with M2M communication and integration. However, the resource-constrained nature of the IoT requires special design considerations to be taken into account to effectively apply the semantic technologies on the real world data [10]. Several information technologies exist for the creation of web-based IoT applications. Barnaghi et al. review [10] the applications of semantic technologies to IoT. The combination of IoT and Semantic Web is also called Semantic Web of Things (SWoT). The main idea is add semantic annotations real-world objects, locations and events. The authors

Fig. 4.19 Semantic web “layer cake”



in [70] give a general framework for the Semantic Web of Things, which is based on an evolution of classic Knowledge Base models and present architectural solutions for information storage, communication and processing. Moreover, in [42] the author also study the SWoT and analyze the impact to resource performance of the use of semantic-annotations. A new paradigm for applying intelligence to IoT is given in [82] called by the authors Cognitive Internet of Things (CIoT). The authors present the definition and propose an operational framework of CIoT.

The use of semantic web technologies in smart grid applications is emerging in the last years. A Generalized data management model of smart grid using ontologies is presented in [38]. The authors in [12] contribute on smart grid and semantic web technology integration by presenting two real-world use cases. Moreover, in [57] the authors introduce a smart aggregation layer device which allows for easy annotation of data with URIs. They present the results of their approach in an application of a smart annotation engine deployment in Austrian Smart Grids model regions. Additionally, the authors in [36] present an implementation of the Universal Smart Energy Framework (USEF) through a multiagent system and a novel semantic web ontology. Thus, the authors align and enrich the relevant existing standards using that ontology. Finally, in a recent book chapter [29] the authors introduce energy semantic networks (ESNs) and their applications for smart grids.

4.6 Conclusion

IoT is a key communications paradigm for future smart grid applications and services. Current IoT existing technologies enable the application development in several domains. The existing SG applications and testbeds show that the technology is mature and thus the number of applications is growing exponentially. Future technologies like 5G, LPWA networks that will bring IoT as a common 5G application will give an extra boost to IoT based smart grid expansion. Semantic web technologies, which are still growing and maturing, will enable the context-aware IoT combined with the semantic smart grid. Other technologies like IEEE802.11ah will also be play an important role to IoT based smart grid applications and they will provide new services.

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Chapter 5

Smart Grid Hardware Security



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Abstract Smart grids are vulnerable to a multitude of attacks, due to their cyber-physical nature. Such attacks can occur at their communication, networking, and physical entry points and can seriously affect the operation of a grid. Thus, the security factor of a smart grid is of an utmost importance. In order to properly secure a smart grid, we should be able to understand its underlying vulnerabilities and associated threats, as well as quantify their effects, and devise appropriate security solutions. In this chapter, we begin with an introduction to smart grids and Hardware Security. Then we continue to describe some grid architecture patterns, so that we can be able to understand a general picture of the grid functionality. In the next section, we discuss the basic and most important aspect of the security of the smart grid; the secure communication between the devices, providing some techniques for a secure device authentication scheme. We, then, discuss the confidentiality of the power usage, explaining various methods for metering data anonymization. In the end, we present solutions related to the integrity of data, software and hardware.

5.1 Introduction

With Smart grid, we consider the evolution and revolution in existing power grids, which intelligently integrates the actions of all connected users to efficiently deliver sustainable power sources, thus creating next generation electricity distribution systems. At the same time, the integration of advanced IT and communications technologies improves both the efficiency and reliability of future power generation systems.

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However, the use of the distributed network information combined with the installation of renewable energy sources is expected to help reduce consumption and losses from the electricity supplier to the consumer.

By improving existing power grids and turning them into smart, we must also take seriously the security issues arising from this evolution. Also, security costs should be weighed against the efficiency of smart grids. Through communications channels, most electronic devices will be interfaced to all critical power plants, with a direct impact on the efficiency and reliability of the entire infrastructure. Incorporating more and more infrastructure into the grid make smart grids a sustainable form of energy infrastructure. Therefore, the uninterrupted, consistent and continuous operation of the smart grid is an imperative need and must be ensured as much as possible.

According to a survey by Komninos et al. [29], a description of the most commonly adopted security targets in a smart grid is:

- Confidentiality, ensuring that data is only disclosed to authorized individuals or systems.
- Integrity, ensuring that there will be no kind of violation of data (destruction, modification, loss), while maintaining consistency and accuracy.
- Availability, ensuring that any network resource (equipment - data - bandwidth) is protected against any occurrence that threatens its availability and will always be available to any authorized entity.
- Authenticity: authenticating the communicating parties. In this case, messages are sent by these parties themselves.
- Authorization: ensuring that each entity's access rights are legal and determined in the system, according to the level of access control of each entity.
- Non-repudiation: ensuring that there will be indisputable proof to ratify the honesty of any assertion of an entity.

Generally, in the smart grid environment, threats continuously attempt to violate some or all of the above security objectives. Threats are categorized as shown below into two broad categories [10]:

- Passive attacks: attacks that do not affect system resources [16] and attempt to learn or make use of system information. Therefore, in passive attacks, the objective of the opponent is to obtain information that is transmitted rather than to modify it; therefore, seeking to gain any kind of knowledge. Passive attacks may formulate into a security disclosure problem, due to unauthorized monitoring of a continuous communication without the assents of the convey parties or motion analysis where the opponent monitors the traffic models to extract useful information from them. It is very difficult to detect these two types of attacks, since they do not alter any data. Our efforts to prevent such attacks focus only on prevention, not on their detection.
- Active attacks: attacks that attempt to modify a system's resources or disrupt its operation. Active attacks include attempts by malicious users or programs, data alteration, or the import of deceitful data into the system. The most ordinary among these attacks are disguise, repetition, message transformation, denial of service

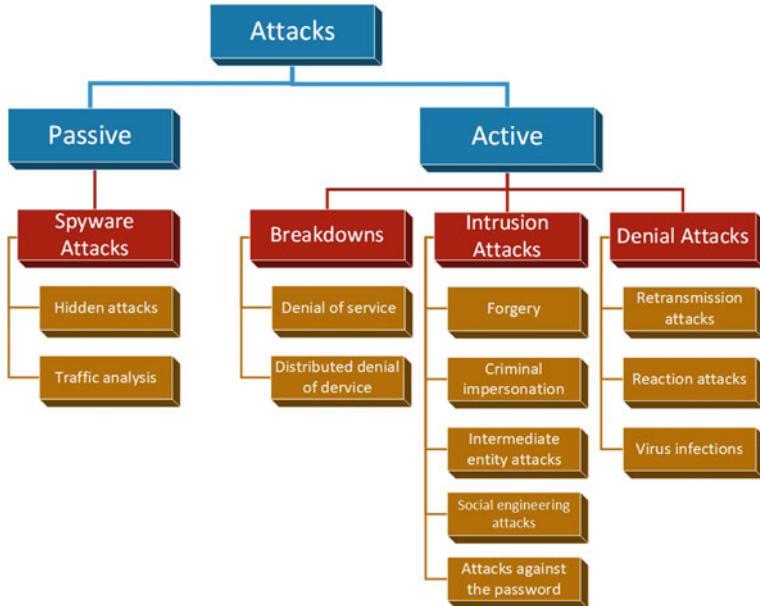


Fig. 5.1 Categories of attacks

and malware injection. A disguise attack occurs when an attacker feign a rightful entity to get administrator rights on the network. A repeat attack done to passively capture messages in a broadcast and retransmit to generate an unauthorized result. A message amendment attack involves modifying content of a rightful message, or delaying or rearranging a stream of messages to yield an unauthorized result. The denial of service attack intended to temporarily or invariably disrupt and interrupt availability of system transmission resources. Finally, attacks with malware, are attacks for exploiting interior network vulnerabilities, modifying, destroying or stealing information, and gaining unauthorized access to system resources.

Figure 5.1 shows a categorization of known types of attacks using malicious users or programs. When smooth operation is disturbed in a smart grid environment, serious damage can be caused, which means that the attackers would gain access to each component of the smart grid. Smart networks are based on existing network communications protocols, without replacing existing infrastructure by adding new communications networks to the transmission and distribution network. The contemporary energy networks do not take into consideration the potential damage that malicious users, could inflict, as much as it is required in the next generation networks. Since smart grids will be based on existing infrastructure, knowledge of energy demand is important. The availability of data is critical and is directly related to ensuring timely availability of information. At the same time, the integrity, as well as the confidence of the data, is correctly transmitted. Data privacy also needs

to be taken into account when all information is transmitted over smart grids. This data contains sensitive information about business and people's habits. The digitization of countries' energy infrastructures leads to more and more information being circulated inside the smart grid. Therefore, there is the possibility that this information may be misused by malicious and non-authenticated users. Energy suppliers are required to incorporate the confidentiality of data onto the day-to-day operations of this new smart grid framework, thus, successfully addresses the protection against data and information that could be intercepted. It must be the most important objective given the importance of the security of an intelligent network as the country's energy infrastructure framework [6, 40].

These aforementioned attackers can be broadly subdivided into the above categories:

- Terrorist attacks from other countries to deactivate the power grid.
- Deliberate false information trying to destabilize the country, manipulating the energy market.
- Violators, watching the energy consumption of smart meters, to find out when homeowners are missing.
- Individuals, violating the smart energy meter, for personal gain.
- Power suppliers or intermediaries involved in the smart grid, which have the potential to manipulate their competitor's pricing systems.

The evolution of the smart grid infrastructure over the last few years has incorporated links from anyone involved in energy sector, such as communications service providers, price comparison websites [18] and other. Each of these stakeholders could potentially and unwittingly be an unauthorized access point to an intelligent network. Also, potential targets for hackers are data communications companies (DCCs), which are part of the Automated Measurement Infrastructure (AMI), and are included in the interconnected nature of smart grids. Variable communications service providers, as well as third parties associated with the smart grid, are some other organizations that need security against possible attacks.

The elimination of such forms of attack is imperative in an intelligent network and must ensure both the confidentiality and the protection of the privacy of all parties involved. Cryptography is the most basic technique used to ensure confidentiality. There are some other techniques used in the case of privacy, such as anonymity [18], homomorphic encryption [15], distortion models [23], reliable synapses [49], verifiable calculation models [54] and data deformation [27]. In a following section, we will talk about confidentiality techniques, along with their possible advantages or disadvantages.

It is now obvious that only through cooperation between industry and the academic world, it is possible to achieve the necessary balance between security, affordability and availability. The continued development of smart grids also provides security companies with the opportunity to offer their expertise. By adapting existing technologies or by developing new security technologies, they can meet the unique needs of the energy sector and potentially provide them with a new revenue stream for their businesses.

5.2 Smart Grid Architecture Patterns

Switching from today's electricity grids to tomorrow's smart power grids requires scalability and strengthening the structure of the communications network [12]. The change of smart grids will accelerate the distribution of electricity in all directions, provide sophisticated load management and advanced self-maintenance mechanisms. As a result, an integrated advanced power system is reliable and energy efficient. The basic smart grids architectures are as follows.

5.2.1 *The Silo Architecture*

This particular architecture can be considered as a silo collection. Charging and distributing energy are the heterogeneous functions of the power grid. Different information silos are used and merged into a thin layer of information technology. This silo-based architecture has worked very well for public utilities for decades. Its success is due to the different level of service that separates business needs as a unit and the business needs of a set of business. Essentially, it evaluates the needs of the network at each level collectively as a unit. Several utilities have been effectively integrated into the silo-based architecture.

5.2.2 *Integration Using Enterprise Service Buses*

The introduction of the back office is the next step, evolving the intelligent network architecture, assisted by Enterprise Service Bus (ESB) [13]. This step is used by several other programs to smoothly integrate them. This step theoretically looks like an easy perspective, but it requires computing managers and business a costly and time-consuming effort. The most important thing to accomplish using ESB is to impose discipline on the implementation of standards by both business and IT managers. Applying this design discipline, if not followed, we essentially create a silo architecture and all the problems it brings. If this design discipline is not followed, then we degrade the architecture to a plain Silo Architecture, carrying the described deficiencies Sect. 5.2.1.

5.2.3 *Adapter Architecture*

Another evolutionary proposal comes from the United States Department of Defense and has been developed similar with a strategic military deployment. This architecture for smart grid has as a characteristic that it gives each consort operational instructions

from a designated central unit, allowing it to know the current situation. In case of a conflict, the unit-defined operational picture (UDOP) informs each adversary with the necessary data, without bombarding them with useless information that is unrelated to their object in the battle. In this strategic architecture, similar functions of the Marine, Navy, Army, and Air-Force are incorporated in order to provide a comprehensive picture of the situation.

5.3 Hardware Device Authentication

The basic and most important aspect of the security in the smart grid is the secure communication between the devices. A private key will be obtained by each smart device within the environment of a smart home [8, 37]. The primary objective of an attacker will be to impersonate a legitimate device or even monitor or modify network communication. All of the above could take part in a cyber-physical attack that, in case it is successful, could cause serious damage to the smart grid environment. In general purpose systems, such as personal computers, we already know that security keys may be threatened by unauthorized access or even malware. Attackers will try to access the private key of the device so that they can eventually be able to carry out these attacks. We cannot remain safe only on the assumption that breaking the cryptographic protocols is not possible. A secondary target of attackers may be to abuse the private key of the device so that the device can be used by unauthorized third party. Since this key considered a form of strong device recognition, this will enable unauthorized users to know crucial information about our smart network. For instance, the above private key's signatures could be used to track the device or user, thus creating a threat to the privacy of users. Therefore, it is imperative and obvious that a protection mechanism for the private key of the device is needed. In addition, this mechanism is capable of acting without the need of user interaction, so that the smart grid environment could actually use it. Based on this framework, the gear of the private key protection must meet the following requirements, consort with the National Institute of Standards and Technology (NIST) [7].

Requirements for Security and Privacy

- S-1: We can use the private key device only, on a particular system or physical device.
- S-2: The private key device can simply be used from a particular software applications' set.
- S-3: We can use the device's private key only to authenticate that device to authorized endpoint points.

Functional Requirements

- F-1: The use of the private key must be facilitated in the standard TLS handshake protocol.

- F-2: Further interaction with the user must not be required after the phase of key initialization.

Based on the above requirements, we conclude that existing generic approaches are not quite suitable in an intelligent network environment to protect private device keys. The key remains vulnerable to malware or unauthorized access to the system and by doing so, no security requirements can be fulfilled. Although functional requirements can be met simply by storing the key in an unencrypted form, both functional requirements and S-2 could be satisfied, provided that deformation is not impaired and using key-guarding techniques. Particular attention is needed in implementing this approach, because applications must be reliable so as not to breach S-1 and S-3. Since the user's secret must only be provided to trusted applications at authorized endpoints for certification purposes, the key encryption solution, along with a secret supplied by the users, satisfy S-1 and possibly S-2 and S-3. However, this approach does not meet F-2, because user interaction is mandatory in this case. Therefore, it is obvious that we cannot broadly use it in an automated smart grid environment. In theoretical approaches using hardware safety, all requirements of security, privacy and operation could be met. However, these approaches have not fully achieved this goal in a practical way, so that such types of previous systems that provide e.g. a key that can be found on a particular platform (S-1), without this limiting the use of the key (S-2 and S-3). This is not yet practical in non-managed systems in the home environment because of various deficiencies of tamper-proof storage. These requirements could be met when storing the key in a specific platform state [30].

5.3.1 *Proposed Solutions*

Six basic approaches for protecting the private key of the device [43] in a smart grid network, are:

- No Specific Security.

Storing the unencrypted key is the most basic option and the simplest solution, thus it is very easy to use anywhere, anytime. The key is unprotected for unauthorized access to the device or any malicious software even. Therefore, this is the approach's main vulnerability. There are cases where this vulnerability does not affect the proper functioning of the network, such as on some embedded systems that are unable to run malicious programs, due to limited resources (low memory, low CPU performance), and do not support remote access. These threats, however, pose a serious risk to both most appliances in the smart home and unprotected private keys.

- Software Obfuscation.

Encryption of a cryptographic key to a particular binary software is called software deformation techniques. They provide protection even though the key is not

encrypted. The attacker should usually design the reverse binary software to capture the original key. This increases the complexity of work required to find and acquire the key. All systems that run this binary software in this approach share the same locked key, which will most likely be used as the key to encrypting a key store that contains the unique private key of the device. Nonetheless, it is accepted that such distortion of software provides only limited security [42]. In the event of a key violation and disclosure, all of the devices' private keys will become vulnerable. In such a case, it will be necessary to replace the locked key on all devices, assuming we will have detected the violation.

- **Encryption with a User Secret.**

A password or PIN is one of the main approaches when it comes to encrypting private keys with a secret provided by the user. Therefore, in cases where it is required, each user's secret code is entered by them and the key is temporarily decrypted into volatile memory. An attacker who takes advantage of vulnerabilities in the operating system or application that uses the key, even in this decrypted state, could cause the key to be still infringed. Some systems of key management allow the user's own key decryption once, at startup. The system then transfers them to volatile memory for upcoming use instead of decrypting the key whenever required. However, the solution mentioned above still requires a user's initial interaction. This increases the vulnerability window for exploiting applications or operating systems. The secret code you provide is also susceptible to attacks of social engineering, which could endanger the key's security. Private keys will be used for the device and not for user identification, as part of an intelligent network. Therefore, you are not considering a suitable solution for user interaction to protect the smart grid's meters.

- **Hardware Security for Private Keys.**

A smart card or Hardware Security Unit (HSM) is a major approach and is included in the use of specialized security hardware to protect private keys. Several solutions have been proposed for this approach, but most of them follow the principle that the private key can only be accessed by HSM. By applying this guideline correctly, we virtually eliminate the ability of an attacker to acquire the virtual key. HSM will use this key when required for any cryptographic function and then produce the desired result. Such systems require additional security mechanisms. They must ensure the authenticity of the requests and do not come from an attacker. Smart cards, for example, require the user's PIN to confirm a function. The Trusted Computing Group (TCG) has a more sophisticated approach when it comes to information protection; that is the use of hardware security as a basic principle.

- **Trusted Computing.**

Various technologies and processes collectively known as Trusted Computing (TC) have been defined by the Trusted Computing Group (TCG) [1]. Many of these are based on the Trusted Platform Module (TPM), a cryptographic co-editor based on templates [50]. The TPM is embedded in the majority of enterprise-centric personal computers as a distinct hardware unit. A future prediction is a TPM's inclusion in both future home appliances and smart devices. This allows each system to create a recording of its software status while using a set of secure platform setup (TPM)

logs in the TPM. A SHA-1 shredder value is stored by any PCR that cannot be written directly, but can be expanded by the TPM, when combining the value that already exists with a new incoming time string and afterwards storing the hash of the result. According to the terminology of TCG, a software's calculation is possible by calculating the fragmentation of the complete software component and expanding it to a PCR. Starting from the initial launch of the platform, for a metered startup, the previous software measures each piece of software before it is executed, thus forming a chain of confidence. Using an asymmetric key of a unique storage root (ASK), the TPM provides secure storage. The TPM is never left without its private part that can contribute to the encryption of any number of symmetric keys, which sequentially provide data encryption. On a specific Storage Root Key (SRK) based platform, it is possible to connect data in this way. If the PCRs match a predetermined value, it is also possible to stamp data in a specific software state, so that the data will not be decrypted by the TPM. Otherwise, another possible solution to the original problem of the private device keys' protection is provided by TC. The device's private key can be sealed to a specific secure state of software by the TPM, after a metered startup. This action results in the current TCG approach in sealed storage having several weaknesses. For example, such a weakness could be the installation of an updated patch or update results in a different PCR values' set that would prevent the TPM from disconnecting the data. Therefore, in order for this challenge to be addressed, we have implemented an alternative approach. Large microprocessor vendors have developed a new technique in the form of Dynamic Merchant Ranging for Measurement (DRTM).

- Dynamic Root of Trust for Measurement.

The idea is based on a delayed firing that allows the system's initialization in an unmeasured state and then goes to a measurement state that provides a dynamic DRM (Dynamic Root of Trust for Measurement), which can be used as a confidence anchor for subsequent operations. An example of the above idea that uses this feature to cater a protected and isolated environment of execution on modern x86 platforms comes from the Flicker [36] research project. Flicker, when enabled, starts a late boot using a special CPU command and temporarily suspends the host operating system. The special command results in the reset of a PCR's subset (known as Dynamic PCRs), the disablement of Direct Memory Access (DMA), and the partial reset of the CPU. Flicker then runs a PAL bit, a small piece of code provided by an application. PAL is unaffected by any other software executed in the system before the delayed firing due to partial CPU restoration. However, we can safely say that PAL is running in a Trusted Execution Environment (TEE). The flicker allows any application's certain functions to perform within this TEE, encapsulating the functions as PAL. However, the functionality of a PAL is naturally limited. This is because host operating system's hardware drivers or libraries should not be used by a PAL, due to their possible pre-launch violation that could affect the whole process. In order to complete the execution of the PAL, as much memory is used by the PAL is deleted and the host operating system is repeated from the suspended state. PCRs' expansion with a well-known value indicates that TEE is inactive.

5.4 Confidentiality of Power Usage

Meter data confidentiality plays an imperative role in the smart grids' security. Data of power usage provides information on usage patterns for individual devices. Malicious users can intercept personal activities through non-attendant monitoring of devices by collecting this data [47]. Confidentiality of information is not important in cases involving price and device control commands and is considered to be public knowledge. System security should not be based on software privacy, so software confidentiality should not be critical. Imperative is, of course, the secrecy of keys, according to the principle of Kerckhoffs [28].

5.4.1 Anonymization of Smart Metering Data

A smart meter is an advanced device that measures power consumption much accurately than a conventional meter. The smart electric meter could also be built-in or working with heat meters, as well as water and gas. The purpose of a future smart meter will be to communicate the information to the local utility for monitoring and charging electrical power. It will also be able to provide communication with a number of the future "smart homes" devices and applications, which are generally expected to automatically cater accurate indications, at required intervals. The utility, a network of electricity or even the wider smart grid will then accept these measurements. We have yet to determine such readings' expected frequency. Assuming that this frequency has a range of a few minutes, imperative privacy issues automatically arise [46]. Processing and availability of such critical data, as mentioned in the previous paragraph, is of the utmost importance. Sensitive, detailed information on energy consumption could abolish the daily energy consumption habits of a household. They could also reach the point, where they could remove the type of device or application that is in use at any time.

5.4.2 Escrow-Based Anonymization

A categorization of data generated by a smart meter could be the following:

- The "High-frequency" measurement data, which is the meter readings taken every few minutes. An intelligent meter often transmits this electrical data that relates to user privacy information (e.g. models of specific electrical appliances).
- The "Low-frequency" measurement data, which is the meter readings that are made every week or month. A smart meter transmits to little use to provide adequate privacy protection.

Conversely, as with conventional smart meters, the difference to a smart meter with a single identifier is the existence of two separate identifiers built into the smart gauge:

- High-Frequency ID (HFID),
- Low-Frequency ID (LFID).

The smart meter transmits the high and low frequency measurement data to the utility. These are collected by the two identifiers linked to measurement-related messages. In practice, this means that HFID will be used in order to transmit the meter readings.

The main idea is the method for maintaining anonymity across HFID measurement metadata, and hence HFID messages. A unique way to preserve the initial anonymity and to stay that way is to restrict the data of the smart meter from the assistant or installer. Therefore, to be able to be used in all HFID-related messages it must be “hidden” within the smart gauge and hard encoded. There is no way a utility to verify the certification integrity of the messages received from a specific HFID. The problem arises because the messages are not verified as legitimate, as the utility does not know the valid HFID.

For the above reason, a third-party escrow service is proposed [46]. It may be the manufacturer of the smart meter itself or another trusted third party with given access to this information. The manufacturer can assign two unique identifiers to each smart meter. Therefore, the utility can access only one LFID, both in procurement and development processes. In fact, the manufacturer is the only one who has the knowledge of the HFID/LFID pair. It is also important to mention that the commitment of the third-party escrow service is required to satisfy a strict privacy policy. It is therefore expected that the escrow can not access neither the processing, nor the storage of smart meter data.

The Fig. 5.2 indicates the distinction between the low frequency measurement data, which the utility receives and the high frequency measurement data that the distribution substation (or other related entity) receives. This figure also provides an internal view of the smart meter, in terms of hardware / software ID. Previously, LFID and HFID values were hard coded in the smart gauge, while only the manufacturer or third guarantor knew their connection within a single smart gauge. They were stored strictly in the smart gauge as part of the identity profiles:

- Personally Identifiable Smart Meter Profile (PISM),
- Anonymous Smart Meter Profile (ANSM).

With the use of a secure protocol setup mechanism, PISM and ANSM, we are able to construct client data profile and an anonymous data profile, respectively [22]. For example, a scenario which we permit a smart meter block to pool their data in a local area. The escrow service provided through the unique HFID is required for the above reason. The total message will be considered anonymous, as long as the parts of the amount attributed to individual smart meters are hidden. Therefore, these actions require a separate algorithm for verifying the authenticity of any intelligent means. Also, in order to maintain the privacy of the user, an authentication mechanism should additionally work, which should not be performed through the utility.

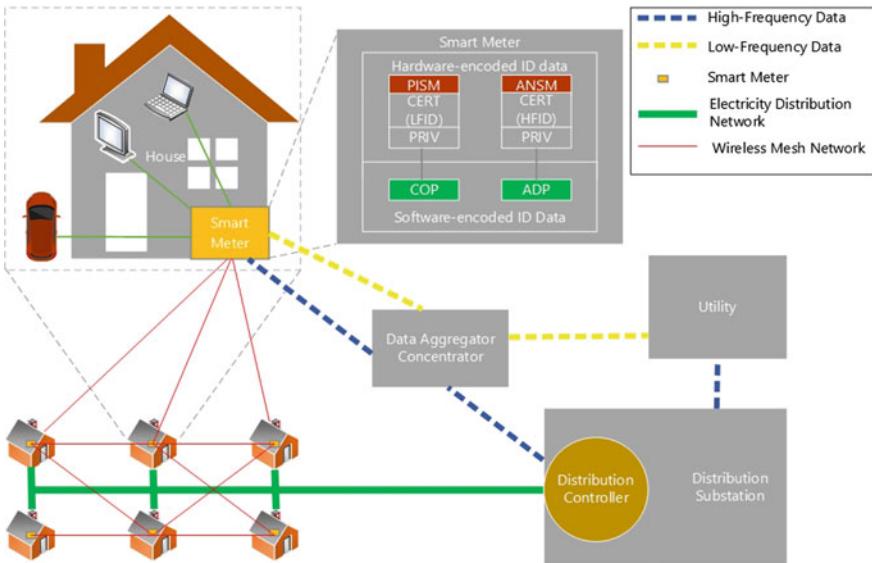


Fig. 5.2 Data structure of smart metering devices and distribution network in a smart grid

5.4.3 Secure Networking Hardware IPs in the smart grid

Today, the integration of electricity networks has led to this smart grid. This is a reason why the need for devices that support newer transmission protocols and comply with the strict processing requirements by the electricity sector, is greater than ever. Manufacturers of intelligent electronic devices (IED), following this framework, with their modern installation architectures, are available to meet smart grid communications, processing and interoperability requirements in real time. In this new generation, Field Programmable Gate Array (FPGAs), supporting advanced switching architectures for smart grids, include the innovative IEEE 1588-aware High-availability Seamless Redundancy/ Parallel Redundancy Protocol (HSR/PRP). Another advantage that FPGAs give us is the ability to upgrade the design or update the software. At the same time, they can be reprogrammed so they can support new requirements that will result from the updated IEC 61850 standards. The architectural update to the FPGA can be done remotely. However, this possibility creates the need for a cyber-security mechanism. An attacker can access the network through the communication link to be installed with the FPGA, so in some cases a vulnerability is created [52].

Research in this field is aimed at proposing [52] a secure protocol and IP core, implemented in the Field Programmable Gate Array (FPGA), to monitor and configure IP networks. This proposed FPGA protocol overcomes the above-mentioned problem by using a Lightweight Layer-2 protocol, with a full implementation of the hardware. In addition, as defined in IEC 61850-90-5, it is protected by strong cryp-

tographic algorithms (AES-GCM). Where remote IP cores in FPGA configuration over Ethernet are required, both the proposed secure protocol and the IP core apply to any field.

Although the ability to remotely configure a system allows for bug fixes or even the addition of new features, it could also expose these systems to security attacks. The accident at a nuclear power plant in 2003 is a typical example of network control by the Slammer worm [44]. Similar to this incident, it is also the Stuxnet infective worm that infected the computer software of several industrial sites in Iran [31]. Also, the recent serious attack on the Ukrainian electricity grid [11] has shown us the critical momentum we need to demonstrate in the review of critical infrastructure security policies. The North American Equipment Council (NAEC) presented the problems caused by the Slammer worm at the power plants supplying North America [32]. Specifically, it was found that the worm has been hacking the company's corporate network via a virtual private network (VPN) connection, ultimately targeting the critical Supervisory Control And Data Acquisition (SCADA) network [34].

The International Electrotechnical Commission (IEC), over the last decade, has been zealous on issues related to future cyber security, and in particular the electrical industry [19]. They proposed the IEC 62315 family of standards dealing with security issues, communication standards and various system functions as defined by the IEC TC57 [14] working group. This specific IEC TC57 Standards Working Group focuses on the specific protocols and applications that will be used in the smart grid. The IEC 62351-6 [25] standard clearly defines the security mechanisms that will provide the necessary protection for IEC 61850 [26] communications not based on the TCP/IP protocol. The general object-oriented sub-frame (GOOSE) framework is defined, in particular, by sampling values (SV) and message identification codes, in order to produce the source authentication encrypted key using Secure Hash Algorithms (SHAs) digitally signed by the Rivest, Shamir Adleman (RSA). The long run times of the RSA digital signatures do not allow the necessary timing to be met. The longer transport time required by some GOOSE messages, with RSA signature 1024-bit keys, cannot be generated and identified within three milliseconds. The processor used is a high-timed ARM with a built-in encryption accelerator and yet can not cover the high cutoff rates. However, IEC 62351-6 will be updated in accordance with the expected safety requirements of IEC 61850-90-5 [21]. In particular, it is proposed to use symmetric cryptography rather than digital signature, due to the reduction of the performance impact.

The Advanced Encryption Standard (AES) algorithm was used as an encryption method for protecting information that is trafficked using an Ethernet connection. According to IEC 61850-90-5 [2] is the safest and most operational encryption method today. The National Institute of Standards and Technology (NIST) proposes the following five traditional modes of operation AES [17]:

- Electronic Codebook (ECB),
- Cipher Block Chaining (CBC),
- Propagating Cipher Block Chaining (PCBC),
- Output FeedBack (OFB),

- Cipher FeedBack CFB),
- Counter (CTR).

For encryption and for message decryption, OFB, CFB and CTR use only one encryption element. The AES operating method unfortunately does not solve the authentication problem, but its operating mode only covers confidentiality issues. The above problem can be resolved by the combined use of an encryption algorithm and a Message authentication (MAC) code, such as HMAC or CBC-MAC. The high complexity of the above archetypes makes them prohibitive in their use for devices with low capabilities [41].

The chip-to-chip communication of the open channel over Ethernet has caused a problem in its implementation and was corrected by creating a Layer-2 protocol. This new Connection-oriented Ethernet (COE) protocol establishes remote access to FPGAs that are deployed on IPs switching infrastructures. Although the basic use of COE is access to internal registers of IP addresses, it can be used for configuration and status reports, creating a communication link between FPGAs located in different physical locations. Therefore, for the data trafficked through communication above, all necessary and appropriate protection measures must be taken to ensure the safe operation of the network.

To secure the COE messages, another version of the COE protocol which focus on security, called Configuration over Ethernet Secure (COEsec), was created, the implementation of this new version is necessary to be able to use the protocol on unsafe communication channels. COEsec is based on some functions of the already used MAC security and is generally called MACsec. The IEEE 802.1AE standard is defined as a single security frame. In this context, communications of the stations connected to the same LAN network and using the MAC service, e.g. Ethernet or Wi-Fi, as given by the IEEE 802 family of standards.

A further advantage of COEsec is that for its operation you do not require a CPU, as it is a small standard layout while also ensuring authentication security and remote connection to the device. The AES-GCM algorithm is applied to the hardware at the same time as an encryption engine in the IP core, which has encryption and decryption capabilities, certifying all COE frames. To provide authentication and encrypted data, this protocol is based on the 128-bit AES-GCM algorithm and uses symmetric key encryption. AES-GCM is suitable because it consumes very few resources, has increased cryptographic capabilities and maximum performance, in particular when implemented in hardware. Although this protocol should support any cryptographic algorithm, COEsec IP was constructed based on the ability to exchange the module responsible for the authentication so that other algorithms can be easily integrated, if needed. However, the protocol has the ability to support most cryptographic algorithms.

As it is obvious from the previous discussion, this cryptographic approach is a complete hardware solution that gives us low resource consumption and increased performance. With respect to other software-based cryptographic solutions, this implementation gives us the least chance of not switching to error and at the same time delivering the best possible performance.

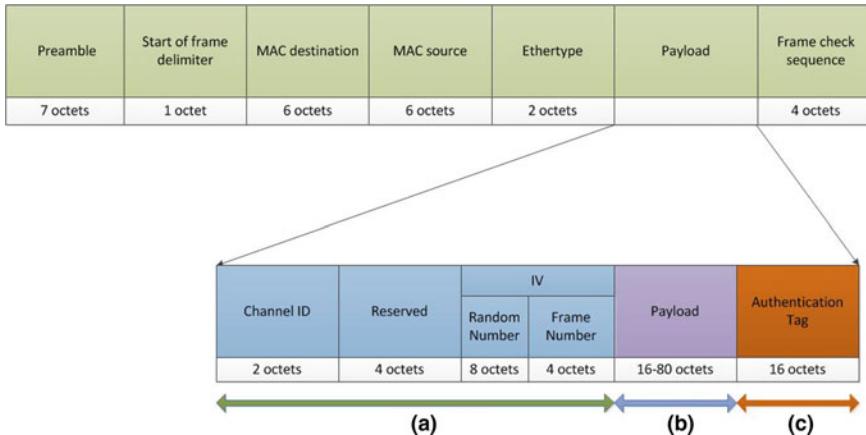


Fig. 5.3 Format of COEsec. **a** Encryption and Decryption data required **b** Encrypted configuration **c** Authentication and integrity tag

The Fig. 5.3 shows how an FPGA is securely deployed on a CPU by the IP networks and they co-exist on the same network. The CPU is responsible for receiving and generating COEsec messages, and for creating the necessary IP networks. Basically, in this scenario, the CPU behavior is in a server role, allowing remote WANs to be managed and using protocols such as HTTPS, which are of the highest level.

However, a framework format has been developed and adapted to provide the required information and to secure every communication. The fields contained in the payload are based on Ethernet frames as mentioned before and the COEsec messages give us the configuration data and the cryptographic information we need. The way that fields are included in the Ethernet protocol is depicted in the Fig. 5.4 that shows how a COEsec message box is applied.

5.5 Integrity of Data, Software and Hardware

As far as the integrity of price information is concerned, crucial safeguards for an intelligent network are required. Assuming that malicious users misrepresent prices, causing an increase or decrease in electricity consumption, at the same time, or smart devices will try to adapt to this change, depending on the benefit of consumers. This action has a substantial impact on the loss of revenue for the individual electricity supplier. Therefore, the integrity of smart meters is important for them at an economic level. Also, the integrity of the software is of utmost importance. Malicious or corrupted software affects all devices on an intelligent network, even the components that make up the network itself. A Trojan program from a smart meter can spread to many interconnected meters, even across the grid.

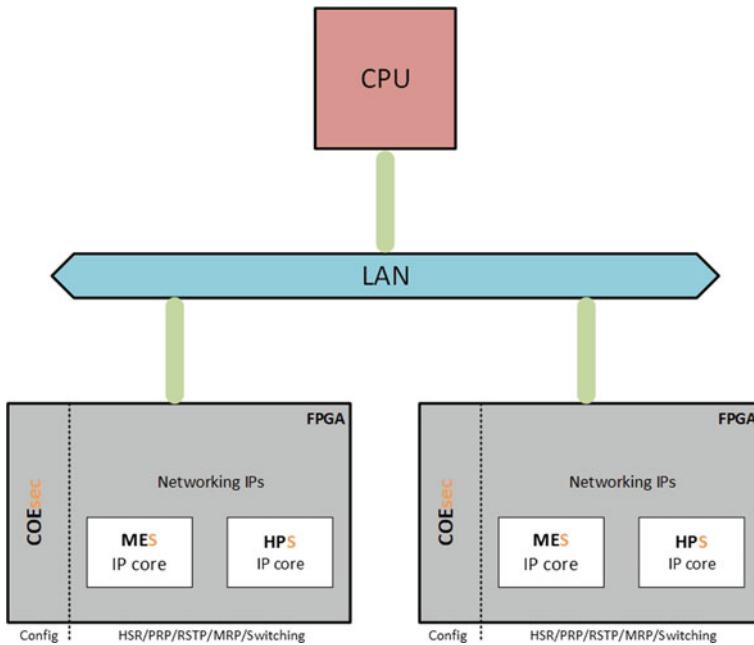


Fig. 5.4 CPU-less Intellectual Properties (IPs) are set up by a CPU on the same network and are securely applied to the two FPGA consisting of two sub-entities Managed Ethernet Switch (MES) and Hard Processor System (HPS)

5.5.1 *Distributed Network Intrusion Detection system*

In an intelligent network besides direct information security, we will also need to use methods to prevent malicious attacks. In traditional computer systems a method of prevention is attack detection systems. A proposal to prevent attacks on distributed systems is the Naive Bayes classifier [45]. In particular, it performs simple comparative calculations on the security features of the network it supervises. Also, the variability of the characteristics of a network does not negatively affect the classifier. One of the main advantages of the Naive Bayes classifier is that a small amount of training data is required to evaluate the means and fluctuations of the variables. That is, it can separate what it should record and when it does not affect the operation of the network.

The Naive Bayes Classifier (NBC) is generally satisfied with the variables in the smart grid data set and therefore the degree of class overlap in such cases is small. Therefore, the above classifier is expected to achieve good results in smart grid. For some optimized datasets that use the wrapping option, NBC may also beat other classifiers, and therefore it is used in the SGDIDS. In general, the Naive Bayes theorem proposes to initially find the class in any case where a number of regular packets or aggressive packets together with the data calculate the probability of each

class and then choose the most likely one. That is why Bayes theorem proposes the equation in a more rough form.

5.5.2 *Training the Classifier*

According to the Naive Bayes probability theorem, values are found according to the data in each particular problem. The probability values vary for different types of problems. For each substation of the smart grid, the maximum amount of data is known; hence, in a Naive Bayes training set the values are fixed according to the substation. The values of the data, though, differ for each substation. This is due to the fact that the values for each substation are given as the training dataset to the training algorithm of the Naive Bayes Classifier, after they have been found. The incoming packets may belong to any type of classes, i.e. it may be an attack packet or may be a number of normal incoming packets. From this training dataset, the Bayes classifier will afterwards test the incoming packets and in case the packets are the same as the training dataset, they will be assumed as normal incoming packets; thus, the source and destination address should be same. If the incoming packets are different from the training dataset, then they are assumed as attacked incoming packets; hence, source and destination address are different.

Finally, the attacked packets are found by this aforementioned probability data classification, according to the Naive Bayes Classifier, which will probably differ for each substation in the smart grid.

5.5.3 *HDL Based Network Intrusion Detection*

The IEEE 802.16 standard of the smart grid Communication Network, in which Smart Grid Network Intrusion Detection System is modelled and implemented, uses the HDL - Hardware Description Language and the evaluation of the SGDIDS (Smart Grid Network Intrusion Detection System), is done through simulation. This simulation is used for testing the Naives Bayes Classifier's dataset. Generally, Smart Grids' communication networks use many protocols in the Transport layer, such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) of the Internet Protocol Suite, commonly categorized as layer-45 protocols within the OSI layer [9]. Network based Intrusion Detection in the smart grid is able to identify threats in the data that are supported by many protocols of the OSI [53].

- Normal Packets. Once the normal packets' testing starts, the testing dataset will compare the packets to the trained dataset. If the incoming packet matches the Naive Bayes Algorithm-trained dataset's packets, the output will be displayed as a number of normal packets.

- Attack Packets. Once the attacked packets' testing starts, the testing dataset will compare the packets to the trained dataset. If the incoming packet does not match the packets of the Naive Bayes Algorithm's trained dataset, then the output will be displayed as a number of attacked packets. Output waveform for the attacked packets is obtained in Questasim [39] software of HDL.

5.5.4 Mitigating Synchronized Hardware Trojan Attacks

Designers and manufacturers of digital circuits can introduce a malicious circuit called Trojan of the hardware when making a device. This can be done either deliberately or by designer failure. Industrial freedom on the market is the main reason that leads us to supply unreliable devices. Manufacturers, on a global scale, of chips and devices are too many and some of them with a doubtful confidence. They do not give us any guarantee of not importing Trojans into their constructions, which puts the smart grid in danger after its development [20]. Therefore, the network can collapse on a large scale and have a loss of electricity, creating serious network problems. Preventing and detecting such vulnerabilities is quite difficult. The embedded Trojan is a clock electronic bomb and can be an offensive attack at any time. Thus, Trojans can easily affect a large part of the nodes on a power grid, and they do not require any interaction from an attacker. If our network is connected to the Internet, Trojans can be turned on and off or waiting for a specific event. As long as they are in the concealed state of the communication channel, they expect a broadcast message to be activated either individually or simultaneously.

5.5.5 Proposed Solution

On a smart network, all nodes are synchronized with global time T via a GPS unit. Modules, such as Phasor Measurement Unit (PMU) and Remote Terminal Unit (RTU), use and coordinate with them. Embedding hardware Trojans into the PMU, from malicious manufacturers that take advantage of this T synchronization time, can trigger a concurrent power outage at any time. The detection of Trojan hardware is quite difficult, as we have been investigating and the researchers first to prevent access to UTC, suggest adding a time delay so that every Trojan's material is at a different time from the activation time of T . They essentially propose a network of nodes, with a module adding its own independent time shift, as shown in Fig. 5.5. Since this time offset t is added over the time provided by the GPS receiver (i.e., the correct global time T), the corresponding module receives time $T + t$, which is unknown to the attackers.

It is suggested that t_1, t_2, \dots, t_N is the time shift of nodes and ranges from t_1, t_2, \dots, t_N across the entire network. The network control center performs initialization on all nodes with these random numbers and stores them in a database.

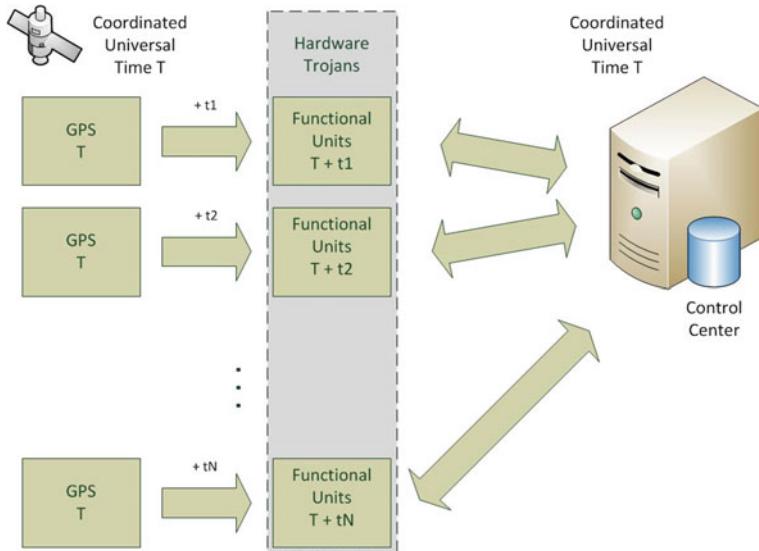


Fig. 5.5 Schematic diagram of the proposed solution

Therefore, only the time transmitted by the GPS receiver is the correct one and each module has its own independent time. So by applying this method, no module on the network has the same time as another module and as a result can not be synchronized with each other. In the event that the attacker somehow achieves the correct time of a module, it will shut down only and will not affect the rest of the network. This avoids a total power failure across the smart grid.

All of the above applies if only one node breaks down and the network will be able to cope with it individually and recover quickly. Over time, random time shifts can co-ordinate and create parallel problems and the other nodes. Of course, these failures will not be across the grid, but sporadic that can be addressed directly.

5.5.6 *Hardware-Based Malware Detection System*

From the Information Systems theory, for malware detection, we can allocate some of our computing resources or separate computer exclusively for this purpose. We can adopt this technique into the architecture of smart grids. Particular attention must be paid to the design and implementation of such systems so that they offer us the desired result and not the same vulnerabilities for our network. Generally, a malware detection system must provide real-time detection, must not degrade efficiency, and must be an economical solution to hardware or software [33]. In the design, we must be careful that our system has the following desirable features:

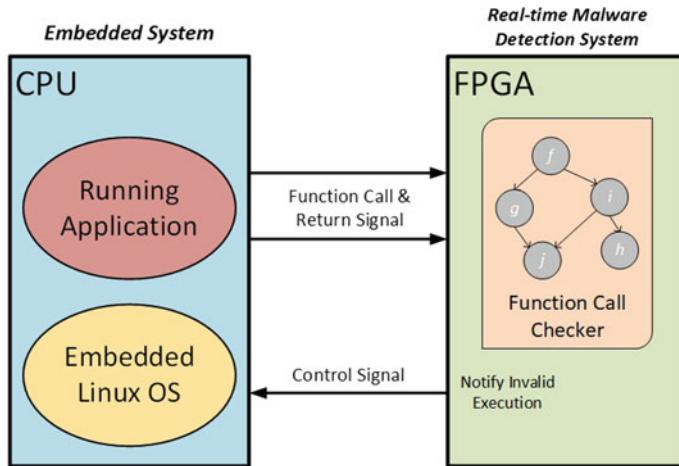


Fig. 5.6 System architecture a malware detection system

- Physical separation from the embedded processor is a key priority in a malware detection system. In the event that we have a processor violation in the tracking system, this malfunction will not affect the smooth operation of the rest of the network.
- The purpose of the attack detection system is to detect malware in real-time network operation. It is not necessary for any programmer to configure different security policies and affect its proper functioning.
- Material implementations outweigh implementation speeds over software implementations. Therefore, the specialized material, during its operation, can easily be detected by an attacker or malicious program by comparing response times with respect to a software-implemented detection system.
- Due to limited resources in both computing power and data storage, a detection system on embedded system must be viable both in terms of money and resource usage.
- In order to have the desired result, i.e. the protection of our system, the information extracted from the application's source code must not be changed. So we do not draw false conclusions about the real situation of our network.

The attack detection system consists of two subsystems. The first is the basic attack detection system and the second is the general purpose system. These two systems use the necessary feedback between them, but they are essentially separate and operate in parallel. Also, the rate of the attack detection in the above-mentioned system could be increased. The Fig. 5.6 shows the hardware architecture of the malware detection system in detail.

The way of identifying an attack detection system implemented in an FPGA and running in real time can be easily modified and dynamically configured, according to the current operational needs that are performed on the processor. Therefore, in

a smart meter, its functionality will be dynamically configured depending on the applications or the application that is currently running. The detection system stores in real-time graphical correct previous operating states. The function that contains the control calls for the current application then undertakes to verify the comparison of the trench operation with the previous states. If there are exclusions from the chart with the allowable control streams, it will automatically trigger a signal and notify or stop the embedded processor from running the illegal application. The detection system considers all unauthorized information flows as malicious and inactive for execution.

The process call graph is a static analysis of the original code and does not need to be run on a real device first. It is also generated offline when the developer creates the application. The first step is creating the syntax tree from an initial code analysis, and then looking for the functions and names of the specified functions to construct the final graph. For the construction of the attack detection system you use the final graph in the design logic and finally, implement the FPGA. The source code and call graph are created in a secure environment. Otherwise, if such a process gains access, hackers will be able to manipulate the original design for their benefit. The binary application load and the crawl bit stream are loaded into the FPGA before execution time.

The behavior of the application is monitored by a proper call flow selected as appropriate for the system. Therefore, it can initially distinguish poor performance flows that deviate from normal behavior and can automatically easily extract from source application code for any program. We also need to ensure that the total hardware costs are reasonable. Expenses incurred for large projects with large processing requirements that create complex and exhaustive high-level charts. This particular design can not detect any malicious security breaches that may be caused by malware. The basic function of this detection system is to detect real-time operation call violations, most likely critical malware infections. By stopping running invalid workflow, we are partially securing the possible infection by malicious applications [48].

5.5.7 Secure Boot with a IoT Device

Moving towards the age of smart interconnected systems, which essentially means connecting different networks of buildings, vehicles, sensors, embedded systems and individuals, we allow all these parties to collect and exchange information in order to perform various functions. These features include smart city monitoring, patient health, system predictions and diagnostics, the environment, smart buildings and smart grids [38]. Specifically in the smart grid, devices are remotely controlled, sharing data, allowing physical objects to interact with existing network infrastructures. The expected outcome of these actions is to improve efficiency, accuracy of performance and, of course, economic benefit. [51]. On the Internet there is a wide variety of applications that serve different needs each. Protecting devices in a smart

grid environment is imperative. Effective security solutions must be adopted to ensure the future of these devices.

In smart grid, unlike other systems, the supply of secure operating solutions is shifted from software to hardware, building on both the physical realization of the network and the effectiveness of material implementations. Computational power requirements are increasing, while the devices we use are shrinking. Therefore, the main challenge in designing a device for smart grid is to address threats and defend in FPGA-based implementations [35]. The types of these attacks and threats are:

- Bitstream decoding, attackers try to extract a Bitstream or prototype netlist in an attempt to decode the bitstream.
- Spoofing, replacing or processing part or all of the Bitstream stream into an FPGA.
- Trojan Horse, which provides access to malicious users who are designed to acquire system design or management and aim to add their own functions or gain access to device data.

For all of the above types of threats and attacks, we must protect and secure IP, by following these steps:

- To protect the device from bitstream decoding and spoofing, encrypting the bit-stream FPGA.
- To enhance system security encrypting boot image.
- To prevent Trojan's falsification and assaults, ensuring that the FPGA works properly, as predicted, through certification.

In order to create a secure boot image, the first thing to do is to generate an AES key by using the appropriate tool and then program this AES key [24]. After that, and with the use of that above-mentioned tool, an image, where both AES encryption and RSA authentication can be enabled, is created. Finally, this boot image, being a BIN file, is loaded onto an SD card. At this point, it is worth mentioning that enabling RSA authentication can also avoid spoofing or Trojan Horse attacks and help to increase system security.

5.5.8 Intellectual Property (IP) Theft Reverse-Engineering

The concerns for Intellectual Property Protection (IPP) have risen, due to the reuse of design. A company often designs IP modules and then sells them to others in a non-physical form (e.g. VHDL, netlist, layout); this way, these IP modules are not physically manifested. The design of the modular IP blocks is integrated within other systems, which usually exist on the chip. Subsequently, when an IP-thief reuses and resells an IP module does not even need to reverse engineer the design, as proving the IP ownership is pretty hard to prove, because of the IP's inherently abstract nature [55].

Some devices in the smart grid will re-use IP to increase the time to market or the productivity of the engineers. Thus, securing IP is of a great importance as it can efficiently detect copying, as well as identify IPs being misappropriated or stolen even, so much as if embedding this IP in a complex system. In addition to that, this technique helps extract simple watermark (or just mark in brevity) and also sufficiently verify design sources, without having to threaten the security of other, already existing designs. These aforementioned embedded marks offer better security against removal attempts.

Mark Preparation

One major difference this above-mentioned technique has in comparison with the original watermarking one is the revised mark preparation method. In this case, mark preparation is specifically focused on embedding multiple small marks. These marks, originated as 7-bit ASCII strings, can be printed with the use of traditional I/O mechanisms. Specifications of the subsequent hash function narrow these marks' sizes and the watermarking system, hereupon, is given the mark strings for embedding in the circuit; the verification program will later verify these strings.

Mark Embedding

A seed along with a secure function resolve watermarking locations, leaving different designs that have the secured set of marks still intact. Arbitrary inputs and outputs are given to the LUTs, which are to be embedded with these marks, so that the latter ones could be further disguised.

Mark Verification

The design seed, claimed to have been used for the block production upon which the mark locations are based, must be generated by the IP vendor. The seed is used by the verification team. This will follow to shift both the embedding process and the preparation of the signature using the LUTs' identification for hiding the marks.

5.5.9 *Establishing a Supply Chain of Trust*

In coming decades, the design, build and deploy of millions of devices are to be expected, so that they can be connected to a smart grid environment. In order to prevent hijack of these devices, as well as protect intellectual property and critical data, continual efforts are required. Therefore, it is of the utmost importance that

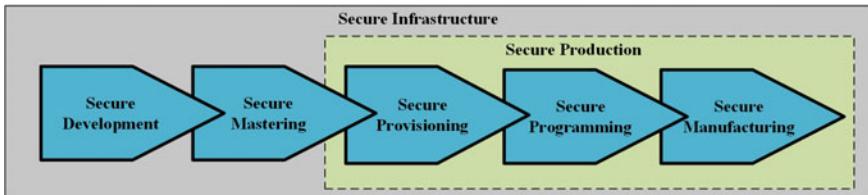


Fig. 5.7 The three critical areas to consider when create a chain of trust are secure development, secure mastering and secure production

manufacturers quickly and effectively develop best practices for the construction of a strong confidence chain and maintenance of the next generation devices' safety.

The security formulation must be established from the beginning of the devices' construction and also provide secure updates throughout its life cycle. Thus, we require the development of a strong root of confidence model in the processor, as well as an encrypted application, with the ability to load images on it. A potential solution for vulnerabilities' and continuous devices' certification reduction is considered an application with zero design philosophy of trust across the supply chain.

The Fig. 5.7 shows three key areas doing so are safe growth, secure development, secure mastering and secure production. The secure production includes secure provisioning, programming and manufacturing.

Secure Development [3]

Initially, both the implementation and design of the devices should have the right security frameworks, namely being the secrets' management, the root of trust and the secure services that are offered both to the application and operating system. While some hard-bound devices have a secure certification, such as SIMs (Subscriber Identification Modules) and MIMs (Machine Identification Modules), they do not have the required flexibility to run applications. The new end devices' generation requires a complex balancing of the device.

To solve the above-mentioned problem, a Secure Boot Manager (SBM) is introduced to the microcontrollers, which provides a strong trust base along with the provision of secure keys and certificates. The Safe Software Administrator bares a connection protocol, in the communication interface, that looks for images to be loaded by the developer, in cases where signed application is unavailable for execution. This developer fuels the Update Key (UPK) and the application's encrypted image into the SBM, which contributes to the UPK validation, image decryption, Flash processing, as well as the application signature panel's update, so that the memory is secure. The SBM allows a secure software update, as well. This software update is transferred by the client application onto a separate memory location and as a result we have an API call update to the SBM. The boot manager, also, provides execution security services, so that software updates can be processed and certificate for client application's access, validation and authentication be enabled. This, along-

side with a secure software delivery and encryption mechanism, enables either a safe production of the software or the product lifecycle's updating over the Internet.

Secure Mastering [4]

Generally, the main objectives of a safe production process are the undermining of the counterfeiting, the theft prevention of intellectual properties and the reduction of both the overproduction and mining. In order for a safe construction to be achieved, the early application software's encryption along with the on-site software decryption to the device is of a great importance, as it ensures the most contact points possible. The OEM designing product develops an application software that in many cases may be targeted by itself for some family of products or even a single product. It also contributes to the identification of some kind of software's personalization or version. An IDE software assists with the security development in terms of creating security certificates and key hierarchies, used for the SBM and MCU delivery. The mastering process accepts the application software image and continues with the image's encryption, using a secure key of the Advanced Encryption Standard (AES), and the Update Key Blocks's (UPK) creation, containing that AES key. After that, a signed version of the information, with the use of a single key mastering encryption, continues with the image encryption using other special product keys. In cases where the identifiers are created by silicon suppliers, mastering uses specific device identifiers, such as UUIDs, or some other type of device identifiers. Initial applications are presumed to be predicted in the secure programming center. The mastering process has as output a pair of the encrypted files, loaded into a safe manufacturing process. As these files are secure, they can only be verified and decrypted by the Secure Boot Manager, provided that the latter knows both the corresponding master key and the product keys.

Secure Production [5]

The only real solution, for truly safe products, is the development of zero trust approach across the supply chain, so that the identity's vulnerabilities, as well as the deliverables' personalization and identity be minimized as much as possible. The steps of a safe production include Safe Programming/ Construction and Safe Procurement. Since the scheduling center is in need of a prepayment model, a model must be implemented by it for safe acceptance and manipulation of the OEM's certificates and keys, along with a device provision that creates the device's secure services. To achieve this, we must implement a safe zero-trust channel, so that the OEM transmits secretly through an unsafe channel is granted, without passing any secrets' knowledge beyond the safe provisioning process. Once the OEM certificates, keys and SBM have been programmed on the device, the OEM's encrypted image must be also accepted by the programming center. This center must continue to acquire information of the system's production, including both the possible targeted devices and the number of the enabled ones. In order for the exchange enabling and security maintenance to take place, a secure channel is created between the Secure Manufacturing device, embedded in the developer itself, and the OEM mastering system. Secure zero confidence planning essentially demands image protection, by

all interested parties through encryption, and zero image action, with its installation on the device. Separation of Secure Programming and Secure Provisioning allows for flexibility in the way that the delivery is achieved, while at the same time allowing for forward planning with secure programming.

5.6 Conclusion

Today's traditional electricity grids are evolving into tomorrow's electricity grids and are known as smart grids. This development of today's networks will offer us with a strong and efficient energy infrastructure for the future. An endeavour that becomes more complex as new technologies are being integrated into traditional power grids. Every device in our current network, even those installed in our home, will undergo its own transformation in the direction towards seamless integration to the electricity network. The benefits of this development are undoubtedly positive and desirable for both companies and consumers. Safety and privacy concerns, arising from the introduction of the smart devices throughout the network, have been the subject of intense research. The outcome of the research, illustrate the need for increased attention in the security and privacy, not only in the design of the smart components, but also on the integration to the global smart grid.

This chapter is focused on the security measures that we can provide at a hardware level to meet a set of high-level security and privacy goals. We have shown some of the dangers that arise from the interaction between smart grid entities by evaluating their impact on the entire network. Also, the two-way communication used in these systems poses a risk to the privacy of consumers. In addition, we have reviewed the latest bibliography on possible solutions and countermeasures to find prevention or defense approaches to attacks that could help us reach the security goals we have set for the smart grid. We have presented recent hardware-level security technology implementations and listed their advantages and disadvantages. These techniques strive to offer secure solutions to authenticity, confidentiality, and integrity issues, without affecting the intelligent network functionality. We have also referred to an early prevention technique for detecting malicious attacks.

Although the presented techniques establish a high security infrastructure, they are useless in case consumers do not trust external entities, such as the energy supplier. The heterogeneity on the intelligent network environment leaves no room for unprecedented security solutions and makes smart grid security a challenging, but promising research field for the future. Overall, the architectures presented in this chapter are promising steps to protect the devices and establish secure communication and privacy in the smart grid.

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Chapter 6

Edge Computing and Efficient Resource Management for Integration of Video Devices in Smart Grid Deployments



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Abstract Internet-of-Things (IoT) as an emerging computing paradigm, refers to interconnected devices with sensing, processing and communication capabilities that promise to offer new intelligent services in many aspects of urban life, such as smart homes, smart cities, smart transportation systems and smart energy. One of the key components of smart energy systems, smart grids, utilize IoT technology in order to exchange data between different devices in the network. In this chapter, we propose an Edge-Computing based methodology that targets to balance the content generation of cameras in an IoT environment deployed for surveillance of a smart grid infrastructure. The purpose of the methodology is to allow smart grid to incorporate devices that generate visual content in the existing infrastructure by meeting the applications' requirements, efficiently utilizing the available resources and achieve the highest Quality-of-Service.

6.1 Introduction

Modern embedded systems tend to incorporate increased computational capabilities and wireless connectivity that have realized ultra-low power and low cost Systems-on-Chip (SoC). Those often battery-operated portable embedded devices are referred as “things” and they participate to a new era of computing, which is named as *Internet of Things (IoT)* [1, 8]. Smart objects that comprise IoT are connected through Internet and they are able to send sensed data from sensors to actuators in order to offer advanced services in different domains of urban life, such as smart buildings, smart cities, health care or automotive systems [15, 24].

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One of the key components of smart energy systems, *smart grids*, is a new concept in power networks that is adopted in order to enable (i) efficient energy utilization in urban environments and (ii) reduce energy consumption in modern cities. IoT infrastructure prevails as a promising technology for further enhancing smart grid infrastructures and deployments [20]. Specifically, smart devices, that already communicate through various protocols, can take advantage of IoT features and assist power grid construction, monitoring and intelligent control [12].

However, cities tend to expand with an enormous pace and urbanization of living is predicted to reach its peak the next few decades. Researchers forecast that by the year 2050, 70% of world's population will be living in cities [14]. As a result, cities must adopt new techniques and become "smarter" by integrating smart grid as a vital part of their services. Consequently, monitor and control of the physical infrastructure of smart grids rises as a major challenge in order to ensure uninterrupted operation of smart city infrastructure.

Existing approaches envision realization of future smart grid utilizing Cloud computing as an inner component of IoT deployments, rising numerous challenges. Next generation power grids are expected to create large amount of data that will need to be transmitted across wireless connection infrastructure. For that reason, devices that frequently exchange data will have to compete over the limited network resources and network congestion seems unavoidable [21]. Specifically, future smart grid will need to dynamically meet customers' requests based on the resource availability. In this way, Cloud computing will need to adjust on dynamically increased bandwidth during peak hours, in order to avoid data congestion [11]. Moreover, real-time monitoring of smart grid systems and always-on applications will push IoT's bandwidth capabilities to its limits, given that IoT has to support multiple devices (home appliances, smart meters, sensor nodes, cameras) that generate a vast amount of data at the same time [2]. In particular, *visual sensors* (e.g cameras) capture rich and resourceful content and they play a key role in multimedia and surveillance applications for smart cities and civil infrastructure [13]. Video surveillance traffic increased by 72% from 2015 to 2016 and reached 883 PB storage per month. Forecasts expect that by 2021 this number will be expanded by a factor of $\times 7$ [6]. As a result, multimedia and surveillance applications for smart grids will experience performance degradation and users Quality-of-Experience (QoE) will be deteriorated.

These challenges depict the necessity of a new architectural paradigm, that could accommodate processing, storage and bandwidth constraints. Smart grid and IoT are moving towards a "post-cloud" era, where a plethora of smart objects generate a huge amount of data that cannot be processed and stored efficiently with the traditional centralized Cloud infrastructure. Based on Cisco Global Cloud Index, due to Internet of Things growth, the total amount of data created (not stored) by any kind of device will reach up to 847 ZB (Zettabytes) by 2021, a $4\times$ increase compared to 2016. As a result, Edge Computing rises as a new alternative that envisions transferring computing power from the Cloud closer to the source of the data, initiating processing and storing at the edge of the network [17]. Edge Computing promises to support real-time processing, significantly reducing latency compared to conventional IoT standards. Specifically, Edge Computing focuses on performing local storage of a

significant amount of data, instead of offloading it to a remote Cloud server. Thus, applications are executed in the edge of the network close to where data is created instead of pushing computational tasks through the backbone network [5].

Bringing computation to the edge of the network creates new challenges for researchers to develop new smart-grid frameworks that monitor the available resources in an heterogeneous environment in terms of resource capacities and types. General purpose CPUs with different characteristics co-exist with GPUs and FPGAs, thus making it a complex task to decide how to distribute resources, while respecting application constraints (latency and throughput) and system's requirements in terms of power consumption and bandwidth. Traditional approaches perform distributed resource management while respecting system's requirements, but they consider application migration only at the same level of devices [7]. Authors in [16] achieve to increase Quality-of-Service (QoS) by 50% by adjusting the offloading levels of the IoT devices to the gateway, while respecting the system's battery, bandwidth and processing constraints. However, their focus is on optimizing application execution in order to respect battery constraints, because they consider Electrocardiography (ECG) arrhythmia detection, as a use case.

Authors in [10] define a set of mobile nodes (e.g *Mobile Fogs*) that can offer resources (computing, communications, caching) closer to the edge of the network. Their purpose is to balance content demand from geographically concentrated users. They are able to increase “virtual cache” closer the edge of the network and their experiments show that in urban scenarios “virtual cache” hits increase with a ratio of 60–85%, compared to state-of-the-art approaches. In [4] authors propose a dynamic video processing scheme that meets real-time video processing, while bringing computation to the edge of the network. Researchers in [22] address the necessity a new framework which will target visual processing closer to the edge of the network. Their goal is to process efficiently video streams utilizing heterogeneous types of *things*, such as edge devices, gateways and servers as computing platforms. Authors in [23] present a new solution that addresses the problem of application offloading for Edge Computing networks. They propose a novel strategy that achieves to maximize the Quality of Experience (QoE) of the user, under power constraint.

In this chapter, we present an Edge-Computing based methodology to integrate and balance the content generation of cameras in an IoT environment deployed for surveillance of a smart grid infrastructure. The goal is to let the smart grid integrate visual devices in the same infrastructure by meeting the applications' requirements, efficiently utilizing the available bandwidth and achieve the highest Quality-of-Service.

6.2 Face Recognition Application

In order to explore the benefits of Edge Computing for smart-grids and the integration with multiple services, we examine a video surveillance application that performs face recognition as a use case. It is considered a topology that contains cameras,

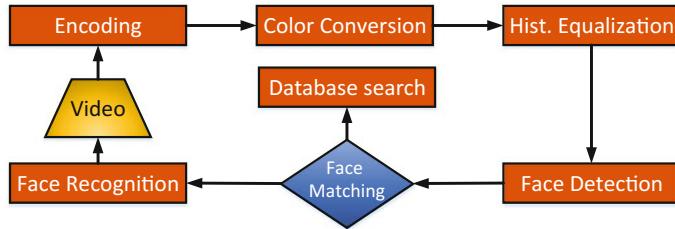


Fig. 6.1 Overview of face recognition application

end devices with processing and storing capabilities, gateways and Cloud Service. That way, we can capture raw video from the cameras deployed in the smart-grid infrastructure, encode it, store it and start video processing in different levels of the topology. Specifically, the face recognition use-case can be partitioned into sub stages that can be executed independently and they can be offloaded to different processing levels in an IoT environment. A general overview of the face recognition application stages is shown in Fig. 6.1.

6.2.1 *Encoding*

For each incoming image of the streaming video, stage 1 performs an encoding process of a raw input image to a JPEG encoded image. In other words, it converts an analog signal to a digital one. Each encoding operation is applied to one instance of the video, which is essentially a static image, named as frame. A frame is a matrix that represents an analog image and each numerical value of the matrix (referred as pixel) reflects the brightness level of the image, which is the digital output of the encoding procedure. In this work, we utilize JPEG digital image compression that can achieve 10:1 compression compared to the raw input. Consequently, it is introduced an image quality loss in favor of reducing image storage size and as a result lower video storage requirements, which translates in more efficient storing and transmitting input video. Encoding process is performed within the camera and besides the settings that the user can adjust (usually temperature and exposure), encoding phase intervenes in image's contrast, brightness, noise reduction and sharpening. When the encoded image - and the video accordingly - are stored, the raw input information is lost and cannot be recovered. The actual encoding procedure depends on the camera model, but when it's finished output images or videos are ready to be displayed and viewed.

6.2.2 *Color Space Conversion*

At stage 2 the encoded streaming video is converted from RGB color space to gray scale, based on the following equation:



Fig. 6.2 Original color image



Fig. 6.3 Gray scale image

$$\text{RGB-to-Gray : } \text{GrayImage} = 0.299 \times R + 0.587 \times G + 0.114 \times B, \quad (6.1)$$

where R , G and B are the 8-bit Red, Green and Blue values of the color image. Because the original image is 24-bit and the output image is 8-bit, it is evident that there is significant loss of information. In Fig. 6.2 it is shown the original color image of RGB color space before the conversion. After the color space transformation, the gray scale image is produced and it is shown in Fig. 6.3.

6.2.3 Histogram Equalization

Stage 3 of the presented application is to perform Histogram Equalization of an image. Histogram Equalization is considered an image processing procedure that aims at increasing the contrast of a frame or video. The histogram of a gray-scale image for brightness level i reflects the number of pixels that have the same brightness

levels. In other words:

$$Hist[i] = \sum_{x,y} \begin{cases} 1, & I[x, y] = i \\ 0, & \text{otherwise} \end{cases} \quad (6.2)$$

The procedure to compute Histogram Equalization is presented in Algorithm 1. In order to calculate histogram of an image, given an N bit image, we need to initialize 2^N histogram values to 0 (lines 2–4). In order to be generic, it is necessary to calculate each pixel's brightness value using module-256 operator (line 7). Then, scanning every pixel (x, y) of the 2D gray-scale array of the image we increment the histogram value that is equal to $I[x, y]$ by 1 (line 8). In the end, histogram values consist of the number of occurrence of a particular pixel value. In other words, Histogram Equalization calculates the frequency distribution of the discrete brightness levels of the digital encoded image. This procedure can improve the contrast of the image, since it re-distributes the brightness values in a more uniform way. Figure 6.4a, b show the histogram before and after the Equalization process. The x -axis depicts the gray scale levels for 8-bit encoding and the y -axis the Intensity value (i.e. brightness) of each pixel of the image. In this case, the input image is a $357 \times 691 \times 3$ (colored version) and the equivalent gray scale is 357×691 . As illustrated in Fig. 6.4a, brightness levels of pixels are concentrated around middle values of the possible brightness levels. On the other hand, Fig. 6.4b shows that after Histogram Equalization has been applied, brightness values are “stretched” to cover a wider range of brightness, making their distribution more uniform. Histogram Equalization process affects the actual image also. Figure 6.5a shows the gray-scale image that is used as the input to the Histogram Equalization Process. It can be observed that this image is dark in regions of interest, such as person's faces. After Equalization, in Fig. 6.5b it can be seen that the image is now brighter, mainly because intensity values are stretched. So, overall brightness of dark pixels has been significantly increased.

Algorithm 1 Histogram Procedure

```

1: Input: Image  $I[x][y]$ 
2: for  $i \leftarrow 0$  to  $255$  do
3:    $H[i] = 0;$ 
4: end for
5: for  $i \leftarrow 0$  to  $\text{width}-1$  do
6:   for  $j \leftarrow 0$  to  $\text{height}-1$  do
7:      $\text{brightness\_value} = I[x][y] \% 256$  //normalize intensity values for 0–255 range
8:      $Hist[I[i][j]]++;$ 
9:   end for
10: end for

```

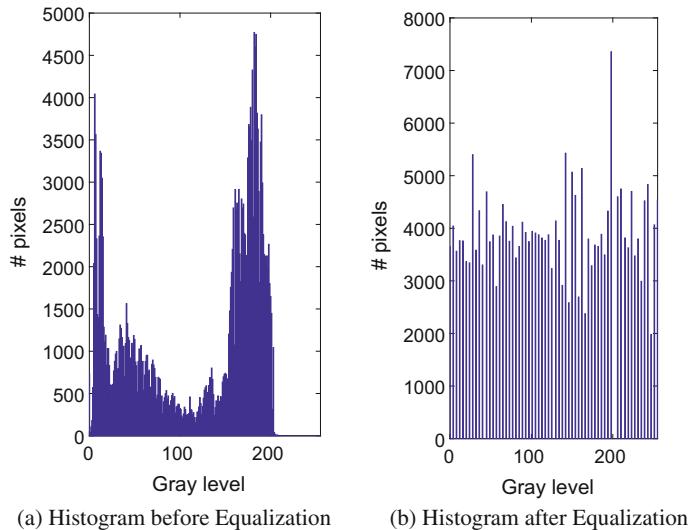


Fig. 6.4 Histogram before and after equalization process



Fig. 6.5 Image before and after equalization process

6.2.4 Face Detection

For the Face Detection stage, one of the most popular approaches in Computer Vision applications is the one presented in [19]. The main characteristics of [19] are (i) considerably fast computation compared to existing solutions and (ii) very high accuracy in face detection, which is translated in very high rate of true-positive predictions (correctly detected faces) and very low false-positive rate (faces that are not detected). Viola-Jones approach consists of three basic steps:

- First, the algorithm computes rectangle features of the image using the “integral image”, which is an intermediate stage that represents a new temporary image that is calculated using summation of the pixel intensity values in four array directions. This procedure leads to a large number of rectangle filters that need to be pruned in order to be computationally feasible.

- For that reason, they build a “cascade” classifier, which includes sub-classifiers that are often referred in literature as “weak” classifiers. The term weak derives from their property that they can’t distinguish alone if an image contains a face or not. Essentially, for each weak sub-classifier it is utilized one of the thousand available features.
- For each one of the sub-classifiers, they calculate its accuracy and finally keep only those features that give accuracy over a predefined threshold (typically over 90%). Then, they apply one by one the classifiers they kept. All these sub-classifiers form a larger classifier or a “cascade classifier”. Consequently, an image is scanned in windows and if a sub-window is classified as not containing any face, it is not forwarded to the next classification stages and it is discarded.

6.3 Proposed Methodology

The proposed work considers an IoT topology with four layers:

Layer 1: This layer contains the cameras that capture the video in 360p, 480p, 720p or 1080p resolution based on their configuration.

Layer 2: This layer contains the computing devices D_i directly connected to the cameras.

Layer 3: This layer contains the gateway G on which the D_i devices are connected and share.

Layer 4: The cloud server to which the gateway G is connected.

Each device D_i and the gateway G are characterized by the following attributes:

$$\begin{aligned} D_i &\longrightarrow \{m_{D_i}, s_{D_i}, r_{D_i}, p_{D_i}, b_{D_i}, t_{D_i}\} \\ G &\longrightarrow \{m_G, s_G, r_G, p_G, b_G, t_G\}, \end{aligned}$$

where m_i denotes the available Million Instructions Per Second (MIPS), s_i is the occupied storage for the device, r_i is the available memory of the device, p_i is the power consumption of the device, b_i the available bandwidth of the device and t_i is the transmission rate of the device.

As a use case, this work considers a face recognition application using streaming video from mobile devices as an input as it was described in Sect. 6.2. Based on the extracted features the algorithm decides whether or not it detects faces on the current frame. All the detected faces are considered candidates for person recognizer. This is the last part of the application that is performed on the Cloud. Every candidate face is matched with the faces in Cloud’s database. If the match is successful, the face is returned as recognized.

Computing devices D_i and gateway G are considered to be able to perform all of the aforementioned stages, except the last one that is the database search and it is performed on the Cloud. They can also execute the same procedure with different image resolution and frames per second (fps). At the gateway level, different number

of devices affect the bandwidth directly. As expected, greater number of devices streaming video simultaneously increases transmission rate (Mbps) and results in lower throughput of the face detection algorithm [18]. Without loss of generality, we assume that our use case has in total L stages and each stage K_i is characterized by the following attributes:

$$K_i \longrightarrow \{m_{k_i}, s_{k_i}, b_{k_i}\}, i = \{1, 2, ..L\}$$

where m_{k_i} denotes the required MIPS, s_{k_i} is the required storage and b_{k_i} the bandwidth utilization of a stage.

6.3.1 Problem Description

We define as *Level of Service* the accuracy a_G of face recognition that is achieved by the employed topology on the gateway G . As aforementioned, the resolution of the video affects the accuracy and thus, a high definition video can achieve higher identification rate. However, the processing and storage needs of a video become greater, as well as the bandwidth utilization to the gateway, as the resolution increases.

In this work, the goal is to select resolution for all the employed cameras in order to achieve maximum accuracy of the employed face recognition in the gateway and satisfy the storage, computational and bandwidth constraints both of the devices D_i and the gateway G .

$$\text{Bandwidth constraint: } \sum_{\forall D_i} t_i \leq b_G \quad (6.3)$$

$$\text{Computational constraint: } \sum m_{k_i} \leq m_G \quad (6.4)$$

$$\text{Storage constraint: } \sum_{i=1}^N \hat{s}_j \leq s_{D_i}, i = 1, 2, .., N \quad (6.5)$$

$$\text{Optimization goal: } \max\{a_G\} \quad (6.6)$$

where \hat{s}_k denotes the storage that is required in order to process stage $l = 1, 2, 3, 4$ of the face detection algorithm.

Each device D_i forms a set of available configurations, given the number of the possible *Levels of Service*. For each level, every device is characterized by the storage and transmission rate of performing the $l = 1, 2, 3, 4$ number of stages locally (Eq. 6.7)

$$d_i^w \longleftarrow \underbrace{\{(\hat{s}_1^w, t_1^w), \dots, (\hat{s}_z^w, t_z^w)\}}_{\text{Stage 1}} \quad (6.7)$$

where \hat{s}_l^w is the available storage of the i^{th} device, whereas (\hat{s}_z^w, t_z^w) , $z = 1, 2, \dots, l$ indicates the last stage that can be computed locally on the device while satisfying Equation 6.5. Moreover, each device operates at w Level of Service, where $w = 1, 2, \dots, W$ and W is the maximum number of Level of Service (LoS). In this work, we assume four LoS for the video resolution: (i) $w_1 = 360p$; (ii) $w_2 = 480p$; (iii) $w_3 = 720p$; and (iv) $w_4 = 1080p$.

For each d_i^w , the gateway selects the element of Eq. 6.7 that has the minimum transmission rate in order to serve as many devices as possible.

Then, for all the selected configurations, the gateway matches the accuracy level with the bandwidth and computational constraints (Eqs. 6.3–6.4) and it creates the set of final configurations for each device (Eq. 6.8).

$$List_{d_i} = [\underbrace{(a_G^1, b_z^1, m_z^1)}_{LoS1}, \underbrace{(a_G^2, b_z^2, m_z^2)}_{LoS2}, \\ \underbrace{(a_G^3, b_z^3, m_z^3)}_{LoS3}, \underbrace{(a_G^4, b_z^4, m_z^4)}_{LoS4}] \quad (6.8)$$

Essentially, $List_{d_i}$ contains the rightmost element of d_i^1 , d_i^2 , d_i^3 , d_i^4 which is considered to offer the optimal resource utilization for the gateway.

6.3.2 Problem Formulation

The objective of our methodology is to optimize the execution of the face recognition application in order to achieve higher accuracy, given the resource constraints. In other words, the problem is to decide how to distribute the execution of the application stages among the available devices and gateway, so as to get the highest accuracy while keeping the device and gateway constraints. For that reason, the problem is formulated as a *Multi-Choice Multi-Constraint Knapsack Problem* (MMKP) and a heuristic approach is presented for solving the MMKP.

The presented approach is build on top of [3] and is summarized in Algorithm 2. From all of the possible configurations of device d_i we define the *Aggregate Resource Configuration* (ARC) = $\frac{b \times B + p \times P}{\sqrt{B^2 + P^2}}$, where b, p are the bandwidth and processing requirement for each stage of the application and B, P are the total bandwidth and processing budget of the gateway accordingly.

In [3] the metric *Value per unit of ARC* (V-ARC) = $\frac{\text{accuracy}}{\text{ARC}}$ is defined, where *accuracy* is the corresponding accuracy of the members of $List_{d_i}$. Then, each device i forms a list named $List_vARC_i$ that contains all the vARC values. This list is sorted in an ascending order (lines 5–9). Then, gateway forms its own list, named $List_ARC_G$ that contains the highest V-ARC values of each device - the rightmost element of $List_vARC_i$ (line 13). Based on the gateway's constraints, the total configuration of the devices has to satisfy Equations 6.3, 6.4. If the initial configuration does not satisfy the constraints, then $List_ARC_G$ is updated. Every element of $List_ARC_G$ is

replaced with the rightmost element of $List_ARC_i$ and then it is calculated again if the constraints are met. The last procedure is repeated until a feasible configuration is found (lines 15–20).

Then, the proposed approach follows a refinement step. After the first feasible solution is acquired, the algorithm iterates over the members of the selected feasible configuration. Starting from the first member, it selects the next vARC value to the right, because this value would produce higher accuracy. If this is a feasible configuration, then it is added to the list and the next item is selected. This procedure is repeated until there is no other feasible solution (lines 22–25). As a result, the optimal solution is produced by the algorithm and gives the higher accuracy.

Algorithm 2 Heuristic Algorithm

```

1: Input:  $List = \{List_{d_1}, List_{d_2}, \dots, List_{d_N}\}$ 
2:  $List\_vARC_i \leftarrow []$ 
3: for  $i \leftarrow 1$  to  $|List|$  do
4:   for  $j \leftarrow 1$  to  $|List_{d_i}|$  do
5:     Calculate ARC for each member of  $List_{d_i}$ ;
6:     Calculate V-ARC for each member of  $List_{d_i}$ ;
7:      $List\_vARC_i.append(vARC_{ij});$ 
8:   end for
9:   Sort  $List\_vARC_i$  in ascending order;
10: end for
11:  $List\_ARC_G \leftarrow []$ 
12: for  $i \leftarrow 1$  to  $|List\_ARC_G|$  do
13:   Append rightmost element from  $List\_vARC_i$  to  $List\_ARC_G$ ;
14: end for
15: Check feasibility;
16: // $j$  is the element from  $List\_vARC_i$  that was originally selected
17: while !feasible do
18:    $j \leftarrow j - 1;$ 
19:   Replace element  $i$  of  $List\_ARC_G$  with item  $j$  from  $List\_vARC_i$ ;
20: end while
21: //Improve feasible solution in order to get the optimal
22: while feasible do
23:    $j \leftarrow j + 1;$ 
24:   Replace element  $i$  of  $List\_ARC_G$  with item  $j$  from  $List\_vARC_i$ ;
25: end while

```

6.4 Experimental Results

In order to validate our approach and test its efficiency, a series of simulations and experiments were conducted. The proposed methodology was build on top of *iFogSim* simulator [9] that models IoT and Fog topologies and measures the impact of different resource management techniques in terms of power consumption and network traffic.

Table 6.1 Experimental profiling results for Jetson TX1, Intel i5, Intel i7

Resolution	Frames Per Second (fps)		
	Nvidia Jetson TX1	Intel i5	Intel i7
360p	12.8	50.5	54
480p	7	29.4	31.5
720p	3	13.7	15
1080p	1.4	5.8	6.77

For Layer 1 of our topology we considered cameras that capture the video in 360p, 480p, 720p or 1080p resolution. For Layer 2, we integrated into the simulator the following computing devices D_i :

- An Intel i5-4590 processor with 4 cores at 3.30 GHz with 8 GB of RAM.
- A Nvidia Jetson TX1 platform that incorporates an 4 core ARM Cortex A57 with 4 GB of RAM and a GPU with 256-cores.

For the gateway, we consider an Intel i7 processor with 4 physical cores and 8 threads at 3.60 GHz with 8 GB RAM, running. We profiled the face recognition application on these devices and below we present the execution results. For all these platforms we measured frames per second (fps) for video resolutions of 360p, 480p, 720p and 1080p respectively, as it is shown in Table 6.1.

The trend that is observed points that the performance of the application is significantly deteriorated when the resolution increases. As expected, the Jetson SoC has distinctively lower performance than the i5 and i7 respectively because of the differences in architecture (pipeline, instruction set, number of cores and clock speed).

Another reason is depicted in Figs. 6.6, 6.7, 6.8, 6.9 which show the detected faces of the same video for different resolutions. As it can be seen, for low resolution the number of detected faces is small, while for higher resolution the number increases. So, the required computations increase, not only because of the larger dimensions of the input frame, but also because the content is richer and includes more information to process.

The proposed approach is compared against the *Cloud-only* [9] placement policy. The *Cloud-only* approach is the traditional IoT strategy which dictates that every service is mapped on the Cloud. Figures 6.10, 6.11 depict the transmitted data to the Cloud of the two compared policies, considering two types of end devices that contain Intel i5 and Nvidia Jetson TX1 processors. The baseline in all of our experiments is the *Cloud-only* approach. As expected, the *Cloud-only* policy offloads significantly more data compared to the proposed solution. On the contrary, the proposed approach scales efficiently, as the number of devices increases, since it achieves to keep more computation closer to the edge of the network. In order to accomplish that, it selects a lower resolution of the incoming streaming videos, which enables it to retain the gateway's bandwidth and computation needs lower than its constraints. As an average, it manages to decrease the transmitted data by 86 and 93% compared to

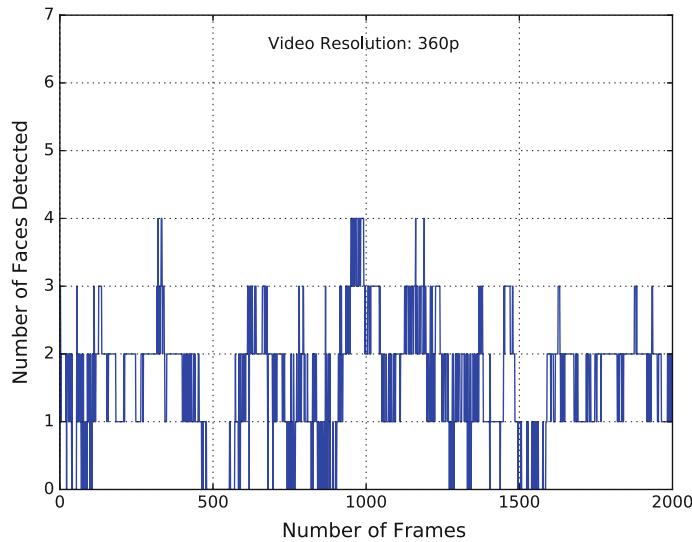


Fig. 6.6 Faces detected for 360p video resolution

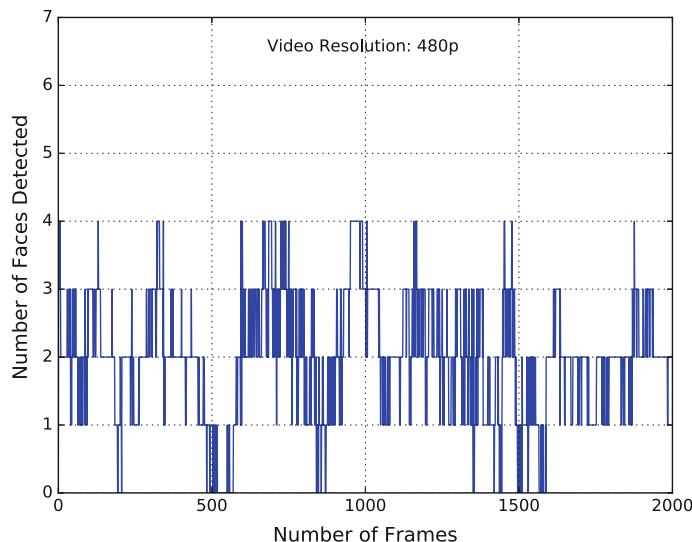


Fig. 6.7 Faces detected for 480p video resolution

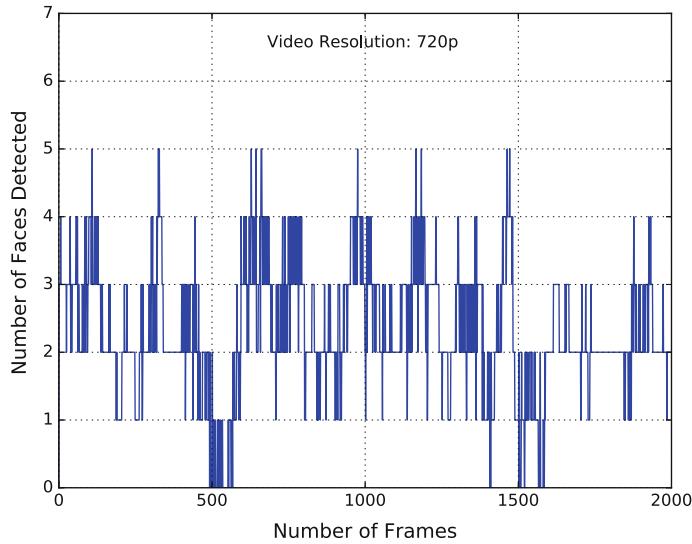


Fig. 6.8 Faces detected for 720p video resolution

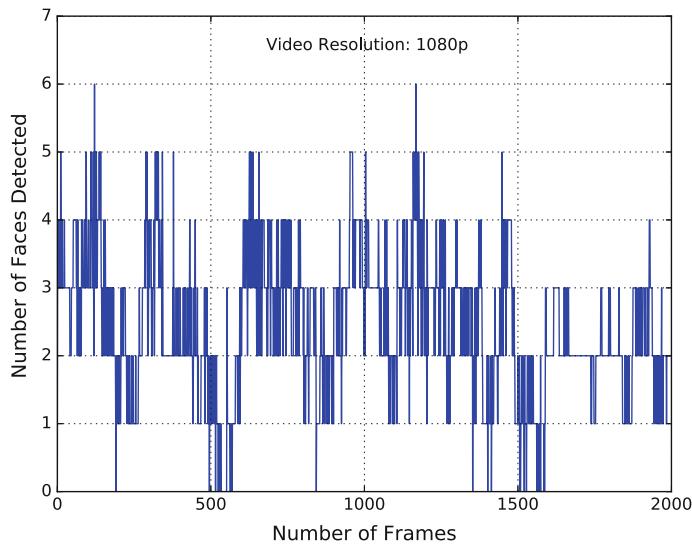
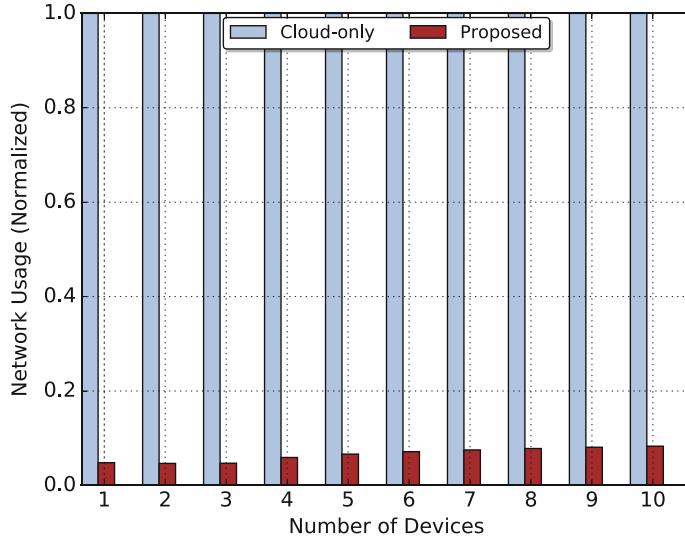
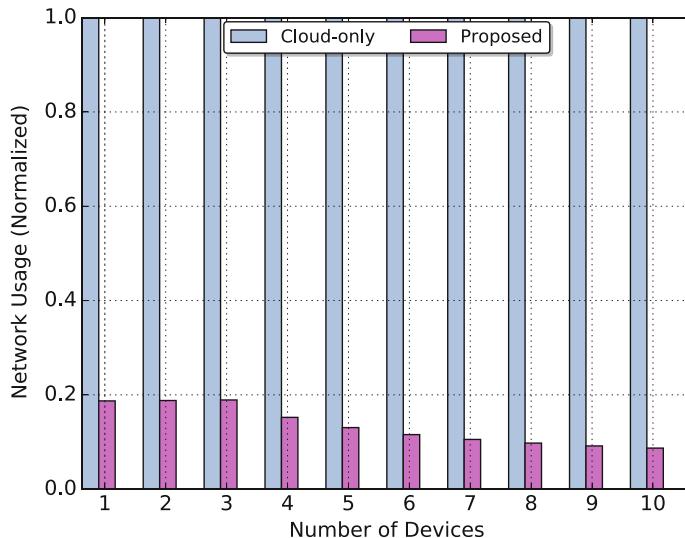


Fig. 6.9 Faces detected for 1080p video resolution

**Fig. 6.10** Network usage utilizing Intel i5**Fig. 6.11** Network usage utilizing Nvidia Jetson TX1

the *Cloud-only* policy, utilizing Nvidia Jetson TX1 and Intel i5 SoC as end devices, respectively.

Figure 6.12 presents the *Level of Service* on the gateway for the proposed approach in the same topology. As the number of devices that share the gateway and the network resources increases, the computational and bandwidth constraints cannot be satisfied.

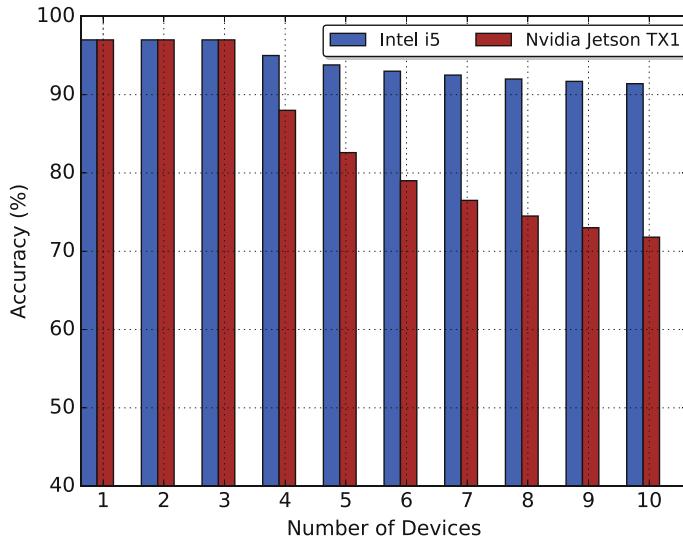


Fig. 6.12 Level of service for the proposed methodology for Intel i5 and Nvidia Jetson TX1

Not all cameras are able to record and stream video in high quality (1080p). Thus, the proposed methodology finds which devices should lower their resolution in order to meet the required constraints. The accuracy drops by a factor of 9 and 29% at 10 devices for Intel i5 and Nvidia Jetson TX1 accordingly, while the gains in network utilization (Figs. 6.10, 6.11) result in efficient resource management for the proposed topology.

6.5 Conclusion

In this chapter, we propose an Edge-Computing based methodology that manages to balance the content generation of cameras in an IoT environment deployed for surveillance of a smart grid infrastructure. As QoS metric we define the *Level of Service* that the system offers to the user in terms of accuracy of the face recognition application. Experiments that were performed show that the proposed solution is able to reduce the network traffic on the Cloud, while keeping the resource constraints. In order to achieve those results, the presented approach solves the optimization problem with selecting lower input video resolutions, based on the devices and gateway's constraints. In particular, the proposed approach is capable of decreasing the network traffic by an average of 93 and 86% compared to the *Cloud-only*, utilizing Intel i5 and Nvidia Jetson TX1 SoCs for the end devices, accordingly. However, accuracy of the application is decreased drops by maximum value of 9 and 29% at 10 devices for Intel i5 and Nvidia Jetson TX1 respectively, while the gains in network utilization result in efficient resource management for the proposed topology.

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Chapter 7

Solar Energy Forecasting in the Era of IoT Enabled Smart Grids



Dimitrios Anagnostos

Abstract This chapter provides an overview about forecast models on temporal and spatial scales to enable smart methodologies for design and control. In order to succeed in this scope, a number of IoT components, such as distributed sensors, actuators, as well as decision-making devices are necessary. Additionally, by integrating smart grid and energy forecast with big data analytics and deep learning services, it enables to produce accurate and detailed local forecasts, in order to control the grid dynamically.

7.1 Introduction

The transformation of the electricity grid has always been driven by novel technologies and consumer's needs. From the adoption of AC power and the need for uninterrupted power supply to the imminent electrification of transports, engineers and scientists have always struggled to provide reliable and affordable solutions. Nonetheless, the upcoming challenges of migrating to no more a passive or reactive electricity grid, rather than an active or "smart" grid have motivated countless research groups and companies. Developing control schemes and strategies for such a network is still a topic under examination, but all techniques require a fair amount of forecasted information, whether it is the production of (renewable) energy for a future window, the possible power consumption in an area or most often both.

Especially in the context of smart cities, or smart grids in urban environments, each building has to behave both as a consumer and producer of energy (prosumer), in order to fully take advantage of all available area and natural resources. Zero-energy buildings are already created in the dense metropoles of Europe [19] and are expected to accommodate not only the basic needs of their inhabitants and users, but also in a way contribute to their transportation by charging their future electric cars.

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Nonetheless, controlling such a complex system efficiently with no information on future conditions is an impossible task. Decisions for the storing of excess energy in local batteries or heat pumps, or even grid-level storage, must be optimized with regards to a plethora of variables[23]. Especially in the context of dynamic pricing of electricity, which is going to be implemented in future distributed grids[7], optimization of both the local system and the grid will become an adversarial task.

The role of IoT in this challenge is crucial both as a provider of data and endpoint of decision making. A dense network of sensors for environmental variables and electricity flow can improve forecasts for demand response and enable techniques based on big data [25]. Additionally, the IoT nodes will be part of the control mechanisms for a plethora of applications, from smart EV charging to building energy management and distributed demand/response of energy.

This chapter gives an overview of the importance of forecasting in deployment of smart grids and how IoT can enable these methods. Solar energy is the most cost effective solution for small installations and urban environments [21], but generates additional hurdles on the way to grid integration. Therefore it is expected to play the biggest role in the transformation of the grid. On this account, the most promising methods of forecasting for solar energy in various temporal and spatial scales are presented, along with typical examples of usage and future prospects.

7.2 The Future Role of Forecasting

As it will be made clear in this chapter, accurate and detailed forecasting of energy production and consumption will become increasingly important in the years to come and IoT will influence both the applied methods and the expected gains. In particular, focus will be given on solar energy forecasting, as it is the form of renewable energy with the highest learning curve and most competitive Levelized Cost of Electricity (LCOE) versus thermal plants, like coal and natural gas [10]. If the additional penalties of CO₂ production are taken into account, then solar energy can be in cases even cheaper than coal, with a favorable future trend.

The main areas of interest for applications of forecasting in the future IoT-enabled smart grid can be listed as:

- Dynamic demand/response
- Integration of novel devices on the grid
- Building energy management
- Energy consumption of IoT itself

These points are surely overlapping and connections will be attempted to each other. Additionally, these are not the only challenges but they do profit from forecasting in a more direct manner

7.2.1 Dynamic Demand/Response

Traditional operation of the passive grid requires profiling of the loads, especially on the low voltage side where most households and office buildings reside. This profiling process consists of collecting data on the consumption per time step, usually an hour, and creating a typical daily load curve per season(s). Based on these calculations, grid operators can plan ahead on the required available power and depending on the country/region use the available tools (energy auctions etc.) to acquire this energy days ahead to ensure stability of the network. With the introduction of the prosumer on the grid, this process becomes extremely more complex [18]. Households can now become producers of energy themselves, even taking part in the energy market trading. Moreover, the traditional methods for load profiling fail due to potential self-consumption of the produced energy by the household itself, resulting in a non-traditional load curve (Fig. 7.1). Therefore, a new necessity has been created, of balancing the production and consumption on the grid not only on the high voltage level, but also on the low voltage level.

But how can an operator attempt to compensate for the lack of or overabundance of energy, if they do not know in which state the system is going to be? As mentioned, solar energy is the most abundant and cheapest for small installations, therefore it has achieved increasing penetrations on the low voltage side, mainly due to households and small businesses [10]. Prosumers are then directly affected by the sun and if it is shining or not. As it will be explained in a later section, the forecast accuracy is strongly dependent on the required temporal and spatial resolution. Producing forecasts over a larger area, like part of a country for some hours ahead is a complex

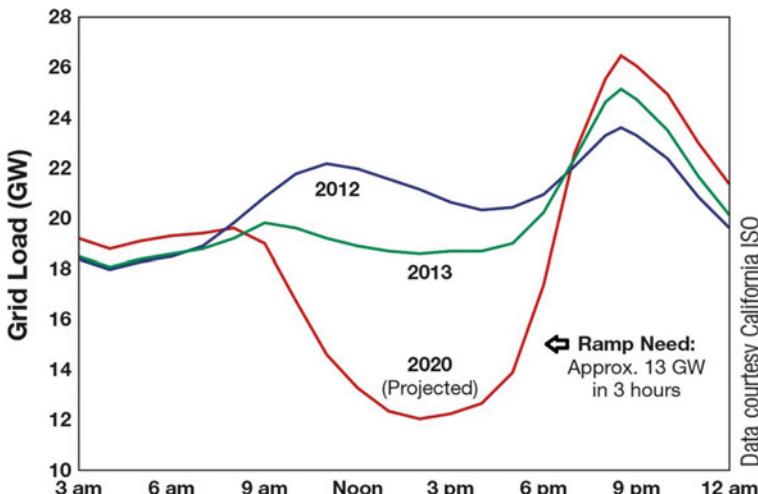


Fig. 7.1 Progression of load curve transformation due to renewable integration in California, USA

task, but still easier than predicting how a specific installation is going to behave in the next minutes [17]. Not surprisingly, both extremes will be needed in the era of IoT powered smart grids. Days/hours ahead planning is important for operators in order to schedule large power plants that may have to cover the difference in expected and produced energy, or supplement the renewable energy capacity. As the scales shrink in both space and time, sub-grids have to optimize the usage of locally produced energy, for example by charging local batteries and electric vehicles. Still this management of resources has to be reflected on higher levels of grid integration by pathways of communication.

IoT in this case are used as both data collection points and management devices [16]. Smart meters will play an important role in dynamic demand/response, as real-time information of energy usage and potential production enables prioritization of activities through dynamic pricing [7]. For example, during hot summer days, smart houses with installed photovoltaic (PV), if forecasts are favorable for production, can be offered high prices for buying energy from the grid, incentivizing consumption of the locally produced energy, instead of storing it for future usage. But IoT nodes will be also used for the forecasts themselves. Data like solar irradiation, ambient temperature, wind speed and direction are always useful no matter the methodology. These variables are also important for other smart grid applications, like smart building and therefore are expected to be available at a relatively high density in urban environments. Additionally, methods that take advantage of measurements on a spatial grid have been developed in the past years [6, 27]. By detecting correlations between the variables on different locations, these methods can extrapolate to produce forecasts for different locations on the proximity. A peer-to-peer communication of the measured data and derived (pre-processed) information is essential for these methods, so the cloud-based operation of IoT fits perfectly for these purposes. Last but not least, specialized IoT nodes can be utilized for the production of highly accurate forecasts specifically for demand/response, as presented in [1]. Sky-imagers can be even assembled by cheap fish-eye lens cameras and as explained later in the chapter, offer advanced capabilities for the deployment of forecasting techniques. As a result, inclusion of such devices in the IoT infrastructure could benefit forecasting activities.

7.2.2 *Integration of Novel Devices*

The concept of smart grids is based on accurate control in multiple levels of energy consumption and production, but also on the assumption that each node or cluster of nodes has a (limited) capability to balance itself and maybe its neighbors in case of an unexpected shortage of energy. For example, an area which is heavily dependent on wind energy will need extra energy from an alternative source in case of an abrupt shortage of wind. These energy shortages are expected to be filled by energy storage devices, which can be distributed on all levels of voltage. Electric batteries, thermal storage and even advanced schemes like conversion of excessive electrical

renewable energy to H₂ or NH₃ for later use are being explored [11]. Optimal design and management of these technologies is crucial for the stability of local and global grids and accurate forecasting can aid at both.

At design time it is essential to maximize several aspects like efficiency, capacity etc. but surely the total cost has to be kept minimal. Unfortunately, these storage solutions are currently more costly than the production of energy itself and therefore must be deployed in moderate amounts [15]. With non-accurate forecasting of renewable energy production, the storage capacity has to be over-engineered, in order to accommodate for the uncertainty in the control of the grid. An increase on the guaranteed accuracy of the production forecasts allows to further minimize the installed storage capacity and the total cost, while at the same time enabling the same level of control over the grid [23]. Furthermore, more accurate forecasts enable better control on the charging policy of these devices, as excess production of renewable energy can be recognized and quantified ahead in time.

Additionally, the grid is soon going to face the challenge of the transformation of transportation from natural fuels to electricity [9]. Electric vehicles of any type will strain the grids when deployed en masse, especially if the users expect to have full control over the charging procedure. Trends are sure to form, as previously with load curves of households, but this time each user will require up to some tens of kW for a fast charge. The current grid is not ready to handle such amounts of power, so several solutions have been proposed, like round-robin charging, pricing incentives etc. [22]. Again, as in the case of storage integration, forecasting of renewable energy production can mitigate some of the issues. Forecasting-aware charging can utilize excess energy to charge electric vehicles in the proximity, minimizing transportation of energy over long distances.

7.2.3 *Energy Management of Buildings*

As explained in detail on Chap. 10, the energy consumption of buildings accounts for a big percentage of the total energy consumed in a city, especially during winter and summer. Ambitious targets have been set by organizations and countries around the globe, for the transition to zero-energy buildings. This can be achieved mainly by proper selection of building materials, smart thermal control and integration of solar/thermal energy collectors and storage. Forecasting is essential for this application, as it allows for more optimized control schemes and increased gains, both in energy and cost savings.

Accurate solar forecasting for example can provide information for the incident irradiation on a building and its PV/T collectors. In the first case, if the building has been modeled in detail, the effect of the extra heat on the outer surfaces of the building can be taken into account for settings in cooling and heating of the internal spaces. In the second case, future energy production can be forecasted for both solar and thermal collectors (or even hybrid PVT devices) in order to allow balancing the

demand/response of the building and even specify what amounts of energy can be stored, as explained in the previous two subsections.

In this application, IoT will be the backbone of data collection and transmission on all levels, starting from the PV/T installations, where measurements are needed for the forecasting and state estimation. Storage status monitoring, thermal and electrical, is essential and will be managed by edge devices, as well as internal and external building measurements. All this information will be managed by the collection of IoT devices in a building, but their function also extends to communication with neighboring buildings in order to allow information exchange and, when needed, even energy exchange to balance the “smart neighborhood” [12, 20].

7.2.4 Energy Consumption of IoT

Last but not least, the energy consumption of IoT itself is a challenge. Projections for the next years forecast an exponential growth of IoT installed devices and revenue produced by them [24]. But tens of billions of IoT devices, along with the respected central processing power they require, could sum to a considerable energy consumption, even surpassing other sectors of the economy like aviation [2]. The challenge is actually twofold, as there will be two main components in the consumption of IoT, the edge devices and the cloud data centers.

The edge devices are designed to be low power and kept in sleep mode for the majority of the time, but usually do not have access to a stable power source and have to utilize a combination of energy harvesting and battery management. As mentioned already, solar power is the most abundant source and can be harvested by very compact solutions, mainly mini PV modules, therefore it is usually preferred for isolated nodes. By utilizing forecasting, the edge device can deploy advanced power management schemes, like energy-aware communication bit-rate scaling or energy storage control [13].

On the other side of infrastructure, huge data centers are already enabling cloud applications for all spectrum of users, as increasingly more business models are developed around distributed computing. These installations require considerable amounts of energy for cooling and computations, while the projections show that their energy consumption will become a bigger contributor to global energy demand [5]. Many of these centers attempt to balance increased energy consumption either with investment in renewable energy projects or with the so-called “green contracts”. The main issue is that these solutions do not offer real time compensation of CO₂ production based on renewable energy, rather than trying to cover it on the long run. However, there is significant research on real time utilization of available renewable energy on the locality of the data center [4, 8]. By performing (forecasted) energy-aware scheduling of tasks on the computing nodes of the center, one can use the produced green energy in a direct manner. This is possible especially for non-real time restricted computations.

7.3 Summary of Solar Forecasting Methods

Whereas the previous sections offered a summary of the benefits of accurate solar energy forecasting for smart grids, this section will focus on the methods themselves. With that said, a detailed description of solar energy forecasting methods is out of this book's scope, therefore a brief summary will be provided for each case and focus will be given on possible IoT synergies. The reader can look into [3, 17, 26] for a complete enumeration of methods for all possible applications.

It is essential thought to explain the relationship between the spatio-temporal resolution of a solar forecast and its expected accuracy. Independent of the method, the rule of thumb is that the larger the area under examination and the larger the time steps between forecasted values, the higher the accuracy of the produced forecast when compared to a reference forecast, usually persistence based. As a result, calculating accurate forecasts for a small installation with a minute time resolution for the next 15 min is far more challenging than producing daily values for the next couple of days over a state or country. This effect is due to averaging on both scales, as data is distributed over larger area/period and acquire statistical significance, therefore being represented more efficiently by statistical parameters.

A simplified categorization of forecasting methods can be attempted either based on their forecast horizons, or the employed techniques. In the first case there are:

- Nowcasting and short term forecasting
- Intra-day forecasting
- Day-ahead forecasting
- Long-term and seasonal forecasting

Day-ahead and seasonal forecasting have always been a valuable tool for grid operators, as they allow long term planning of power plants. Even the less accurate techniques of the past have enabled reliable operations, through energy transmission and production scheduling. This statement though will not hold true in the era of smart grids, when decision making will be required to be almost real-time and distributed in local grid nodes. Therefore, to really enable the transition from a passive-reactive grid to an active one, the other two groups have to provide relevant forecasts. These two groups of forecasting are also the ones that will mostly benefit from the power of IoT, as they are based on trustworthy, frequent and dense data collection. We can detect a symbiotic relationship between forecasting and smart grids, with one enabling the other with IoT as the connecting medium.

A second categorization can then be made on the applied methods:

- Imaging techniques
- Statistical methods
- Physics-based models and numerical weather prediction (NWP)
- Machine learning

Imaging techniques refer to the more popular satellite imaging analysis, where geo-stationary satellites provide pictures of a large area, usually the size of a country or

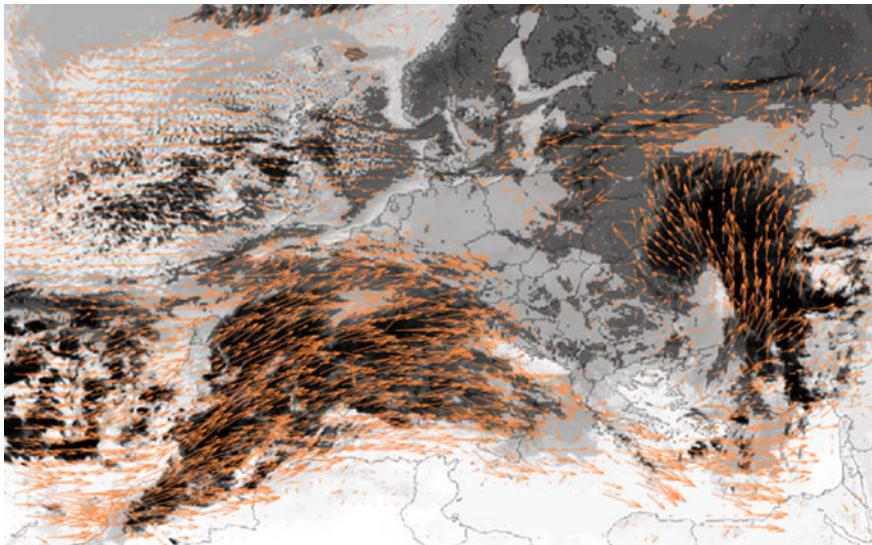


Fig. 7.2 Example of cloud movement detection for satellite images over Europe

a continent, usually every 15 min and possibly over a several bands of the visible and non-visible spectrum [17]. Several techniques can then be applied to detect and predict cloud movements, and combine them with ground data to produce the forecast (Fig. 7.2). The physical limitations of signal transmission from the satellite to earth does not enable these technique to run in real time, but still offer accurate forecasts for horizons above 1 h. These images are also important for the initialization of parameters for NWP models, which require solving complex differential equations with a multitude of initial conditions [17].

In order to compliment satellite imaging, ground based cameras are being explored for the creation of detailed short term forecasts. These cameras either point towards the sky, taking successive pictures and using image analysis techniques to create the forecast [1], or they point towards the ground from a vantage point in order to capture the ground shade of clouds [14]. Either way, these methods have shown to be very effective for short forecast horizons, up to 30 min, but have the drawback of spatial limitation. Therefore in an IoT enabled smart grid, cooperation of the devices could provide a larger effective area of operation.

Statistical methods and machine learning techniques have also been employed in multiple instances, either utilizing historical measurements of a location/installation [26], correlations between neighboring installations to detect spatio-temporal correlations [6, 27], or even a combination of the two with improving success. Again, as mentioned in previous sections, IoT will be the backbone of data collection and transmission for these data-hungry techniques. A small summary of the forecasting methods and their distinctive features is illustrated in Fig. 7.3.

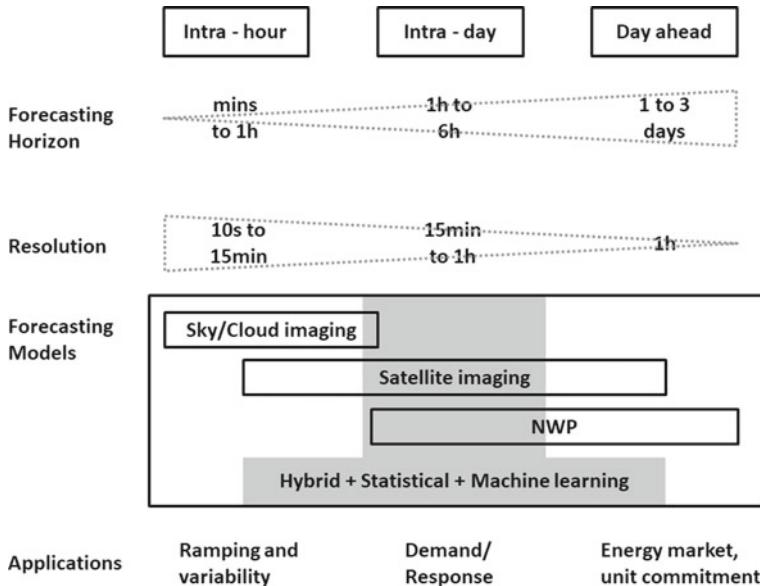


Fig. 7.3 Overview of forecasting methods

In general, smart grids contain an inherent notion of dynamic control and “fast” response. In this context, the forecasting techniques that are expected to play a major role in enabling the transition to the smart grid are those dealing with detailed, high resolution forecasts, enabling cooperative schemes, like peer-to-peer data and energy exchange and local grid balancing. These are all applications perfectly fitting the role of IoT as a backbone and therefore concurrent development of these sector and methods will be crucial for successful realization.

7.4 Example of a Detailed, Short-Term Forecasting Method

Through this chapter, a strong case has been made for solar energy and detailed forecasts regarding it. These claims are supported by evidence that in a future of IoT enabled smart grids, especially in urban environments, the cheapest and most abundant energy source is the sun, so eventually the grid will have to cope with the intermittent nature of its power. This section provides an example of how imaging techniques and neural networks can be combined to produce detailed, highly accurate forecasts that enable control in all the major applications mentioned in the previous sections. The complete description of this work can be found in [1].

7.4.1 Image Acquisition and Measurement Installation Description

The data set used for the studies has been acquired at the University of Oldenburg (53.15232 N, 8.166022 E) and spans from the 19th of July until 31st of August 2015. The logged information is diffuse horizontal irradiance (DHI, measured with a ventilated and shaded K&Z CM11), direct normal irradiance (DNI, measured with Eppley NIP) and photovoltaic output parameters (Current and Voltage in MPP, Backsheet Temperature). The investigated PV module is a 180 W peak BP Solar panel installed with a tilt angle of 51° and orientated south. All parameters are sampled with 1 Hz frequency and data quality has been ensured through visual inspection and statistical analysis.

Moreover, sky images are retrieved every 10 s from sunrise to sunset. The sky imager used in Oldenburg is a commercial VivOTEK FE8172 V network camera equipped with a fisheye lens. The typical application of this camera type is surveillance of wide, open areas. Compared to cameras developed specifically for sky and cloud observations, commercial network cameras are less expensive (<1000 euros) and therefore of interest for solar energy applications. The most important technical specifications of the camera are a full semi-spherical field of view, a circular fisheye frame in a 1920 × 1920 pixels image plane and a dynamic range of more than 57 dB. The camera configurations including color settings, white balance and exposure settings are applied browser-based. A Python-based interface has been developed to control most of the settings fully automatic.

The sun tracker equipped with a pyrheliometer for DNI and a shaded pyranometer for DHI measurements is placed three meters north-west of the camera. All sensors are maintained and cleaned typically once per week. The investigated PV module is located about 19 m from the camera and suntracker. In this study all sensors are assumed to be at one location.

7.4.2 Image Feature Extraction

Specific image features are computed for each image, then provided as inputs for the machine learning applications. The features are quantified characteristics like image textures, color values and other metrics. These features are selected to quantify special image characteristics discriminating for example a full cloud cover from mixed cloud conditions. In terms of irradiance modeling, features describing the pixel intensity in the circumsolar area are used as the implicit information about direct solar radiation. For example, in overcast conditions with thick clouds, the circumsolar area pixel intensity value will be much lower than in clear sky conditions. The features are computed on the masked image, so that non-sky parts of the image are masked out (stationary or moving obstacles) before image features are computed. In this study, the extracted image features are used for irradiance modelling (k -neighbors neural

network model), cloud classification (support vector classification model) and the energy yield prediction with neural networks.

7.4.3 Neural Network Modeling

The choice of a neural network topology was based on the requirements of the output as well as the capabilities of the available input. Energy yield calculations inherently include a form of accumulation or regression, since the acquired energy also depends on the short-term history of the system production. Additionally, the RGB forecasted values should be included in the training and testing of the model as they provide a future look into the status of the circumsolar sky. For these reasons a non-linear auto-regressive network with exogenous input was selected (NARX).

An abstract view of such a network is provided in Fig. 7.4, where the utilized inputs and feedbacks are also visible. After extensive testing, a two hidden layer structure was chosen. The dataset was segmented into training (70%) and testing/validation (30%) sub-sets. In order to take advantage of each cloud class characteristics separately, a NARX was developed for each class and trained with its classified input, with the purpose of combining all 7 networks with a final layer.

7.4.4 Comparison to State of the Art

Typical values of improvement vs baseline for published methods range from almost zero to 10% for power forecasts, depending on the aggregation period, the integrated area, the forecast horizon etc. In this case, the time resolution is high (1 s) in order to enable controlling schemes and the data correspond to one location, meaning that there is almost no gain in performance from averaging effects. Nonetheless, the state of the art model used as a reference achieves improvement of up to 10%, being at least

Fig. 7.4 Neural network topology

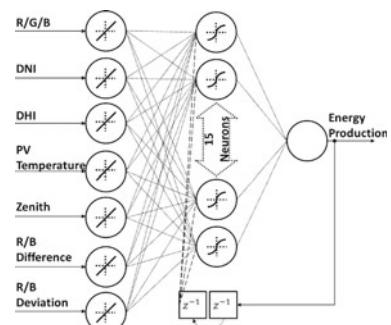
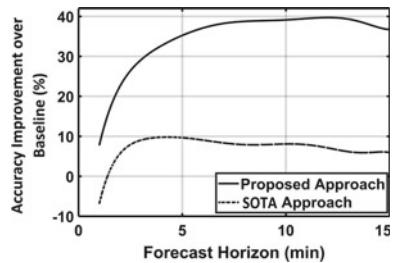


Fig. 7.5 Comparison of accuracy improvement vs state of the art method



at par with similar models. Therefore a comparison can be made with the developed model in order to quantify the improvements such an approach can achieve.

The proposed model performs clearly better on all forecast horizons with regard to baseline (persistence) vs. the benchmark power model (Fig. 7.5). Accuracy gains are always positive, as high as 39%, highlighting the inability of persistence to capture all the stochastic effects in such conditions, where averaging is not significant. Of course for longer horizons, bigger area of integration and longer time-steps reported the persistence is expected to improve its performance but this falls outside of the focus of this work, which is detailed, local, energy forecasts.

7.5 Conclusions

Upcoming challenges in the production and distribution of renewable energy will require forecast models on all temporal and spatial scales, in order to enable smart methodologies for design and control. A plethora of novel devices and methodologies are required to be integrated into the smart grid and cooperate with the help of IoT. As explained, these three notions, smart grid, IoT and forecasting are intertwined, enabling and empowering each other. Building on established techniques for long term forecasting and utilizing more recent tools, like big data analytics and deep learning, will be an essential step to produce accurate and detailed local forecasts, in order to control the grid dynamically. IoT will be the main point of data collection and communication for this. As an example, a method for detailed PV energy yield forecasting is provided, utilizing a local sky-imager and neural networks. The proposed method eliminates the usual chain of models, from irradiation forecast to energy yield estimation, reducing the propagated errors. Additionally, the thermal dynamics of the PV system are considered, in order to better estimate the output yield based on previous research in dynamic modeling of PV systems. This methodology can prove useful for a multitude of application requiring accurate, detailed PV energy forecasting, from storage control to datacenter workload management.

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Chapter 8

Data Analytic for Improving Operations and Maintenance in Smart-Grid Environment



Nikolaos Karagiorgos and Kostas Siozios

Abstract The Smart-Grid concept relies on a collection of generation, transmission and distribution components that undertake power production and delivery to various types of loads. Since multiple components have to be collaborated in this procedure, advanced system orchestrators are absolutely necessary. The decision of these intelligent mechanism typically rely on the analysis of large amount of data, also known as “big data analytic”, in order to optimize among others the environmental and economic constraints. This chapter provides an overview of recent advances in the domain of big data analytic, which are suitable for being applied to the smart-grid environment.

8.1 Introduction

In today’s competitive business environment, companies are facing challenges in dealing with big data issues of rapid decision-making for improved productivity. This is also the case for the majority of power plants, which usually have tremendous amounts of data stored in their historians, asset management systems, as well as in their control and monitoring systems. Such an issue is also inline to the trend towards an Industry 4.0 factory, where machines are connected as a collaborative community. In order to improve the performance of overall system, proper data analysis have to be performed. By utilizing advanced prediction tools, so that data can be systematically processed into information to explain uncertainties, and thereby make more “informed” decisions.

Although promising, the majority of grids (both energy producers, as well as energy operators) are not ready to manage big data due to the lack of smart analytic tools. A good example is the data analytic software plants use to improve operations and maintenance through root cause analysis, asset optimization, report generation,

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and more. A typical data analytic approach in most plants today is the spreadsheet, the go-to tool for process engineers in every industry, and now more than 30 years old. While it provides unquestionable flexibility and power, this general-purpose tool lags in the innovations that have been introduced in information technology (IT) departments, and even in consumers' lives.

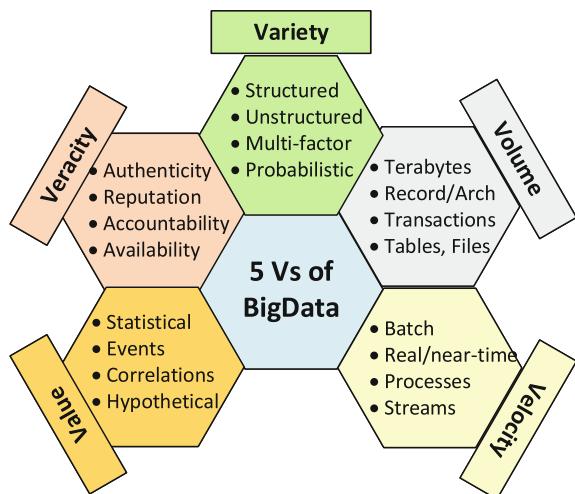
To make matters worse, the grids today focus mostly on control-centric optimization and intelligence. Additional intelligence can be achieved by interacting with different surrounding systems that have a direct impact to machine performance.

Achieving such seamless interaction with surrounding systems turns regular machines into self-aware and self-learning machines, and consequently improves overall performance and maintenance management. Even though the autonomous computing methodology has been implemented successfully in computer science, self-learning machines are still far from implementation in current industries. Transformation from todays status into more intelligent machines requires further advancement in the science by tackling several fundamental issues, where the Big Data and the Cloud have a centric role.

By the term Big Data we refer to the data collection capabilities provided by process instrumentation, coupled with improved methods of networking and storage. These fundamental technologies have created an environment where energy producers, electricity companies and consumers accumulate vast amounts of time-series data from plant operations, labs, suppliers, building energy requirements and other sources. Together, these data sources contain potential insights into the operation and maintenance of virtually every major item of equipment and every important process in a typical power plant (Fig. 8.1).

The reason for calling this data "big" is due the five V-s (Fig. 12.1):

Fig. 8.1 The five V's of big data



1. Huge in **volume**, which refers to the amount of all types of data generated from different sources and continue to expand. The benefit of gathering large amounts of data includes the creation of hidden information and patterns through data analysis.
2. Highly complex **value**, which is the most important aspect of big data; it refers to the process of discovering huge hidden values from large datasets with various types and rapid generation [6].
3. Variable **veracity**, which highlights the fact that tried and tested data management principles data quality, data cleansing, master data management, and data governance are not completely redundant in a world of Big Data.
4. **Variety** (diverse) means the types of data. Difference sources will produce big data such as sensors, devices, social networks, the web, mobile phones, etc. For example, data could be web logs, RFID sensor readings, unstructured social networking data, streamed video and audio, which this data can be captured either in structured or unstructured format.
5. **Velocity** (constantly increasing): This means how frequently the data is generated. For example, every millisecond, second, minute, hour, day, week, month, year. Processing frequency may also differ from the user requirements. The contents of data constantly change because of the absorption of complementary data collections, introduction of previously archived data or legacy collections, and streamed data arriving from multiple sources [14]. Some data need to be processed real-time and some may only be processed when needed. Typically, we can identify three main categories: occasional, frequent, and real-time.

It is estimated that by year 2020, we will have 6.1 billion smartphones globally, our accumulated digital universe will increase from 4.4 trillion gigabytes to 44 trillion gigabytes. At least third of all this data will pass through the cloud, and the open source software market will grow by 58%, surpassing \$1 billion. Organizations that invest in and leverage big data are anticipated to increase their operating margins by 60%.

Under the aforementioned explosive increase of global data, the term of big data is mainly used to describe enormous datasets. In contrast to traditional datasets, big data typically includes masses of unstructured data that exhibit excessive demand for real-time analysis. Furthermore, big data also brings about new opportunities for discovering new values, helps us to gain an in-depth understanding of the hidden values, and also incurs new challenges, e.g., how to effectively organize and manage such datasets.

The above examples demonstrate the rise of Big Data applications where data collection has grown tremendously and is beyond the ability of commonly used software tools to capture, manage, and process within a “tolerable elapsed time”. The most fundamental challenge for Big Data applications is to explore the large volumes of data and ex-tract useful information or knowledge for future actions [20]. In many situations, the knowledge extraction process has to be very efficient and close to real time because storing all observed data is nearly in-feasible. As a result,

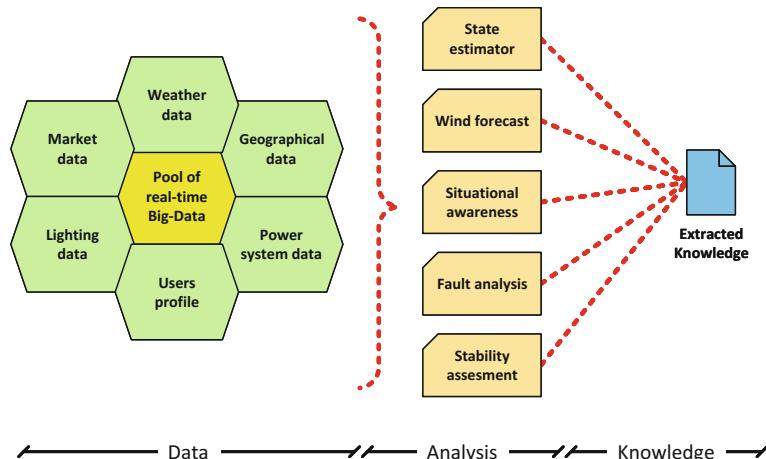


Fig. 8.2 Power plant personnel often find themselves drowning in data, but lacking in the information required to improve operations and maintenance. *Courtesy: Seeq Corp*

the unprecedented data volumes require an effective data analysis and prediction platform to achieve fast response and real-time classification for such Big Data.

Due to its impact on the quality of decisions, recently the majority of industries become interested in the high potential of big data, and many government agencies announced major plans to accelerate big data research and applications. In addition, issues on big data are often covered in public media, such as The Economist, New York Times [18], and National Public Radio [22], as it has impact not only to the industry domain, but also in our lives. In line to this trend, two premier scientific journals, Nature and Science, also opened special columns to discuss the challenges and impacts of big data [1, 2]. The era of big data has come beyond all doubt [21].

The data management and its distribution in Big Data domain is especially critical in order to achieve efficient self-aware and self-learning machines. Moreover, the importance of leveraging additional flexibility and capabilities offered by cloud computing is inevitable, but adapting prognostics and health management algorithms to efficiently implement current data management technologies requires further research and development (Fig. 8.2).

8.2 The Critical Role of Analytic

The data architecture must provide a sound platform on which to apply relevant and sophisticated data analytic. Grid data is simply too voluminous for people to comprehend directly, and a large amount of data will be used by systems without human intervention. As the smart grid taxonomy in Fig. 12.3 illustrates, technical

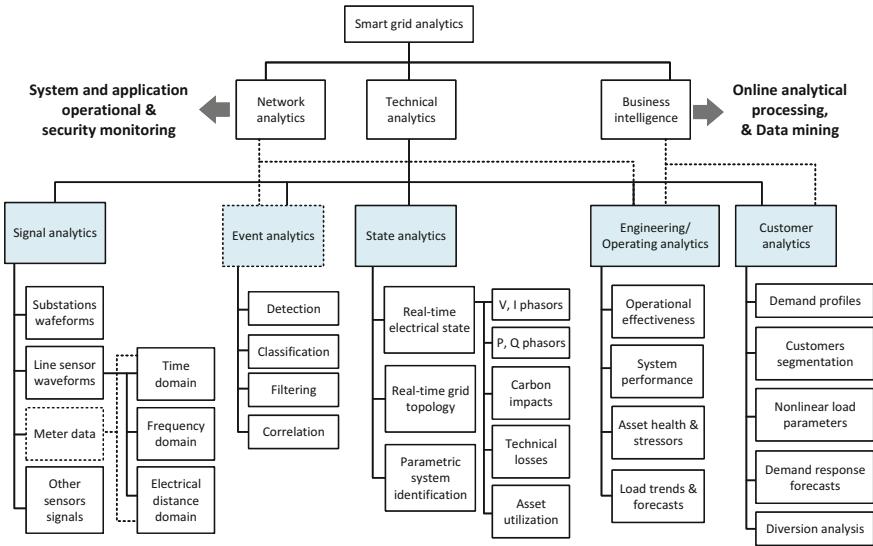


Fig. 8.3 Smart grid taxonomy, showing the role of analytic

analytic are critical software tools and processes that transform raw data into useful, comprehensible information for operations decision making.

As the taxonomy shows, creating operational intelligence is one important aspect of analytic, but in a smart grid environment there is much more to consider. To date, Accenture has catalogued more than 200 smart grid analytic and several classes of technical analytic such as (Fig. 8.3):

- Electrical and device states (including traditional, renewables and distributed energy resources).
- Power quality.
- Reliability and operational effectiveness (system performance).
- Asset health and stress (for asset management).
- Asset utilization (e.g., transformer loading).
- Customer behavior (especially in terms of demand response).

8.2.1 Relationship Between Cloud Computing and Big Data

The concept of cloud computing is tightly firmed to the big data. Fundamentally, big data is the object of the computation-intensive operation and stresses the storage capacity of a cloud system, whereas the main objective of cloud computing is to use huge computing and storage resources under concentrated management, so as to provide big data applications with fine-grained computing capacity. Due to this

relation, the development of cloud computing (e.g., in terms of storage and processing) is accelerated from the challenges posed by big data and vice versa. For instance, regarding the two previously mentioned objectives, the distributed storage technology based on cloud computing can effectively manage big data; the parallel computing capacity by virtue of cloud computing can improve the efficiency of acquisition and analyzing big data.

The evolution of big data was driven by the rapid growth of application demands and cloud computing developed from virtualized technologies. Therefore, cloud computing not only provides computation and processing for big data, but also itself is a service mode. To a certain extent, the advances of cloud computing also promote the development of big data, both of which supplement each other. Although these two technologies are somehow complementary, they differ in the following two aspects. First, the concepts are different to a certain extent. Cloud computing transforms the IT architecture while big data influences business decision-making. However, big data depends on cloud computing as the fundamental infrastructure for smooth operation. Second, these two technologies focus on different target customers. Specifically, cloud computing is a technology and targets to an advanced IT solution, whereas the big data is a product that focuses on business operations. With the advances of big data and cloud computing, these two technologies are certainly and increasingly entwine with each other. Cloud computing, with functions similar to those of computers and operating systems, provides system-level resources; big data operates in the upper level supported by cloud computing and provides functions similar to those of database and efficient data processing capacity (Fig. 8.4).

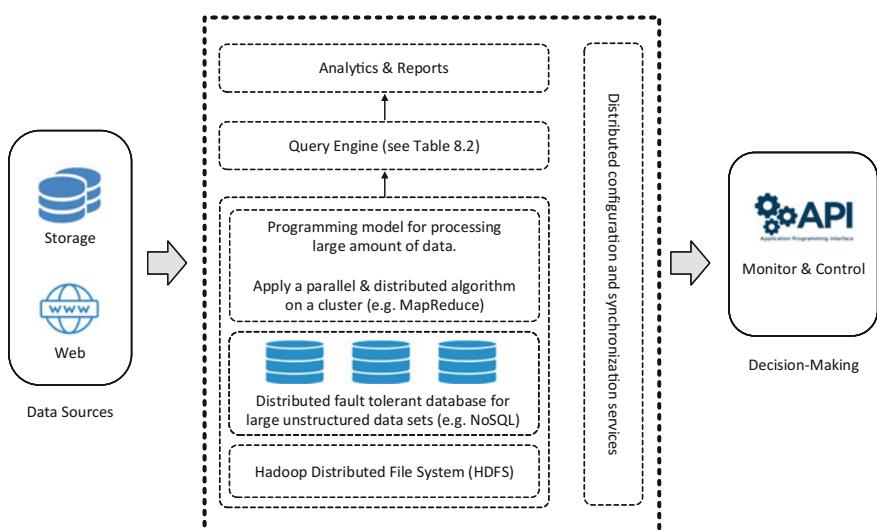


Fig. 8.4 Cloud computing usage in big data

8.2.2 Relationship Between IoT and Big Data

The explosive growth in the number of devices connected to the Internet of Things (IoT) and the exponential increase in data consumption only reflect how the growth of big data perfectly overlaps with that of IoT. This goal is also affected by the fact that the majority of IoT applications do not only focus on monitoring discrete events but also on mining the information collected by IoT objects. For instance, the data generated from IoT devices can be used in finding potential research trends and investigating the impact of certain events or decisions. These data are processed using various analytic tools.

Although IoT has created unprecedented opportunities that can help increase revenue, reduce costs, and ameliorate efficiencies, collecting a huge amount of data alone is insufficient. To generate benefits from IoT, enterprises must create a platform where they can collect, manage, and analyze a massive volume of sensor data in a scalable and cost-effective manner [21]. For instance, in large-scale industrial automation applications, thousands of automated machines are fabricated with such trillions of IoT chips to technically contrast the IoT objects and the networks of such trillions of IoT objects may constitute a large-scale industrial IoT environment, from where huge structured, semi-structured, and unstructured IoT big-data are produced in a real timescale.

The demand for higher data storage posed by IoT applications influence among others the task of data management and knowledge discovery. In heterogeneous depository the IoT big-data sources are associated with different frameworks having different logical schemas, as it is depicted in Fig. 8.5, where in each logical schema the data structure is defined. The previously mentioned heterogeneity refers to the different models, name, scale, structure and level of abstraction. Consequently, it is tedious for the IoT big-data management and knowledge discovery manager to synchronize the data access so as to run more complex analytic.

8.2.3 Relationship Between Data-Center and Big Data

We have already mentioned the current trend towards a digital universe, where information and technology are not only around us but also play important roles in dictating the quality of our lives. This imposes that a lot of applications rely on big data concepts, in which data has grown unrestrainedly. The limited efficiency of conventional data processing technologies to process this data within a tolerable elapsed time started the discussions about new technological platforms that overcome these limitations.

A technology that promises to overcome these drawbacks is the data-center clouds [3, 25], which promise on-demand access to affordable large-scale resources in computing (such as multicore CPUs, GPUs, and CPU clusters) and storage (such as disks)

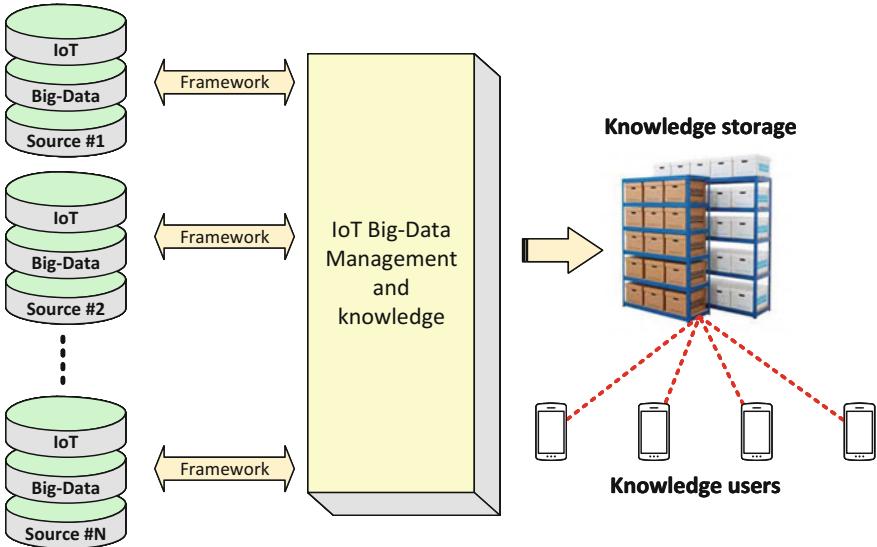


Fig. 8.5 Typical heterogeneous knowledge depository framework

without substantial upfront investment. More precisely, datacenter cloud services are a natural fit for processing big datastreams, because they allow data mining algorithms (and underlying application programming and database frameworks) to run at the scale required for handling uncertain data volume, variety, and velocity [8, 32, 33]. However, to support a complicated, dynamically configurable big data ecosystem, it is upmost important to innovate and implement novel services and techniques for orchestrating cloud resource selection, deployment, monitoring, and QoS control.

An objective for data-centers, which is continuously gains importance both in research and commercial communities, relies on the support of real-time analytic. This is extremely challenging because handling large volumes of streaming and historical data this task imposes powerful processing cores and excessive amount of on-chip storage. Although datacenter clouds offer abundant resources, they don't support QoS-driven autonomic resource provisioning or deprovisioning in response to changes in the 5 Vs (that is, in the big data applications behavioral uncertainties).

The datacenter cloud resource provisionings uncertainty [5, 17, 29] has two aspects. First, from a big data application's perspective, it is not straightforward to estimate workload behavior in terms of the data volume to be analyzed, data arrival rate, datatypes, data processing time distributions, and I/O system behavior. Second, from a datacenter resource perspective, without knowing the big data's requirements or behaviors, it's difficult to make decisions about the size of resources to be provisioned at any given time. Furthermore, the availability, load, and throughput of datacenter resources can vary in unpredictable ways, due to failure, malicious attacks, or network link congestion. In other words, we need reasonable workload and

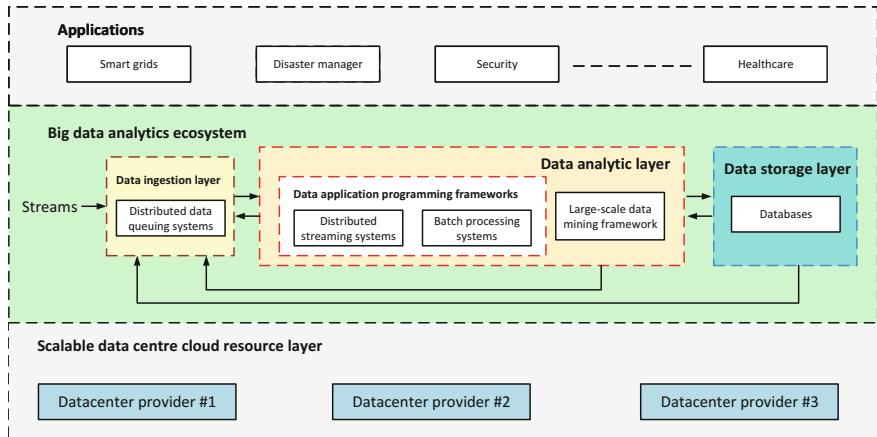


Fig. 8.6 A high-level architecture of large-scale data processing service. The big data analytic architectures have three layers – data ingestion, analytic, and storage and the first two layers communicate with various databases during execution

load resource performance prediction models when making provisioning decisions for datacenter resources that host instances of data mining algorithms, distributed message queuing systems, and data application programming frameworks (Fig. 8.6).

8.3 Deriving Value from Big Data

Realizing that all this data is available, a challenge is to derive value from them. A number of objectives have to be met for this analysis in order to maximize the potential gain of this asset. Among others, plant managers are demanding and expecting more insights, faster, to drive improvements in plant operations and maintenance. These improvements could be increased asset availability via predictive analytic, improving compliance through monitoring of key metrics, or simply greater productivity when accessing contextualized data as input into plans, models, and budgets. However, we have to mention that such an approach apart from the efficiency in the part of data analytic itself, impose also effort at the execution phase, where powerful and performance efficient data centers have to be involved in order to guarantee near real-time data processing.

This is the managerial burden of the “big data” era, where awareness of innovation has created pressure to take advantage of it. Unfortunately, full utilization of many of the big data solutions available today requires extensive programming expertise and knowledge of data science, to say nothing of IT and other department costs to implement and manage – resulting in high failure rates during implementation.

The challenge for value from data is tightly firmed to the amount of data that is stored and then analyzed. When the focus first shifted from data storage to the value of Big Data, it was easy to collect and store as much data to do with every aspect of running the business as possible in the likelihood that it might be used sometime in the future. However, the last years there is a shift from simple data collection to the collection of relevant data; data that adds value to the business. Only collecting lots of data is not enough. Collecting data on a large scale gives you big data; thus, plenty of data; but it does not necessarily mean that you have valuable data. It is crucial to note that useful data not only needs to be big data, but it also needs to be high-quality, practical information. In other words, companies need to collect data about each subject that is detailed enough to allow analytic tools and models can drill down into as much detail as required.

This is where *data mining* comes into the picture. Essentially, data mining is the methodology which is employed to sort through large data sets to identify patterns and relationships. These patterns and relationships are then used to solve problems and predict future trends. The data mining methodology is only implemented once the raw data has been extracted, transformed and loaded into a data warehouse.

8.3.1 Beyond Spreadsheets to Modern Data Analytic

The previously mentioned challenges impose a continues demand towards a new era in data analytic solutions for application domains with excessive amount of data, such as the power plants and the smart-grid in general. Even though the spreadsheet may live forever for some types of analysis, it becomes obvious that its time for better solutions for data analytic that go beyond the limited expectations defined by legacy software technology, with employees working alone to produce paper reports.

More specifically, there are new technologies and solutions that accelerate machine learning enabling among others faster insights for improved process and business outcomes. These solutions promise to bridge the gap among complementary tasks and service innovations, organizational needs, and access to insights by leveraging technologies like machine learning and web-based deployment, while remaining accessible to process engineers and experts.

8.4 Data Analytic Technologies

Since big data is not only large, but also varied and fast-growing many technologies and analytical techniques are needed in order to attempt extracting relevant information. Many of these are topics large enough to support an entire review on them alone. As such, this chapter is not designed to provide an in-depth knowledge of all these tools. Rather, it gives a broad overview of some of the most commonly used

techniques and technologies to help the reader better understand what tools big data analytic is based on.

There is a myriad of candidate analytic approaches that could be employed when attacking a big data project. The selection process usually has to take into consideration the type of data being analyzed, the technology available to you, as well as the research questions you are trying to solve. Next, we provide an overview of well-established technologies that can be employed for this purpose. As we will discuss later, each of these technologies can be implemented with alternative software tools that trade-off their efficiency with other crucial metrics, such as the computational complexity, the execution run-time, the quality of derived results, etc.

- **Association rule learning** is a rule-based machine learning method for discovering interesting relations between variables in large databases. It is intended to identify strong rules discovered in databases using some measures of interestingness [26, 30].
- **Data mining** is a set of combining methods from statistics and machine learning with database management in order to pin-point patterns in large datasets. Since data mining is tightly firmed to the data-driven decision-making process, this approach is described as searching, or digging into, a data file for information to understand better a particular phenomenon [33].
- **Cluster analysis:** Cluster analysis is a convenient method for identifying homogeneous groups of objects called clusters, whose characteristics of similarity are not (always) known in advance. Research effort in this domain is paid to algorithms that aim to discover with automated way what the similarities are among the smaller groups, and if they are new groups, what caused these qualities [28].
- **Crowdsourcing:** Energy system models require large and diverse datasets, increasingly so given the trend towards greater temporal and spatial resolution. This challenge can be ad-dressed with the crowdsourcing which engages a “crowd” or group for a common goal often innovation, problem solving, or efficiency [10]. It is powered by new technologies, social media and web 2.0. Crowdsourcing can take place on many different levels and across various industries. Thanks to our growing connectivity, it is now easier than ever for individuals to collectively contribute whether with ideas, time, expertise, or funds – to a project or cause. This collective mobilization is crowdsourcing. Thus, the crowdsourcing is used more for collecting data than for analyzing it.
- **Machine learning:** Traditionally computers only know what we tell them, but in machine learning, a subspecialty of computer science the emphasis is to develop algorithms that allow computers to evolve based on empirical data. A major focus of machine learning research is to automatically learn to recognize complex patterns and make intelligent decisions based on data [9].
- **Text mining (or text analytic)** is the process of deriving high-quality information from text. A large portion of generated data is in text form (e.g., emails, internet searches, web page content, corporate documents, etc) are all largely text based and can be good sources of information. High-quality information is typically derived through the devising of patterns and trends through means such as statistical

pattern learning. Text mining usually involves the process of structuring the input text (usually parsing, along with the addition of some derived linguistic features and the removal of others, and subsequent insertion into a database), deriving patterns within the structured data, and finally evaluation and interpretation of the output [4].

8.4.1 Overview of Alternative Platforms

The increased number of cloud providers, in conjunction to the variety of supported features per platform, makes the selection process a difficult task. This task becomes far more savage if we take into account that different application domains and services exhibit considerable different demands among others in terms of data analytic, data storage and data transfer. For this purpose, there is a continues effort towards quantifying the performance of these solutions in order to rank the efficiency of alternative cloud services. For instance, Table 8.1 shows a qualitative comparison of several big data cloud providers.

Next, we study in more detail one of the well-established programming models for processing large numbers of datasets pioneered by Google for data-intensive

Table 8.1 Comparison of several big data cloud platforms [14]

	Google	Microsoft	Amazon	Cloudera
Big data storage	Google cloud services	Azure	S3	N/A
MapReduce	AppEngine	Hadoop on Azure	Elastic MapReduce (Hadoop)	MapReduce YARN
Big data analytic	BigQuery	Hadoop on Azure	Elastic MapReduce (Hadoop)	Elastic MapReduce (Hadoop)
Relational database	Cloud SQL	SQL Azure	MySQL or Oracle	MySQL, Oracle, PostgreSQL
NoSQL database	AppEngine Datastore	Table storage	DynamoDB	Apache Accumulo
Streaming processing	Search API	Streaminsight	Nothing prepackaged	Apache Spark
Machine learning	Prediction API	Hadoop+Mahout	Hadoop+Mahout	Hadoop+Oryx
Data import	Network	Network	Network	Network
Data sources	A few sample datasets	Windows Azure marketplace	Public Datasets	Public Datasets
Availability	Some services in private beta	Some services in private beta	Public production	Industries

Table 8.2 Current MapReduce projects and related software [14]

Reference	Software	Brief description
[31]	Hive	Hive offers a warehouse structure in HDFS
[12]	Hbase	Scalable distributed database that supports structured data storage for large tables
[24]	Madout	Mahout is a machine-learning and data-mining library that has four main groups: collective filtering, categorization, clustering, and parallel frequent pattern mining; compared with other pre-existing algorithms, the Mahout library belongs to the subset that can be executed in a distributed mode and is executable by MapReduce
[23]	Pig	Pig framework involves a high-level scripting language (Pig Latin) and offers a run-time platform that allows users to execute MapReduce on Hadoop
[16]	Zookeeper	High-performance service to coordinate the processes of distributed applications; ZooKeeper allows distributed processes to manage and contribute to one another through a shared hierarchical namespace of data registers (z-nodes) similar to a file system; ZooKeeper is a distributed service with master and slave nodes and stores configuration information
[34]	Spark	A fast and general computation engine for Hadoop data
[27]	Chukwa	Chukwa has just passed its development stage; it is a data collection and analysis framework incorporated with MapReduce and HDFS; the workflow of Chukwa allows for data collection from distributed systems, data processing, and data storage in Hadoop; as an independent module, Chukwa is included in the Apache Hadoop distribution
[11]	Twister	Provides support for iterative MapReduce computations and Twister; extremely faster than Hadoop
	MAPR	Comprehensive distribution processing for Apache Hadoop and Hbase
	YARN	A new Apache Hadoop MapReduce framework
[19]	Cassandra	A scalable multi-master database with no single point of failure
[15]	Avro	The tasks performed by Avro include data serialization, remote procedure calls, and data passing from one program or language to another; in the Avro framework, data are self-describing and are always stored with their own schema; this software is suitable for application to scripting language, such as Pig, because of these qualities

applications. This model, also known as MapReduce [7], was developed based on GFS [13] and is adopted through open-source Hadoop implementation, which was popularized by Yahoo. Table 8.2 provides an overview of recent MapReduce-based projects, as well as the related software that support and automate each of them. Apart from the MapReduce framework, several other current open-source Apache projects are related to the Hadoop ecosystem, including Hive, Hbase, Mahout, Pig, Zookeeper, Spark, and Avro.

8.5 Conclusions

A number of technologies employed for the scope of data analytic in the domain of smart-grid, was discussed. These analytic can support the decision-making mechanism for orchestrators assigned at different layer of abstraction spanning from energy production up to the end customers.

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Chapter 9

On Accelerating Data Analytics: An Introduction to the Approximate Computing Technique



Georgios Zervakis

Abstract Approximate computing is a computation technique which returns a possibly inaccurate result rather than a guaranteed accurate result, and can be used for applications where an approximate result is sufficient for its purpose. This technique is gaining traction as a computing paradigm for data analytics and cognitive applications that aim to extract deep insight from vast quantities of data, such as those that affect the smart-grid domain. This chapter introduces the technology drawbacks for enhancing further the processing power of computational resources and then proposes the concept of approximate computing. A survey for these techniques applied both at software and hardware level are also discussed.

9.1 Introduction

A prominent example of the importance of energy efficiency are data centers. Data centers are basically computer warehouses that store very large amounts of data and support a multitude of applications, systems, and functions [62] (e.g., streaming media, email, internet content, e-commerce, social networking [30]). Today, these applications are used more and more by our computers, mobile devices, sensors, and networks through the ever-growing cloud [72]. Because of the need to run incessantly [57], data centers require huge amounts of energy to operate (typical power densities of 538–2153 W/m², up to 10 KW/m² [4, 9]). A 2013 example shows that U.S. data centers consumed an estimated 91 billion kWh of electricity [56] (Table 9.1), a trend that's only going to grow to an estimated 140 billion kWh by 2020; to put things into perspective, this translates to the the annual output of 50 power plants, costing American businesses \$13 billion annually in electricity bills and emitting nearly 100 million metric tons of carbon pollution per year. In Europe the respective numbers

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Table 9.1 Data centres Energy consumption estimations and projections in TWh from a European, American and Global perspective. Source [9]

Consumption (TWh)	Reporting year
EU consumption	
18.3	2000
41.3	2005
56	2007
72.5	2010
104	2020
US consumption	
91	2013
140	2020
Global consumption	
216	2007
269	2012

are 72.5 billion kWh for 2010 and a projection of 104 billion kWh for 2020 [9]. If we also consider the amount of data these centers are handling (350 m terabytes of data as of 2015 [72]) and the consequent power consumption (over 100TWh of electricity annually by 2020, the amount of public attention power-hungry data centers have drawn comes as no surprise.

In addition to data centers, there is another major domain of the information and communication technology (ICT) sector that exhibits increased energy efficiency demands: embedded systems. An embedded system is an engineering artifact involving computation that is subject to physical constraints. These constraints affect available processor speeds, power, and hardware failure rates [26]. Many embedded systems feature very tight power budget (an order of some Watts) while ultra low-power ones (e.g. wearable systems) only a few milli watts [20]. The importance of energy efficiency for embedded systems becomes apparent if we consider the example of mobile or wearable systems. Although their small size comes with a tight power budget, they need to perform high performance functions, such as 3G/4G. If we add into the mix the ever-growing number (Fig. 9.1) of embedded and internet-connected (IoT) devices (15 billion in 2015, est. 75 billion by 2025), it becomes obvious that the systems' ability to perform efficient computations will be absolutely essential.

Lastly, there is also an environmental reason behind the significance of energy efficiency. Close to 2% of the global CO₂ emissions comes from the Information and Communication Technology (ICT) sector (including data centers), a percentage which is only projected to grow due to technological advances such as the cloud computing, as well as the rapid growth of the use of Internet services and IoT/internet-connected devices [9]. To put it into numbers, the ICT industry is forecasted to use 20% of the world's electricity by 2025, which also translates to 5.5% of the world's carbon emissions by then. Therefore, we can easily support that this is an issue that extends far beyond the ICT sector; it has a global effect on countries and communities.

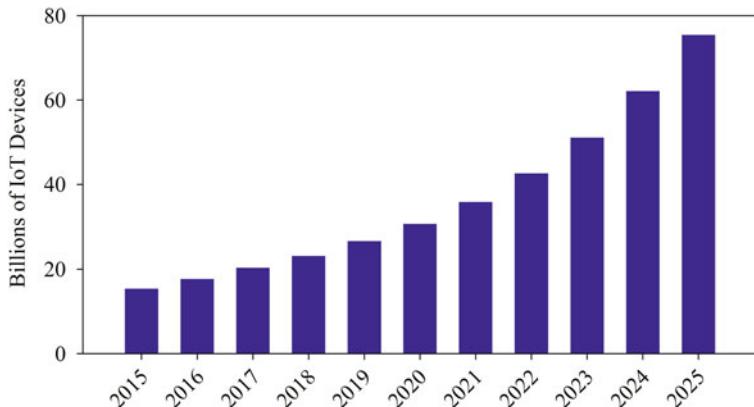


Fig. 9.1 Internet of Things (IoT) connected devices (in billions) installed base worldwide from 2015 to 2025 (in billions). Source www.forbes.com

For example, this is well reflected on EU energy policies [14] that aim to improve energy efficiency in virtually every sector of the economy.

9.2 Moore's Law and Dennard's Scaling

Moore's Law [51] has been a fundamental driver of computing for more than four decades [15]. For the last forty years, industry's unrelenting focus on Moore's Law transistor scaling has constantly delivered increased transistor performance and density. Throughout all these years of technology advancements and computer science evolution, leading researchers and technologists have awaited and forecast the "end of scaling" within one or two next generations. Nevertheless, every time the technology reached the anticipated transistor scaling break off, scaling continued (Figs. 9.2 and 9.3) [34]. Inspired and innovative new solutions were developed to further prolong Moore's Law and maintain the transistor scaling roadmap [35].

Moore's law is the observation that the number of transistors in a dense integrated circuit doubles approximately every two years. The period is often quoted as 18 months because of Intel executive David House, who predicted that chip performance would double every 18 months.

One of the main challenges of doubling the number of transistors on the chip is powering them without melting the chip and incurring excessively expensive cooling costs [15]. Although, considering the Moore's Law, the number of transistors in a dense integrated circuit (Fig. 9.3) has immensely increased, in the past 40 years, the chip power consumption has slightly increased. It is remarkable that with the same amount of power two times more transistors can be driven. In 1974, Robert Dennard [13], formulated how the transistor fabrication process technology

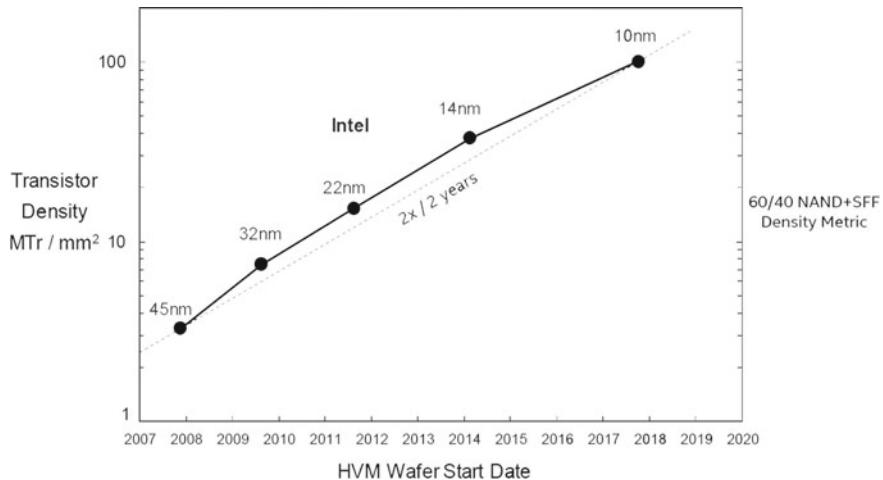
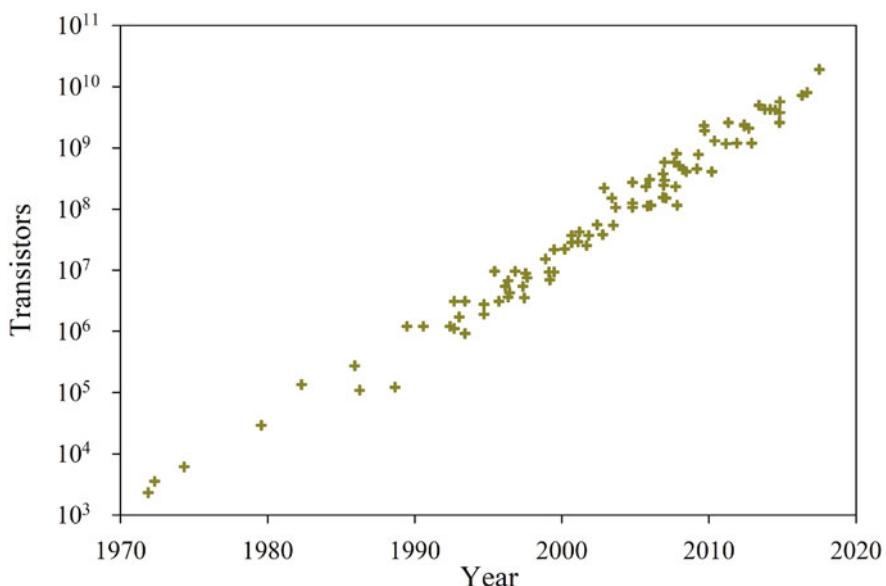


Fig. 9.2 Transistor density improvements continue at a rate of doubling every 2 years. Source [6]



source: Karl Rupp, 42 Years of Microprocessor Trend Data (github.com/karlrupp/microprocessor-trend-data)

Fig. 9.3 Number of transistors with fit into a microprocessor

can provide such physical properties. In fact, Dennard's theory of scaling is the main force behind Moore's Law [15].

Dennard scaling, also known as MOSFET scaling, is a scaling law based on a 1974 paper co-authored by Robert H. Dennard [13]. Originally formulated for MOSFETs, it states, roughly, that as transistors get smaller their power density stays constant, so that the power use stays in proportion with area: both voltage and current scale (downward) with length.

With Dennard's scaling rules, the total chip power for a given area size remained the same from process generation to process generation. Hence, a new process technology could double the transistors' count in a fixed chip size without increasing the power dissipation of the chip. Dennard's formulation [13] provided to our industry a concrete guide to the future, a way for setting goals and expectations for the next process technology generations. This paper, [13], provided a specific transistor scaling formula, needed to continue Moore's Law, which was first articulated by Gordon Moore in 1965 and was in effect being followed by the semiconductor industry since the early 1960s [5]. Moore's and Dennard's papers gave a roadmap to our industry on how to develop new integrated circuits on a constant pace, that deliver regularly improved performance and power. Reducing the critical dimensions while keeping the electrical field constant, yields higher speed and a reduced power consumption of a digital MOS circuits [13]. Every new process technology generation was expected to reduce minimum feature size by approximately $0.7 \times$ and it provided roughly a $2 \times$ increase in transistor density [5]. Starting in the mid-1990s our industry started introducing new technology generations once every 2 years. The trend of increasing chip size has slowed due to cost constraints, so we have settled into a trend of doubling transistor density and count every 2 years [5].

*Moore's law gives us more transistors... Dennard scaling made them useful. — Bob Colwell,
DAC 2013.*

9.3 The End of Dennard's Scaling

Voltage scaling was a crucial component of Dennard's scaling because it maintains constant electric field, which is important for reliability, and it lowers transistor power, which is needed to maintain constant power density [5]. However, voltage scaling has run into lower limits imposed by threshold voltage (V_T) scaling limits [71]. Dennard's scaling law assumed that V_T would scale along with operating voltage, and thus provide improved performance and power [13].

Nevertheless, Dennard's scaling did not consider the impact of sub-threshold leakage. By 1970, sub-threshold leakage was quite small and its contribution to the total power consumption of the chip was negligible. However, by 2005 V_T has scaled to the point where sub-threshold leakage has increased more than $10,000 \times$ (from $< 10^{-10}$ amps/mm to $> 10^{-7}$ amps/ μm) and further reduction in V_T was not feasible anymore. Therefore, voltage scaling slowed down, since it was no longer possible to scale further the threshold voltage due to rising leakage currents [27]. Furthermore,

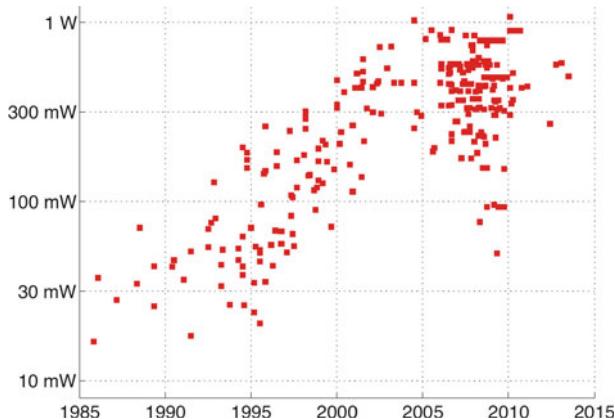


Fig. 9.4 Scaling of power density (mW/mm^2) over years. Source [27]

another limiting factor in Dennard's scaling law was the assumption that the ability to scale gate oxide thickness would be retained.

On the contrary, gate oxide thickness scaling reached the point of five atomic layers and the contribution of direct tunnel leakage current to the overall chip power highly increased [28, 32]. Hence, although during the past years the number of transistors closely followed the Moore's Law, the power density of the processors has not scaled as predicted (Fig. 9.4). The underlying cause of the observed exponential power growth can be traced to two factors: the fact that we did not scale power supply voltages at the constant field rate [12], and the fact that in our quest for performance, we scaled clock frequencies faster than dictated by constant-field scaling [27].

As long as Dennard's scaling was still in the spotlight, computer science leveraged the transistors' increase to produce higher frequency processors and equip them with more capabilities to further improve their performance [15]. With the end of Dennard's scaling, power densities in today's integrated circuits are rapidly reaching unmanageable levels. Future technology generations can sustain the doubling of devices every generation, but with significantly less improvement in energy efficiency at the device level. This device scaling trend presages a divergence between energy-efficiency gains and transistor-density increases [16]. Driven by the regularly maintained $2\times$ increase in transistors' count and the failure of Dennard scaling power management and efficiency emerges as a primary issue across most domains of the computing industry and is now essential for practical realizations. Therefore, computer science is forced to explore and adopt new computing alternatives in order to maintain the power scaling and increase the energy efficiency of the modern computing systems.

9.4 Approximate Computing

We are at the threshold of an explosion in new data, produced not only by large, powerful scientific and commercial computers, but also by the billions of low-power devices of various kinds [1]. Energy efficiency is now a first-class design constraint in computer systems. Its potential benefits go beyond reduced power demands in servers and longer battery life in mobile devices, since improving energy efficiency has become a requirement due to limits of device scaling and the so called “dark silicon” [17] or “power/utilization wall” problem. Computing and information technologies have entered now the “no-free lunch” era, meaning that radical departures from conventional approaches are needed to sustain and further improve the performance and efficiency of the computing systems.

Guaranteed numerical precision of each elementary step in a complex computation has been the mainstay and the fundamental principles of traditional computing systems for many years. But abstractions with perfect accuracy come at a cost. This era, fueled by Moore’s law and the constant exponential improvement in computing efficiency, is at its twilight: from tiny nodes of the Internet-of-Things, to large-scale HPC computing nodes and data-centers, energy efficiency has become the paramount concern in design of computing systems [24]. To overcome the “power wall”, a shift from traditional computing paradigms is now mandatory and imposes the computing society to re-think these principles and investigate new computing alternatives. While precision is crucial for some tasks, many modern applications are fundamentally approximate. Recent research by Intel [48], IBM [52], and Microsoft [7, 18] has demonstrated that there is a large body of resource-hungry applications that exhibit an intrinsic resilience to approximation errors and a significant portion of their functions/computations still produce outputs that are useful and of acceptable quality for the users. They observed that, in many modern online services it is acceptable to approximate rather than produce accurate outputs. Such services include search engines (Google, Microsoft Bing, Yandex, and Yahoo search), recommendation systems (Youtube, Facebook, Amazon, and Netflix), speech recognition (Apple Siri and Google voice search), and computer vision (online games). The “correctness” or quality of output of these services is defined as providing good enough or sufficient quality of results for users satisfaction [60]. Perfect answers are unnecessary or even impossible in several application domains [11, 74]. Today’s systems waste time, energy, and complexity to provide uniformly precise operations for applications that eventually do not require it. For example, based on the work of Misailovic et al. [47], the preferred quality loss range is between 0 and 10% for applications such as video decoding. Moreover, another research by Park et al. [58], that recruited 700 users, showed that the level of acceptable quality loss significantly varies across applications, e.g., to satisfy the 90% of the users, 8% quality loss is acceptable for jpeg while they tolerate 26% accuracy loss for audio-enc.

Approximate computing forms a radical paradigm shift in systems design and operation, based on the idea that we are hindering computer systems’ efficiency by demanding too much accuracy from them [66]. Approximate computing trades

accuracy of computation for savings in execution time and/or energy by leveraging the error tolerance of the respective applications and by exploiting approximation opportunities across the computing stack [49].

Computing workloads with intrinsic error resilience are all around us, both in the embedded and cloud worlds, and they include digital signal processing, multimedia processing (image, video, audio), network processing, wireless communications, web search and recognition and data mining [10]. As discussed in [10], the error forgiving nature of these applications may be attributed to a variety of factors (Fig. 9.5), such as:

- Applications that process data from real world (e.g., inputs from sensors) feature and intrinsic error resilience. The input of those applications is innately noisy, and thus, they are designed in such a way to encompass and tolerate this noise in the performed tasks. Hence, they can be also resilient to inaccuracies in their computations.
- Applications that deal with large input data that feature high redundancy. The nature of such applications enables them to accommodate errors in their calculations without deteriorating their output quality.
- Applications that feature several satisfactory outputs. In such applications a perfect output, i.e., single unique result, is not mandatory or even impossible and multiple results are equivalently adequate.
- Applications that produce outputs for human consumption, e.g., audio and video media applications. The perceptual systems of the human exhibit a limited ability in detecting slight degradation in the digital content produced by such applications. As a result, small inaccuracies in their calculations produce results of acceptable quality.
- Applications that perform statistical and/or probabilistic computations. Such applications can mainly tolerate errors in their numerical calculations due to the nature of the implemented algorithms.

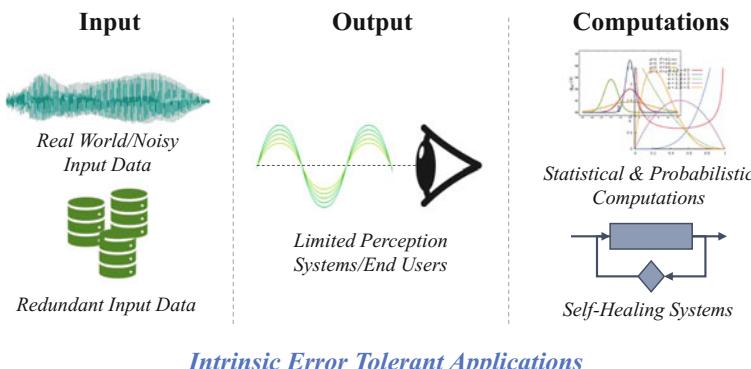


Fig. 9.5 Various sources of inherently error resilient applications. Source [11]

- Applications that perform self-healing computations. Such applications implement iterative computations where the result in every iteration is refined until meeting a certain threshold or satisfaction test. In these applications errors occurred in early computations can be corrected/refined in the later ones.

In the past years significant research activities have been performed in the field of Stochastic/Probabilistic computing [55, 59]. However, approximate computing should not be confused with them. Stochastic computing uses random binary bit streams for computation and Probabilistic computing exploits the intrinsic probabilistic behavior of the underlying circuit fabric. The distinctive feature of Approximate computing is that it does not involve assumptions on the stochastic nature of any underlying processes implementing the system. It does, however, often utilize statistical properties of data and algorithms to trade quality for energy reduction. Approximate computing, hence, employs deterministic designs that produce imprecise results [49].

Our present treatment of error is unsatisfactory and ad hoc... Error is viewed (in this work), therefore, not as an extraneous and misdirected or misdirecting accident, but as an essential part of the process under consideration—J. von Neumann [55]

Resilient applications are not, however, a license for computers to abandon predictability in favor of arbitrary errors. We need abstractions that incorporate approximate operation in a disciplined way. Applications and runtime systems should be able to exploit these richer abstractions to treat accuracy as a resource and trade it off for more traditional resources such as time, space, or energy. Different applications feature varying error resilience and exhibit different quality requirements [58]. Approximation needs to be done carefully as it can lead to unacceptable outputs and/or system failure. Hence, a primary target of approximate computing is to determine what degrees of approximations are feasible so that the delivered results are acceptable, albeit possibly different from those obtained using precise computation [1]. Approximate computing adds a third dimension in the modern systems design, i.e., the one of the error (Fig. 9.6). The addition of this extra dimension induces an extra overhead to the already increased complexity of efficient systems design, since the design space may increase exponentially [1, 79]. Moreover, the designers have to find the Pareto front points that optimize the efficiency but also guarantee that the output quality constraints are satisfied. Therefore, systematic approaches with predictable (and bound) error characteristics are mandatory in order to enable and expand the application of approximate computing.

The potential benefits of approximate computing, as previously discussed, have attracted significant research interest in almost all the computer science domains. Notably, approximate computing research targets programming languages, compilers, runtime systems, software applications [2, 7, 8, 19, 21, 33, 46, 47, 61, 63–65, 67–69, 73], hardware circuits/accelerators [3, 22, 23, 25, 29, 31, 36, 38–45, 50, 53, 54, 70, 75–78, 80], and processor micro-architectures [18, 19]. Hardware level approximation mainly targets arithmetic units, such as adders and multipliers and/or accelerator synthesis. Approximate hardware circuits, contrary to software approximations, offer transistors reduction, lower dynamic and leakage power,

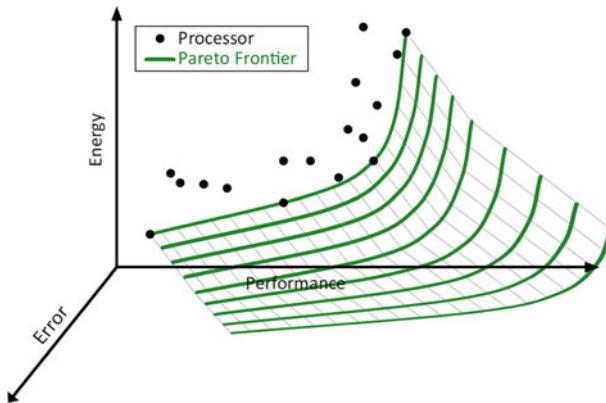


Fig. 9.6 Adding the error dimension in the Pareto front of systems design. Source [15]

lower circuit delay and opportunity for down-sizing. Moreover, another significant research domain in approximate computing is the Approximate Software–Hardware Co-design, i.e., how approximations in the hardware level can be exposed at the software level and how this synergetic nature of software and hardware approximations can be efficiently exploited.

9.5 Software-Level Approximate Computing

A wide research has been conducted in the field of software approximate techniques, comprising approximate computing languages, compilers, algorithmic transformations as well as quality-aware runtime systems. However, all the existing state-of-the-art works exhibit intrinsic limitations that prohibit them from fully exploiting the benefits of the approximate computing application. Approximate programming languages such as EnerJ [67] and Rely [8] expose approximation to the programmer through language syntax. EnerJ and Rely let a programmer annotate their program with approximate type information. In EnerJ, programmer must explicitly delineate flow from approximate data to precise data, while in Rely the compiler tries to reason statically about how an approximate type flows through to others. EnerJ automatically maps approximate variables to low-power storage and operations. Rely is an imperative language that enables developers to specify and verify quantitative reliability specifications for programs that allocate data in unreliable memory regions and incorporate unreliable arithmetic/logical operations. Approximate compilers use approximations and algorithm analyses, to transform and the semantics of programs to trade accuracy for performance and/or energy consumption. Loop perforation is a software-only technique that modifies the algorithm loops and skips the execution of some iterations [47]. A compiler can also automate the placement of operations that

execute on approximate hardware [46]. Moreover, [63, 69] reduce the bit width of floating-point operations at compile increasing the program's performance. In [68] the authors lift the semantics of a program from its concrete operations on values to operations over distributions of values. In [19] the most intensive part of the algorithm is replaced by an artificial neural network. The compiler automatically performs the neural transformation and replaces this part with an invocation of a neural hardware accelerator. However, all these works apply do not exploit the synergetic cooperation of multiple approximation techniques. They either operate over unreliable hardware, lower the operations voltage, simplify the computations complexity, or reduce the operations' precision. Moreover, they are statically applied at compile time and no run-time quality guarantees are proposed. Targeting to tackle this inefficiency, several software approximate techniques are proposed that incorporate a runtime system to monitor the output quality. In [33] data approximation is proposed and Spark streaming is extended to operate over representative small samples of the input data. Similarly, [21] approximates Hadoop MapReduce by operating over samples of data and/or by not executing some tasks. Nevertheless, these frameworks are specific to Spark streaming and Hadoop MapReduce. The Green system [2] supports energy-conscious programming using loop and function approximations, but it is targeted for streaming applications in which the system is given a sequence of inputs such as a sequence of video frames, and the results from processing an input can be used to adjust the approximation settings for succeeding inputs. Uncertain<T> [7], provide abstractions that encapsulate approximate data within standard object-oriented programming languages and propagates approximate data through a program's variables at runtime. When a program needs to act on that approximate data (i.e., at a conditional) the Uncertain<T> runtime uses hypothesis tests to make statistically correct branch choices. Sage [65] produce approximate CUDA kernels with varying levels of approximation for applications running on GPUs, by applying selective discarding of atomic operations, data packing, and thread fusion. Similarly, Paraprox [64] produces approximate kernels of varying accuracy for OpenCL or CUDA parallel applications kernels by substituting common computation idioms found in data-parallel programs with approximate ones. At runtime Sage and Paraprox check the output quality once in every N invocations of the approximate kernel, in which they compare the quality between approximate computation and exact computation and adjust the approximate modes for the subsequent computations accordingly. However, checking the accuracy every N cycles may lead to unacceptable errors in the meantime, a proper value of N is application dependent and its selection is not comprehensively examined, remaining unclear. Reference [61] proposed the fuzzy memoization technique, which records previous inputs and outputs of a code segment and predicts the output of its current execution with respect to the past executions with similar inputs. Finally, Capri [73] uses machine learning to learn cost and error models for a program, and uses these models to determine, for a desired level of approximation, knob settings that optimize metrics such as running time or energy usage. The error and cost behaviors are substantially different for different inputs. Nevertheless, although these approximate runtime systems deliver better output quality and with higher confidence levels the delivered power/performance are still limited since they

apply software-only techniques and do support execution over approximate hardware and/or voltage over-scaled systems. Moreover, apart from Capri, the decisions made by these systems are not input-driven, limiting even further the potential benefits originated by the approximate computing application.

9.6 Hardware-Level Approximate Computing

In this section, related research in the field of hardware approximate computing is discussed. Both general-purpose approximation techniques [31, 39, 42] applied to any arithmetic circuit, as well as circuit-specific approximation either to adder [23, 77, 80] or multiplier designs [25, 36, 40, 50, 53], have been presented. Regarding to the general approximation techniques, VOS [42, 76] and truncation [3, 31, 70] have been proposed. VOS is applied in any circuit by lowering the supply voltage below its nominal value. Decreasing the supply voltage reduces the circuit's power consumption, but produces errors caused by the number of paths that fail to meet the delay constraints [76]. In [3], the authors proposed an automated generation of large precision floating point multipliers in FPGAs, using sophisticated truncation over underutilized DSPs. In [70], a truncated multiplier with a constant correction term is proposed, significantly decreasing the error imposed by typical truncation. Reference [31] proposed a truncated multiplier with variable correction that outperforms [70] in terms of error. Extensive research has been conducted targeting the implementation of approximate adders [23, 77, 80]. In [77], the authors developed a probability proof, estimating that the longest carry chain in an n -bit adder is $\log n$, and produced a fast inexact adder limiting the carry propagation. In [80], approximation is performed by decomposing the addition circuit in an accurate and an approximate inaccurate part. In [23], the authors build imprecise full adder cells, requiring fewer transistors, by approximating their logic function and then use them to build imprecise adders. Reference [43] designs a multiplier in which the LSBs of the additions are approximated by applying bitwise OR to the respective input bits. Approximate adders are generated in [45] by reducing the carry chains and then decreasing accordingly the voltage value. Although the authors propose the use of such adders targeting to build approximate multipliers, it is not clear how they can be used in different tree architectures and how their error scales in the case of multi-operand addition. Targeting the creation of approximate multipliers, [36] proposed a simplified imprecise 2×2 multiplier cell used as the basic block for constructing larger multiplier architectures. Reference [50] presented two approximate 4:2 compressors by modifying the respective accurate truth table, which were then used to build two approximate multipliers outperforming [36]. The approximate compressors of [50] are used in Dadda tree with 4:2 reduction. However, different multiplier architectures were not explored. Based on an approximate adder that limits the carry propagation, [40] presented a fast and low-power multiplier scheme with higher error than [50]. However, in all the aforementioned approaches, the imposed error cannot be predicted as it depends on carry propagation and the circuits' imple-

mentation and requires simulations over all possible inputs in order to be calculated. The authors in [78] proposed a multiplier that rounds the input operands into the nearest exponent of two. Reference [22] replaces the floating-point operations with fixed-point ones, and by applying the proposed stochastic rounding, achieve good accuracy results in training deep neural networks, while delivering high energy savings by limiting the data precision representation. Reference [25, 53] proposed the use of $m \times m$ multipliers to perform an $n \times n$ multiplication (with $m < n$). In [53] the authors statically split the multiplicand in three m -bit segments and perform the multiplication utilizing the segment containing the most significant ‘1’ (leading one). However, as stated in [25], m needs to be at least $n/2$ to attain acceptable accuracy, thus limiting the energy savings and the scalability of this approach. In [25] the authors extended the idea of leading-one segments to enable dynamic range multiplication and added a correction term. Although [25] delivers higher accuracy designs than [53] using smaller values for m , their approach requires the allocation of extra complex circuitry, i.e. two leading one detectors, two complex multiplexers for segment selection, one $\log(n)$ -bit comparator, a $\log(n)$ -bit adder, and one $2n$ -bit barrel shifter. These extra components are expected to highly increase the circuit’s complexity introducing non trivial delay, area, and energy overheads that may considerably decrease the approximation benefits [53]. This is expected to be more evident in designs targeting very small error values, in which the need of larger m values is required. The modified Booth encoding is commonly used in signed multipliers [29, 41]. Jiang et al. [29] propose an approximate radix-8 booth multiplier that uses an approximate adder for producing $3 \times A$, and combine this idea with the truncation method. Liu et al. [41] designed approximate modified Booth encoders by modifying its K-Map, and combined them with the approximate compressors of [50]. Several recent research works have proposed techniques for automating the generation of approximate circuits. Probabilistic pruning and logic minimization techniques have been presented in [39], using a greedy approach to generate approximate circuits. These techniques systematically eliminate circuit’s components and simplify logic complexity according to the circuit’s activity profile and output significance. Both techniques heavily depend on the application’s characteristics, and in addition the induced approximation error are not rigorously bounded. In [44, 75] the authors systematically synthesize logic approximate circuits by exploiting the “don’t care” conditions. Reference [54] applies several approximate transformation operators on the circuit’s behavioral description and through a greedy approach identifies their optimal combination. The authors in [38] propose approximate accelerator synthesis through precision scaling using an integer linear programming problem formulation. Reference [37] extends [38] and incorporates also voltage scaling to leverage the critical path delay reduction. However, in [37, 45] voltage reduction is not used as an approximation method, mainly due to the increased complexity of modeling-quantifying errors due to VOS, limiting thus, the potential energy savings obtained by aggressively decreasing the voltage value. All the aforementioned state-of-the-art works exhibit several limitations since they are either very time consuming and/or do not leverage the full spectrum of approximate computing techniques. They mainly focus on the application of a single type of approximation to avoid design complex-

ity, neglecting, thus, the potential benefits originated by the synergetic incorporation of multiple approximation techniques to structure the final accelerator circuit, e.g., none of these works incorporates logic and algorithmic approximations as well as VOS.

9.7 Conclusions

Recent advances in the domain of hardware and software acceleration within the same power budget are discussed in this chapter. The concept of approximate computing is introduced and a recent survey about relevant solutions is discussed.

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Part II

**Case Studies About Computerized Monitor
and Control of Energy Systems**

Chapter 10

Towards Plug&Play Smart Thermostats for Building's Heating/Cooling Control



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Abstract Buildings are immensely energy-demanding and this fact is enhanced by the expectation of even more increment of energy consumption in the near future, while the building's cooling and heating has a significant impact on the overall energy consumption (around 40%). Therefore it is necessary to find proper ways for mitigating the increasing energy cost of HVAC systems (Heating Ventilation and Air Conditioning). The problem of increased energy requirements becomes far more crucial by taking into consideration the sub-optimal operation of HVAC systems by the occupants. In order to alleviate these drawbacks, throughout this chapter we introduce a decision-making mechanism in order to support the temperature control within buildings. For this purpose, a smart thermostat concept is applied, where emphasis is given to lowering the cost and deployment flexibility, in order to be widely adopted in different buildings and regions. The proposed mechanism incorporates supervised learning and reinforcement learning techniques in order to solve a multi-objective problem that comprises both satisfying occupant's thermal comfort and minimize energy consumption.

10.1 Introduction

Buildings are immensely energy-demanding, as they account for approximately 40% of the total European Union's energy consumption [22]. Additionally, the total consumption of the residential sectors increases by 1% per year [21]. As a result, the need of solutions that aim to alleviate this problem becomes mandatory. There is a wide

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variety of ways and techniques that are employed in order to solve this problem and consequently to optimize the financial and ecological cost of buildings. Novel design methods, new materials and modern appliances are utilized during the construction of new buildings. For instance improved wall insulation is used, more energy efficient HVAC systems are designed and installed after examination of finding the most suitable for each building type and climate. Additionally green buildings include several components that target energy saving, such as renewable sources, heat pumps etc. This design is intended to be followed for the new buildings, especially for large public buildings, offices, hotels etc. However a rapid solution is mandatory for the existing old buildings and for small residential ones, as the infrastructure is difficult to be replaced quickly, due to the increased cost. Furthermore even these infrastructure parts of the green buildings and modern smart grids, that are used for energy saving, need fine-tuning and control in order to bestow the maximum performance.

A feasible approach that ensures improvements of existing old buildings consumption or optimizes modern green building's performance, is smart thermostats; computerized platforms for applying advanced control methods on HVAC systems. Smart thermostats promise to achieve energy reduction and better thermal conditions, by proper automatic configuration of the HVAC system. A recent report estimates that the global smart thermostat market is expected to generate a revenue of \$1.3 billion by 2019 [40]. These systems enable monitoring and controlling parts of the HVAC system at real-time, such as heating, ventilation and air conditioning, based on environmental parameters, for example inside and outside weather conditions, building's state parameters, such as type, activity, equipment, windows and occupants preferences. A Smart Thermostat system can incorporate operations that range from simple remote control to complex sensor networks that perform optimization decision-making tasks. Such a system also includes communication interfaces for the interaction with the sensors and the actuators of the HVAC system, data storage capabilities, and a central control unit that is usually an embedded micro-controller or microprocessor for supporting the task of decision-making. Finally such a device contains an interface for the interaction with the users.

The problem of deciding upon an automatic HVAC configuration has attracted the interest of many researchers over recent years and thus a huge number of techniques has been proposed. A detailed survey of these approaches, advantages and disadvantages as well as the possible application of them to our specifically formulated problem is presented in Sect. 10.3. We focus on a lightweight, plug&play solution that is applicable in a wide variety of buildings from existing old buildings to modern smart grids. Additionally we aim at a rapid prototyping solution (low design time) that promises to alleviate the time-to-market pressure and reduce the cost of installation as it does not require additional, expensive infrastructure.

In accordance with these requirements, throughout this chapter we introduce a plug&play solution which does not require detailed modeling of the building's infrastructure and dynamics. In fact, it's applicable in a wide variety of buildings as it learns the building's behavior using the information gained from the environment

and it reduces the complexity in order to be part of an embedded Smart Thermostat. We propose a novel decision making framework for supporting the building's cooling/heating control. For this purpose, both thermal comfort and energy are taken into account constructing a multi-objective optimization problem. In order to support the tasks of our Smart Thermostat, fast yet accurate mechanisms for computing the temperature set-points based on an Supervised and Reinforcement Learning, are introduced. This design, in terms of the machine learning model architecture and training, makes it feasible to compute the best thermostat's set-points that lead to minimum cost according to weather conditions. Experimental results, using popular simulation software (EnergyPlus), on a real building block in Chania (Greece) highlight the effectiveness of this work. According to the experimental analysis, the introduced solution achieves comparable performance (in terms of the computed temperature set-points) compared to relevant state-of-the-art approaches that are completely specified to this buildings. Additionally it should be mentioned here that the proposed method does not require any prior information and exhibits significantly lower computational complexity.

The rest of this chapter is structured as follows: Sect. 10.2 formulates the problem at hand, while Sect. 10.3 describes the related work and current approaches to the problem. After providing a clear problem instance in Sects. 10.4, 10.5 provides the technical background that is considered necessary in order for the reader to have a clear view of the aspects that will be discussed afterwards. The experimental setup is presented in Sect. 10.6. Section 10.7 presents our approach to the problem. More precisely an additional mechanism in order to support on-line learning and retraining is proposed and then the reinforcement learning inspired approach for supporting the tasks of a Smart Thermostat is presented. Finally, in Sect. 10.9 we draw the conclusions of this chapter.

10.2 Problem Formulation

The concept of smart buildings has been around for many years. This infrastructure enables real-time monitoring and reaction, in order for the system to be self-adjusting, while approaching an optimal state. Nowadays, a number of electric utilities, such as market-driven pricing, renewable sources etc are available. Since the building must remain balanced at all times, novel techniques that guarantee efficient building-to-microgrid, as well as microgrid-to-grid integration have been studied [33].

In Fig. 10.1 the template of a modern smart grid is depicted. Assuming that a number of renewable power sources are available, their usage could reduce the building's energy cost. If the available power from renewable sources is not enough to meet the occupants' demands, additional electricity can be purchased from the grid (according to the available funds (AF). Otherwise, the spare energy can be either stored in batteries, or sold to the grid (which increases the value of the AF). The decision making relies on the pricing, the batteries' capacity and the estimated building's demand.

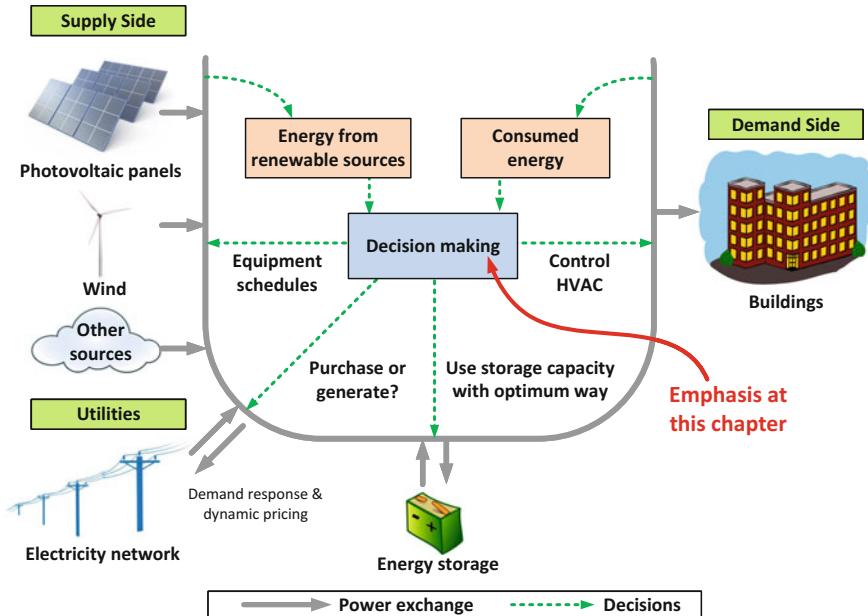


Fig. 10.1 Overview of micro-grid problem formulation

Buildings with no generation capabilities are simpler cases. There is just the energy purchased from the grid that covers the building's needs. Here a proper decision making mechanism can improve the performance as it focus on minimizing this energy while maximizing or keeping occupant's comfort at a desired level.

In this chapter, emphasis is given to the Decision Making Mechanism, which is responsible for controlling the thermostat's set-points that make up the configuration of the HVAC system. These selections are performed by satisfying the objectives of energy saving, and thus minimizing the cost of buying energy from the grid, and maximizing the occupants' comfort, which is the main goal of the HVAC system.

10.3 Related Work

The problem of deciding upon the configuration of smart thermostats, which is tackled in this chapter, has attracted the interest of many researchers over the years. In this section, first we will describe the general techniques that are usually employed for this type of control. We will present the advantages and disadvantages for using them in the problem formulated previously. Afterwards a special study of the current state-of-the-art approaches, developed recently, will be presented.

10.3.1 HVAC Control Methods

The first approaches to this problem were simple ON/OFF and PID controllers [25, 31]. However this type of controllers, due to their simplicity, are not capable of optimizing metrics such as energy or thermal comfort, and they usually lead to inconsistent results. However they are still used for giving a very simple solution to the problem, or for controlling some individual components of the HVAC system [1, 19].

Pursuant to literature there are two ways of deciding upon the configuration of systems like the one examined in this chapter [17]. The first one is the online decision-making, while the second one is the Model Predictive Control (MPC). Each of the two ways has a number of advantages and disadvantages and hence a detailed analysis is required in order to follow the way that fits each problem better.

The online algorithms usually require much shorter design time. Thus they can provide a more generic rapid prototyping solution compared to MPC methods. However MPC methods are usually more efficient, especially in cases where the control was designed along with the system and usually lead to more robust controllers, while the usual “black-box” approach of machine learning on-line methods is sometimes criticized [1]. An additional advantage of online methods is the fact that are more reactive to real-time conditions, whereas the accuracy of MPC techniques is occasionally affected by the precision of the weather forecasting and building dynamics models.

MPC control techniques have been successfully applied in a wide range of related or similar non-linear applications [34, 36], including HVAC system control [1]. In most cases the design of the controller requires extensive analysis of the system, which leads to high-dimensional mathematical problems [19] that can not be generated on-line due to high computational power. As a result a great amount of design and customization time for every different type of system and building (detailed experimental and mathematical analysis) is needed. This fact creates problems especially if we take into account the tight time-to-market pressure, that imposes the need of rapid prototyping solutions. Thus, MPC methods can not support real time design and plug&play application but they rely on simulating the impact of different control strategies by moving forward in time. MPC is better for controlling low-level processes and components of HVAC systems that have been modeled at the design phase of the system and are not affected by the building’s behavior.

Nonlinear control theory techniques can lead to very good results [5] but usually their computational requirements create obstacles for implementing as a part of smart thermostats. Furthermore, stochastic methods, for example Monte Carlo, can also lead to very impressive results for complex problems that include energy market and HVAC behavior [39]. However, taking into account the increased complexity that imposes a significant overhead to their employment, they can only be part of the BMS (Building Management Systems), that are included mainly in large buildings (offices, hotels, public buildings). Additionally these methods may also need models, or simulations of the building in order to search for solutions efficiently. As a result

these solutions are out of the scope of this chapter, as they can not be used for the designing of a lightweight, plug&play controller.

For the aforementioned reasons, and more precisely the need of rapid prototyping and applicable solutions on existing buildings, the need of designing adaptive controllers appeared. Embedded smart thermostats will play the key role to alleviate this necessity and consequently a more generic way to face the problem of efficient HVAC control is required. Therefore, in order to solve this problem various heuristic approaches that have been already studied, use more computational efficient and sophisticated methods, usually relying on fuzzy logic or machine learning. Some examples of these methods are artificial neural networks [30], genetic algorithms [27], fuzzy rules [2, 12] or combinations of these techniques [17].

Fuzzy rules [44] alleviate the necessity of a detailed mathematical model, by the utilization of a fuzzy approximation scheme. The controller follows a (usually predefined) action plan according to the information received by the environment. This plan is stored and described in the fuzzy rule base of the system. Sometimes an additional component, usually based on genetic algorithms, is employed in order to support, tune, optimize and facilitate the fuzzy controller [3, 28].

Supervised machine learning techniques such as Artificial Neural Networks (ANNs) [8], are recently gaining a lot of attention, due to the fact that they do not require a detailed study of the underlying dynamics of the building. Contrariwise, they can be trained, basing on historical data and learn the behavior of the building's physics. Due to this inherent ability, these methods can offer rapid solutions in a wide variety of buildings, taking into account a plethora of parameters measured by sensors as well as user preferences feedback [32].

Although these techniques are in-line with the model-free controller idea, they have a number of limitations. Machine learning models usually need long time to be trained and calibrated and they are difficult to implement in practice, especially as a lightweight plug&play solution, while fuzzy rules create fuzzy classes of some parameters and as a result they are not able to learn building's behavior in detail, in order to react on real-time dynamics. Therefore either a stage of "pre-training" is performed based on historical data of the specific building that they target to, or building modeling tools (e.g. EnergyPlus, Modelica) at initial stage are used.

A very new technique that turned out to be very popular these days is the Reinforcement Learning. Reinforcement Learning promises to give a solution by continuously learning through the results of different inputs in the system. This is achieved by matching each action to a reward that accrues by the evaluation of the produced output. Several state-of-the-art approaches use reinforcement learning for HVAC control [6, 16, 49]. It is worth mentioning that in [6] it is referred that commercial thermostats are rumored to use similar techniques in order to learn occupant's preferences standing on their manual configuration, but of course they have never published their algorithms in detail. Usual criticism to this approach is the human factor of defining rewards, the instability and the bad results of the system at the beginning phase and the potential requirement of long time for the system to learn [1].

In order to face the necessity of a plug&play solution, we might conclude that emphasis has to be given on a decision making technique that supports on-line learn-

Table 10.1 HVAC control methods

	Optimization	Design time	Model free	Plug&Play	Support real time	Building learning	Complexity
ON/OFF	No	Low	Yes	Yes	No	No	Low
PID	No	Low	Yes	Yes	No	No	Low
MPC	Yes	High	No	No	No	No	High
Fuzzy	Partially	Medium	Partially	Partially	Partially	No	Low
Stochastic	Yes	Medium	No	No	Partially	No	High
Superv. learn	Yes	Medium	Partially	Partially	Yes	Yes	Low
Reinfor. learn	Yes	Low	Yes	Yes	Yes	Yes	Medium

ing by receiving information from the environment, striving for rapid prototyping. For those reasons we aim on supervised learning methods, with additional optimization in order to get over their limitations, or on reinforcement learning techniques that are formulated in a proper way in order to solve our multi-objective problem efficiently and without any prior information.

Table 10.1 summarizes the aforementioned characteristics of each technique. It should me mentioned here that this table is constructed from our problem formulation (lightweight, rapid and plug&play solution) point of view and selectively includes the characteristics that are important for this specific approach.

10.3.2 Current Approaches

During the last years various approaches have been developed to face the problem of HVAC control efficiently.

There are several works that try to optimize energy. Some of them take into account the energy market, trying to satisfy a desired threshold set by users. They try to satisfy this threshold either by controlling the HVAC system [51] or escaping from the limits of available thermostat choices by choosing a purchase-bidding strategy for the building [37]. The first approach [51] uses a simulation program in order to develop a linear regression model that is related only on temperature difference, while the second one [37] assumes a full model for estimating energy consumption, based on modeled building parameters. Additionally the second technique uses a computationally expensive Monte Carlo approach. Another approach focuses on optimizing the energy while keeping the comfort unchanged [18].

On the other hand a big number of proposed solutions are attempting to serve occupant's preferences standing on their manual modifications on temperature set-points. So they take into account basically the thermal comfort. These approaches attempt to build a schedule, based on which they lead to energy savings by avoiding

unnecessary adjustments, by normalizing fluctuations and by turning off the HVAC when the zone is not occupied. In order to achieve this, some works ask the user to identify the comfort zone manually [7, 13]. Some other approaches construct a temperature zone that satisfies the occupants [9].

According to the approaches described beforehand, in the majority of the cases the controller is focused on optimizing only thermal comfort or only energy. Some other approaches try to optimize just one of the metrics, keeping the other in an acceptable range. However, we aim to take into account both energy and thermal comfort as a multi-objective optimization problem. Inline with this direction, [4] proposes a control method that comprises energy with a comfortable lifestyle and provides a solution to the whole Smart Home tasks scheduling with impressive results. This work uses a detailed model of the building (wall insulation etc) and a defined thermal comfort model.

A low cost and flexible solution to the smart thermostat problem is devised in [17]. In this work Neural Networks coupled with Fuzzy rules are used. However the solution employs a NN that is pre-trained using a detailed design space exploration. The results highlighted that a machine learning technique can be very efficient as it achieves near to optimal results but with significant lower computational complexity.

Reinforcement Learning has been used in some recent works. An examination of the application of reinforcement learning on smart thermostats has been introduced in [6]. In this work energy cost corresponds to a reward of -1 when the HVAC is on but no actual energy costs are integrated. Additionally in this chapter the controller tries to achieve a predefined temperature by occupants. Another approach based on reinforcement learning formulates a reward function that focuses only on minimizing energy cost taking into account a desired range for the temperature [49]. Additionally, this work often violates the range that it defined and does not consider more realistic thermal comfort values. Finally [16] is the only work on reinforcement learning that comprises both energy and thermal comfort in construction of the reward function. However it seems that the comfort exceeds the acceptable limits for a lot of periods, no details about the implementation is given and some prior information such as the maximum energy consumption is needed.

As a result of the previous presentation, we might claim that there is a need of focusing on a solution that solves a multi-objective problem that take into account actual energy costs and thermal comfort retrieved from users or thermal comfort models. This solution needs to be lightweight, flexible and applicable to existing buildings without any prior information.

10.4 Problem Instantiation

The problem we tackle throughout this chapter deals with the control of HVAC systems, through proper decision-making mechanisms implemented in smart thermostats.

The control of an HVAC system is deemed to be successful when it leads to thermal conditions that satisfy the occupants. As mentioned in the previous section this goal is enriched with the energy consumption minimization. Determining the temperature set-points that are optimal according the aforementioned goals can not be considered trivial. More specifically energy and comfort are conflicting quantities that are affected by building dynamics, weather conditions, energy market and a large number of other factors. As a result a proper problem instantiation is needed and is introduced in this section.

Our approach is based on optimal control, the controller aims to minimize a certain cost function. Considering that the two orthogonal metrics that comprise our problem, namely the energy consumption and the thermal comfort, are in conflict with each other, the derived solutions are quantified according to Eq. 10.1. Assuming a building consisted of k thermal zones, each time-step t the *energy cost* for heating or cooling the i th thermal zone is $E_i^G(t)$ and the resultant thermal comfort in the form of *dissatisfaction* is $C_i(t)$. As mentioned before, no single optimal solution can be found and consequently a trade-off (tr) that determines the compromises among the conflicting metrics is used.

$$Cost(t) = \sum_{\forall timestep} \left(tr \times \sum_{i=1}^{i=k} \left(E_i^G(t) \right) + (1 - tr) \times \sum_{i=1}^{i=k} \left(C_i(t) \right) \right) \quad (10.1)$$

The target use-case corresponds to five neighborhood buildings, as they are summarized in Table 10.2. Without loss of generality for the introduced solution, we consider that people occupy the buildings only during the operating hours. Each building is equipped with a number of weather sensors that monitor indoor/outdoor air temperature, humidity and radiant temperature values. It's worth mentioning that these sensors are rather simple and usually part of smart buildings, but also affordable and easy to install on older buildings. Furthermore PhotoVoltaic panels are also employed in favor of minimizing the energy cost. If the energy requirements of the building exceed the available energy from the PV, the building can interact with the main grid in order to purchase energy. In the same way energy can be sold to the main grid, when surplus energy is available.

Table 10.2 Summary of building properties

Building	Surface area (m ²)	Thermal zones	Operating hours	Warming-up pre-cooling	Random occupancy
#1	350	8	6:00am–9:00pm	No	Yes
#2	525	10	8:00am–9:00pm	Yes	Yes
#3	420	10	8:00am–5:00pm	Yes	Yes
#4	280	6	7:00am–8:00pm	Yes	Yes
#5	228	4	6:00am–6:00pm	No	Yes

The energy cost, mentioned beforehand, is formulated by Eq. 10.2. More thoroughly, in case that the building's energy requirements ($E_i(t)$) exceed the energy provided by the PV panels ($E_i^{PV}(t)$), the excessive demand is met by purchasing additional energy from the grid at the current trading rate $P(t)$. On the other hand, if the available energy from PVs ($E^{PV}(t)$) suffices to meet the desired comfort for the occupants, only renewable sources are used (zero energy) while the rest of the produced energy is sold to the grid at the current trading rate.

$$E_i^G(t) = \begin{cases} \left(E_i(t) - E_i^{PV}(t) \right) \times P(t), & \text{if } E_i(t) \geq E_i^{PV}(t) \\ 0, & \text{otherwise} \end{cases} \quad (10.2)$$

Experimental results evaluate the efficiency of the introduced framework. The test case was developed using the EnergyPlus suite [20]. The studied buildings grid is modeled in a detailed manner¹ [15, 20], while the employed weather data correspond to publicly available information collected in 2010 [48].

10.5 Technical Background

This section contains a brief description of the technical background that is needed, in order the reader to understand better the description of the problem and the details of the decision-making mechanism. The reader should be familiarized with these concepts before presiding with this chapter.

10.5.1 Thermal Comfort Models

Thermal comfort measures the satisfaction of people in a thermal environment. Thermal comfort can not be measured directly and therefore can only be estimated using a number of parameters. For this purpose there are some well-known models and a large variety of research approaches for improving existing techniques through feedback from the occupants or other statistical and machine learning methods. The most recognized methods for measuring the thermal comfort are the Predicted Mean Vote (PMV), scale from cold (-3) to hot (+3) and the Predicted Percentage of Dissatisfied (PPD). The basic inputs of the thermal comfort models are [23]:

- Air temperature
- Mean Radiant Temperature
- Relative Humidity
- Relative Air Velocity

¹The modeling of the building was part of the PEBBLE FP7 project (<http://www.pebble-fp7.eu>) funded by the European Commission under the grand agreement 248537.

- Metabolic Rate
- Clothing Insulation

The air temperature and humidity are the most important values and can be captured by sensors. The mean radiant temperature is the temperature that surfaces release and depends on the material. It can also be measured by sensors, but usually there are some approximated values given. Air Velocity can be affected by the HVAC (for example by the fan speed) but this value of closed thermal zones in buildings is also usually approximated between some limits. The metabolic rate depends on the individual activity level and the environmental conditions and its values are selected according to the building, for example $met = 1.1$ corresponds to people sitting and writing/typing in an office [23]. The clothing insulation is a value that depends on the season and the type of the building, for example usual values for an office is 0.8 in winter (suit-shirt-trousers), 0.6 in summer (shirt-trousers). Fanger's comfort model was first published in 1967 by P.O. Fanger and then in 1970. P.O. Fanger used heat balance equations and empirical studies about skin temperature to define comfort. It was the first thermal comfort model developed.

10.5.2 Machine Learning - Support Vector Machines

Machine learning is a sub-field of computer science. Using the term “learning” we consider:

- The ability of gaining information from the environment without deterministic programming (adding new elements and functions)
- The inherent ability of the system to be adjusted and self-improved without reprogramming

In *supervised learning*, by receiving as input known observations (input-output) the algorithm produces a general rule that finds the output of future inputs. In other words the model tries to produce a function that describes the given data.

Support Vector Machines (SVMs) are supervised learning models that analyze data for classification and regression analysis [26]. SVMs are part of supervised learning. The method was first designed by Vladimir Vapnik and his colleagues in 1963 (only linear classification) but in 1992 Bernhard E. Boser, Isabelle M. Guyon and Vladimir N. Vapnik suggested the kernel trick for nonlinear classifiers. The basic idea of SVMs is that given a set of data (observations) that are labeled, belonging in one of two categories, there is a hyperplane that splits the data in two areas and helps to categorize new data (the data are represented as points in n-dimensional space, where n is the number of features) [26].

10.5.3 Reinforcement Learning

In line with the lack of a detailed modeling of the HVAC system, as was assumed in the problem's description, a deterministic approach for decision making is restricted by approximations regarding the system's behavior, that have to be reached at runtime. Thus, the definition of deterministic functions that link each state to a specific outcome is unfeasible. For these type of problems Reinforcement learning (RL), a machine learning approach, has attracted more and more interest in recent years. Successful applications include backgammon [47], driving a real robot car [42] and playing a variety of video games [38]. Tasks of greater difficulty have been tackled as well, in fields like neuroscience and psychology [45].

A Reinforcement Learning problem, includes a set S of states, a set A of actions, and a function $r : S \times A \rightarrow R$, called the reward function. At each instance of the problem, an action $a_i \in A$, which will lead from $s_i \in S$ to a new state s_{i+1} is chosen. We assume that A is finite. The tuple (s_i, a_i, s_{i+1}) is called a *transition*. A real value r_i is assigned to each of the transitions. The smart agent's goal is to find a series of transitions t_1, t_2, \dots, t_n that maximizes the R value (called *the return*) in Eq. 10.3. The $\gamma \in [0, 1]$ is a discounting factor that controls the importance of future rewards and ensures convergence of the sum in Eq. 10.3 when $n \rightarrow \infty$.

$$\text{Maximize } R = \sum_{i=0}^n \gamma^i r_i \quad (10.3)$$

Given a state s and an action a , the action-value of the pair (s, a) is defined by Eq. 10.4, where R now is the random return associated with first taking action a in state s , thereafter. As a result, estimating Q plays the most important role on the overall performance as it quantifies the efficiency of the possible alternative selections.

$$Q(s, a) = \mathbb{E}[R|(s, a)] \quad (10.4)$$

In this chapter, Reinforcement Learning is employed via Neural Fitted Q -iteration (NFQ), which has proven successful in real world applications [41]. NFQ uses a multi-layer perceptron (MLP) in order to approximate the Q function. The agent acts ε -greedily on each state encountered based on its current approximation of the Q function.

10.6 Experimental Setup and Compared Techniques

10.6.1 Simulation Testbed

The proposed controller will be evaluated and tested using a well-known simulation and testing framework, that is depicted in Fig. 10.2. This framework is provided in

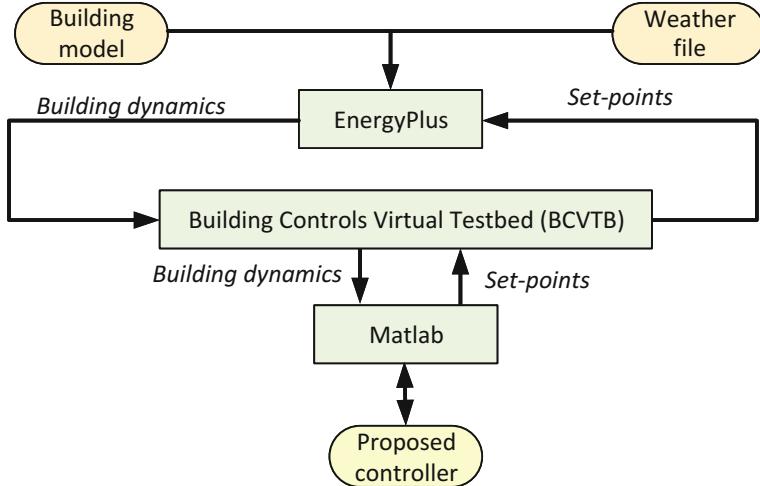


Fig. 10.2 Simulation testbed for proposed controller evaluation

its completeness by [29, 43] and is used in a variety of works [17, 35]. The building dynamics and all useful information (sensor data) for the controller are outputs of the EnergyPlus suite [20]. The controller receives these data and provides the set-points through MATLAB. For the data exchange, the BCVTB (Building Controls Virtual TestBed) [50] is used.

10.6.2 Methods Used for Comparison and Evaluation

We quantify the efficiency of the introduced framework to design a flexible decision-making mechanism that targets Smart Thermostats against different approaches. The reference solutions to this comparison are the Ruled Based Configuration or Rule Based Control (RBC) and the well-established *Fmincon* solver [11].

Most of the common thermostats are configured by the occupants to some set-point, which don't neither ensure the quality of the thermal comfort results nor the energy consumption. Therefore in some offices or large commercial buildings, a constant set-point during some periods is selected as the one that leads to better performance. This approach, according to which the HVAC system is configured to a static set-point, is called Rule Base Control (RBC).

Fmincon solves the problem using iterative simulations, while the objectives (energy and comfort) are known a priori through detailed modeling of the buildings dynamics and based in weather forecast. More precisely, using this method the control procedure moves forward in time and by simulating different set-points and HVAC configuration it finds the possible outcome of applying different strategies. Consequently, the efficiency of this method is limited by the accuracy of the model-

ing of each particular setup, which is an ineffective online solution. For our case in this chapter we assume that both the building's model as well as the weather forecasts are 100% accurate, due to the fact that we evaluate our controller at the same "simulated" model. This means that the results of the *Fmincon* solver are considered as the *optimal* results in the context of this chapter.

10.7 Proposed Decision Making Mechanism for Smart Thermostats

The proposed smart thermostat tries to solve the problem of optimizing both energy and thermal comfort dynamically. The basic concepts that the framework is consisted of, will be presented at the following paragraphs.

10.7.1 The “Time-Step”

The control of the smart thermostat is a discrete procedure, which means that there is an iterative control cycle. This cycle is repeated with a time-step until the end of the schedule (when the HVAC system is turned off). We adopt a 20 min time-step, which means that the thermostat is configured once per 20 min. We claim that choosing this range will lead to faster learning, because in that way the smart agent collects a greater amount of experience every day. Moreover, a small time-step guarantees that if the controller makes a mistake, it will not affect the occupants for long.

10.7.2 Data, State and Actions

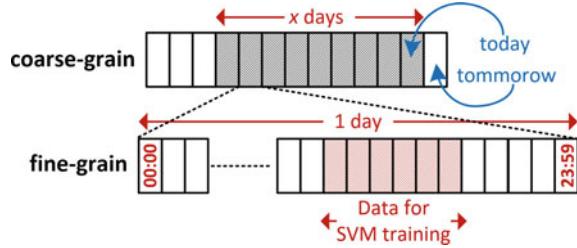
Each time-step, the control cycle starts with collecting of data acquired by:

- Weather sensors (indoor/outdoor temperature, humidity, solar radiation)
- Occupant's activity (e.g. existence, number, activity)
- Building's sensors (data from energy metering devices)

It's worth mentioning that these sensors are rather simple and usually part of smart buildings, but also affordable and easily installable on older buildings.

The data and the outcome of these sensors are stored temporary to support the task of learning (historical data). Furthermore these data at each time-step are used in order for the controller to retrieve the *state*, S . For supporting the learning task, the definition of the state has to contain all the information that satisfy the Markovian property. Therefore the state signal has to describe both energy consumption and thermal comfort (the metrics that we want to optimize).

Fig. 10.3 The concept of sliding windows for dataset manipulation



The term *action* refers to the temperature set-point that is assigned to the smart thermostat at each time-step.

10.7.3 The Sliding Window Concept

As mentioned in Sect. 10.3 we aim to find a way for the Smart Thermostat to learn without any prior information and to be calibrated in order to adapt to the behavior of the building. Therefore two complementary mechanisms, namely the coarse- and the fine-grain sliding window are used for properly manipulating the amount of data stored. This concept is proposed and evaluated in [35]. According to these mechanisms, instead of storing the whole row of data that sensors give, the controller stores only the data that were acquired during the last x days (coarse-grain sliding window). Additionally, we gain a further improvement by selectively emphasizing only to a specific duration of the day, by using the fine-grain window. To sum up, instead of using the entire batch of historical data, only a small subset is used. The windows sizes are dynamically adjusted in order to better support the learning procedure and to match the available resources. This concept is depicted in Fig. 10.3. As we will show in the next paragraph this concept enables the ability of periodically retraining on-board and achieves to deliver close to optimal results with significantly lower computational requirements.

10.7.4 Energy Estimation Using SVM

We tried to estimate Energy consumption using the Support Vector Machines mechanism. Similar to relevant machine learning algorithms, SVM is trained usually based on a large training set at the beginning, in order to construct a generalized model that will be used to estimate or predict the target value. This training imposes considerable computational and storage complexity. In this work we apply the introduced sliding windows in order to allow retraining to improve system efficiency. Note that this is not the usual concept of machine learning. However the main contribution of this approach does not rely on the usage of SVM itself, but rather on designing an

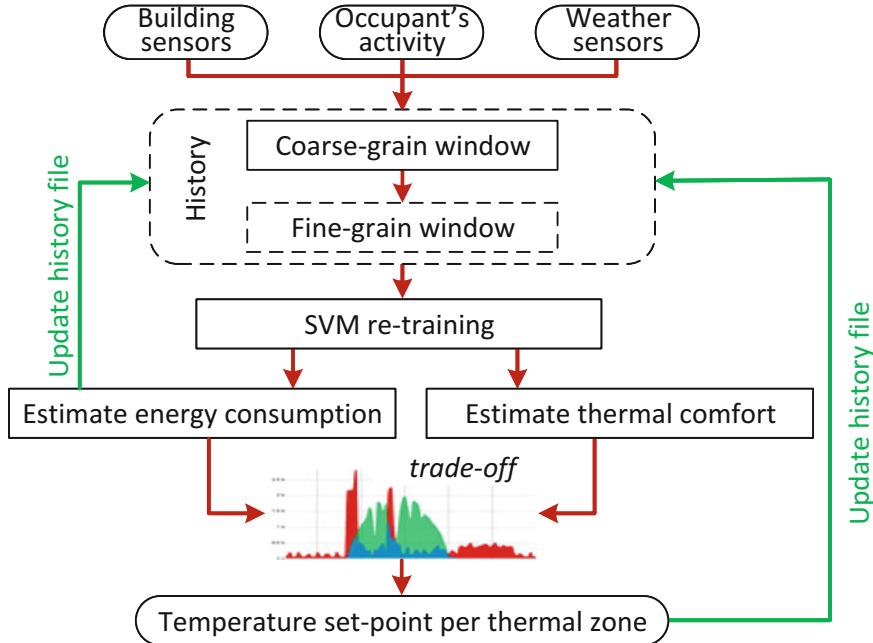


Fig. 10.4 Proposed windows-SVM framework [35]

efficient low-complexity plug&play mechanism and highlight the efficiency of the proposed sliding windows concept. The complete proposed framework is depicted in Fig. 10.4.

The output of our mechanism is a model for estimating the energy consumption per thermal zone. Since the efficiency of the proposed decision-making technique relies on the estimation of the energy (this information is not known a-priori), Fig. 10.5 evaluates the accuracy of the prediction compared with the actual energy consumption gathered from the sensors. For demonstration purposes, only active time-steps of a summer week are reported. According to this analysis, the windows-SVM mechanism leads to negligible errors.

10.7.5 First Results and Limitations

Figure 10.6 evaluates the efficiency of the aforementioned framework, when used to minimize cost (Eq. 10.2), for a representative summer day. Depending on user's priorities, the mechanism could lead to minimum energy consumption ($tr = 1$), maximum comfort ($tr = 0$), or any trade-off between the two metrics. Without loss of generality we chose a balanced configuration, where $tr = 0.5$. We see that the proposed mechanism achieves to improve the cost as compared to RBCs by 27% on

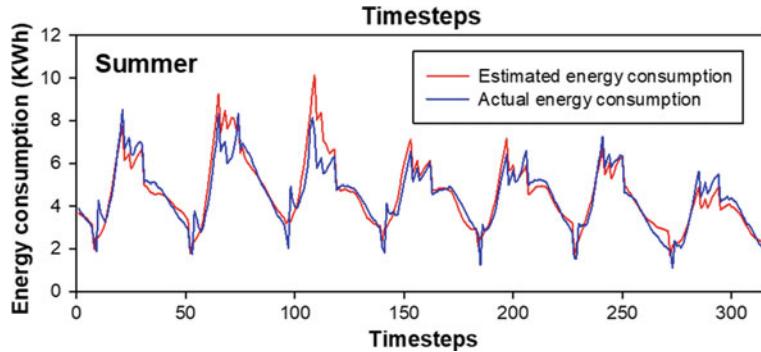


Fig. 10.5 Evaluation of energy estimation mechanism [35]

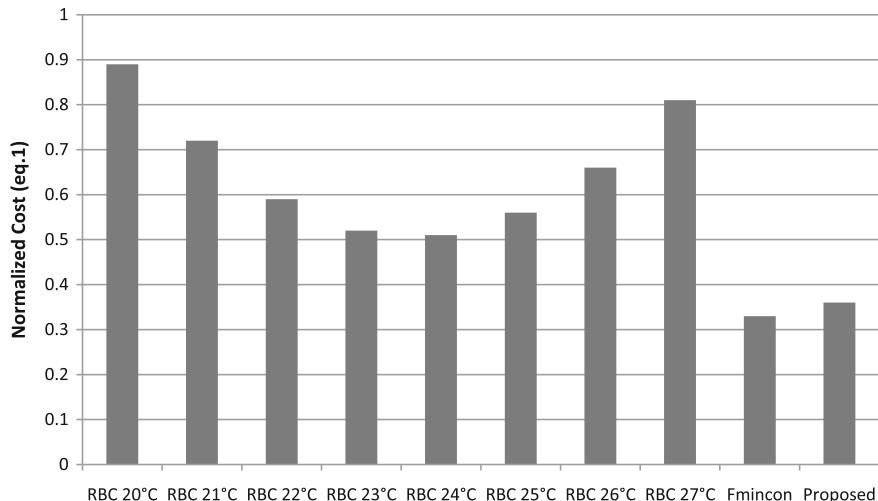


Fig. 10.6 Comparison among different strategies

average. Furthermore the result that the set-points produced by the proposed mechanism achieve, is very similar to *Fmincon* solver [11] (4% worse), which results are considered as optimal as we mentioned in Sect. 10.6.2. Such a solver is not possible to be implemented as part of a Smart Thermostat due to its huge computational complexity (10^{14} cycles instead of 10^8 of our technique). Additionally this solver requires an accurate simulation of the building and accurate weather forecasts. In our case we assume that these models are 100% accurate, which would not be the case in a real application.

Although this technique seems to have superior performance and sets the first steps towards a plug&play, low-complexity solution it has a number of limitations. The basic limitation of this technique is the fact that some information has to be known a-priori. The range of the energy and the scaling has to be known in order

to normalize the cost function (Eq. 10.1) in a proper way that respects the user's priorities regarding the trade-off parameter tr . For example, if energy has a way bigger range than thermal comfort then $tr = 0.5$ would not lead to balanced results as only energy would be taken into account. Moreover well-known thermal comfort models were used, without considering user feedback. Finally this procedure has the risk of being trapped in a sub-optimal solution due to the absence of exploration. In the following paragraphs we are going to extend this framework to also face these limitations.

10.7.6 A Mechanism Inspired by Reinforcement Learning

The proposed framework aims to dynamically solve the optimization problem presented in Eq. 10.1. Inspired by Reinforcement Learning [45], we model our system using a set of states (S), a set of actions (A) and a reward function. Since maximizing a reward is equal to minimizing a cost, with the said cost defined as the negative of the reward, we will refer to c as the cost function for the rest of this chapter. The mathematical formulation of this problem is given by Eq. 10.5, while the minimization of total cost instead of maximization of the total reward, is the differentiator compared to conventional Reinforcement Learning problem.

$$\text{Minimize} : \sum_{i=0}^n \gamma^i c_i \quad (10.5)$$

The overall proposed framework for the controller is presented schematically in Fig. 10.7. Details about every stage of the controller are given at the rest of this paragraph.

The cost function evaluation is critical for achieving control of the HVAC. As stated, the cost function is composed of a weighted sum of objectives (see Eq. 10.1). Adopting ideas from [42], with respect to the constraints that must be satisfied for thermal comfort,² an action is deemed *terminal* (corresponds to a terminal cost of value \max_cost) if:

- the action leads to prohibitive results regarding the thermal comfort $PPD > 15\%$
- constraints were already unsatisfied $PPD > 15\%$ and the action further increased PPD value

Consequently, we quantify the quality of derived or candidate actions by formulating a cost function as shown in Eq. 10.6. E_{norm} and PPD_{norm} are the standardized values for energy and PPD respectively.

$$c = \begin{cases} tr \times E_{norm} + (1 - tr) \times PPD_{norm}, & PPD \leq 15\% \\ \max_cost, & \text{else} \end{cases} \quad (10.6)$$

²This threshold is the acceptable limit for buildings due to the EN15251 European standard.

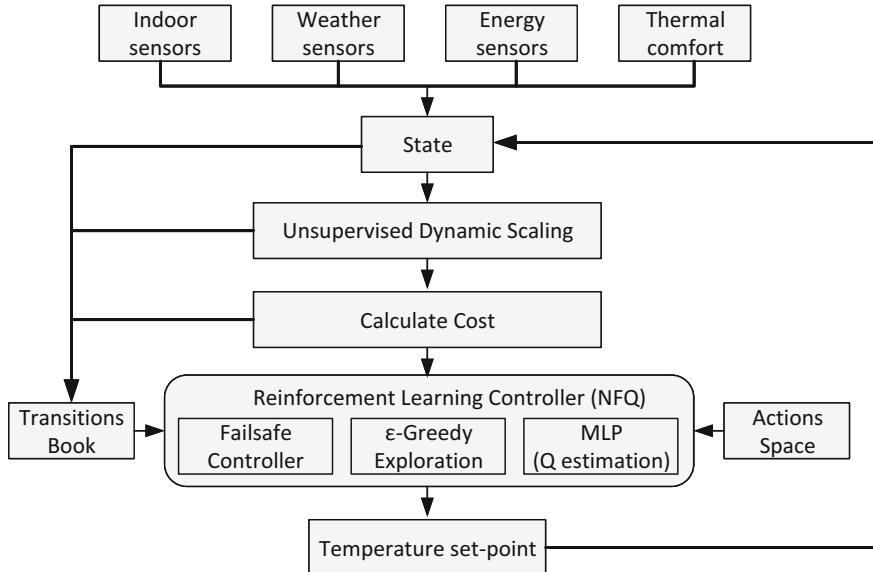


Fig. 10.7 Proposed framework for applying reinforcement learning on smart thermostat

When terminal costs surface, the following two procedures take place: Initially, the fail-safe controller takes action temporarily (for the next set-point) and then the learning model is re-trained (sliding windows concept is used here in order to improve training complexity). More specifically, the fail-safe controller chooses an action, which is more likely to lead to a better result in terms of thermal comfort. It rectifies the previous “sub-optimum” action. If $PMV < 0$ (see Sect. 10.5.1), which means that the room is warmer than it should be, the controller decreases the temperature by 1°C , otherwise it increases the temperature by 1°C .

A problem in online model-free control is the abundance of information regarding the data encountered. Energy consumption and thermal comfort belong in different scales, but they ought to be treated equally when computing the cost function. So an accurate scaling is needed and it is important to be achieved without any prior information. A satisfying solution, used in this work, is unsupervised dynamic scaling [10]. A running average and standard deviation are kept for both the energy consumption and the PPD. As new data arrive, the scaling parameters are re-computed, ensuring the scaling is up-to-date. The costs saved in Transitions Book (TB) are also renewed with every update of the scaling parameters.

Given a state and the available actions, the agent has to produce a set-point which will minimize the expected return (that is, the cumulative future costs in the time horizon defined by γ in Eq. 10.5). The value of γ is equal to 0.98 in our case. Due to the incremental nature of the thermostat’s actions, we desire set-points optimized with a long-term horizon in mind. In Neural Fitted Q-iteration, the Q function of Eq. 10.4 is represented in parametric form via the synaptic weights of an MLP. The

MLP weights are updated every time the agent has received a terminal cost. The patterns used for training the MLP are extracted from TB in the form of (s, a) (s :state, a :action) tuples. The targets, as defined by the NFQ framework, are given in Eq. 10.7. In the equation above, Q denotes the output of the current neural network.

$$\text{target} = c(s, a, s') + \gamma \times \min_a Q(s', a) \quad (10.7)$$

Every time, the agent has to decide whether it will exploit its current knowledge, or it will seek a possibly better solution. The agent's knowledge sources from transitions, things it has tried in the past. It cannot know the optimality of a certain action in a certain state if it never picks that action. This is the exploration/exploitation dilemma. In this chapter, it is dealt via ε -greedy action selection, with ε being self-regulated as described in [46]. The work cited defines time intervals in which "positive outcomes" are counted and then used to regulate ε . In this chapter's case, such positive outcomes are determined by the validity of the MLP's prediction. This validity is represented by the Temporal Difference (TD) error given in Eq. 10.8. A decision of the agent is thus deemed positive if $|TD| > 0.15$. This bound, on the one hand, is small enough to represent an accurate approximation. On the other hand, it is elastic enough in order to encourage early stages of learning. The association of the TD error with the agent's exploration mechanism was inspired by [24].

$$TD = c(s, a, s') + \gamma \times \min_a Q(s', a) - Q(s, a) \quad (10.8)$$

10.8 Experimental Results

Figure 10.8 evaluates the proposed controller's efficiency against RBC values, for a typical summer day, concerning the two basic metrics: consumption and thermal comfort. The controller actually verges on the ideal comfort level for $tr = 0$ and leads to less consumption for $tr = 1$. For the first case the proposed controller achieves up to up to 41.8% mean comfort savings and for the second one 59.2% mean energy savings on average.

Figure 10.9 show the proposed controller's ability to adjust in the trade-off's value. It is also apparent that the thermostat's performance improves over time. There results evaluate the contribution of dynamic scaling in this work, in order to achieve a "real" trade-off between the two metrics: Energy consumption and thermal comfort.

Finally, we quantify the efficiency of the introduced framework to design a flexible decision-making mechanism targeting Smart Thermostats, able to optimize both energy consumption and thermal comfort. Figure 10.10 quantifies the actions taken by the proposed framework in terms of the total annual weighted cost against RBCs and F_{mincon} .

According to Fig. 10.10, the proposed framework achieves superior performance against RBCs, as the total cost is reduced from 41% up to 147%. Additionally, the introduced solution exhibits comparable results against F_{mincon} . However, the

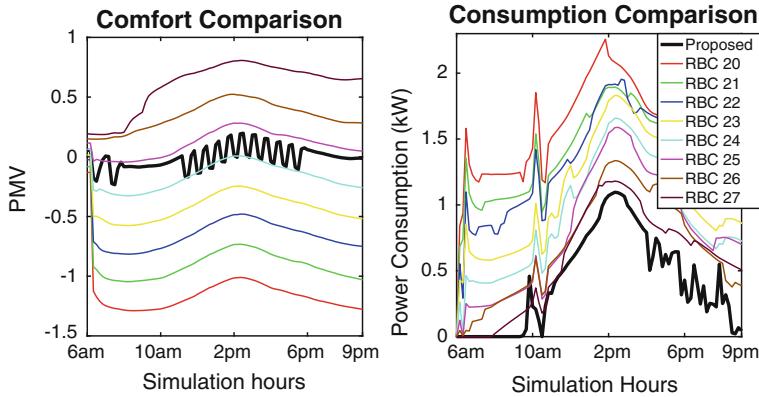


Fig. 10.8 Daily performance of proposed controller against RBCs (left $tr = 0$, right $tr = 1$)

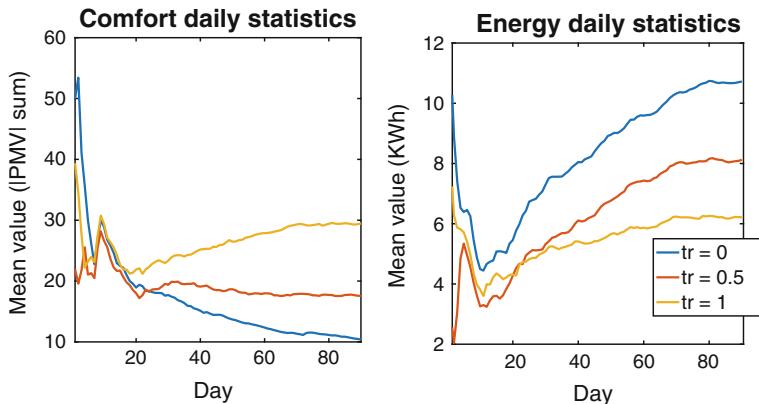


Fig. 10.9 Variation of mean scores for different values of trade-off (tr)

assumptions of *Fmincon* solution, described in Sect. 10.6.2 limit the applicability of the overall system.

10.8.1 Hardware Implementation

Apart from the efficiency in term of optimizing energy and thermal comfort, the computational complexity for computing these configurations is also crucial. In order to study in detail this parameter, we need to evaluate the run-time requirements of this problem, since our approach targets low-cost Smart Thermostats. Our target platform is based on an ARM Cortex A8 [14] operating at 600 MHz, using 1 GB of system memory. While our framework consists of various building blocks, the most computationally intensive one is the online re-training of the machine learning model,

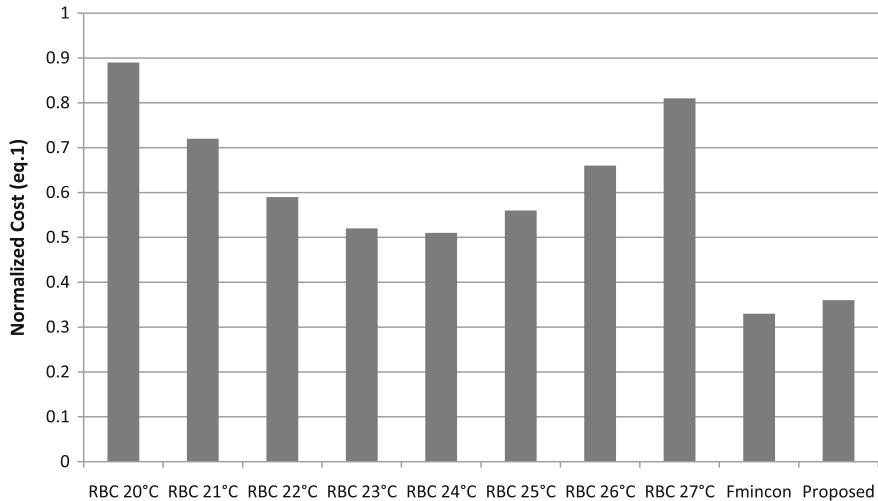


Fig. 10.10 Evaluation among different strategies (annual results)

which enables the estimation of the objective functions. Using the concept of sliding windows we can ensure that our framework has a worst execution time of under 1 s. Taking into account that the time-step duration in which the Smart Thermostat is called upon to make a decision is 20 min, these results emphasize the feasibility of the proposed controller's implementation on a low-cost embedded platform.

Comparing these results with the execution time of *Fmincon* solver, which needs about 5×10^{14} execution cycles, or 12 h execution time, for simulating an 1-day building's operation experiment in Intel i7-6700K@4GHz, we might conclude that our approach performs comparable results but exhibits significant lower computational complexities and thus it can be part of a Smart Thermostat.

10.9 Conclusion

Cooling/Heating control plays the most important role in total building's energy consumption. Furthermore, offering comfort for the occupants is the main goal of HVAC systems (Heating Ventilation and Air Conditioning). Smart Thermostat are called to offer solutions both in modern smart grids as well as in existing old buildings. As a result a design of a low-cost, flexible and high-quality Decision Making Mechanism for supporting the tasks of a Smart Thermostat is needed. In this chapter, a detailed description and formulation of the problem is provided. Afterwards a number of current control techniques and approaches are presented, as well as their advantages and limitations. Finally a method towards flexible plug&play Smart Thermostats is proposed and its efficiency is highlighted through experimental results in EnergyPlus suite.

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Chapter 11

A Framework for Supporting Energy Transactions in Smart-Grid Environment



Kostas Siozios

Abstract With the increasing connection of Distributed Energy Resources (DER), traditional energy consumers are becoming prosumers, who can both consume and generate energy. This enables Peer-to-Peer (P2P) energy trading, where direct energy trading between small-scale DERs takes place. This chapter introduces a P2P platform based on market theory for supporting the energy trading in micro-grid environment. Rather than employing a centralized auction mechanism, the introduced solution follows a distributed approach, where auctions are initiated ad-hoc by energy producers. Experimental results based on real data validate the efficiency of proposed framework, as we achieve considerable energy savings.

11.1 Introduction

The demand for energy efficiency, the deployment of renewable energy sources and the onset of smart-grid technologies, foretell that in the near future an increased number of building facilities will become active participants in the energy market. From the system's point of view this will lead to autonomous micro-grids with energy trading capabilities and flexibility in regard of shifting or reducing electrical loads as needed. A number of electric utilities (i.e., market-driven pricing), are already available even to the end users, where instead of having a flat-rate (24 h a day, 7 days a week) pricing scheme, variable pricing mechanisms exist allowing the cost per kilowatt-hour may change based on the day, time of day, or a more dynamic event, such as the weather conditions or the expected load requirements [1].

The dynamic pricing is a concept that has immense possibilities for application in the energy sector, since it can be considered as a demand-side management tool that facilitates the offering of different prices at different demand levels, while it

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also supports producers postpone investment decisions by shifting peak loads from peak to non-peak hours [2]. Although academicians and researchers see the study of dynamic pricing of electricity as useful and interesting, however regulators, suppliers and customers have stayed away from large-scale deployment of this concept. This mainly occurs because there are concerns regarding the potential benefits over the costs of implementation and possible excessive high bill values to customers. Thus, the wide adoption of this scheme raises the question about how participants can benefit from such a competitive energy environment. Towards this direction, a recent analysis indicates the potential ways that dynamic pricing can be useful to customers in terms of monetary savings, while suppliers can benefit from the reduction in peak capacity investments, better planned operations and cost-reflecting prices [3].

The importance of energy trading has grown rapidly worldwide during the past decade as a result of increased energy consumption, as well as due to the market integration. Almost no country can cover its energy needs from its own sources today. Energy trading offers the possibility to ensure the needed supply of energy and protects from supply shortages and price fluctuations. For instance, regarding Europe there are more than twenty different energy exchanges. The most liquid exchanges are the European Energy Exchange (EEX) in Leipzig and the Nord Pool Spot/Nasdaq Omx Commodities in Oslo. There are two main markets within an energy exchange, namely the *spot market* for short-term trading, and the *forward market* where the physical delivery of, for example, electricity or gas takes place at a future date.

A key point for the wide adoption of this concept relies on the efficiency of energy transaction system. The question of how energy producers can benefit from a competitive environment has been raised recently and several approaches have been proposed. Typical solutions are based on a combined and coordinated use of power from renewable sources and energy storage technologies [4]. The main drawback of these approaches relies on the limited availability of utility-scale storage. Another class of solutions are using financial options as a tool for energy producers to hedge against generation uncertainty [5]. The orchestrator that supports the task of energy transactions is responsible for a number of decisions, such as the energy production and forecast, the bidding strategy, etc. Hence, effective control algorithms are absolutely necessary in order to optimize the overall system's behavior.

The mainstream way of deciding upon system's selections is to develop an orchestrator that provides either online decision-making [6], or system's configurations based on Model Predictive Control (MPC) [7]. Although MPC for nonlinear systems has been extensively analyzed and successfully applied in various domains during the recent decades [8, 9], it likewise encounters dimensionality issues: in most cases, predictive control computations for nonlinear real-time systems amount to numerically solving a non-convex high-dimensional mathematical problem whose solution may require formidable computational power. On the other hand, although online algorithms exhibit limited efficiency compared to MPC, they are reactive to real-time constraints (e.g., energy trading prices, current energy load, etc). Additionally, since online algorithms do not rely on simulation (e.g., move forward in time

to simulate the impact of control selections), it is more likely to be employed in commercial products.

The mechanism for deciding upon optimal selections is also of high importance in order to compute a solution that meets the constraints. A commonly used approach to tackle the energy trading problem is based on single objective optimisation [10]. Specifically, it uses a centralised approach, where an independent controller is in charge of solving the optimisation problem. Indeed, a trading model needs to evaluate the behaviour of all participants and incorporates their individual preferences. As the actions of one influences all the others, solutions based on game theory concept (dealing with the analysis of competitive situations, where the outcome of one participant does not only depend on their own strategy but also on the strategies of the others) is a commonly used approach to tackle this problem [11].

The increased computational complexity of the aforementioned solutions make them affordable only to enterprise environments, e.g., as part of a Building Energy Management (BEM) systems. However, recently there is an emerging need for solutions that are also applicable to accommodate residential buildings as well. Hence, decision-making algorithms able to be executed onto low-performance (and low-cost) embedded devices is upmost important. To manipulate the complexity overhead posed by the system's multi-objective optimization goal, various heuristic methods, such as the stochastic dynamic programming [12] and the genetic algorithms [13], have been proposed. Furthermore, methods that rely on empirical models [14], simulation optimization [15], artificial neural networks (ANNs) [16], SVM classifiers [17] and fuzzy logic [18] have also studied for similar problems. Although these solutions trades-off the quality of decisions with the associated problem's complexity, they are rarely adopted because they impose excessive training or customization phases. Additionally, none of the aforementioned algorithms address the design of a lightweight solution, able to be efficiently executed onto low-cost embedded platforms.

Apart from these, methods based on probability distribution, such as the stochastic models, are also applied to compute optimal bidding strategies for renewable power sources participating in the day-ahead or adjustment market [19]. Although promising, the previously mentioned solutions exhibit increased computational complexity especially for multi-dimensional auctions, where multiple goods (i.e., energy budgets from different sources) are allocated in each auction. Moreover, the signaling overhead from a continuous centralized auction is also notable as bidders have to submit bids repeatedly to reach an agreement, which makes the mechanism unsuitable for large-scale applications [20]. To overcome this drawback, P2P energy trading has also been investigated at the distribution network level. In [21], a paradigm of P2P energy sharing among neighboring micro-grids was proposed for improving the utilization of local DERs and saving the energy bills for all micro-grids.

Inline to this trend, we propose a framework for energy trading in micro-grid environment. The introduced solution relies on market theory and supports a number of auctions to be initiated ad-hoc in a distributed manner leading to increased scalability. Additionally, we have developed a hardware prototype of the proposed decision-making mechanism onto a low-cost, low-performance embedded device

(Raspberry Pi 3). During the hardware development phase, emphasis was given in minimizing the computational and storage complexity of the employed algorithms which realize the decision-making process. Additionally, as compared to similar approaches which mainly pre-request powerful processing and storage resources, the proposed framework is able to be executed sufficiently onto low-cost embedded devices. Experimental results highlight this superiority, as we achieve comparable results but with significant lower deployment cost.

The rest of this chapter is organized as follows: Sect. 11.2 discusses the related works in the domain of mechanisms for supporting the task of energy transactions. The employed case study is introduced in Sect. 11.3, whereas the proposed framework of supporting distributed energy transactions is discussed in Sect. 11.4. Experimental results that highlight the superiority of introduced framework is quantified in Sect. 11.5. Finally, Sect. 11.6 concludes the chapter.

11.2 Related Work

The European energy system is about to undergo a major transformation in the near future. In contrast to the trend for building centralised large scale electricity generation and distribution systems, a new energy landscape is emerging, where the system will be increasingly interconnected, but also more decentralised (centralised production work in parallel, and integrated with, decentralised production). Key drivers of this change are the 20–20–20 targets adopted by the EU [22], where the emphasis are on reducing CO_2 emissions by 20% over 1990 levels by 2020, increase the share of renewable energy sources in the energy mix to 20% and increase energy efficiency 20%. Another important political driver of change is the Energiewende (energy transition) in Germany that, among other things, concerns the phase-out of nuclear power and sets targets for renewable energy and energy efficiency [23].

The previously mentioned conversion involves an increasing share of renewable energy sources, more small-scale generation, more active consumers and improved connections between electricity grids. In the meantime, people's demands and consumption have changed, and will change even more. Smart grids use Information Technology (IT) to gather and act on information such as supply and consumption patterns, resulting in cheaper and more efficient, reliable and sustainable production and distribution of electricity. In relevant literature there are several approaches for addressing the competitive environment both for energy producers and consumers.

Typical solutions towards this direction employ financial options as a tool for energy producers to hedge against generation uncertainty [5]. Further enhancement is achieved with a combined and coordinated use of power from renewable sources and energy storage technologies [4]. Methods based on probability distribution, such as the stochastic models, are also employed to compute optimal bidding strategies for renewable power sources participating in the day-ahead or adjustment market [19]. In [24], an energy sharing model with price-based demand response was proposed. As the actions of one influences all the others, solutions based on game theory

concept (dealing with the analysis of competitive situations, where the outcome of one participant does not only depend on their own strategy but also on the strategies of the others) is a commonly used approach to tackle this problem [11]. A similar non-cooperative game-theoretical model of the competition between demand response aggregators for tackling the energy selling problem was discussed in [25].

Although promising, the previously mentioned solutions impose their execution, or management, in a centralized manner, where an independent controller is in charge of solving the optimization problem. This challenge becomes far more savage for multi-dimensional auctions, where multiple goods (i.e., energy budgets from different sources) are allocated per auction. Indeed, a trading model needs to evaluate the behavior of all participants and incorporates their individual preferences. This concept was also applied in smaller scale (e.g., support energy trading in micro-grid level) [26]. However, even in this case, the increased computational complexity makes these solutions candidate only for enterprise environments, (e.g. as part of BEM systems).

The scalability issue of multiple auctions affects also the communication complexity, since the signaling overhead from a continuous centralized auction is notable, as bidders have to submit bids repeatedly to reach an agreement [20]. To overcome this drawback, recently peer-to-peer (P2P) energy trading mechanisms were proposed for energy transactions at the distribution network level [27]. In [21], a paradigm of P2P energy sharing among neighboring micro-grids was discussed for improving the utilization of local DERs and saving the energy bills for all micro-grids. Authors in [28] aim to minimize energy cost by integrating a demand side management system coordinated with P2P energy trading among the households in the smart grid environment. A similar paradigm of P2P energy sharing among neighboring micro-grids was proposed for improving the utilization of local DERs and saving the energy bills for all micro-grids is discussed in [29].

The aforementioned approaches typically exhibit increased computational and/or storage complexities; thus, their execution is limited by the availability of powerful processing units. On the other hand, the configuration and implementation of the proposed energy transaction framework is sufficient even to low-cost embedded devices with limited hardware resources.

11.3 System Model

Figure 11.1 gives a schematic view of the studied approach, which consists of three entities: (i) the *supply side*, (ii) the *demand side*, and (iii) the *utilities*. The *supply* and *demand* sides include energy producers and buildings (acting as energy consumers), respectively. More precisely, assume a smart-grid system having a number of nodes that are in need of energy and a number of distributed energy sources that service an area or group of consumers (e.g., buildings). We assume that a certain percentage of these consumers is unable to meet their demand due to factors such as intermittent generation and varying consumption levels at the grid's loads. In this respect, these

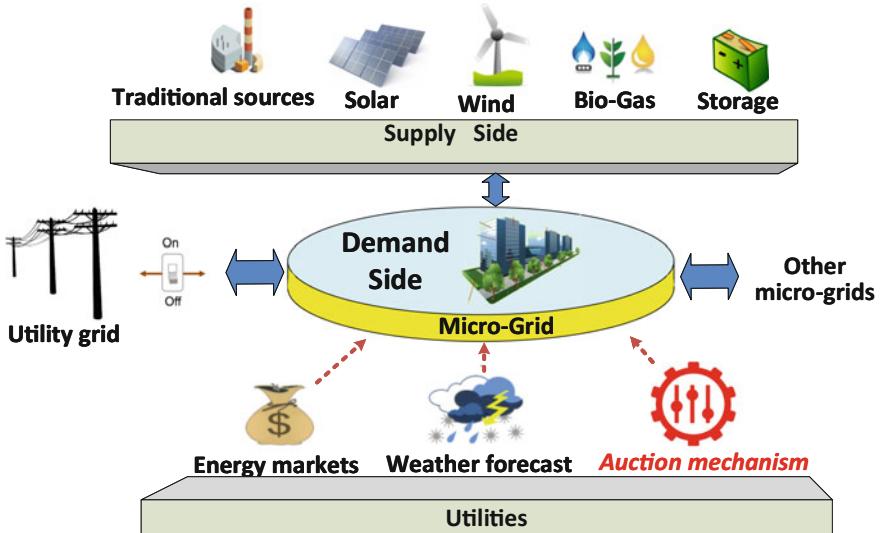


Fig. 11.1 Template of our case-study

Table 11.1 Template of installed energy per micro-grid

	#1	#2	#3	#4	#5
Demand	A_1	A_2	A_3	A_4	A_5
Meet	$\leq 80\% \text{ PVs}$	$\leq 60\% \text{ PVs}$	$\leq 40\% \text{ PVs}$	$\leq 20\% \text{ PVs}$	$\leq 80\% \text{ Wind}$
Energy		$\leq 20\% \text{ Wind}$	$\leq 40\% \text{ Wind}$	$\leq 60\% \text{ Wind}$	
Demand	$P \geq 20\% \text{ Grid}$	$\geq 20\% \text{ Grid}$			

consumers have to find alternative sources of energy by acquiring this energy from other energy producers. For this purpose, we consider a number, N , of storage units that have excess energy that they wish to sell. In our analysis we assume that N and K denote the sets of all sellers and buyers, respectively.

For our experimentation we consider a case study composed by five micro-grid templates, each of which includes a building (with energy demand A_j) and a set of renewable power source(s), as it is summarized in Table 11.1. The energy requirements per building $A = \{A_1, A_2, \dots, A_5\}$ are computed based on our former implementation that relies on Neural Network and Fuzzy Logic [30]. Depending on the energy production and the forecasting about energy demand per building, the spare energy is stored in Virtual Energy Storage (VES) systems. Both the integration of renewable energy resources and the distributed energy storage are key elements of the smart-grid concept. Such a system enables cooperative group of micro-grids to save energy in a common VES. We define as $C_{j,\max}$ being the maximum storage capacity for battery of micro-grid j . Without affecting the generality of introduced solution, we assume that the installed renewable power per studied micro-grid and the

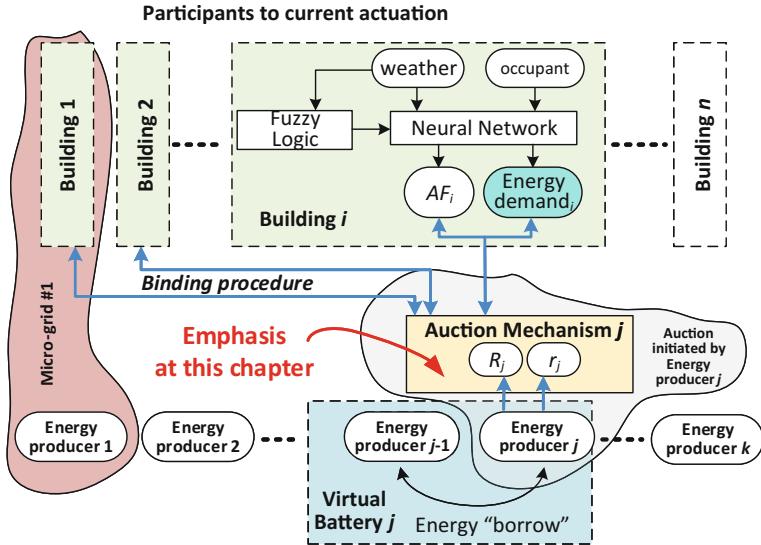


Fig. 11.2 The proposed energy trading framework

associated battery's side are enough in order to meet 70% and 10%, respectively, of the maximum daily building's energy demand. The additional energy production per micro-grid is sold to the rest micro-grids, or to the main-grid, through the proposed auction mechanism (*utilities*) depicted in Fig. 11.2.

Finally, each buyer $k \in K$ has a maximum unit price, or reservation bid b_k , at which it is willing to participate in an energy trade with a seller. Similarly, sellers choose an amount of energy to sell such that with B_i being the maximum total energy that seller wants to sell in the market, and D_i being the energy that each storage unit wants to keep and is not interested in selling. For each seller i , we define a reservation price s_i per unit energy sold, under which seller i will not trade energy.

11.4 Proposed Energy Transaction Framework

The proposed decision-making mechanism relies on market theory. Such an approach corresponds a formal representation of a situation in which a number of individuals interact in a setting of strategic independence. There are four elements this auction, namely: (i) the *players*, (ii) the *rules* of the auction, (iii) the *outcomes*, and iv) the *payoff* and *preference* (utility functions) of the players. Rather than performing a centralized auction, we focus on a distributed approach depicted schematically at Fig. 11.3, where auctions are initiated ad-hoc by energy producers in order to decide to whom to sell, the amount of energy that will be sold and the price for this transaction. In other words, the energy producer acts as the auctioneer, and the other micro-grids

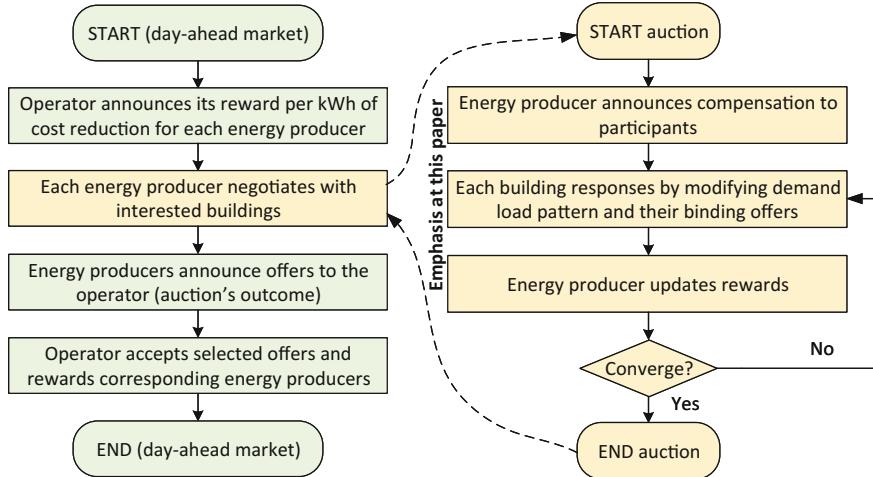


Fig. 11.3 Auction mechanism

(who need energy) act as bidders, bidding for the amounts of energy opportunities. Let i is an energy producer that aims to sell an energy budget b_i ($b_i \leq B_i$) at price p_i by initiating auction a_i . Each building j with energy demands (A_j) higher than the energy production from the associated renewable source (e_j) submits its bids ($bind_j$) for a power budget in order to charge the battery $C_{j,max}$.

In this chapter, different energy suppliers and energy consumers are the players of the auction. For a given auction, the each of the participant players has the historical information of other players' past actions, while a strategy is a rule that tells the players which action(s) they should take. Assuming a non-cooperative auction mechanism, each player tries to maximize its own payoff function while considering its rivals' bidding strategies, while the Nash Equilibrium will occur when no player will have the incentive to change its offering/bidding strategy [31]. The offer price $bind_j$ from building j for an energy budget required at time t is defined by Eq. 11.1:

$$bind_j(t) = bind_j(t - 1) + T_w \times \Delta bind_j(t) \quad (11.1)$$

where $bind_j(t - 1)$ denotes the previous price of the energy budget and T_j is the number of auction's rounds building j waiting until satisfy its energy requirements. As we proceed to the maximum number of auction's iterations, the building's binding ($bind_j$) increases so that the probability of a match in the next round is elevated. If there is no equilibrium at the end of this procedure, the building j buys the requested energy budget from main-grid at the regulator's guarantee price (it is higher than the energy trading price during auctions). Similarly, if a micro-grid cannot succeed in selling the energy budget, this budget is sold to the main-grid at the regulator's guarantee price (it is lower than the trading price). In any case, the auction price is computed according to the feed-in tariff, which refers to the regulatory, minimum

guaranteed price per kWh that an electricity utility has to pay to a private, independent energy producer into the grid. Finally, $\Delta bind_j(t)$ expresses the sensitivity of the price. All the auctions in our framework are performed a day-ahead, which is the widely used approach in energy market. Additionally, we enable a micro-grid to get involved in multiple auctions in parallel in order to guarantee the maximum profit for the overall system $V = \sum_{V_j}(AF_j)$. For our analysis we consider and evaluate a multi-dimensional auction mechanism based on the following scenarios:

1. *Auction 1 (ascending-bid)*: potential buyers start bidding at a low price and the highest bidder wins and pays the last price bid.
2. *Auction 2 (descending-bid)*: starting from a high price, the level is decreased until a buyer accepts the given price.
3. *Auction 3 (first-price sealed-bid)*: buyers submit sealed bids, and the winner pays the bidden price.

A parameter that highly affects the performance of overall framework is the chronology of auctions, which refers either to *simultaneous* or *sequential* auctions. Specifically, in a sequential auction binders move in turns and eventually reach the end of the auction (equilibrium) where the outcome is defined by a utility function. Moreover, in each turn buildings might have different actions available. In contrast, players of simultaneous auctions (also known as “one-shot”) do not have the ability to react to their opponent, since they choose their actions at the same time. A major differentiator between these approaches is the way that players selections are evaluated. Specifically, whereas the utility function can be evaluated after each round of a simultaneous auction, it can only be evaluated once at the end of a sequential auction.

11.5 Evaluation Analysis

The efficiency of the proposed framework is concluded by studying its impact to support distributed auctions in a scenario consisted of 100 micro-grids randomly selected among those depicted in Table 11.1. For this purpose an implementation onto low-cost, low-performance embedded device (Raspberry Pi 3) is performed. Each of these micro-grids is formed by a renewable source (energy producer i) and a building (energy consumer j) that has to meet occupants requirements for cooling/heating services. The daily energy requirement per building, as well as the energy production from renewable sources, for the one year experiment are computed based on our former implementation [30].

In order to enable buildings to participate in auctions, an initial amount of funds (AF_{jinit}) is assigned per building. This amount is equals to 60% of the yearly building’s j energy cost, as it is defined by the average regulators guarantee prices per year [32], without considering any savings from renewable energy sources. The energy trading price per kWh for the auctions is dynamically defined (based on supply and

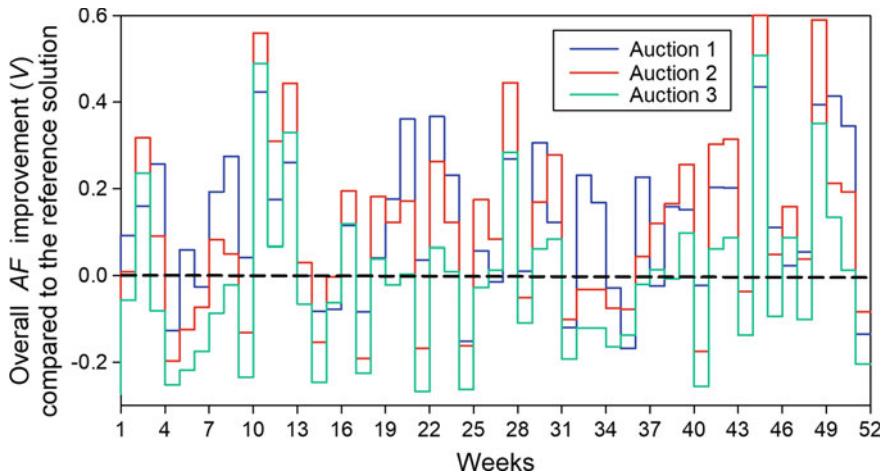


Fig. 11.4 Evaluation of alternative auction mechanisms

demand) but in any case it cannot exceed the guarantee price as defined by the regulator. Finally, we have to mention that our experimentation relies on real data both for weather conditions [33], as well as regulator's guarantee prices [32].

The objective of our experimentation is to meet occupant satisfaction level in terms of cooling/heating (as it is derived from [30]) and at the same time maximize the overall *AF* parameter at the end of the year. Towards this direction, initially we quantify the efficiency of alternative auctions mechanisms discussed previously. The results of this analysis are plotted in Fig. 11.4, where vertical axis gives the variation of overall funds (*V*) for the 100 micro-grids in normalized manner over the case where energy produced from renewable sources is sold directly to the main-grid at the regulator's guarantee price. The results of this figure highlight that Auction mechanism 3 leads to slightly lower performance compared to reference solution (on average 2%), whereas Auction mechanisms 1 and 2 outperform on average the overall *AF* by 12 and 9%, respectively. Since all these mechanisms exhibit almost identical computational complexity, rest evaluations affect only the Auction mechanism 1, as it maximizes the *AF* cost metric.

The size of VES is crucial parameter that dominates the efficiency of our decision-making mechanism, since it defines the maximum energy storage capacity per group of collaborated micro-grids (discussed in Fig. 11.2). To study in more detail the impact of this parameter, we explore cluster sizes ranging from 2 up to 10 partners (smart-grids) per VES, where participants are randomly selected from the five templates depicted at Table 11.1. The outcome from this analysis is plotted in Fig. 11.5, where the vertical and horizontal axes give the average improvement in *AF* parameter compared to the reference solution (i.e., without considering VES clustering) and the cluster size (number of micro-grids per VES), respectively. The diagram at Fig. 11.5 indicates that larger clusters improve the overall profit for participant

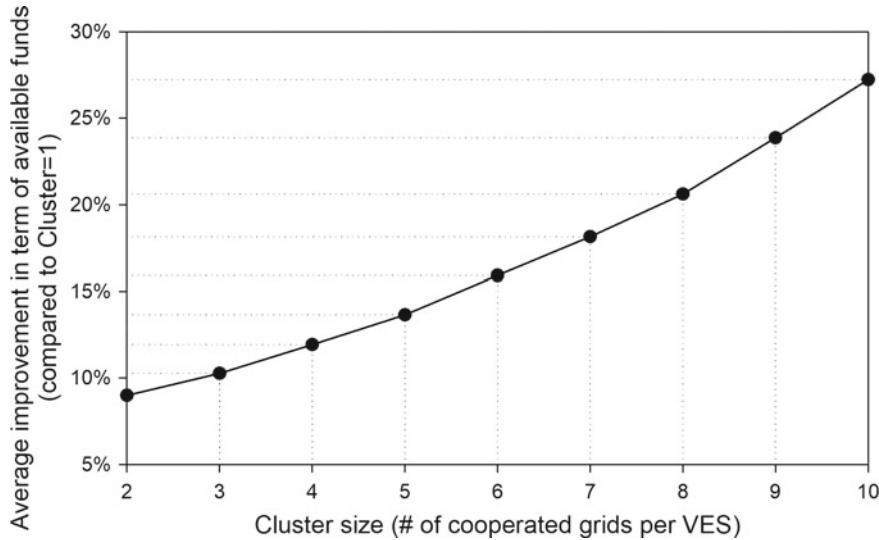


Fig. 11.5 Exploration of cluster size and iterations per auction

micro-grids (V) because it is more likely the building's energy requirements to be met from local batteries rather than from the auction mechanism, or the main-grid.

We have to notice that such a conclusion is tightly firmed to the weather climate, as well as the energy efficiency of studied buildings and renewable sources. Without affecting the generality of introduced solution, for the rest of our experimentation we consider VES clustering with size equals to 6. In case larger clusters are employed, the energy savings are expected to be even higher; thus, the studied VES size can be considered as a worst-case solution for our experimentation. Additionally, buildings exploit with the same manner energy from their renewable sources, as well as energy stored in their local VES. Consequently, in order to guarantee proper building's operation, energy forecast per building is necessary based on statistical analysis. For the scopes of this manuscript, the energy forecast per building was performed with a methodology initially discussed in our previous publication [30].

The maximization of AF parameter, and hence the energy cost per kWh, depends also on the quality of derived solutions. Since our algorithm relies on game theory, the maximum number of iterations per auction in order to achieve an equilibrium, and thus derive a solution, is of high importance. The higher number of iterations favor buyers (buildings) to bind with a more conservative approach. On contrast, auctions with few iterations enforce buyers to exhibit a more aggressive strategy (pay higher price per kWh) in order to reserve the energy budget from market rather than from the main-grid. This trend is also depicted in Fig. 11.6, where we study the impact of maximum number of iterations to the trading energy cost. Specifically, horizontal axis corresponds to the maximum number of iterations per auction for deriving an equilibrium, while vertical axis gives the corresponding energy cost per kWh. For

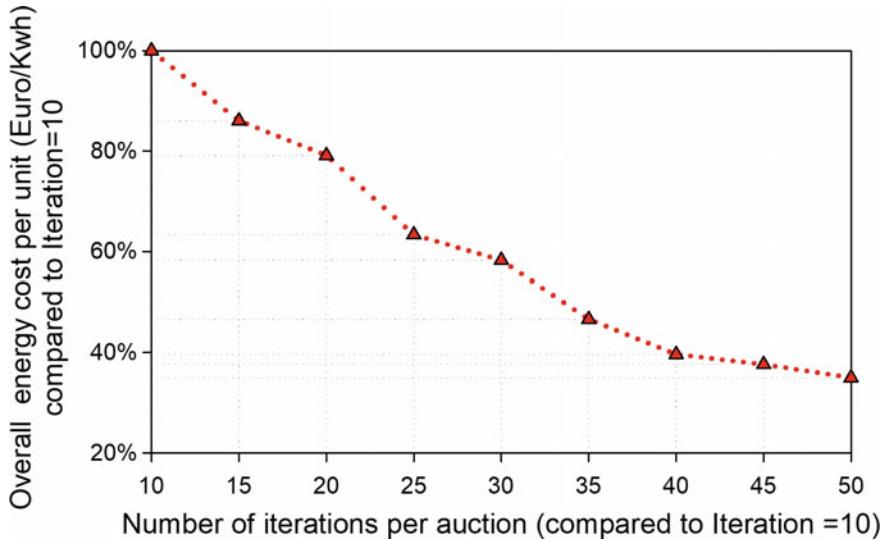


Fig. 11.6 Exploration of maximum iterations per auction

demonstration purposes, both horizontal and vertical axes are plotted in normalized manner over the corresponding results for auctions with 10 iterations. Since larger number of iterations lead to higher computational complexities, we might conclude that the relative improvement of overall energy cost per unit is almost constant for more than 40 iterations per auction. Thus, for the rest of our analysis we consider that an auction is though as successive in case it leads to an equilibrium at less than 40 iterations.

The goal of the aforementioned auction mechanism is to maximize the available funds for the participant micro-grids, while respecting the buildings' energy requirements. Specifically, according to the day-ahead energy forecast for building j and the outcome from auctions, the amount of building's available funds (AF_j) increases or decreases proportionally by whether the connected energy producer sells, or buys, energy to/from other grids, respectively. The amount of funds that increases/decreases AF_j is equals to cost of energy budget that is sold/bought from the associated renewable source. To study in more detail this parameter, Fig. 11.7 gives the overall AF (summary for the 100 micro-grids) for the 52 weeks experiment regarding auctions that take place *simultaneous* and in *sequential* manner. The values in vertical axis are plotted in normalized manner versus the total reference cost in weekly basis. This cost is computed by assuming that building's energy requirements that cannot be satisfied from the associated VES are met by buying energy from the main-grid at the regulator's guarantee price. Based on the results, we conclude that both auction mechanisms improve on average the total AF compared to the reference solution. Specifically, this improvement is higher for *sequential* auctions (on average 18%), whereas the corresponding enhancement for *simultaneous* auctions is 10%.

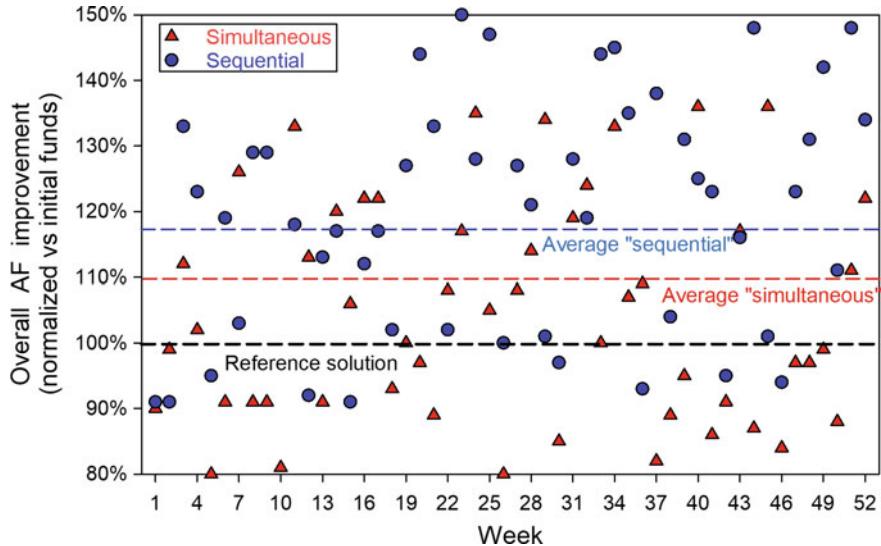


Fig. 11.7 Evaluation of proposed energy transaction framework

By enabling buildings (consumers) to participate in multiple auctions concurrently, it is expected to improve their efficiency during the energy trading procedure. In order to prove this statement, detailed exploration was performed with real data. The results from this analysis, summarized in Fig. 11.8, also confirms this conclusion. The vertical axis at this figure gives the average energy cost per kWh among participant buildings, whereas the horizontal axis denotes the average number of energy producers that initiate an auction, which in turn corresponds to different instances of game theory. More specifically, the curves at this figure evaluate multiple instances of game matrix with: (i) one sub-game per auction, and (ii) multiple sub-games per auction (up to 50 sub-games). For demonstration purposes, values at vertical axis are plotted in normalized manner over the corresponding energy cost per kWh from the main-grid.

These results of Fig. 11.8 indicate that buildings can achieve significant cost reduction by trading energy price through multiple auctions, while this saving is even higher in case there are also multiple auctions with the same energy producer (multiple instantiations of game theory). Specifically, according to our analysis, the average reduction at energy cost for single and multiple sub-games are $0.6 \times$ and $0.73 \times$, respectively, as compared to the corresponding energy cost from the main-grid. So, for the rest of our analysis we consider that buildings can trade the energy price with multiple energy producers and multiple sub-games simultaneously.

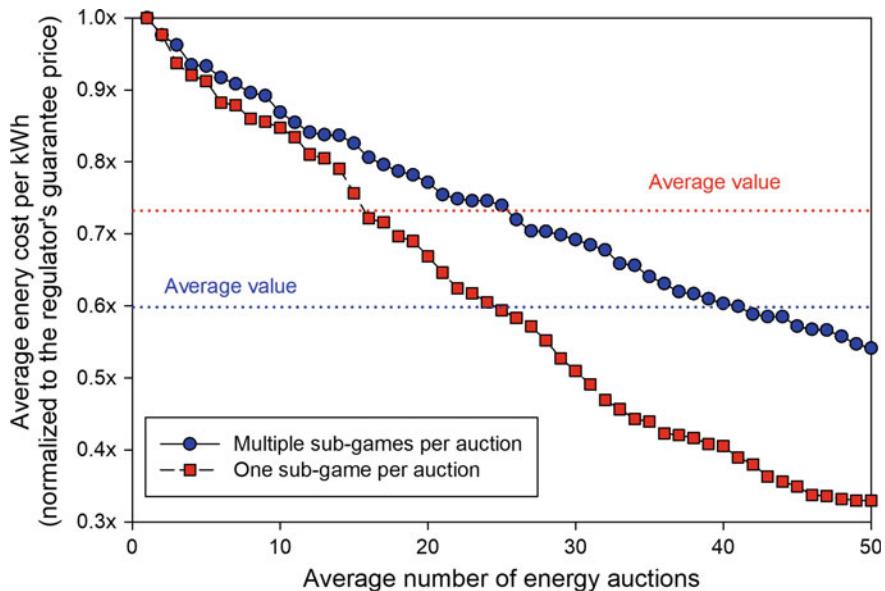


Fig. 11.8 TBD

11.6 Conclusion

A P2P framework for supporting distributed auction mechanisms in smart-grid environment, was introduced and implemented as part of a low-cost embedded device. Experimental results, based on real data, highlight the superiority of this approach in terms of profit maximization.

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Chapter 12

Centralized Monitoring and Power Plant Controller Targeting Smart-Grids: *The Inaccess Platform*



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Abstract A complete framework for supporting the monitoring and orchestration of Smart-Grid infrastructure is analyzed in this chapter. The solution presented has been developed by Inaccess since 2010, a global leader in Renewable Energy providing a mix of innovative hardware, intelligent software and value-added services to its clients worldwide. Inaccess Power Plant Controller (PPC) is one of its most innovative products, an intelligent vendor-independent system offering grid compliance, PV plant (or other type) control and yield maximization. Inaccess PPC is constantly evolving as more features are added in order to ensure compliance to the increasingly demanding grid code requirements globally while providing better and more effective management of the clients renewable asset. The PPC is also interoperable with Inaccess Central Monitoring System (CMS), offered for extended monitoring, visualization, reports and analytics.

12.1 The PV Plant - An Overview

A photovoltaic plant is an installation which produces energy using the sun as a source. The PV plant is interconnected to the Electrical Power System (EPS, which is also called utility grid), so that the produced energy is forwarded to the customer loads. The generic architecture of a PV plant is presented in Fig. 12.1.

The PV plant production facilities consist of:

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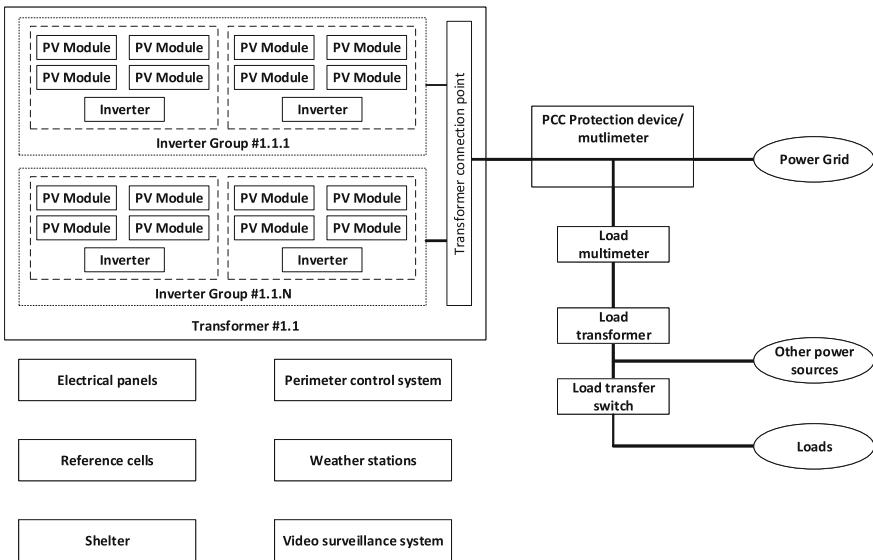


Fig. 12.1 PV plant components and interconnections

- A number of PV modules, depending on the PV plant nominal power.
- A number of strings, each consisting of a number of PV modules. The grouping of PV modules into strings is decided at installation time. Strings are equipped with a temperature sensor and a solar irradiance sensor (pyranometer, placed at the inclination of the PV modules), together with the associated transducers. Most often, readings from temperature sensors and pyranometers would have to be correlated to multiple modules, since, for cost reasons, fewer sensors than strings are deployed. Additionally, the DC current of each string may be monitored through a string monitor unit.
- A number of Inverters converting the DC output of the PV modules to AC power. Which strings belong to which Inverter is decided at installation time. All modern inverters provide monitoring of a number of operational parameters and events.
- A number of Inverter groups, each consisting of a number of Inverters. Which Inverters belong to which Inverter groups is decided upon by the PV plant designer.
- A number of step-up transformers, connected in parallel, which raise the 220 VAC output of the inverters to the voltage of the EPS. The number of transformers depends on the PV plant nominal power and which Inverter groups are connected to which transformer is decided by the PV plant designer. The input to/output/from the transformers are monitored through 2 multimeters, connected on the primary (LV side) and secondary (MV side) windings. A protection device connected on the secondary winding, automatically disconnects the transformer from the EPS whenever certain conditions are met. This protection device may also act as the MV multimeter. Each step-up transformer may provide a set of devices monitoring

its proper operation (a DGPT relay, a Buchholz relay and a thermostat, depending on the transformer type). Each step-up transformer and associated multimeters/protection devices are collectively denoted as the Transformer Connection Point (TCP) in the ensuing and multiple TCPs may exist in a PV plant.

- The Point of Common Coupling (PCC), which is the point of interconnection with the EPS as referred to within relevant bibliography. This is the point where all requirements mandated on the PV plant by the EPS operator apply, so it is considered that only one PCC can exist per PV plant. The quality of the power delivered to the grid is monitored through a multimeter and a protection device undertakes the task of automatically disconnecting the PV plant under certain conditions. The protection device may also act as an additional multimeter.
- The Load Connection Point (LCP), which is the point of interconnection of PV plant loads, which are PV plant auxiliary equipment, consuming part of the produced power during the morning and power from the EPS during the night, since, of course, the PV plant does not operate when the sun is down. Loads are connected in parallel to the PCC via a step-down transformer. The step-down transformer may provide a set of signals so that its operation and status can be monitored, in analogy to the TCPs. The LCP is monitored through a multimeter. The loads can be fed with electrical power either by the EPS/PV production or by other power sources, depending on the position of a transfer switch. The PCC protection device is usually placed in such a way that the power supply to the loads is not interrupted when the PV plant is disconnected from the grid. Only one LCP is supposed to exist per PV plant.
- A number of electrical panels, which are part of the PV plant electrical installation and may contain a subset of the following component groups, whose state can be monitored through contacts:
 - Circuit breaker groups
 - Surge arrester groups
 - Fuse groups
 - Switch groups
- A number of weather stations, monitoring the environmental conditions at the PV plant, which may be used to quantify the PV plant production performance. These weather stations may include:
 - An ambient temperature sensor and transducer
 - A horizontal solar irradiance sensor (pyranometer) and transducer
 - A wind speed sensor
 - A wind direction sensor
 - A relative humidity sensor
 - A barometric pressure sensor
 - A water precipitation (rain gauge) sensor

- A number of reference cells, which are in fact contain an actual PV cell, which is short-circuited. The short-circuit current is directly analogous to the irradiance, as perceived by the PV cell. The reference cell also contains a temperature sensor, soldered at the back of the PV cell, which provides a measurement of the cell temperature as well as a correction factor for the irradiance measurement. The reference cell measurements are mostly used for PV module performance modeling and prediction.
- A number of shelters, each of which is assumed to have multiple rooms. Access to the doors of some rooms is controlled and the status of each room is monitored through a set of sensors (fire, flood, occupancy and temperature together with the associated transducers).
- A PV plant site perimeter control system, which consists of a number of alarm and actuator zones. The former indicate security breaches through infrared barriers or motion detectors and the respective actuator zones activate sirens or perimeter lights to avert intruders.
- A multi-camera video surveillance system, which may or may not interact with the perimeter control system.
- A security system, which may or may not interact with the perimeter control system.

Depending on the nominal power of the PV plant and the country, the PV plant may be connected to either low voltage (220 VAC) or high voltage. In the former case, the generic architecture presented in Fig. 12.1 is different, since all transformers are absent and the loads are connected directly in parallel to the inverters.

In the case the PV plant is connected at high-voltage the PV plant architecture presented in the figure above has to be extended with an additional step-up transformer which converts the medium voltage which is output by the TCPs to the high-voltage range necessary to inject the produced electrical power into the grid. The necessity for the existence of an HV transformer is imposed by the peak output power and may vary according to applicable rules and regulations, depending on the country the PV plant is installed. In that case, the PCC is moved to the output of this HV transformer.

12.2 System Architecture

InAccess platform aims at providing centralized monitoring of a number of remote PV plants (as per Fig. 12.1) to a number of solar park owners/developers, O&M companies and any other involved party. The interaction of the users with the platform relies on the public internet and the GSM/3G/4G network. The overall abstract architecture of the solution is presented in the figure below (Fig. 12.2).

The system has been designed to provide 5 main services to its users [1]:

1. The monitoring service, operating over the public internet (Web). The user is capable, through an Internet browser, to get information (parameters, events and status) regarding the PV plants of interest to him/her.

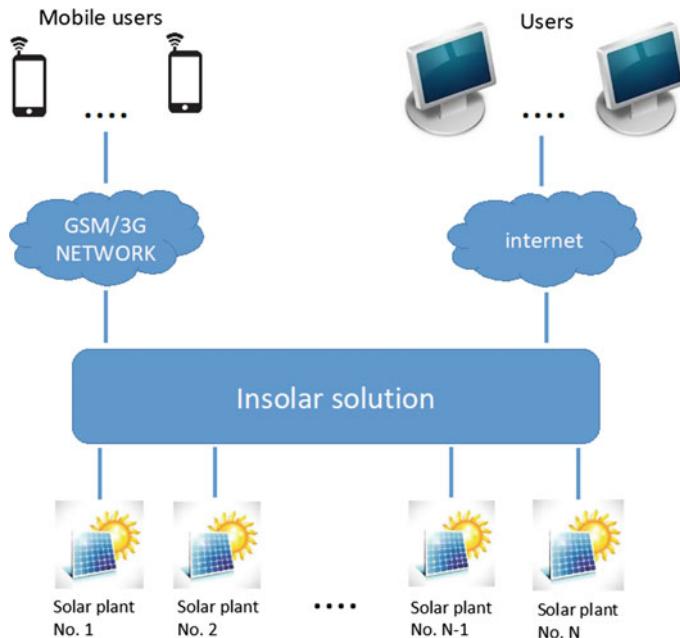


Fig. 12.2 The abstract architecture of the inAccess platform

2. The notification service, operating both over the Web and the mobile network and delivering notifications to the mobile phones or e-mails of the users who have subscribed to the service whenever certain events related to the PV plants of interest to them occur.
3. The report generation & delivery service, operating over the Web and delivering reports to the e-mails of users who have subscribed to the service in a periodical manner. These reports include extensive information on the plants regarding operational, maintenance and financial aspects.
4. The graphing service, creating comprehensive graphs of parameters and events to be presented through the Web interface of the PV plant monitoring service or to be included in reports, created by the report generation & delivery service.
5. The export service, allowing the user to store locally in his/her computer data retained within the inAccess platform.

On top of these 5 main services, a Computerized Maintenance Management System (CMMS) can optionally be integrated providing a seamless interconnection of the two systems to ease the operation and management workflow.

12.2.1 *The Service Architecture*

PV plants are almost always placed at hard to reach areas, away from terrestrial communication infrastructures. This is why data communication to/from the field

has to be carried out using mostly either the GSM/3G network or satellite means. Both share the common characteristic of scarce bandwidth and/or occasional service unavailability. Data reduction and local data storage in the field is thus a mandatory requirement. Additionally, due to the vast variety of equipment deployed in the plant, it is expected that the inAccess platform has to interface them using an equivalent variety of physical connection methods and protocols. Finally, there are certain requirements that mandate the existence of logic in the field, which operates irrespective of whether a connection to the outside world is operational or not.

The 3 abovementioned facts intone the need for a stand-alone infrastructure, installed at the field which undertakes the responsibilities of:

- Interfacing with all equipment installed at the PV plant (multimeters, protection devices, inverters, sensors, actuators etc) to acquire data, irrespective of the connection method and/or protocol.
- Reducing the volume of data to something representative, yet less bandwidth hungry.
- Conveying events that are generated directly by field equipment upon their occurrence and generating events that are necessary yet not implemented within the equipment in the field.
- Storing all necessary parameters and events in a cyclical manner in the case of failure of the communication with the outside world.
- Implementing all necessary control loops that have to operate locally and in an independent manner.

This infrastructure is essentially a set of programmable networked controllers employing all necessary interfacing and storage functionality deployed at each PV plant separately.

Continuing with this approach on the service architecture, the inAccess platform is required to monitor a number of PV plants in a centralized manner. This means that data from a large number of PV plants have to be concentrated, stored and managed by a single entity (the service backend). The responsibilities of this back-end are:

- To collect, store and manage information from a variety of PV plants.
- To store and manage information regarding the users accessing the service.
- To generate and send notifications towards users.
- To allow the users to configure the service back-end itself or the field-deployed controllers.
- To carry out and post-acquisition calculations.

As far as the field-deployed controllers are concerned, inAccess usually employ their own hardware in the field, although collection of data from third party local monitoring systems is also supported. The service back-end incorporates an independent module, denoted as the Communications Adapter Module (CAM) in the ensuing, which undertakes the task of acquiring data from the remote PV plant and feeding them to the service back-end as well as conveying data from the service backend to the remote PV plant.

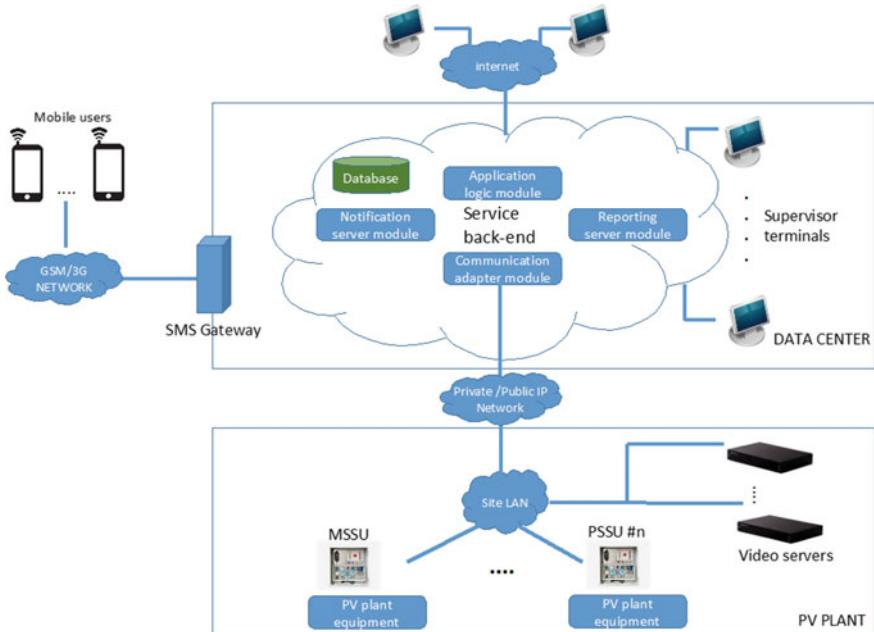


Fig. 12.3 Overall service architecture

The service back-end also incorporates an Application Logic Module (the ALM), which calculates the derived parameters. This module can be extended at will with new calculation functions. Other service back-end modules include the Notification Server Module (NSM), which undertakes the notification of the inAccess platform users via SMS or e-mail as well as the Reporting Server Module (RSM), which handles the generation and delivery of reports. All necessary data are stored in a database.

Finally, the inAccess platform includes a front-end, capable of operation with a standard Web browser (preferably Mozilla Firefox or Google Chrome). The service architecture is presented in the figure below (Fig. 12.3).

12.2.2 Information Modeling Supported by Inaccess Platform

The inAccess platform models the PV plant in the hierarchical manner presented below which is a tree representation of the PV plant architecture depicted in Fig. 12.1.

The nodes of the tree can be broadly categorized as:

- Nodes representing virtual entities, i.e. entities that do not contain actual equipment installed at the plant. Such entities are for example the PV plant, the PCC, the Inverter etc. These nodes are denoted as virtual segments in the ensuing.

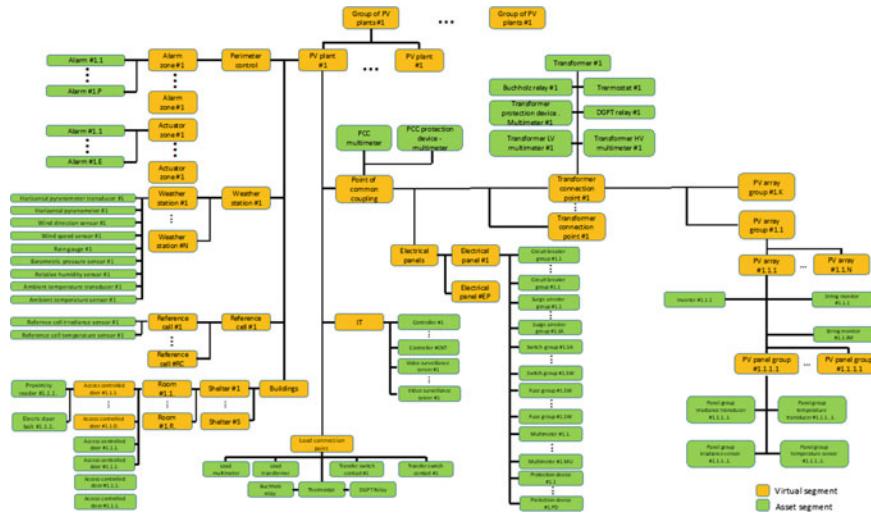


Fig. 12.4 Hierarchical model supported by the inAccess platform

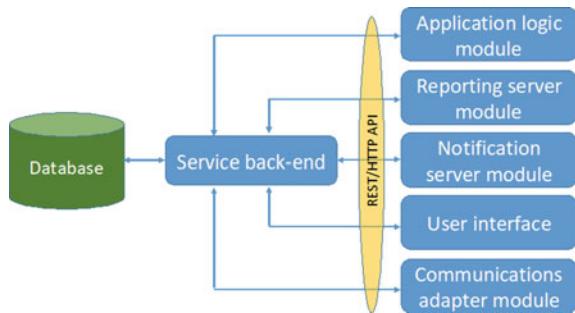
- Nodes representing equipment entities, i.e. entities that contain a specific piece of equipment installed at the plant. Such entities are for example the numerous sensors/transducers, the multimeters, the protection devices etc. These nodes are denoted as asset segments in the ensuing.

Both virtual and asset segments are used in the ensuing as placeholders for the data that are handled by the platform. It has to be noted that certain parts of the tree may be absent in certain cases. For example, a low-power PV plant does not incorporate transformers. As another example, a certain PV plant may not employ perimeter or access control. In such cases, the simplifications that should be applied are evident. This model can be arbitrarily extended to match further customer requirements (Fig. 12.4).

12.2.3 The Software Architecture

The service architecture presented in Sect. 12.2.1 has been implemented with the software architecture presented in the figure below, as a 3-tier architecture following a Web services approach. The software modules have been implemented using widely accepted operating systems and software components. The interface among the SW components is implemented as a collection of HTTP resources. The system database can also be accessed by external entities using this REST/HTTP API (Fig. 12.5).

Fig. 12.5 Software architecture



12.3 The Monitoring Service

The main duty of the inAccess monitoring platform is to provide, in a timely and concise manner, information to its user on the operation of a group of PV plants. The monitoring service functionality can be broadly categorized into 5 categories:

- Monitoring of the production of the PV plant.
- Monitoring of the interconnection of the PV plant with the EPS.
- Monitoring of the status of circuit breakers and surge arresters.
- Monitoring of the shelter/site status & security.
- Monitoring of the PV plant equipment operational and communication status.

12.3.1 PV Plant Monitoring Basics

The monitoring service of the inAccess platform is based on the IEC standard 61724 [2], which provides extensive information on the physical quantities which will have to be measured from site-deployed equipment and sensors as well as the data acquisition method to accomplish such measurements and the post-processing necessary to end up with meaningful results that must then be displayed and recorded. The methodology is depicted in the figure below (Fig. 12.6).

Compared to Fig. 12.1, IEC 61724 is a subset, since it does not consider the step-up transformers but rather models a PV plant directly connected to the power grid at low voltage. All parameters can, however, be and have been modified accordingly to match the general architecture of Fig. 12.1. The IEC 61724 approach has been extended as presented in the figure below (Fig. 12.7).

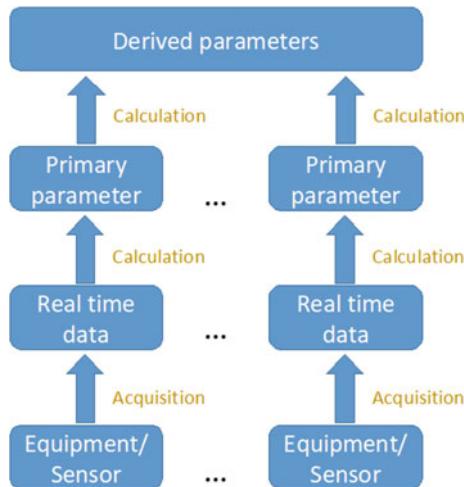


Fig. 12.6 The IEC 61724 approach

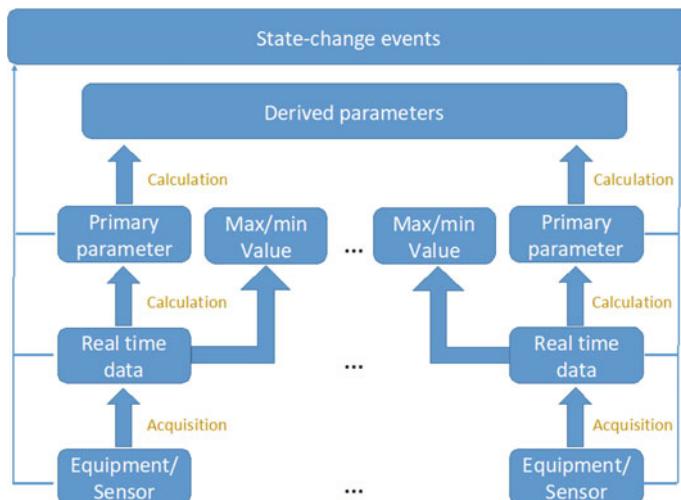


Fig. 12.7 The extended IEC 61724 approach

12.3.2 Supported Information Elements

The inAccess platform supports the collection, storage, visualization and post-processing of the whole history of a large variety of types of information for each node of the hierarchical model presented in Fig. 12.4. These include:

- **Primary parameters:** As per IEC standard 61724, primary parameters are calculated as the timeseries average of real-time data after a certain set of validations

have been applied. The span of this average (the recording period) has to be an integer sub-multiple or multiple of an hour. The inAccess platform supports any recording interval, though it has to be the same for the whole of a single PV plant. Daily, monthly and yearly averaged values are also supported for each primary parameter separately. Data acquisition and the calculation of primary parameters are considered to be carried out by field-deployed controllers in order to reduce the data that is conveyed to the service back-end and minimize bandwidth requirements.

- *Maximum/minimum value parameters:* These parameters are assumed to be calculated in much the same way as primary parameters, except for the operation applied on the real-time data. Daily, monthly and yearly maximum/minimum values are also supported. The calculation of maximum/minimum value parameters are considered to be carried out by field-deployed controllers in order to reduce the data that is conveyed to the service back-end and minimize bandwidth requirements.
- *Derived parameters:* Derived parameters are calculated using a specific mathematic formula which operates on a specific set of values or vectors of values of primary (and/or other derived) parameters. The inAccess platform provides the infrastructure that is necessary to carry out all derived parameter calculations in the service back-end so as to further minimize the necessary bandwidth and storage at the PV plant. In the case that derived parameters are calculated in the field, they can be considered as primary parameters within the service back-end. Daily, monthly and yearly values are supported for each derived parameter separately.
- *Raw, real-time data:* The service back-end has been designed to present raw, real-time data sets as they are acquired from the field-deployed controllers.
- *Real-time monitored data:* In certain cases, it is necessary to present to the user the real-time data as they are recorded by the field-deployed controllers, without any processing or storage. This functionality has to be supported by the equipment deployed at the PV plant.
- *Status, states & state-change events:* The concept is presented in detail in the following section. Each parameter sample and event is collected, stored and visualized with its acquisition timestamp and engineering unit. Primary and derived parameters as well as raw real-time data are collected from the field based on a time schedule, aligned with the recording period. Status-change events are collected upon their occurrence and real-time monitored data upon user request.

12.3.3 *Status, State-Sets, States, State-Change Events and the Concept of Severity*

The inAccess platform records and presents to the user the current status of entities that are either internal or external to the solution. This concept is considered to be a powerful tool in terms of the user getting an immediate grasp on whether any PV plant entity operates properly or not. Status information actually encodes the

severity of the condition of each entity independently, which is a number on a scale from 0 (everything normal) to 100 (critical alarm). The status update mechanism shall become apparent in the ensuing.

Apart from status information, the inAccess platform also supports an arbitrary number of statesets per entity. Each state set encodes a set of states, which are mutually exclusive, i.e. the entity can be found in only one of them. Each state has a preset severity level associated with it. Changes among states are triggered by state-change events, which are either directly generated by sensors and equipment connected to the dataloggers in the field (primary events), or by the inAccess platform itself (derived events).

The inAccess platform provides all means necessary for the user to acknowledge (validate) that he/she has been notified on any specific state-change event and has taken appropriate actions. This acknowledgement is a simple form of bookkeeping of user actions for further investigation.

Each state-change event is stored and presented to the user per state set with the following data:

- The entity generating the event
- The state the event led to in a descriptive form
- The event date/time, in the timezone of the PV plant
- The date/time of the reception of the event, in the timezone of the PV plant
- The event acknowledgment status and acknowledgment text

Since all entities are organized in a hierarchical structure (see Fig. 12.8), the current status of a certain entity cannot depend solely on the state (or states) it is into, but the statuses of all underlying entities within the hierarchy are used as well. This is a basic concept within the inAccess platform, since it enables the efficient notification of the user if something calls for his/her attention. Moreover, this hierarchical status propagation, as it will be denoted in the ensuing, can help the user realize the effect that an entity being in a certain state of a certain state set has on the operation of the PV plant as a whole.

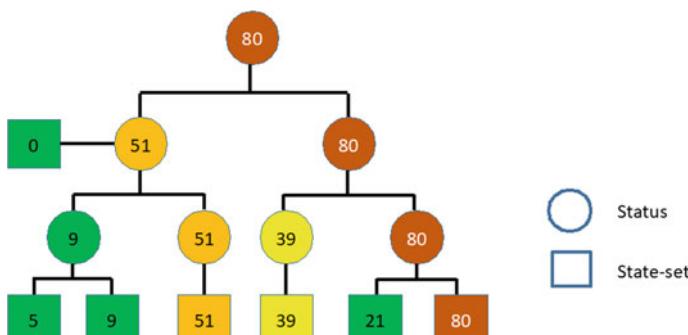


Fig. 12.8 The hierarchical status propagation concept

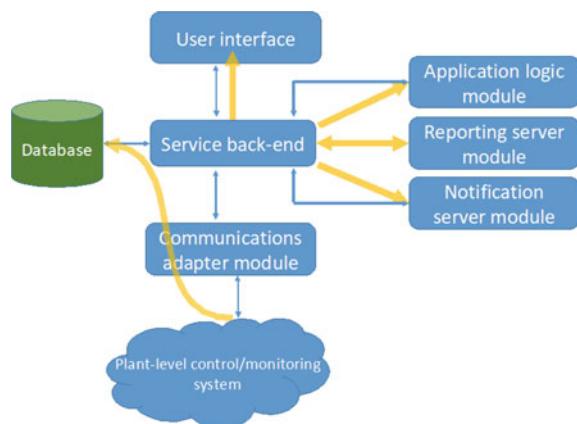
The status of each entity of the plant hierarchy is always equal to the maximum severity of the states of all underlying entities at any given point in time. In order to further elaborate on this hierarchical status propagation, let us refer back to Fig. 12.4 and imagine that a certain inverter breaks down. An event encoding this state shall be generated and presented to the user. Furthermore, the status of the inverter shall change since it is in error. Should such an event occur, it is also expected to affect the group of inverters the specific inverter belongs to, the PV plant as a whole and consequently, the group of PV plants the specific PV plant belongs to. The statuses of all involved entities is presented to the user in an easily understandable form (e.g. color encoding, based on a set of severity thresholds) so that his/her attention is drawn not only to a specific event but also to the effect it has on the operation of the whole PV plant. The approach is further clarified through the following figure, presenting an exemplary hierarchy with the related statuses and state-sets for each node. The related severities are also depicted, so that the hierarchical status propagation is apparent.

12.3.4 The Monitoring System Architecture

As far as the monitoring service is concerned, the flow of data through the software architecture of Sect. 12.2.3 is presented in the figure below (Fig. 12.9).

The Communication Adaptor Module (CAM) retrieves information necessary for the addressing of data items within the plant-level monitoring system from the service back-end. It then connects to the field-deployed equipment based on a schedule, collects the necessary data and submits them to the service back-end, which caches them in case some other module requests them and writes them to the database. The Application Logic Module (ALM) retrieves the necessary primary data to calculate the derived values, also based on a schedule and submits the results to the service

Fig. 12.9 Monitoring system architecture



backend, which again caches and stores them in the database. The remaining software modules (the Graphical User Interface, the Reporting Server module and the Notification Server module) connect to the back-end, either in a scheduled manner or upon user request and collect data in order to depict them or use them in reports or notifications.

12.3.5 *The Monitored Parameters and Events*

The inAccess platform can collect, store, process and present to the user a variety of parameters related to PV plant operation, performance evaluation and fault detection and management. Some key parameters and events are presented below. The list depends on the equipment installed in the field and further information can be provided upon request:

- **String-level monitoring:**

- Voltage, current and power
- Module temperature
- Solar irradiance

- **Inverter monitoring:**

- Electrical parameters (voltage, current and power for DC and AC quantities, frequency, power factor, energy)
- Operational and error status (normal, night shutdown, disturbance, fault)
- Key performance indicators:
 - Yields (reference, energy, final)
 - Losses (array capture, system)

- **Transformer monitoring:**

- Electrical parameters (voltage, current and power for DC and AC quantities, frequency, power factor, energy) at both low and mid-voltage
- Operational and error status (DGPT relay status, protection device status)
- Transformer efficiency

- **Point-of-Common Coupling monitoring:**

- Electrical parameters (voltage, current and power for DC and AC quantities, frequency, power factor, energy) at both the production point (transformer output) and PCC
- Operational and error status (protection device status)

- **Load connection point monitoring:**

- Electrical parameters (voltage, current and power for DC and AC quantities, frequency, power factor, energy)

- Operational and error status of the service transformer (DGPT relay status, protection device status)
- **Building monitoring:**
 - Fire, occupancy, flood and temperature
- **Meteorological station support:**
 - Irradiance, ambient air temperature, precipitation, humidity, barometric pressure, wind speed, wind direction
- **Reference cell support (temperature, irradiance)**

12.4 The Notification Service

Except for the monitoring service described in the previous sections, the inAccess platform is also capable of notifying the user on the occurrence of critical events via SMS or e-mail. The generation of such notifications is not triggered by individual state-change events but rather by the status changes of each node of the hierarchy presented in Fig. 12.4 which is affected by them, according to Sect. 12.3.3. More specifically, if the severity of the status goes above a certain user configurable threshold and remains there for a preset period of time, a notification is generated to alert the user. Additionally, if the status falls below the same threshold, another notification is generated in order to notify the user on the expiration of the criticality. The user is capable of subscribing to the status changes of and configuring the severity thresholds for each hierarchy node separately. It is understandable that if he/she, depending on the subscription he/she has configured, may receive multiple notifications upon occurrence of the same event or set of events affecting the statuses of a certain set of nodes in the hierarchy. For example, if the user subscribes for status changes of an inverter and the PV plant which contains it, he/she shall be notified twice when the inverter breaks down. Once because of the subscription to the status of the inverter and once more because of the subscription to the PV plant status. Moreover, the user is capable of subscribing separately to the positive edge (status going above threshold) or the negative edge (status going below threshold) for each hierarchy node separately. Finally, the inAccess platform logs all notifications sent with the following information:

- Notified user
- Notification method used
- Which subscription triggered the notification
- Time/date
- Delivery status

12.5 The Graphing Service

In order for the user of the solution to reach useful conclusions regarding the state of the monitored PV plant and possible faults as well as their probable causes, there is a definite need for concise presentation of the numerous monitored parameters and events using a multitude of graphs. This functionality is offered by the graphing service, which is built around 3 graph types:

- The x vs. y plot, presenting, in a scatter form, the values of 1 parameter vs. the values of the other.
- The time plot of several parameters on a time axis, as a bar, stacked bar or line plot. The inAccess platform provides the user with the capability to plot state-change events on top of already plotted parameters, as individual data points.
- The timeline plot of state-change events vs. their time of occurrence.

For the time plot, the user is able to select whether it will be of the line or bar type. If 2 parameters with different engineering units are presented on the same plot, 2 y-axis are used to cater for parameters which do not share the same range. The inAccess platform provides the user with the capability to configure:

- The time period for which a plot shall be produced (“from/to” selection, aligned on day boundaries as well as pre-sets including current day, yesterday, last month, last year, from the beginning of operation).
- The data values to be used for the plot (recording period, daily, monthly, yearly).

The necessary graphing functionality is specified in detail within the list below, which follows the hierarchical structure presented in Fig. 12.4:

1. Plots related to strings:
 - a. Module temperature/total irradiance in the plane of the array vs. time.
 - b. State-change events vs. time.
 - c. o Any 16 parameters vs. time.
2. Plots related to Inverters:
 - a. Relative array efficiency vs. temperature.
 - b. Relative array efficiency vs. irradiance.
 - c. Relative array efficiency vs. performance ratio.
 - d. Inverter efficiency vs. DC power.
 - e. Final yield/array capture losses/system losses vs. time.
 - f. State-change events vs. time.
 - g. Any 16 parameters vs. time.
3. Plots related to Inverter groups:
 - a. Final yield/array capture losses/system losses vs. time.
 - b. State-change events vs. time.
 - c. Any 16 parameters vs. time.

4. Plots related to the PV plant:
 - a. Final yield/array capture losses/system losses vs. time.
 - b. State-change events vs. time.
 - c. Any 16 parameters vs. time.
5. Plots related to points monitored by multimeters and/or protection devices:
 - a. Current (for L1, L2 and L3) vs. time
 - b. Voltage (for L1-L2, L2-L3 and L3-L1) vs. time
 - c. THD-R current (for L1, L2, L3 and neutral) vs. time
 - d. Power factor (for L1, L2, L3 and total) vs. time
 - e. Current unbalance (for L1, L2 and L3 total) vs. time
 - f. State-change events vs. time
 - g. Any 16 parameters vs. time
6. Plots related to a shelter room:
 - Shelter room temperature vs. time
 - State-change events vs. time
7. Plots related to other nodes of the PV plant hierarchy:
 - State-change events vs. time
 - Any 16 parameters vs. time

Apart from these, any other custom graphs can also be created.

12.6 The Exporting Service

The users of the inAccess platform are capable of exporting data from any entity presented in Fig. 12.4 in Excel Microsoft Office Spreadsheet format or a Comma Separated Value (CSV) format. The source of data to be exported may be:

- Primary parameters
- Derived parameters

The users are capable of selecting the time-span for the export as well as the reporting period for the exported data for primary and derived parameters. The values of real-time monitors are also exportable using the same format but this applies only for the period a real-time monitor was activated by the user.

12.7 The Report Generation and Delivery Service

The inAccess platform user is capable of subscribing to multiple reporting periods (days, weeks, months or years), in order for the inAccess platform to deliver to him/her, via e-mail, 2 different types of reports for the PV plant of interest:

- Reports based on templates, delivered to the user as pdf or open office documents.
- Reports including any user selectable primary or derived parameters for the specified reporting period, delivered to the user as excel or csv files.
- Reports including any user selectable states for the specified reporting period, delivered to the user as excel or csv files.

The reports may contain information of a single solar plant or a user selectable portfolio of solar plants. The reporting service is easily extensible and modifiable to match further user requirements.

12.8 The Graphical User Interface

The inAccess platform features a Web client application based on Javascript technology designed to operate on all popular browsers such as Mozilla Firefox and Google Chrome. The main components around which the UI has been engineered are:

- The navigation panel, located on the left handside of the application page and it contains the various buttons required for efficient user navigation.
- The header panel, located on the topside of the application page displaying at all times the username of the current logged in user as well as the name of the plant that is currently monitored.
- The status bar, residing at the bottom of the application page and providing information regarding the current state of the selected PV plant and the last events (effective or unacknowledged) which have driven a specific plant to its current state.
- The content area, which is the main place-holder for the information displayed to the user.

An overview of the look and feel of the GUI is presented in the Fig. 12.10.

12.9 Inaccess Power Plant Controller

The previously mentioned monitoring and reporting services are employed in order to support the decisions for the inAccess Power Plant Controller (PPC), which is an intelligent vendor-independent system for dynamic and accurate PV power plant control and grid code compliance, customizable to satisfy any grid requirement while ensuring interoperability with plant SCADA systems. InAccess PPC controls the output of the PV plant at the Point of Common Coupling, using the plant inverters, meters, statcom, capacitors, breakers and peripheral controllers - providing near real-time capabilities for plant disconnection or generation stop, active and reactive power control, as well as power ramp rate control.

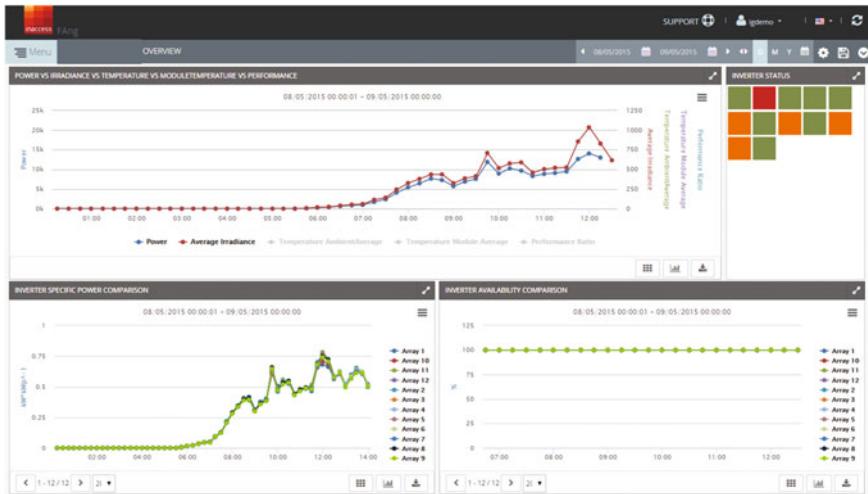


Fig. 12.10 Sample screenshot

InAccess PPC offers control and monitoring capabilities to the grid and plant operator, intelligent closed-loop control of active and reactive power, circuit breaker control, as well as monitoring of electrical, meteorological quantities, breakers and power control modes and states. Interoperability is ensured for a wide variety of inverters and meters. Customization for new grid code requirements is implemented upon request. Communication with grid operator systems is performed using a number of standard IP or RS-485 protocols (IEC 60870-5-104, DNP3, Modbus) as well as digital or analogue interfaces (Fig. 12.11).

InAccess PPC is fully integrated with inAccess PV monitoring system and network in order to cover any demanding architecture: with fiber-optic networks for connection to the plant subsystems or standard Ethernet, with IP or RS485-based inverter connectivity. The PPC is able to utilize peripheral substation units (PSSU) acting as protocol gateways, in order to satisfy grid code requirements even with low bandwidth networks.

12.9.1 Supported Features

InAccess PPC functionality integrates in a unique manner Control, Monitoring and Grid Integration:

- Active and reactive power closed-loop control with ramp rate and grid limitations: Control of P, Q, cosphi based on static, dynamic setpoints or grid code curves integrating centralized ramp rate control and grid code limitations (Q-V, P-Q).

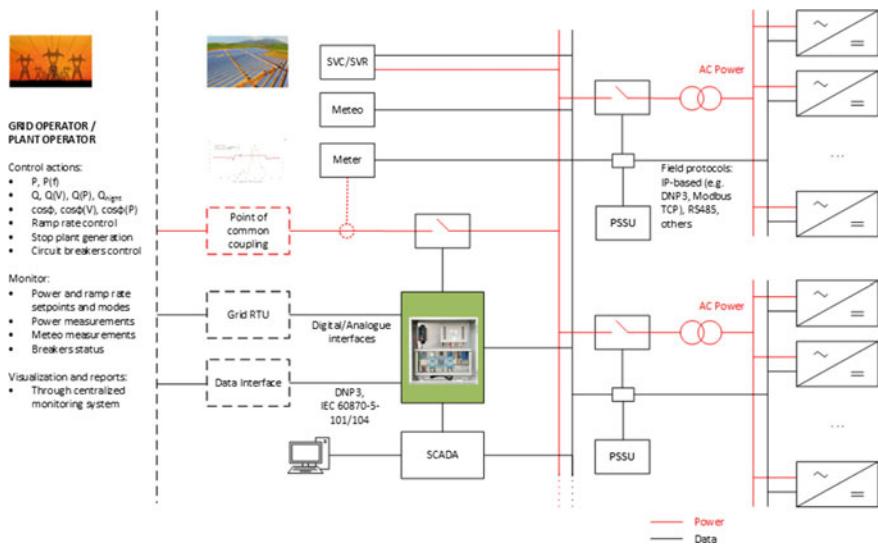


Fig. 12.11 InAccess Power Plant Controller

- Grid integration with any protocol, digital and analogue interface, fully extensible and customizable: Standard IP protocols (DNP3, IEC 60870-5, Modbus TCP), analogue inputs (0–20 mA, 4–20 mA, 0–10 V) or Digital inputs and outputs.
- Support for nearly any market inverter, meter and protection device, on demand support of new devices, reactive power compensation devices and battery systems.
- Interface of any available monitored plant and device measurements to the grid, from generation and compensation assets, meteorological instruments, circuit breakers and other equipment.
- Circuit breakers control, automation of substations disconnection and connection: for user operations or compliance with grid code requirements (transformers pre-magnetization automation).
- Integration of project-specific, new grid code or plant operator requirements upon request, customized for any plant design or network architecture: Ensuring on-time integration while satisfying any project-specific user or grid operator requirement.
- Interoperable with inAccess monitoring system for enhanced grid integration monitoring: Offering intelligent user interface, monitoring, visualization, exporting and reporting services, as well as monitoring of grid integration.
- Advanced system and network redundancy schemes are integrated and provided upon request. Active/passive redundancy or simple switchover models may be employed for the PPC.

12.9.2 Control Functionality

The PPC system offers flexible closed-loop control functionality easily adaptable to regional requirements to address the grid control needs. The active/reactive power can be controlled in discrete steps or continuously depending on the grid operators requirements and the capabilities of the installed equipment. Active power can be controlled as a function of frequency and the reactive power as a function of voltage or active power following the grid operators characteristic curves. Ramp rate limitations are enforced during both active power control functions as well normal plant operations. Reactive power compensation of passive components and reactive power injection into the grid is supported using fast or slow reactive compensation components.

Closed-loop PID control algorithms integrated with feed-forward techniques ensure high accuracy and fast response time:

- High accuracy in PPC-based active and reactive power control is ensured through intelligent closed loop PID control algorithms taking into account grid code requirements and limitations.
- Fast PID response time is ensured through proper control loop tuning and accelerated through knowledge of the plant system performance and losses.

12.9.2.1 Active Power Control

Active power control is performed in the range of plant nominal power or contract limit, with any analogue or discrete setpoints provided by the plant or the grid operator. Ramp rate limitations may be enforced either at inverter or PPC level. Depending on the grid requirements, over-frequency or under-frequency response may be configured based on grid code specified $P(f)$ curves. The following diagram provides an overview of the active power control mechanism of inAccess PPC. Devices controlled include inverters of any vendor (Fig. 12.12).

P SETPOINT may be set either by the grid operator or the plant operator, through IP based or serial protocols (DNP3.0, IEC60870-5-104, Modbus) or digital/analog contacts. Setpoints may also be set using the grid code $P(f)$ curve, when frequency based active power control is enabled.

RAMP RATE limitations are enforced in the control actions or normal active power ramp up by gradually applying the power control functions or limiting the possible active power ramp up while continuously monitoring the produced power. Active power gradient control is significant for the grid stability, minimizing voltage fluctuations from ramp up or ramp down active power commands, as well as solar irradiance variability.

PID ALGORITHM is used to enforce the final setpoints using a properly tuned closed-loop control scheme. The closedloop algorithm is further enhanced with feed forward logic and modelling of losses, maximizing accuracy and minimizing PID response time and control loops required. The PID algorithm calculates the error

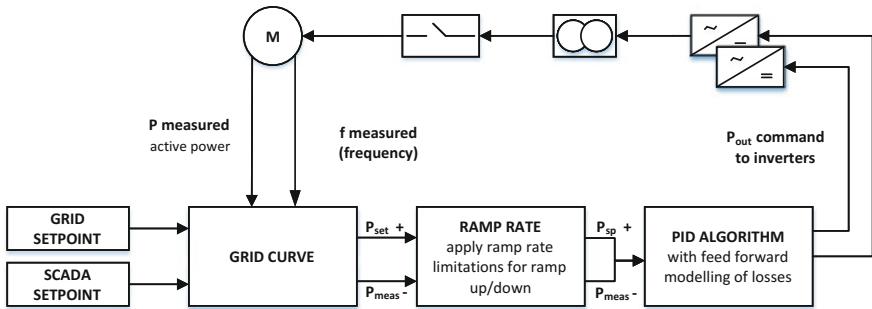


Fig. 12.12 Active Power Control generic flow chart

between setpoint and measured quantities and corrects the commands (P_{out}) sent to the inverter based on a proportional factor (K_p) correcting the error (e), integral factor (K_i) (accelerating the control success and maximizing accuracy) and derivative factor (K_d) improving settling time and stability.

METER at the point of connection measures the active power (P) and frequency (f) quantities providing the necessary feedback for the closed-loop control, ramp rate calculations and frequency grid-curve based setpoints.

12.9.2.2 Reactive Power Control

Reactive power control is performed in the range of reactive power limits specified by the grid operator, in a static or dynamic manner. The following diagram provides a high-level overview of the mechanism used by inAccess PPC. Equipment controlled include inverters of any vendor and nominal power, mechanically switched capacitors and reactors. Similar algorithms are applied for power factor control (Fig. 12.13).

SETPOINT may be set either by the grid operator or the plant operator, through IP based or serial protocols (DNP3.0, IEC60870-5-104, Modbus) or digital/analog contacts. Setpoints may also be set using a $Q(V)$ or $Q(P)$ grid code curve.

PID ALGORITHM is used to enforce the final setpoints using a properly tuned closed-loop control scheme. The closed-loop algorithm is further enhanced with feed forward logic and modelling of intra-plant reactive power absorption and internal losses, maximizing accuracy and minimizing PID response time and control loops required. The PID algorithm calculates the error between setpoint and measured quantities and corrects the commands (Q_{out}) sent to the inverter or compensation systems based on a proportional factor (K_p) correcting the error (e), integral factor (K_i) (accelerating the control success and maximizing accuracy) and derivative factor (K_d) improving settling time and stability.

REACTIVE POWER COMPENSATION RESOURCES: the Q command generated by the PID algorithm is distributed across the fast acting reactive power resources

REACTIVE POWER CONTROL THROUGH STATIC, DYNAMIC SETPOINTS, AND VOLTAGE Q(V) OR ACTIVE POWER Q(P) GRID CURVES

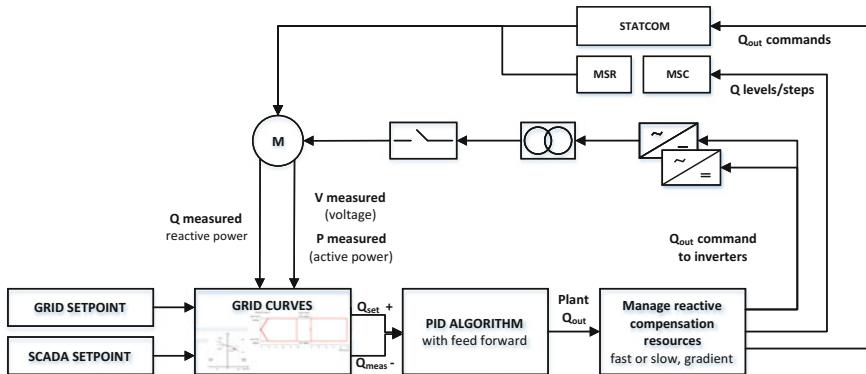


Fig. 12.13 Reactive power control generic diagram

(inverters), integrating slow acting devices (MSC, MSR) in parallel when required so that the maximum fast acting resources are available.

METER at the point of connection measures the reactive power (Q), voltage (V) and active power (P) quantities providing the necessary feedback for the closed-loop control, grid-code reactive power limitations and $Q(V)$ or $Q(P)$ curve-based setpoints.

12.9.2.3 Power Factor Control

Power factor control is performed in the range of power factor or reactive power limits specified by the grid operator, in a static or dynamic manner. The control is performed with a similar strategy as reactive power control and a dedicated PID controller, with PPC maintaining the specified power factor at the point of connection. Compensation resources used are the same as in fixed or dynamic Q control. SETPOINT may be set either by the grid operator or the plant operator, through IP based or serial protocols (DNP3.0, IEC60870-5-104, Modbus) or digital/analog contacts. Setpoints may also be set using a cosphi(V) or cosphi(P) grid code curve. The METER at the point of connection measures the power factor (cosphi), reactive power (Q), active power (P) and voltage (V) quantities providing the necessary feedback for the closed-loop control, grid-code reactive power limitations and cosphi(V) or cosphi(P) curve-based setpoints (Fig. 12.14).

12.9.2.4 Frequency Support

Frequency support is required by grid operators in order to respond to over-frequency or under-frequency events, with curtailment on the active power exported by the plant.

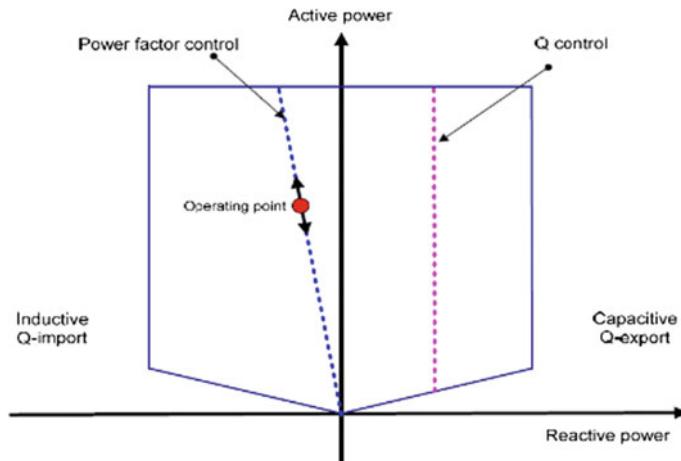


Fig. 12.14 Power factor control

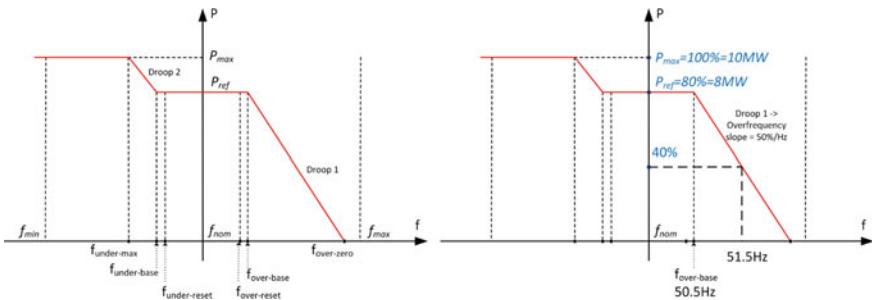


Fig. 12.15 Frequency support

Responding to over-frequency or under-frequency events takes priority over normal active power control or ramp rate limitations, effecting active power curtailment immediately (Fig. 12.15).

12.9.2.5 Voltage Control

InAccess PPC provides two modes of Voltage Control at the point of connection, slope-based or direct voltage regulation. Slope-based voltage control is a form of feed-forward reactive power control, where based on the voltage control setpoint, voltage measurement at the point of connection and grid code reactive power limits, the PPC applies closed-loop $Q(V)$ reactive power control setpoints.

Direct voltage regulation is a continuously variable and acting closed loop voltage regulation that controls the voltage level at the point of connection using reactive power control, within the plant design and grid code limitations (Fig. 12.16).

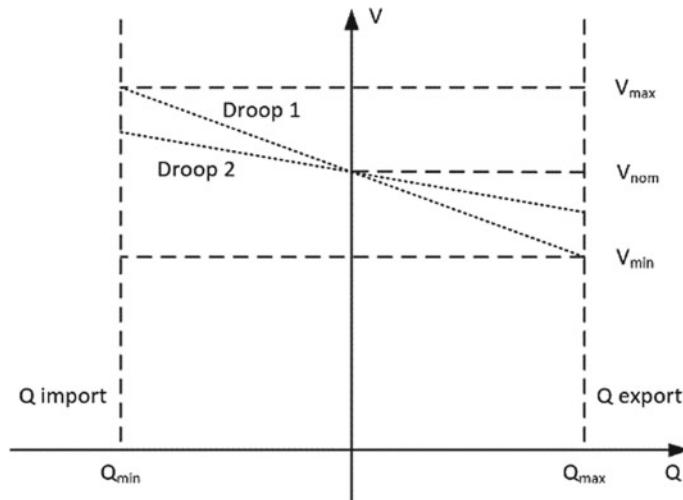


Fig. 12.16 Voltage control

12.9.2.6 Apparent Power Limitation

Apparent power at the point of connection may be limited to a specified level, limiting PV plant generation capability within the agreed generation limit. Apparent power control is usually performed by curtailing the active power generated by the inverters with a priority over existing active power setpoints.

12.9.2.7 Plant Shutdown and Power Up

The PPC is able to shut down and power up on demand, in a scheduled manner or triggered by an external event any of the plant generating components. Fully powering off the inverters through their built-in capabilities shuts down their capacitive and generating elements instead of just curtailing their power. Shutdown and power up may be configured to work along with ramp rate limitations and standard active power control.

12.9.2.8 Circuit Breaker Control and Monitoring

The PPC provides control and monitoring for circuit breakers, enabling automated upon an event or on demand connection or disconnection of the plant or specific plant segments. The PPC provides a fully customizable and vendor independent solution for complying to regional voltage fluctuation regulations, enabling the proper management of transformer connection and disconnection integrating pre-magnetization systems as needed.

12.9.2.9 Failsafe Operation

The plant response to grid interface failures, communications unavailability or grid disconnection is fully configurable depending on the grid code or plant design requirements. Pause of control, fallback to predefined limits or other limitations may be configured to satisfy even the most complex grid code or design requirements.

12.9.2.10 Integration of any External Device

Grid code and design requirements vary, so does the need for integration of external devices: InAccess PPC may provide integration to any telecom, electrical or other device that affect the proper plant control: UPS that may provide the current battery level or battery low alarms, communication units that provide availability and quality of service indications (for example cellular interface to communicate to the grid operator).

12.9.2.11 Meteo Stations Integration

The PPC provides access to any of the measurements available by meteo stations, pyranometers or other sensors, integrating irradiance, module temperature, ambient temperature, precipitation, wind, humidity or other environmental measurements to the grid interface.

12.9.3 Grid Integration Interface

Grid operators worldwide require integration of PV plants in their central SCADA systems, with full control and monitoring of the main plant characteristics that affect the grid. InAccess PPC offers native support of most standardized solar plant buses as well as proprietary protocols that may be used for grid integration. It includes full TCP/IP support, RS-232, RS-485 and USB, direct connection of analogue or digital I/O signals through off-the-shelf I/O modules, IEC 60870-5, DNP3.0 and Modbus TCP/RTU. In the level of information modelling and grid operator custom signals and logic, inAccess PPC is based on a modular application structure and is fully extensible to adapt to any grid code requirements or even changes (Fig. 12.17).

12.9.3.1 Network Interface

InAccess PPC supports the following protocols for integration with grid operator central SCADA systems or RTUs:

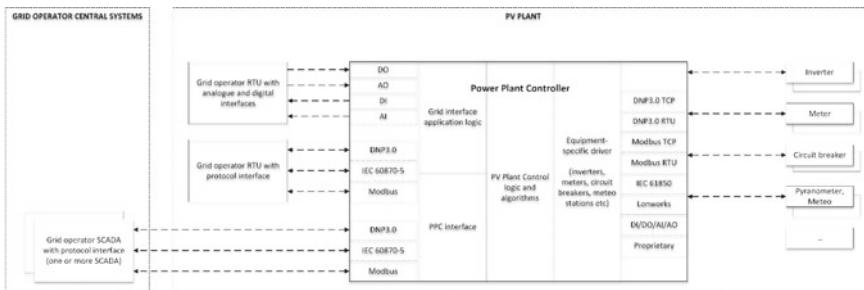


Fig. 12.17 PPC network and I/O interfaces

- DNP3 TCP/IP, DNP3 over serial
- IEC 60870-5-104
- Modbus TCP, Modbus RTU

The connection to the grid operator may be performed through standard wired mediums (e.g. F/O, DSL), wireless (GPRS) or satellite. Compliance to specific grid code requirements for network communications and information technology is carefully planned and ensured per case, with our without dedicated control networks.

12.10 Conclusions

A complete framework for supporting the monitoring and orchestration of smart-grid infrastructures, was described. Technical aspects of this solution in order to be widely adopted in large-scale deployments were also analyzed.

References

1. IEEE Std 929-2000 (Revision of IEEE Std 929-1988), IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems (30 January 2000)
2. IEC 61724 Standard, Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange and Analysis, 04/1998

Chapter 13

A Survey of Research Activities in the Domain of Smart Grid Systems



Nikolaos Karagiorgos and Kostas Siozios

Abstract In a fast evolving and competitive global landscape, Europe pays effort to develop and mature the next generation of competitive technologies and services for the distribution grid at medium and low voltage levels, which are clearly going beyond the state of the art and will be ready to integrate the market in five to ten years' time. Different topics on this domain, such as the technologies for the storage of energy in the distribution network and their integration and exploitation in the smart grid context, including decentralised storage at user premises or at substation level, synergies between energy networks, tools and technology validation for demand response forecast, profiling, segmentation, load forecasting, innovative and user-friendly services for customers based on smart metering, as well as intelligent electricity distribution grid consisted of tools for the optimisation of the distribution grid, technologies for autonomous and self-healing grids, energy management and control systems, technologies for advanced power electronics, for enhanced observability, e.g. real-time system awareness; secured communications in the smart grid in particular cyber security and big data analytics have been introduced. This chapter summarizes a number of recent Horizon 2020 projects in the domain of smart-grid.

13.1 Introduction

Several geographies across the world have already recognized the need of upgrading to smart grids and have taken initiatives to encourage this transition. The US, for instance, allocated USD 4.5 billion initially towards grid modernization; the investment increased over the years under the American Recovery Reinvestment Act of 2009. In Europe, the European Technology Platform (ETP) SmartGrids was formalized in 2005 to create a vision for the European networks till 2020 and beyond. A

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Table 13.1 Overview of investments in the domain of smart-grid

Country/Region	Forecast Smart Grid investments (€/\$)	Funding for Smart Grid development (€/\$)	Number of smart meters deployed and/or planned
European Union	€56 billion by 2020 [52] (estimated Smart Grid investments)	<ul style="list-style-type: none"> • €184 million (FP6 and FP7 E.U. funding for projects in the JRC catalogue) • About €200 million from European Recovery Fund, ERDF, EERA • National funding: n/a 	45 million already installed (JRC catalogue, 2011) 240 million by 2020 [52]
USA	\$338 (€238) to 476 (€334) billion by 2030 [51] (estimated investments for implementation of fully functional Smart Grid)	\$7 (€4.9) billion in 2009 [53]	8 million in 2011 and 60 million by 2020 [54]
China	\$101 (€71) billion [49] (Smart Grid technology development)	\$7.3 billion in 2009 (€5.1) [53]	360 million by 2030 [55]
South Korea	\$24 (€16.8) billion by 2030 [50] (estimated Smart Grid investments)	\$824 (€580) million in 2009 [53]	500,000 in 2010, 750,000 in 2011, and 24 million by 2020
Australia	n/a	\$360 (€253) million in 2009 [53]	2.4 million by 2013 in State of Victoria
India	n/a	n/a	130 million by 2020 [55]
Brazil	n/a	\$204 (€143.6) million in 2009 [53]	63 million by 2020 [55]
Japan	n/a	\$849 (€143.6) millions in 2009 [53]	n/a

recent 2017 report by Joint Research Centre (JRC) included 950 smart grid projects (R&D and demonstration) across Europe; across these, a total of EUR 5 billion has been invested.

According to the JRC database of R&D and demonstration projects, Table 13.1 provides a bird's eye view of the main developments in the field of smart grids worldwide [56].

13.2 E.U. Funded Projects in the Domain of Smart Grid

13.2.1 AnyPLACE

The AnyPLACE (Adaptable Platform for Active Services Exchange) project [1] develops a modular smart metering platform to enable energy remote metering in areas such as electricity, gas, heating and cooling. The system will provide a service exchange channel to help the interaction between end users, market representatives, electricity networks operators and ICT providers. It also emphasis on a more efficient use of electricity networks and turn end-users into active energy market players. To enable the development of the platform, the project is analysing the different regulatory frameworks, energy and telecommunications standards, potential scenarios of deployment, technical requirements of the solution and technologies currently available. Additionally, the project is building a set of prototypes with different combinations of modules to deal with different scenarios, which will be validated in state-of-the-art smart grid laboratories and a smart factory as well as tested in field trials. Near-market prototype versions will be then produced, accomplishing the project knowledge and technology transfer to industry and service providers. The AnyPLACE project also addresses behavioural issues related to public acceptance of the designed solutions. Thus, different participation strategies will be proposed to stimulate the end-user engagement.

13.2.2 CROSSBOW

CROSSBOW (CROSS BOnder management of variable renewable energies and storage units enabling a transnational Wholesale market) project [2] proposes the shared use of resources to foster cross-border management of variable renewable energies and storage units, enabling a higher penetration of clean energies whilst reducing network operational costs and improving economic benefits of RES and storage units. The objective is to demonstrate a number of complementary technologies in order to increase the flexibility and robustness of Transmission System Operators. For this purpose, effort will be paid to introduce: (i) a better control of exchange power at interconnection points; (ii) new storage solutions (distributed and centralized), offering ancillary services to operate Virtual Storage Plants (VSP); (iii) better ICT and Communications through better network observability, enabling flexible generation and Demand Response schemas; (iv) the definition of a transnational wholesale market, proposing fair and sustainable remuneration for clean energies though the definition of new business models supporting the participation of new players. The CROSSBOW results will be evaluated by 8 TSOs in Easter Europe, grouped to form clusters that will validate each of the projects outcomes in at least three different countries, demonstrating in all cases how CROSSBOW tackles the transnational challenges faced by these TSOs.

13.2.3 CryoHub

The CryoHub (Developing Cryogenic Energy Storage at Refrigerated Warehouses as an Interactive Hub to Integrate Renewable Energy in Industrial Food Refrigeration and to Enhance PowerGrid Sustainability) innovation project [3] investigates and extends the potential of large-scale Cryogenic Energy Storage (CES), which is a promising technology enabling on-site storage of RES energy during periods of high generation and its use at peak grid demand. Thus, CES acts as Grid Energy Storage (GES), where cryogen is boiled to drive a turbine and to restore electricity to the grid. By employing Renewable Energy Sources (RES) to liquefy and store cryogens, CryoHub will balance the power grid, while meeting the cooling demand of a refrigerated food warehouse and recovering the waste heat from its equipment and components.

13.2.4 DOMINOES

The DOMINOES (Smart Distribution Grid: a Market Driven Approach for the Next Generation of Advanced Operation Models and Services) project [4] aims to enable the discovery and development of new demand response, aggregation, grid management and peer-to-peer trading services by designing, developing and validating a transparent and scalable local energy market solution. The market can be leveraged to share local value, increase renewable energy accessibility and make better use of local grids by Distribution System Operators (DSO), Prosumers/Consumers, Energy Retailers and other key stakeholders. The DOMINOES project will depict how DSOs can dynamically and actively manage grid balance in the emerging future where micro-grids, ultra-distributed generation and energy independent communities will be prevalent. Best value will only emerge if these resources and stakeholders can be connected to both DSO activities and the centralized market mechanism. The project will establish solutions for this challenge by addressing the following steps: (i) design and develop a local energy market architecture, (ii) develop and demonstrate ICT components enabling the local market concept, (iii) develop and demonstrate balancing and demand response services supporting the local markets, (iv) design and validate local market enabled business models and (v) analyze and develop solutions for secure data handling related to local market enabled transactions. These delivered results will be validated in three validation sites in Portugal and Finland.

13.2.5 DRIVE

DRIVE (Demand Response Integration tEchnologies: unlocking the demand response potential in the distribution grid) [5] links together cutting edge science in Multi-Agent Systems (MAS), forecasting and cyber security with emerging innovative

SMEs making first market penetration in EU Demand-Response (DR) markets. In doing so, near market solutions are strengthened with lower TRL, higher risk functionalities that support a vision of an “internet of energy” and “collaborative energy network”. From the research side, MAS will move closer to real-time operations and progress from a limited number of assets toward decentralized management of a larger number of assets providing DR services to prosumers, grid stakeholders and DSOs. The research will deliver a fully-integrated, interoperable and secure DR management platform for aggregators with advanced hybrid forecasting, optimization, fast-response capabilities and enhanced user participation components in a standard-compliant (Open ADR) market-regulated (USEF) manner, empowering a true cost-effective mass-market (100s millions of heterogenous assets). The DRIVE project features 5 pilots across 3 countries consisting of a stadium, wind farm, 7-floor office, tertiary and residential buildings within medium-large districts, resulting in over 25 MW of potential flexible capacity. Direct engagement of 100 households and 2 tertiary buildings (over 1000 persons) is attained and replication to over 75,000 persons is possible. The pilots will be running in real DSO environment with real engagement of grid players. Overall, DRIVE will make available average 20% of load in residential and tertiary buildings for use in DR, resulting in up to 30% cost-saving (price-based DR) and also maximizing revenue for prosumers (incentive-based DR). DRIvE will also allow a minimum 25% increase of renewable hosting capacity (distribution grid) and up to 30% of overall reduction of CAPEX and OPEX costs for DSOs.

13.2.6 eDREAM

Smart automated DR represents a valid alternative to grid reinforcement for electricity DSOs to procure in a cost-effective way the necessary flexibility for integrating larger shares of intermittent RESs, while not compromising security of supply and network reliability. However DR potential has been exploited so far to a very limited extent due to a number of technological, regulatory, economic barriers. To cope with these challenges, eDREAM (eDREAM - enabling new Demand REsponse Advanced, Market oriented and Secure technologies, solutions and business models) project [6] aims to deliver a novel near real-time DR scalable secure blockchain-driven technological and business framework in order to optimize aggregated system services flexibility provisioning to DSOs. The project will research and develop tools and services for: (i) optimal DR system design, which includes early detection of flexibility potential via multi-modal fusion of aerial, LIDAR and thermal imaging, end users profiling and segmentation by leveraging on big data clustering and large data sets visual interactive exploration and DR optimization services for energy end users; (ii) optimal DSO-driven DR management, including novel applications of blockchain decentralized ledger for secure data handling, market-based micro-grid control and near real time closed loop DR verification aimed to improve system observability and enable fair DR financial settlement.

13.2.7 ELSA

Integration of distributed small/medium size storage systems can allow operating distribution grids much more flexibly, thus realizing smart grid features like local demand-supply balancing, congestion relief, peak shaving and effective RES integration. However, few technologically mature decentralized storage systems are commercially available today at affordable prices, while both viable business models and the underlying legal and regulatory framework are lagging behind. As an answer ELSA (Energy Local Storage Advanced system) project [7] implements and demonstrates an innovative solution integrating low-cost second-life Li-ion batteries and other direct and indirect storage options, including heat storage, demand-side management, as well as use of intermittent RES. The core idea is to consider Storage as a Service towards building and district managers for local energy management optimization, and towards DSO for enhanced network operations. ELSA will adapt, build upon, and integrate close-to-mature ($TRL \geq 5$) storage technologies and related ICT-based energy management systems for the management and control of local loads, generation and single or aggregated real or virtual storage resources, including demand response, in buildings, districts and distribution grids. Additionally, data models ensuring interoperability among building, districts and DSOs and novel business models enabled by energy storage “as-a-service” will be proposed. Safety issues and social acceptance will be dealt with by communication and product reliability demonstration. A technical, economic and environmental validation, involving relevant stakeholders, will be carried out to nurture the European-wide replication of the ELSA concept, prepare the ground for a concrete roll out of the resulting TRL9 technologies and provide input for regulatory framework adaptation.

13.2.8 EMPOWER

The EMPOWER (Local Electricity retail Markets for Prosumer smart grid pOWER services) project [8] is investigating the concept of a regional market and associated services to manage the exchange of energy, communication and monetary credit assignment. The project aims to encourage and enable the active participation of citizens that consume and produce energy in the electrical system. Specifically, the main objective of EMPOWER is to create of local electrical markets to promote the prosumer role in smart grids. Aiming to develop and verify a local market place and innovative business models, including operational methods, the project encourages micro-generation and the active participation of prosumers to exploit the flexibility created for the benefit of all connected to the local grid. By providing incentives for all players, EMPOWER exploits the flexibility the electricity distribution net offers to its users. The project enables the establishment and operation of local energy cooperatives that can manage renewable energy resources and serve members, while operating in an open, competitive market environment. It puts coordinated prosumers into the centre of future local power market design. This solution helps create a shared

engagement of local supply and therefore reduces the need of traditional DSOs to invest in centralised sourcing. The project also proposes a definition of a new role in the local electricity market, the Smart Energy Service Provider (SESP), with the tasks to handle the operation of the market place and the coordination between the participants, and to offer services to the market participants.

13.2.9 *Flex4Grid*

The transition towards distributed power sources gives rise to energy prosumers (producer-consumer) who both generate and consume electrical energy. The Flex4Grid (Prosumer Flexibility Services for Smart Grid Management) project [9] is creating an open data and service framework that enables a new concept of prosumer flexibility management. The project provides a system for new market players offering data analytics and aggregation services for DSOs to forecast and influence the load on the grid to avoid blackouts caused by network overloads or lack of power suppliers. Based on the anonymised and aggregated information supplied by Flex4Grid applications, the DSOs will be able to plan and react to consumption and generation peaks by providing business incentives to prosumers in the value chain to balance the energy load. Flex4Grid will also enable communication between prosumers' grid tie inverters to control the amount of power coming to the network to avoid network overload. The project will create benefits for all key stakeholders. Cloud service providers will be able to offer new services to DSOs and prosumers.

13.2.10 *FLEXCoop*

FLEXCoop (Democratizing energy markets through the introduction of innovative flexibility-based demand response tools and novel business and market models for energy cooperatives) [10] introduces an end-to-end Automated Demand Response Optimization Framework. It enables the realization of novel business models, allowing energy cooperatives to introduce themselves in energy markets under the role of an aggregator. Additionally, it equips cooperatives with innovative and highly effective tools for the establishment of robust business practices to exploit their micro-grids and dynamic VPPs as balancing and ancillary assets toward grid stability and alleviation of network constraints. Optimization in FLEXCoop applies to multiple levels. It spans local generation output, demand and storage flexibility, as well as the flexibility offered by EVs to facilitate maximum RES integration into the grid, avoidance of curtailment and satisfaction of balancing and ancillary grid needs. This is achieved via automated, human-centric demand response schemes with the participation of appropriately selected residential prosumers. To enhance prosumer acceptance, the FLEXCoop innovative services will feature non-intrusiveness, comfort and well-being preservation, non-violation of prosumer daily schedules as well

as maximization of benefits through transparent and open participation in markets. It will also guarantee easy switching between DR service providers, vendor lock-in avoidance, customized DR service contracts and objective settlement and remuneration, thus establishing an energy democracy context and empowering prosumers to become active energy market players.

13.2.11 FLEXICIENCY

The objective of FLEXICIENCY (energy services demonstrations of demand response, FLEXibility and energy effICIENCY based on metering data) [11] is to demonstrate that the deployment of novel services in the electricity retail markets (ranging from advanced monitoring to local energy control and flexibility services) can be accelerated thanks to an open European Market Place for standardized interactions among all the electricity stakeholders and opening up the energy market also to new players at EU level. Four major DSOs ENEL Distribuzione (Italy), Endesa Distribucion (Spain), ERDF (France) and Vattenfall Distribution (Sweden) with smart metering infrastructure in place, representing the majority of smart meters installed in Europe, are running a set of four complementary large-scale demonstrations with real customers, covering one or several new services related to advanced monitoring, local energy control and flexibility exploitation and valuation. Relevant meter data will be made available by the DSOs in a non-discriminatory way close to real-time, in order to enable the emergence of new energy services. Furthermore, advanced interoperable platforms for making available metering data to all the interested players, either new or existing ones, will be enhanced and run in the project building on open standards. The project is assessing economic models of these new services. Based on the five demonstrations, the dissemination activities will support the preparation of the market place exploitation strategies, as well as the promotion of the use cases tested during the demonstration activities.

13.2.12 FLEXITRANSTORE

FLEXITRANSTORE (an integrated platform for increased FLEXibility in smart TRANSmision grids with STORage Entities and large penetration of renewable Energy sources) [12] project aims to develop a next generation of Flexible Energy Grid (FEG), which provides the technical basis to support the valorisation of flexibility services, enhancing the existing European Internal Energy Market (IEM). This FEG addresses the capability of a power system to maintain continuous service in the face of rapid and large swings in supply or demand, whatever the cause. Thus, a wholesale market infrastructure and new business models within this integrated FEG should be upgraded to network players, incentivize new ones to join, while demonstrating new business perspectives for cross border resources management

and energy trading. The main objectives of this project are to enhance and accelerate the integration of renewables into European energy systems, as well as to increase cross border electricity flows across Europe. Flexibility is one of the keys to meeting these strategic objectives. A range of state-of-the-art ICT technologies and control improvements will be exploited to enhance the flexibility of this novel energy grid while increasing the utility of the existing infrastructure by integrating storage and demand response management. From a market perspective, similar approaches will be applied to develop an enhanced market model on an integrated platform, for flexibility services and to support cross border auctioning and trading of energy.

13.2.13 FLEXMETER

The FLEXMETER (Flexible smart metering for multiple energy vectors with active prosumers) project [13] is developing a flexible smart metering architecture based on cheap and already available components that can be implemented in a plug and play way, combining metering of different services (electricity, water, gas, district heating), providing advanced services to the users, to the DSOs and to the other utilities and enhancing the possibilities of the retail market. The metering architecture is deployed in two demonstrators Italy and Germany, on real systems, with the involvement of the local DSOs and volunteer prosumers. The results on the demonstrators will then be scaled up to the size of the cities in order to evaluate the advantages on a real scale. The proposed architecture will provide innovative services for the prosumers, for example, accessible data and historical records of their consumption and analysis of the electric consumption with saving suggestions. The architecture will also provide innovative services for the DSOs, for example, fault detection, detection of energy thefts, network balancing and storage integration.

13.2.14 FutureFlow

The FutureFlow (Designing eTrading Solutions for Electricity Balancing and Redispatching in Europe) [14] project is designing a unique regional cooperation scheme between four European Transmission System Operators (TSOs) of Central-Eastern Europe (Austria, Hungary, Romania, Slovenia), associated with power system experts, electricity retailers, IT providers and renewable electricity providers. The scheme aims to open balancing and redispatching markets to new sources of flexibility and supporting such sources to act on such markets competitively. The project is investigating the role of large power consumers and distributed generation owners to become secondary reserve market provider. This, together with cross-border exchanges, should reduce the costs of secondary reserve and redispatching and reverse the system reliability trends (more providers spread out over a wider geographical area). The project is expected to improve the competition in national bal-

ancing markets by facilitating the cross-border integration of these markets and the full participation of new electricity producers and advanced users from adjacent control areas in the provision of balancing and ancillary services.

13.2.15 GOFLEX

The GOFLEX (Generalized Operational FLEXibility for Integrating Renewables in the Distribution Grid) project [15] innovates, integrates, further develops and demonstrates electricity smart-grid technologies. It aims to enable the cost-effective use of demand response in distribution grids, increase the grids' available adaptation capacity and support an increasing share of electricity generated from renewable energy sources. The GOFLEX smart-grid technologies deliver flexibility solutions that are both general (across different loads and devices) and operational (solving specific local grid problems). GOFLEX supports an active use of distributed sources of load flexibility to provide services for grid operators, balance electricity demand and supply, and optimise energy consumption and production at the local level of electricity trading and distribution systems. Building on existing, already validated technologies for capturing and exploiting distributed energy consumption and production flexibility, the project develops solutions providing more flexibility for automatic trading of general, localised, device-specific energy as well as flexibility for trading aggregated prosumer energy. The generalised demand-response services developed in the framework of the project are based on transparent aggregation of distributed, heterogeneous resources to offer virtual-power-plant and virtual-storage capabilities. The sources of load flexibility include thermal (heating/cooling) and electric (electric vehicles charging/discharging) storages. A backbone data-services platform offers short-term predictions of energy demand/generation, and flexibility in order to support effective data-driven decisions for various stakeholders. Smart-grid technologies, such as increased observability and congestion management, contribute to the platform. The project plans to demonstrate the benefits of the integrated GOFLEX solution in three use-cases, covering a diverse range of structural and operational distribution grid conditions in three European countries.

13.2.16 GRIDSOL

GRIDSOL (Smart Renewable Hubs for Flexible Generation: Solar Grid Stability) [16] aims to improve stability and efficiency of electricity produced from various renewable energy sources. The project proposes the concept of smart renewable hubs, where a core of synchronous generators (in the concentrated solar power and biogas combined cycle HYSOL) is integrated with solar energy under a dynamic control system (DOME). These smart renewable hubs are designed to be self-regulating and to provide ancillary grid services thanks to firm, flexible generation on a single

output, tailored to a specific location. In turn, this will help relieve pressure on TSOs. The project will carry out research on an advanced control system to ensure operation efficiency and stability of electrical grids with a high-level of renewable energy sources. It will also develop a multi-tower concept for reducing costs of concentrated solar power and improving its efficiency. By getting the most of each renewable primary source, the GRIDSOL projects hopes to contribute to providing secure, clean and efficient electricity in Europe.

13.2.17 InteGrid

InteGrid's (Demonstration of INTElligent grid technologies for renewables INTEGRATION and INTERactive consumer participation enabling INTERoperable market solutions and INTERconnected stakeholders) [17] vision is to bridge the gap between citizens, technology and other players of the energy system. The project demonstrates how DSOs may enable all stakeholders to actively participate in the energy market and distribution grid management. InterGrid develops and implements new business models, making use of new data management and consumer involvement approaches. It also tests scalable and replicable solutions that help DSOs plan and operate the network with a high share of Distributed Renewable Energy Sources (DRES) in a stable, secure and economic way by using flexibility offered by specific technologies and by interaction with various stakeholders. InterGrid has established a complementary partnership covering the distribution system value chain. The consortium includes three DSOs and their retailers in three countries, innovative ICT companies, equipment manufacturers and customers, a start-up in the area of community engagement and R&D organisations. InteGrid's concept is based on the role of the DSO as system optimiser and as market facilitator, as well as the integration of existing demonstration activities in three different regions allowing to move from single solutions to an integrated management at a higher scale while focusing on the scalability and replicability in current and future markets, and in evolving regulatory conditions. To succeed in this direction, the three conceptual pillars are: (i) proactive operational planning with DRES; (ii) business models for flexible DRES; (iii) information exchange between different power system actors. If successful, InterGrid will help maximise the economic, societal and environmental gains from the combined integration of DRES and flexible DER. Moreover, a market hub platform coupled with smart grid functions and innovative business models will open opportunities for new services and an effective roll-out of emerging technologies in the future.

13.2.18 inteGRIDy

The inteGRIDy (integrated Smart GRID Cross-Functional Solutions for Optimized Synergetic Energy Distribution, Utilization Storage Technologies) project [18] integrates cutting-edge technologies, solutions and mechanisms in a scalable cross-

functional platform of replicable solutions. Through enhanced visibility of generation and consumption profiles, this platform connects existing energy networks to diverse stakeholders. The project aims to facilitate the optimal and dynamic operation of the distribution grid. It also fosters stability of the electricity grid and coordination of distributed energy resources, virtual power plants and innovative collaborative storage schemes within an energy system with an increasing share of renewable energy. Project's innovations are built upon: (i) integration of existing smart-metering/automation systems, together with intelligent IoT infrastructure, enabling interoperability through a standardized Application Programming Interface (API)s and efficient data collection and monitoring of grid's distributed assets; (ii) novel modelling and profiling mechanisms allowing the creation of network topology and demand response models, together with battery cycling and charging profiles, (iii) predictive algorithms enabling dynamic scenario-based simulation and multi-level forecasting engine for satisfying conflicting demand and supply of energy in real-time, (iv) powerful and efficient visual analytics and end-user applications based on the use of novel human-machine interaction techniques, (v) a security access control framework, for privacy and data protection, and (vi) innovative business models for the energy market aiming to dynamically involve demand-response strategies and allowing new entrants to the market to participate in the distribution grid's operations. The inteGRIDy project plans to implement and demonstrate a solution covering the above innovations under a variety of environmental, market and societal conditions at ten sites across the EU.

13.2.19 InterFlex

InterFlex (Interactions between automated energy systems and Flexibilities brought by energy market players) [19] aims to empower DSOs in the transition to more flexible local energy systems. The flexibility of distribution networks, the innovative IT solutions, as well as the increased network automation will be evaluated on six demonstrations in five European countries (Czech Republic, France, Germany, Netherlands and Sweden). Demonstrations are designed to run 18 use cases involving one or several of the levers increasing the local energy system flexibility: (i) energy storage technologies (electricity, heat, cooling); (ii) demand response schemes with two coupling of networks (electricity and gas, electricity and heat/cooling); (iii) integration of grid users owning electric vehicles; (iv) further automation of grid operations including contributions of micro-grids. Moreover, InterFlex aims to disseminate the project results to European DSOs and all the stakeholders of the electricity value chain through publishing roadmaps for the most promising use cases, thus nourishing the preparation of the future electricity market design.

13.2.20 INTERPLAN

The goal of INTERPLAN (INTEgrated opeRation PLAnning tool towards the Pan-European Network) project [20] is to provide an INTEgrated opeRation PLAnning tool towards the pan-European network, to support the EU in reaching the expected low-carbon targets, while maintaining network security. A methodology for proper representation of a “clustered” model of the pan-European network will be provided, with the aim to generate grid equivalents as a growing library able to cover all relevant system connectivity possibilities occurring in the real grid, by addressing operational issues at all network levels (transmission, distribution and TSOs-DSOs interfaces). In this perspective, the chosen top-down approach will actually lead to an integrated tool, both in terms of voltage levels, going from high voltage down to low voltage up to end user, and in terms of building a bridge between static, long-term planning and considering operational issues by introducing controllers in the operation planning. Proper cluster and interface controllers will be developed to intervene in presence of criticalities, by exploiting the flexibility potentials throughout the grid.

13.2.21 INVADE

The INVADE (Smart system of renewable energy storage based on INtegrated EVs and batteries to empower mobile, Distributed and centralised Energy storage in the distribution grid) project [21] aims to enable a higher share of renewable energy sources in the energy grid by proposing an advanced ICT could-based system for flexibility management integrated with Electric Vehicles (EVs) and battery storages. The goal is to change the way energy is used, stored and generated by utilising renewable energy more effectively, optimising the supply of electricity and making services more focused on end-users. The project integrates several components: (i) flexibility and battery management systems; (ii) ICT solutions based on active end-user participation; (iii) efficient integration of energy storage in the transport sector (EVs); (iv) novel business models supporting an increasing number of different actors in the energy grid. The platform, based on the ICT technologies developed in the project, will be integrated into existing infrastructure and systems at pilot sites in Bulgaria, Germany, the Netherlands, Norway and Spain. It will be validated it through mobile, distributed and centralised use cases in the energy distribution grid in large scale demonstrations. INVADE also develops novel business models and undertakes extensive exploitation activities to ensure a balance between maximising profits for a full chain of energy grid stakeholders and optimising social welfare, while contributing to the standardisation and regulation policies for the European energy market.

13.2.22 MAGNITUDE

In the framework of the achievement of the EU Climate and Energy packages for the decarbonisation of the energy sectors, the integration of variable renewable energy sources will put at stake the stability and provision security of the electricity system: there is a growing need for flexibility provision to ensure a reliable and stable electric system. MAGNITUDE (Bringing flexibility provided by multi energy carrier integration to a new MAGNITUDE) project [22] addresses the challenge to rise flexibility in electricity systems, by increasing the synergies between electricity, heating/cooling and gas networks and associated systems. MAGNITUDE will bring technical solutions, market design and business models, to be integrated on ongoing policy discussions. Additionally, the project aims to define technological and operational means for maximising flexibility provision to the electricity network. It will identify the regulatory framework to bring such flexibility service to the energy markets and will provide enhanced market designs and related business mechanisms. MAGNITUDE is built upon 7 real life case studies of multi energy systems, located in different European countries, under different regulatory and geopolitical environments and with different technological development levels. It will: (i) simulate the multi energy systems in the case studies and optimise their operation strategies maximising the provision of specific flexibility services; (ii) from existing regulations, propose improved market designs, and integrate them in a market simulation platform for evaluating its performance among the case study countries and (iii) quantify the benefit of pooling flexibilities from decentralized multi energy systems for energy markets through an aggregation platform. MAGNITUDE results will define policy strategies and recommendations in a pan-European perspective. Achievements will be spread among stakeholders to raise awareness and foster higher collaboration among the electricity, heating and gas sectors to achieve the common goal of a less carbon intensive, yet reliable energy system.

13.2.23 MIGRATE

In the future, both electricity production and consumption will increasingly be linked to the electricity grid through Power Electronics (PEs). By 2020, several areas of the heating, ventilating, and air conditioning (HVAC) pan-European transmission system will be operated by PE-interfaced generators. This will lead to new challenges due to the large amounts of electricity fed into it from wind and solar sources, including upgrading existing protection schemes and measures to mitigate the resulting decline in power quality. The MIGRATE (Massive InteGRATion of power Electronic devices) project [23] aims to devise various approaches to solving key technical issues relating to grid stability, supply quality, and control and security of supply that arise owing to the challenge posed by the ever-increasing use of renewable energy feed-in sources. The project has proposed an innovative solution to adjust the

HVAC system operations: (i) developing a replicable methodology for estimating and monitoring in real time the network's instability in all EU 28 control zones caused by PE-proliferation, along with a portfolio of incremental improvements to existing technologies, (ii) designing innovative power system control laws to cope with the lack of synchronous machines, (iii) by using numerical simulations and laboratory tests, the project will deliver control solutions and recommendations for new PE grid connection rules and for developing a novel protection technology to counteract the expected power quality disturbances, (iv) analysis of technology and economic impacts and barriers will be carried out in order to recommend future deployment scenarios and (v) the project will undertake dissemination activities among European Commission's stakeholders to support the deployment of the project outputs.

13.2.24 NAIADES

The NAIADES (Na-Ion bAttery Demonstration for Electric Storage) project [24] is one of the first large research projects developing a sodium-ion (Na-ion) battery for stationary electric energy storage applications and aims to demonstrate it under realistic conditions as an effective alternative to the lithium-ion (Li-ion) battery. The concept of the project is based on two complementary approaches: the former focusing on developing the materials and the latter on developing the system. In the framework of the project, the Na-ion battery will be developed up to a module demonstration in a realistic application environment, based on the knowledge and successes accomplished at the laboratory scale. The work encompasses developing all the battery components, i.e. active materials and electrolytes, final electrodes and electrochemical cells, as well as the battery management system. A 1kW Na-ion cell model will be tested in a grid environment at substation level. By the end of the project, a full electricity storage system based on the Na-ion battery will be developed. The new battery has a huge potential for reducing costs compared to the already mature and widespread Li-ion technology. An increasing demand for lithium, and the challenges posed by its extractions, will further emphasise this difference. As sodium is widely available and low-cost, sodium-based batteries could meet the energy storage needs of the electricity grid and therefore facilitate the use of renewable energy sources. The project is also elaborating policy proposals on how to integrate the Na-ion battery in smart grids and promote renewable energy in the electric network.

13.2.25 Net2DG

Reliable and efficient electricity supply to geographically distributed customers is the main task of the DSOs. An increasing number of grid-related data sources is in principle accessible to DSOs, but this information is in most cases not yet utilized

for grid operation. Leveraging measurements and ICT reachability of Smart Meters and grid connected systems (such as Intelligent Electronic Devices) for digital distribution grid operation is challenging as it requires resilient and secure data collection, and data-quality aware processing and distribution system control solutions. The Net2DG (Leveraging Networked Data for the Digital electricity Grid) project [25] aims to develop a proof-of-concept solution based on off-the-shelf computing hardware that uses existing communication technologies to leverage measurement capabilities of Smart Meters and DER inverters deployed in Low-Voltage (LV) grids. The solution will correlate this data with information from existing DSO subsystems in order to provide novel LV grid observability applications for voltage quality, grid operation efficiency and LV grid outage diagnosis. The resulting observability is subsequently used by specifically developed robust control and coordination approaches, which utilize existing actuation capabilities for voltage quality enhancement and loss minimization in the LV grid. The use of off-the shelf components, the system level resilience and security solution, and the offered customizability of the Net2DG approach specifically address the needs of small and medium-sized DSOs (less than 100.000 clients). Therefore, the Net2DG solution will make small and medium-sized DSOs early adopters of digital technologies for LV outage diagnosis, grid operation efficiency and voltage quality. The Net2DG solutions will be developed by a consortium including two small and medium-sized DSOs from two different European countries, academic partners, SME and startup technology companies, as well as Smart Meter and inverter vendors.

13.2.26 NETFFICIENT

The NETFFICIENT (Energy and economic efficiency for today's smart communities through integrated multi storage technologies) project [26] is testing different local small-scale energy storage technologies in a real electrical grid on the German island of Borkum. These technologies include ultracapacitors, Li-ion batteries, old batteries from electric vehicles, thermal storage and home hybrid technologies. An energy management system to exploit the synergies between the different local energy storage technologies, the smart-grid and citizens is being developed. Real environment testing is being carried out using real cases such as Peak shaving and ancillary services in the market, Street lighting, Heating integration. Peak shaving use case will connect a high-capacity storage system, based on Ultracapacitors and Li-ion batteries, to the medium voltage grid of the island to make the grid functioning more efficient and stable. The main aim of the street lighting use case is to consume the energy supplied by the sun during daytime for lighting at night. Heating integration use case will transform and store available electricity generated by PV into cool or hot water to regulate the temperature of water in the local island aquarium. The thermal energy stored in that way can then be used later in accordance with different needs. The project identifies viable business models and set out proposals for changes of the regulatory framework to reduce the barriers for deployment of

small scale storage technologies in the grid environment. If successful, the energy storage concepts and technologies could be widely replicated, complementing and encouraging the use of variable renewable energy sources.

13.2.27 NOBEL GRID

NOBEL GRID (New Cost Efficient Business Models for Flexible Smart Grids) project [27] is developing, deploying and evaluating advanced tools, ICT services and business models for all actors in the smart grid and electricity market, in order to ensure shared benefits from cheaper prices, more secure and stable grids and cleaner electricity. These tools and services are enabling active consumers' involvement and the innovative business models for new actors and facilitate the integration of distributed renewable energy production, in order to improve the quality of life of European citizens. The main outcomes of the project are ICT tools that offer secure, stable and robust smart grids, allowing DSOs to mitigate management, replacement and maintenance costs of the electricity distribution grid, in presence of large share of distributed renewable energy resources. Also, new services and business models will be provided for all the actors of the distribution grid. The project proposes innovative business models for the new players in the electricity panorama, such as prosumers, aggregators and energy service companies, with the objective to facilitate the integration of next generation distributed renewable energy sources and active participation of the European citizens in the energy market (demand response schemas). Finally, the most innovative aspect of the project is the innovative and affordable smart low-cost advanced meter allowing more extended functionalities for consumers and prosumers in order to empower and protect European citizens.

13.2.28 OSMOSE

The OSMOSE (Optimal System-Mix Of flexibility Solutions for European electricity) project [28] captures synergies across needs and sources of flexibilities, such as multiple services from one source, or hybridizing sources, thus resulting in a cost-efficient power system. OSMOSE proposes four TSO-led demonstrations (RTE, REE, TERNA and ELES) aiming at increasing the techno-economic potential of a wide range of flexibility solutions and covering several applications, i.e.: synchronisation of large power systems by multiservice hybrid storage; multiple services provided by the coordinated control of different storage and FACTS devices; multiple services provided by grid devices, large demand-response and RES generation coordinated in a smart management system; cross-border sharing of flexibility sources through a near real-time cross-border energy market. The demonstrations are coordinated with and supported by simulation-based studies which aim (i) to forecast the economically optimal mix of flexibility solutions in long-term energy

scenarios (2030 and 2050) and (ii) to build recommendations for improvements of the existing market mechanisms and regulatory frameworks, thus enabling the reliable and sustainable development of flexibility assets by market players in coordination with regulated players. Interoperability and improved TSO/DSO interactions are addressed so as to ease the scaling up and replication of the flexibility solutions. A database is built for the sharing of real-life techno-economic performances of electrochemical storage devices. Activities are planned to prepare a strategy for the exploitation and dissemination of the project's results, with specific messages for each category of stakeholders of the electricity system.

13.2.29 P2P-SmarTest

The P2P-SmartTest (Peer to Peer Smart Energy Distribution Networks) project [29] is investigating and will eventually demonstrate a smarter electricity distribution system integrated with advanced ICT, regional markets and innovative business models. It employs peer-to-peer (P2P) approach to ensure the integration of demand-side flexibility and the optimum operation of Distributed Energy Resources (DER) and other resources within the network while maintaining second-to-second power balance and the quality and security of the supply. The proposed project will built upon an extensive experience of the consortium on ICT. P2P-SmartTest project quantifies the value from significantly increased system interaction and integration, and assesses the required development in ICT and power networks in conjunction with commercial and regulatory frameworks to enable P2P trading to realise its full potential. The project also develops and demonstrates the distributed wireless ICT solutions capable of offloading the required traffic of different applications of energy trading, network optimisation, automated meter reading data and real-time network control, to name a few. The result will be integrated in a demonstration and validation environment to provide real-life results of distributed energy system designs.

13.2.30 Plan4Res

Plan4RES (Synergetic Approach of Multi-Energy Models for an European Optimal Energy System Management Tool) project [30] is a collaborative research and innovation project which aims at developing an end-to-end planning tool to successfully increase the share of renewable energy into the European Energy system without compromising on system reliability. The targeted platform will account for the Pan-European interconnected electricity system, potential synergies with other energy systems, emerging technologies and flexibility resources, providing a fully integrated modelling environment. Moving away from a monolithic approach will enable to overcome mathematical and computational challenges. The objective is to strive towards a system where a multiplicity of models, properly organized in a

functional hierarchy, synergistically contribute to the analysis of such complex systems. Targeting all main stakeholders of the power system, from generation to retail through grid operators, this innovative modelling platform will deliver a full system planning capability while considering a large set of future uncertainties, thus acting as a decision making tool for future investments. Allocation of multi-energy resources, system flexibility, assets portfolio assessment, advanced ancillary services or impact assessment of regulation are among the key features that the tool will deliver.

13.2.31 PLANET

The future electricity generation mix evolution, EU projects 97% generation from variable RES by 2050, will render current solutions for grid balancing and stability insufficient. Intermittent generation will require extensive electricity demand flexibility - beyond conventional solutions - to alleviate the unpredictable grid stresses in high VRES times. This flexibility cannot only come from electricity end-uses, the volatility and variability of RES generation is too high. Energy system decarbonisation will necessitate the use of novel conversion and storage in alternative energy carriers and their networks to achieve the avoidance of RES generation curtailment. The PLANET (Planning and operational tools for optimising energy flows and synergies between energy networks) project [31] aim is to design and develop a holistic decision-support system for grid operational planning and management in order to explore, identify, evaluate and quantitatively assess optimal strategies to deploy, integrate and operate conversion/storage systems on the distribution grid of several energy carriers within boundary constraints of real deployments outlined in the future energy system scenarios. Such tools are crucial for policy makers and network operators who need support in decision making process. The simulation of the integration between electricity, gas and heat networks models, together with conversion/storage technologies models for power-to-gas, power-to-heat and virtual thermal energy storage, will help to understand and quantify how these conversions can affect network stability, reliability and responsiveness as well as to optimize these metrics across networks. The PLANET tools will be demonstrated and validated using information from the actual premises and customers of two distribution network operators in Italy and France. They manage electricity, natural gas and district heating networks, hence they provide a solid testbed corresponding to real-world solution deployments to evaluate the actual benefits of PLANET solutions.

13.2.32 PROMOTION

In order to unlock the full potential of Europe's offshore resources, a network infrastructure linking offshore wind parks and on-shore grids in different countries is urgently required. High-Voltage Direct Current (HVDC) technology is envisaged but

the deployment of meshed HVDC offshore grids is currently hindered by high costs, lack of experience and immature international regulations and financial instruments. The objective of the PROMOTIoN (PROMOTIoN - Progress on Meshed HVDC Offshore Transmission Networks) project [32] is to bring meshed HVDC offshore grids and their associated technologies to the level of large scale real-life application. The project will significantly accelerate the deployment of meshed HVDC offshore grids in the North Sea area and beyond towards continental power corridors and will be a major step in bringing them into commercial application in near future. PROMOTIoN demonstrates three key technologies, a regulatory and financial framework and an offshore grid deployment plan for 2020 and beyond. A first key technology is a “diode rectifier”. This concept challenges the need for complex, bulky and expensive converters, reducing significantly investment and maintenance cost and increasing availability. The second key technology is an HVDC grid protection system which is developed and demonstrated utilising multi-vendor methods within the full scale Multi-Terminal Test Environment. The third technology pathway demonstrates for the first time the performance of existing HVDC circuit breaker prototypes to provide confidence and to demonstrate technology readiness of this crucial network component. The additional pathway develops the international regulatory and financial framework, essential for funding, deployment and operation of meshed offshore HVDC grids.

13.2.33 RE-SERVE

The RE-SERVE (Renewables in a Stable Electric Grid) project [33] is looking for a new way to stabilise energy systems with up to 100% RES to help them maintain a stable and sustainable energy supply. The project will address this challenge by developing new energy system concepts. They will be implemented as new system support services and will enable distributed, multi-level control of the energy system through the use of pan-European unified network connection codes. The project will propose innovative, 5G-based ICT solution to provide near to a real-time control of the distributed energy network. RE-SERVE energy system models will be based on energy system use scenarios supplied by various energy providers. Through integrating energy simulations and live 5G communications, the project will assess the performance of the new control mechanisms. By bringing together the best facilities in Europe, Re-SERVE also plans to create a pan-European multi-site simulation test bed. The project expects to develop new models of system support services based on an innovative architecture. Moreover, it will develop a model for pan-European unified network connection codes. RE-SERVE results will be promoted to standardisation organisations. When commercialised, the project results will provide a wide range of enhanced professional solutions and services for the energy system based on RES. for me ok your re drafted version.

13.2.34 *RealValue*

The project will test whether using smart domestic electric radiators and boilers to store heat brings cost-reductions to consumers and helps increase the use of energy generated from variable renewable sources. RealValue (Realising Value from Electricity Markets with Local Smart Electric Thermal Storage Technology) [34] installs smart electric radiators and boilers in 1250 homes in Germany, Ireland and Latvia to feed the results into modelling of the technology's technical and commercial potential. To validate the trial at large scale, RealValue uses desktop techno-economic modelling to predict the future potential of local small-scale energy storage in millions of homes across more broadly representative EU regions. The project also carries out in-depth analysis of the potential European market for local small-scale energy storage, including socio-economic, policy and regulatory aspects. Consumer engagement is a key aspect of RealValue and behavioural analysis studies are carried out during the whole life of the project. RealValue will provide an innovative means to mitigate the challenges associated with, and maximise the value of clean energy from renewable sources. It has a strong focus on developing new and innovative business models and will bring benefits in terms of energy balancing, grid security and supply, network congestion and management, price arbitrage, new tariff development, decarbonisation and future market design.

13.2.35 *RESOLVD*

RESOLVD (Renewable penetration levered by Efficient Low Voltage Distribution grids) project [35] aims to improve the efficiency and the hosting capacity of distribution networks, in a context of highly distributed renewable generation by introducing flexibility and control in the low voltage grid. An innovative advanced power electronics device, with integrated storage management capabilities, will provide both switching and energy balancing capacities to operate the grid optimally. Continuous power flow control between storage and the grid, and also between phases, will result in a flatter and reduced demand curve at the substation level with an associated loss reduction and an improved voltage control and quality of supply. The enhanced observability of RESOLVD, provided through cost-effective PMUs and state-of-the-art short-term forecasting algorithms that predict demand and renewable generation, will permit a reduction of uncertainty in grid operation and an increased efficiency. RESOLVD proposes hardware and software technologies to improve low voltage grid monitoring with wide area monitoring capabilities and automatic fault detection and isolation. This improved observability and monitoring system combined with the capability of actuating on the grid will benefit from robust scheduling methods to support self-healing and grid reconfiguration. This will allow efficient grid operation and a maximised renewable hosting capacity. The integration of these technologies, allowing interoperability with legacy systems and third parties in a cyber secure

way, envisions new business models that will be analysed during the project. Some of them focused on the role of the DSO as a facilitator, but others simply to exploit a second-life of certain types of batteries.

13.2.36 SENSIBLE

The SENSIBLE (Storage-Enabled Sustainable Energy for Buildings and Communities) project [36] demonstrates different types of small-scale energy storage that can be integrated into buildings and communities in Evora (Portugal), Nottingham (UK), and Nuremberg (Germany). Such storage can improve the integration of variable renewable energies, improve the customers' energy security and facilitate self-production and consumption. By integrating different storage technologies into local energy grids as well as homes and buildings, and by connecting these storage facilities to the energy markets, the project SENSIBLE will have a significant impact on local energy flows in energy grids as well as on the energy utilization in buildings and communities. The impacts range from increased self-sufficiency, power quality and network stability all the way to sustainable business models for local energy generation and storage.

13.2.37 SmarterEMC2

Power systems are undergoing massive technological changes due to the increasing concerns for environmental and energy sustainability. The increase of RES and distributed generation penetration is one of Europe's main goals in order to meet the environmental targets. However, these goals will require new business cases and must be based on innovative ICT tools and communication infrastructure. In parallel, following the M/490 EU Mandate, the standardisation bodies CEN, CENELEC and ETSI proposed a technical report describing the smart grid reference architecture and the smart grids architecture model framework. Key objective of the SmarterEMC2 (Smarter Grid: Empowering SG Market Actors through Information and Communication Technologies) project [37] is to provide ICT tools and solutions compatible with standardisation activities in Europe. SmarterEMC2 implements ICT tools that support Customer Side Participation and RES integration, and facilitate open access in the electricity market. These tools take into account the SGAM architecture as well as the future structure of the Distribution Network. The project supports standardization activity by proposing adaptation to data models of market-oriented standards (IEC 62325-351) and field level standards (IEC 61850). Moreover, the project is fully dedicated towards achieving a maximum impact. To validate the proposed technologies, the project includes three real-world pilots and a large-scale simulation in three laboratories. The former will demonstrate the impact of Demand Response and Virtual Power Plants services in the real world settings, while the latter will reveal the ability of the communication networks to support massive uptake of such services.

13.2.38 *SmartNet*

Integrating increasingly large quantities of electricity from renewables is a challenge for the European energy system. To ensure the security of the operation, it is key that all the connected units, including RES generators as well as flexible loads and storage systems, provide ancillary services. This can be done for the entire system through developing connection points to the transmission grid. The aim of Smartnet (Smart TSO-DSO interaction schemes, market architectures and ICT Solutions for the integration of ancillary services from demand side management and distributed generation) project [38] is to provide solutions and architecture for optimised interaction between TSOs and DSOs in exchanging information for monitoring and acquisition of ancillary services (reserve and balancing, voltage regulation, congestion management) for local needs and for the whole European system. The project involves distributed generation, demand-side and storage-to-system services. The impacts of SmartNet include: (i) deployment of solutions for improving flexibility and capacity of European electricity grids at high voltage levels to integrate both renewable and other new electricity producers and users; (ii) demonstrating advanced grid technologies and system architectures and enhancing the competitiveness of European industries; (iii) devising new architecture and business models and disseminating most effective architecture and models across Europe; (iv) demonstrating the infrastructures, processes and information management to encourage active participation of actors from the demand-side and new players (such as aggregators) in energy markets.

13.2.39 *SMILE*

The SMILE (SMart IsLand Energy systems) project [39] demonstrates a set of both technological and non-technological solutions adapted to local conditions targeting the distribution grid to enable demand response, smart-grid functionalities, storage, and energy system integration. The overall objective is to pave the way for their introduction in the market in the near future. The technological solutions vary from integration of battery technology, power to heat, power to fuel, pumped hydro, electric vehicles, electricity stored on board of boats, an aggregator approach to Demand Side Management (DSM) and predictive algorithms. Three large-scale pilot projects will be implemented in three different regions of Europe with similar topographic characteristics but different policies, regulations and energy markets. The objective is to test solutions while establishing mutual learning processes and providing best practice guidance for replication in other regions. The three pilots will test different combinations of technological solutions according to local specificities and conditions and the existing infrastructure and will involve all value chain actors needed to efficiently implement projects system-wide. Moreover, cross-cutting activities among the pilots will be devoted to solve common technical, organizational, legal,

regulatory and market-related issues as well as to evaluate the solutions from the economic and business points of view.

13.2.40 SOGNO

The energy systems of 2025 will be based on increasing levels of RES penetration and DSO's will need new insight into how their networks are performing to optimise their operations financially. At the same time, the 5G mobile networks will be deployed by 2025 offering low latency, high availability services enabling data driven control. The evolution of the energy sector is increasingly focused on energy as a service. What DSOs now need is to accelerate their ability to introduce innovations, such as those based on the sharing economy, by themselves using services increasing their flexibility to adapt and reducing their need for fixed investments. SOGNO (Service Oriented Grid for the Network of the Future) project [40] aims to address this challenge by combining the application of deep intelligence techniques, industry grade data analysis and visualisation tools, advanced sensors, an advanced power measurement unit and 5G based ICT to provide fine grained visibility and control of both MV and LV power networks using end to end automation in a virtualised environment. Our results are provided as turnkey services, validated in DSO field trials (to TRL level 6) preparing them for market introduction beginning shortly after the project ends. An Open API will be provided to enable third parties to market their services in our eco-system creating further market growth. Regulatory and standards changes needed to enable the deployment of advanced techniques will be prepared by the project. Ethical business models will support the market introduction of turnkey services. Commercialisation of the project results, as energy services, will result in disruptive change in the DSO energy market enabling breakthroughs in the speed and cost effectiveness of DSO large scale roll out of automation and growth in the energy services market in Europe and beyond. The SOGNO vision will unlock a new service-oriented market making Europe's energy sector the most advanced and open in the world.

13.2.41 Spine

Spine (Open source toolbox for modelling integrated energy systems) project [41] will create a toolbox for modelling integrated energy systems. The Toolbox will be modular and adaptable, making the toolbox suitable for both detailed modelling of complex features in energy systems as well as for large-scale problems. This is a novel approach to energy system modelling, which allows a much broader set of problems being addressed within a single modelling tool. The adaptability comes from a design where the input data defines the temporal, spatial, technological, regulatory and sectoral dimensions of the model instance. Model instances can also be

chained in order to allow iterative approaches for solving especially large problems (e.g. planning a large system while considering high operational detail). The Spine Toolbox will support the full modelling chain from data acquisition to processing of results. Through automated features of the toolbox it will be easy to generate a large number of scenarios from user-defined data collections. It can connect to different tools and models, both external and internal. The internal tools developed in the project include an input data verification tool, a tool to post-process outputs, parallelization service and the actual Spine Model. The Spine Toolbox and the Spine Model will be deployed by open sourcing all the developments. The project will initiate, grow and support a user community where the project partners will participate as they will replace many of their existing tools with the Spine Toolbox. The Spine project will use the toolbox to contribute to the expected impacts of the call. A series of case studies will help the project to expand specific modelling capabilities in the Spine Model, deploy the Toolbox to potential users, and produce analysis relevant to the expected impacts of the call. Policy and business relevant results will be communicated to the relevant stakeholders, demonstrating the future uses of the toolbox in policy-support and business decision-support.

13.2.42 STOREandGO

The STOREandGO (Innovative large-scale energy STOragE technologies AND Power-to-Gas concepts after Optimisation) project [42] is to demonstrate three innovative “Power-to-Gas” concepts in Germany, Italy and Switzerland that will help to accommodate more renewable electricity in the energy mix. The main idea is to convert excess electricity produced from renewable energy sources to gas (methane). The gas produced will be then stored in the existing gas storage infrastructure, which is connected to the gas grid, and used later for heating or reconversion to electricity. The demonstrations will pave the way to an integration of PtG storage into flexible energy supply and distribution systems with a high share of renewable energy. Using methanation processes as bridging technologies, the project will demonstrate and investigate in which way these innovative PtG concepts will be able to solve the main problems of renewable energy: its fluctuating production, consideration of renewables as suboptimal power grid infrastructure, high costs and a lack of storage solutions for renewable power at the local, national and European level. At the same time, PtG concepts will contribute to maintaining natural gas or SNG within the existing huge European infrastructure and to improving its environmental footprint as an important primary/secondary energy carrier. So, STORE&GO will show that new PtG concepts can bridge the gap associated with renewable energies and security of energy supply.

13.2.43 STORY

The main objective of the STORY (Added value of STORage in distribution sYstems) project [43] is to show the added value that energy storage can bring to a flexible, secure and sustainable energy system. STORY provides relevant and wide-covering demonstrations that serve as input for a thorough and transparent analysis on what the impact of energy storage can be for the involved stakeholders. Energy storage is considered as a mean, while not neglecting other competing technologies that could provide a similar or complementary functionality. The project is testing the potential of different energy storage concepts and technologies such as batteries, small scale thermal storage, seasonal thermal storage, fuel cells, compressed air and improved monitoring and control tools in real-life settings. All of these concepts have innovative aspects, such as the storage technology, the storage integration and control systems, and the business model. It is expected that the project will provide strong evidence of the opportunities and the benefits provided by the intelligent integration of energy storage in the grid. STORY will also provide a comprehensive guide for policy makers and regulators showing the pros and cons of different approaches to the integration of energy storage. If successful, the energy storage concepts and technologies tested within the project could be widely replicated, and could complement and encourage the use of variable renewable energy sources.

13.2.44 TDX-ASSIST

The TDX-ASSIST (Coordination of Transmission and Distribution data eXchanges for renewables integration in the European marketplace through Advanced, Scalable and Secure ICT Systems and Tools) project [44] aims to design and develop novel ICT tools and techniques that facilitate scalable and secure information systems and data exchange between TSO and DSO. The three novel aspects of ICT tools and techniques to be developed in the project are: scalability (ability to deal with new users and increasingly larger volumes of information and data); security (protection against external threats and attacks); and interoperability (information exchange and communications based on existing and emerging international smart grid ICT standards). The project focuses on TSO-DSO interoperability. While this interoperability is currently well-established by ENTSO-E through implementation of the Common Grid Model Exchange System, TSO-DSO interoperability will also benefit future TSO-TSO interoperability. In this context the project will also consider DSO to other Market-participants (DSOs, Aggregators, Distributed Energy Resource Operators, Micro-grid Operators) and information or data access portals that enable business processes involving relevant actors in the electrical power sector.

13.2.45 TILOS

The TILOS (Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage) project [45] is testing the integration of an innovative local-scale, molten-salt battery (NaNiCl_2) energy-storage system in the real grid environment on the island of Tilos (Greece). It is planned to test smart-grid control system and provision of multiple services, ranging from micro-grid energy management, maximisation of RES penetration and grid stability, to export of guaranteed energy amounts and provision of ancillary services to the main-grid. The battery system is used to support both stand-alone and grid-connected operations, while ensuring its interoperability with the rest of micro-grid components and demand side management. New case studies examining different battery technologies and micro-grid configurations (stand-alone, grid connected and power market-dependent) are being prepared using advanced micro-grid simulating tool (the Extended Microgrid Simulator). Social issues are also well considered through public engagement, and by developing novel business models and policy instruments. The prototype molten-salt, battery-storage system will improve micro-grid energy management and grid stability, increase renewable energy use and provide services to the main grid. If successful, this energy storage technology could be widely replicated on islands to complement and encourage the use of variable renewable energy sources.

13.2.46 UNITED-GRID

UNITED-GRID (Integrated cyber-physical solutions for intelligent distribution grid with high penetration of renewables) project [46] aspires to be the arrow-head within Integrated cyber-physical solutions for intelligent distribution grid with distributed energy resources' and addresses the challenges in the "competitive low-carbon energy", relevant to next generation of active distribution grids. UNITED-GRID will develop a tool-box with technologies enabling at least 80% renewable-based energy production on an annual basis, with an increased reliability performance of 50%, while decreasing grid losses by 10%. The developed technologies include e.g. solutions for real-time system awareness and control, short term generation and load forecasting, setting-less protection schemes and new business models. The toolbox will be integrated into a professional system ensuring interoperability and smooth integration with existing EMS/DMS on the market. To enhance future impacts, at least 2/3 of novel solutions which have been positively validated will have an agreed and financed development processes for the next TRL level beyond the project.

13.2.47 UPGRID

The LV networks are still managed as before: no visibility of power and voltage or grid components status, poor knowledge of connectivity, manual operation of switches, few support tools. The LV grid characteristics limit the possibilities for constructing and refurbishing LV electric infrastructure and pose a barrier for integrating on it grid remote monitoring, operation and automation resources. It results in difficulties in implementing the LV smart grid and in integrating distributed generation resources and active demand management. The smart metering and smart grids rollout in the EU aims to maximise the benefits of developing and integrating innovative grid and ICT infrastructure, functions, services and tools which can improve the grid's operation performance and quality and reduce annual household energy consumption and decrease emissions in the EU by up to 9%. The smart metering and smart grids rollout paves the way for new business opportunities for the involved actors (DSOs), customers, retailers and energy service companies). The UPGRID (Real proven solutions to enable active demand and distributed generation flexible integration, through a fully controllable LOW Voltage and medium voltage distribution grid) project [47] focuses on developing, deploying and demonstrating innovative solutions (grid systems, functions, services and tools) for advanced operation and exploitation of LV/MV (low/medium voltage) networks in a fully smart grid environment. It aims to improve the capacity of these networks as enablers for distributed generation and ADM, as well as to empower customers and create new business opportunities.

13.2.48 WiseGRID

WisGRID (Wide scale demonstration of Integrated Solutions and business models for European smartGRID) project [48] integrates, demonstrates and validates advanced ICT services and systems in the energy distribution grid in order to provide secure, sustainable and flexible smart grids and give more power to the European energy consumer. WiseGRID's main objective is to provide a set of solutions and technologies to increase the smartness, stability and security of an open, consumer-centric European energy grid. The project will combine an enhanced use of storage technologies, a highly increased share of RES and the integration of charging infrastructure to favour the large-scale deployment of electric vehicles. It will place citizens at the center of the transformation of the grid. The project goes beyond empowering prosumers. On top of having a consumer-centric approach, it will make a difference in the market by delivering tools that facilitate the creation of a healthy, open market where not only "traditional" utilities but also players such as electric cooperatives and small and medium-sized enterprises can play an active role, contributing therefore effectively to the transition to energy democracy. WiseGRID follows European Commission's ambition to put the consumer back at the center of the energy system, to promote

and support sustainable energy communities. WiseGRID integrated solution will be demonstrated and evaluated under real life conditions in 4 large scale demonstrators - in Belgium, Italy, Spain and Greece - under different technical, regulatory, legislative and social conditions. Demonstration sites will involve more than 1700 users, 60 batteries (totalling more than 300KWh of installed capacity), 50 heat pumps (over 160kWh of installed capacity), 180 electric vehicles, 40 charging stations and more than 70MWh of RES.

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