1

Storing Electrical Energy in Habitat: Toward "Smart Buildings" and "Smart Cities"

1.1. Toward smarter electrical grids

1.1.1. *The move to decentralize electrical grids*

The traditional organization of an electrical grid is based on centralized management, at the level of the transport grid to which conventional nuclear, thermal or hydraulic production systems are connected. Originally, the distribution grid only supplied consumers, and only carried power flows from high voltage points, through connections to the transport grid, toward lower voltage points. The possibilities for adjustment at the distribution level are limited, and ancillary services (voltage and frequency control) are provided by production units connected to the transport grid [ROB 12c, ROB 15].

The development of decentralized production, generally low power, unplanned and not monitored by a central entity, has brought about significant changes. Producers are often connected to a distribution grid and dispersed across a territory, contrasting with the classic model of high-power production on a few, clearly defined sites. The effects of integrating this production, which generally comes from wind and solar sources, are becoming increasingly noticeable and bring in new constraints. The variable nature of wind and photovoltaic sources, which is difficult to predict, adds a further level of complexity to grid management issues.

The liberalization of the electricity market within the European Union, beginning in the early 21st Century, has resulted in a clear separation between the management of energy production, which is subject to competition, and the management of

transport and distribution grids: evidently, the infrastructure involved cannot be duplicated. In France, the CRE (*commission de régulation de l'électricité*, Electricity Regulation Commission) [CRE] is charged with ensuring that the new competition mechanisms are respected, that competition does not have a negative effect for consumers and that there is no danger to an infrastructure crucial to both the economy and security of the country. Liberalization has led to a need for new approaches to managing the electricity system, alongside new market mechanisms integrating the characteristics of new decentralized sources. Given that the electricity grids themselves cannot be rebuilt, development is needed at three specific levels:

– at the source level, using the possibilities offered by power electronics to develop new control and supervision strategies and provide ancillary services, notably through the implementation of energy storage; to develop multi-source systems (integrating intermittent renewable production, classic, predictable sources and storage) featuring integrated and optimized energy management [ROB 15];

– at the grid level, rolling out smart grids and developing new grid architectures, such as micro-grids, in order to increase the efficiency, security and availability of electricity grids, and increasing energy storage capacity, either at a central point or dispersed across these grids [ROB 15];

– at the consumer level, in industrial processes, tertiary buildings and homes, through electric and rechargeable hybrid vehicles, and in guided transport systems (trains, subway systems and trams) [ROB 16], with the aim of modulating energy demands to correspond to consumption, renewable production availability and the constraints inherent in electric grids.

Interactions between these different aspects need to be coordinated to some extent, and this raises questions regarding the optimal and most acceptable level of decentralization; a system for communication between components is also required. These issues are not purely technological in nature, including economic and sociological aspects, and requiring new developments on the judicial stage.

1.1.2. *Smart grids*

It is thus essential that we install and use new communication technologies as part of advanced management mechanisms. The level of intelligence in a grid depends on two factors. The first corresponds to the installation of a telecommunications network, mechanisms and equipment for remote control and automated network management within transport and distribution grids. The second involves advanced management of production (centralized and/or decentralized) and of loads, notably via the development of new products and services by producers and distributors, including network managers which increase the level of freedom available in piloting a grid. Final consumers may also benefit from special services and pricing offers, allowing

the adoption of ambitious approaches to mastering instant demands for electricity and the integration of renewable energy sources (Figure 1.1).

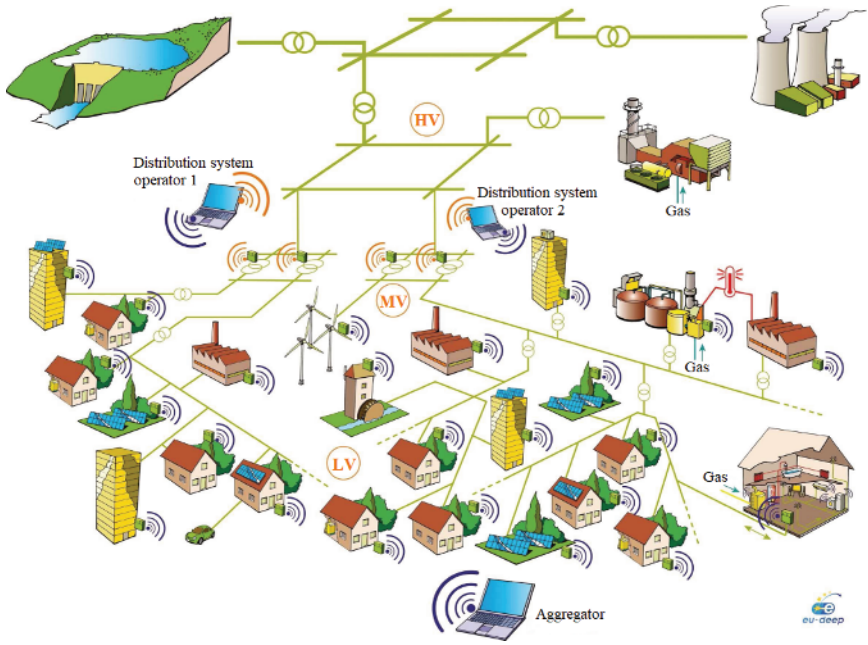

Figure 1.1. *Example of a future smart grid, including the distribution of regulation capacities across multiple sites via the Internet. HV = high voltage grid, MV = medium voltage grid, LV = low voltage grid (EU-Deep project). For a color version of the figures in this chapter see www.iste.co.uk/robyns/buildings.zip*

There are important issues to consider in relation to the infrastructure and reliability of communication grids, the "top layer" of infrastructure management software, the normalization of communication processes, and the security and confidentiality of data. Rapid and efficient management of extremely large quantities of data is essential for an electric system of this type to function effectively. For example, grid topology may need to be altered in response to an accident, or customer erasure may be decided upon in accordance with their contract conditions, in response to an unexpected change in local consumption. The rollout of large numbers of captors and measurement instruments (such as the Linky connected meters in France) means that the volume of information produced and used to manage the electric system is constantly increasing. A modular, evolutive and extendable grid architecture is therefore necessary.

In France, in 2016, buildings absorbed 45% of total final energy consumption (across all energy types). It is thus crucial to increase their energy efficiency and to

develop their capacity to produce and store energy, integrating mechanisms for efficient energy management in connection with the existing distribution grid.

1.2. Storage requirements in buildings

A priori, buildings which are directly powered by the grid have no need to store electrical energy, with the exception of certain critical buildings which have their own backup supply for safety and security reasons, maintaining services such as lighting in public buildings, ensuring equipment continues to function in hospitals or guaranteeing that certain business systems continue to operate to avoid economic losses (e.g. data servers or sites devoted to specific sensitive industries). Renewable energy, which may be produced locally using solar panels, for example, creates different requirements. The inherent variability of production, uncertainty in predictions and the priority given to local consumption, reducing transportation losses, create a greater need for local electrical storage. Unlike onboard systems, storage solutions in buildings are not subject to weight constraints as they are not carried by the system; however, volume remains a significant consideration. Another point to consider is that the grid used should correspond to the application, for example in terms of DC voltage and current.

The increase in the use of electrical energy in buildings is due to the flexibility it offers, as well as to the fact that pollution may be avoided at the point of use. If electricity is produced by burning fossil fuels at a power station, for example, the pollution emitted – including greenhouse gases – will not be released in the building itself, but elsewhere, i.e. at the power station. In order to reduce emissions, electricity needs to be produced using non-polluting renewable resources; furthermore, construction and de-construction phases of the production unit need to minimize consumption of energy from non-renewable sources, and, more generally, polluting emissions need to be minimized across the whole lifecycle.

Storage systems, which will become increasingly present in buildings in coming years, respond to the needs of these applications, compensating for the variation in renewable energy production while potentially providing services for other actors in the electrical system. Although prices are likely to decrease somewhat, storage systems remain expensive; the provision of services to other actors is a means of financial valorization, as long as the implications of aging are also taken into account. In this regard, work is currently ongoing to identify ways in which electric vehicles may provide services to the electrical distribution grid, or, more locally, to the buildings to which they are connected for charging purposes; this is known as Vehicle to Grid (V2G) [SAR 13, SAR 16a] or Vehicle to Home (V2H) [VEN 16, VEN 17]. The same considerations apply to storage systems included in commercial, tertiary (office) buildings and residential neighborhoods.

1.3. Difficulties in storing electrical energy

The main drawback of electric power is the high cost of storage. While electrostatic energy and magnetic energy can be stored (in capacitors and superconducting magnetic energy storage, SMES, respectively), these solutions only provide a very partial response with regard to the timescale under consideration. To obtain high-capacity storage at an acceptable price, electrical energy must be transformed into another form of energy. Electrochemical storage, using lead batteries, has long been used for onboard applications and emergency power supplies. Storage in the form of kinetic energy, using flywheels, has been used over the last few decades in fixed applications such as emergency power supplies and for certain onboard applications, for example in satellites.

Electrochemical batteries store electrical energy supplied in continuous form. Flywheel storage involves electrical machines which must be able to operate at variable speeds, i.e. variable frequency. Since the grid provides electricity in the form of alternating voltage and current at a fixed frequency, these storage techniques were little used until the development of power electronics in the 1970s. We now possess the capacity to transform the form and characteristics of currents and voltages as required.

Ragone plots, showing power density and energy density, are often used to compare different technologies and highlight the specific energy/power balance of each [ROB 15]. Figure 1.2 shows a simplified example, comparing several electrochemical technologies and supercondensers [MUL 13].

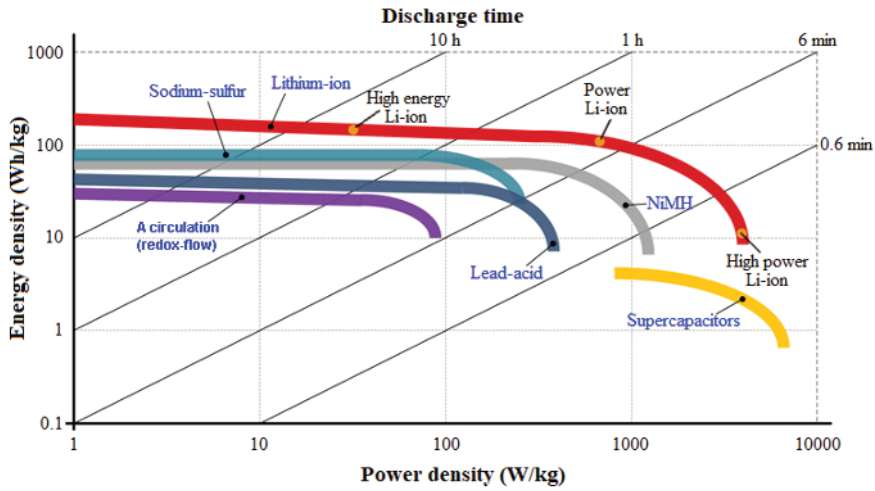

Figure 1.2. *Example of a Ragone diagram showing several electrochemical technologies and supercapacitors [MUL 13]*

In addition to power and energy, we need to take account of factors including life expectancy, response time and yield.

Life expectancy still represents a major technological constraint with regard to battery usage. It depends on the temperature of the battery, which should be neither too high nor too low, the frequency of charge–discharge cycles and the depth of discharge (DoD). The manufacturers of electrochemical solutions give figures of between 1000 and 10,000 charge–discharge cycles, with a maximum DoD and for a specified range of operating temperatures. Based on daily charge–discharge cycles, life expectancy thus varies from 3 to around 20 years. Life expectancy may be increased by reducing the operating temperature (e.g. via air conditioning) and DoD.

The energy capacity of supercapacitors is considerably lower than that of batteries, but they provide far higher power dynamics and a longer life expectancy in terms of charge–discharge cycles, in excess of 10,000. The combination of supercapacitors with Li-ion batteries is a useful solution for dynamic global storage systems, providing high storage capacities with high life expectancy. The supercapacitors handle rapid electrical variations, while the electrochemical batteries respond to regular energy needs. Note that flywheel storage systems can also provide high dynamic levels with a far higher number of charge–discharge cycles than that which is possible with electrochemical batteries [ROB 15].

Hydrogen is another possibility, enabling electricity to be produced via a fuel cell, and it can be produced from electricity (from renewable sources, for example) using an electrolyzer. However, the yield of the charge–discharge cycle is relatively low at approximately 25–30%; this means that the cost over a lifecycle remains excessive for the moment.

In the context of buildings, direct energy consumption presents the advantage of a better overall energy yield. The energy conversion required for storage results in losses, which differ widely depending on the storage technology in question. Over a full cycle, these losses may vary from less than 10% to 50%, or even more in the case of hydrogen. Nevertheless, this notion of yield needs to be relativized if stored energy comes from a source where energy shedding is used in the case of overproduction, for example in wind or solar power. We need to look at the overall balance in order to identify the best strategy (shedding or storage with a certain rate of loss) in response to economic or even environmental criteria.

Finally, note that electrical energy may be stored as a different form of energy before being used. This is the case for hot water tanks in domestic networks, where energy is finally used in thermal form, and for hydrogen produced through electrolysis, which may then be used for combustion. Certain loads include storage capacities which may be exploited to give flexibility by modulating their power supply from the grid. This is the case for cold storage in supermarket freezers, for example, and for storage in the batteries of electric vehicles.

1.4. Electricity supply in buildings

1.4.1. *Building supply and consumption*

The electrical energy consumed by buildings may be produced locally or supplied by the distribution grid. Buildings are generally powered by the grid, unless they are isolated (e.g. a mountain chalet) or have their own power supply. This situation is increasingly common with the development of renewable wind and photovoltaic solar supplies.

Figures 1.3 and 1.4 show typical profiles for domestic and commercial consumers. They show the way in which consumption varies depending on the time of day, the season and the load type.

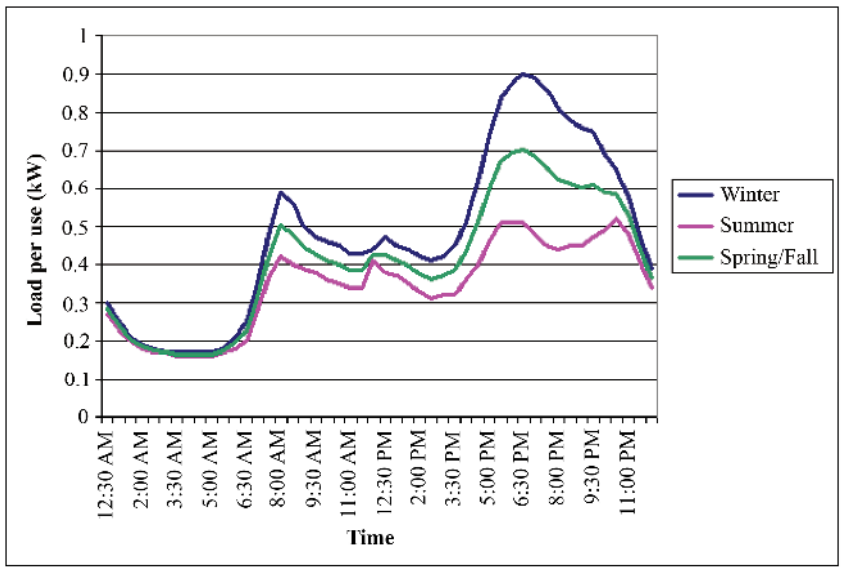

Figure 1.3. *Typical profiles for domestic consumers excluding electric heating (RTE)*

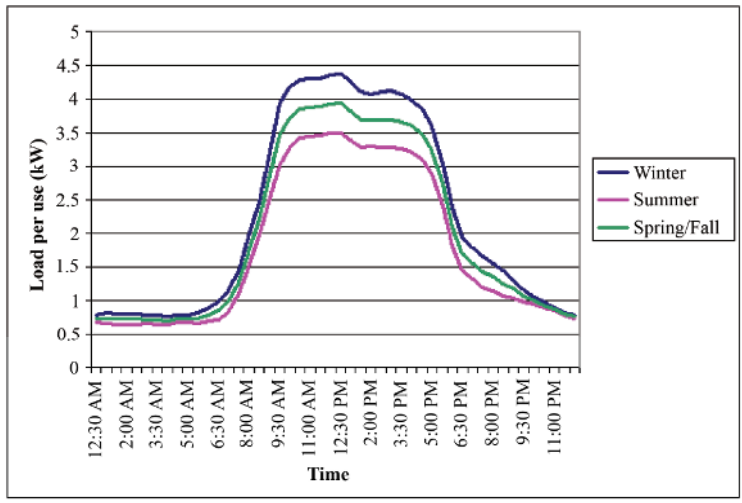

Figure 1.4. *Typical profiles for tertiary and small-scale manufacturing consumers (RTE)*

Figure 1.5 shows the power consumption profile for a large supermarket over the course of a week. The subscribed power in the example shown is 1200 kW. This is a non-optimized value, ensuring that this limit is never exceeded; going over this threshold would mean paying expensive penalties to the network operator. The addition of local storage and production would enable the optimization of subscribed power, reducing the cost of energy drawn from the grid.

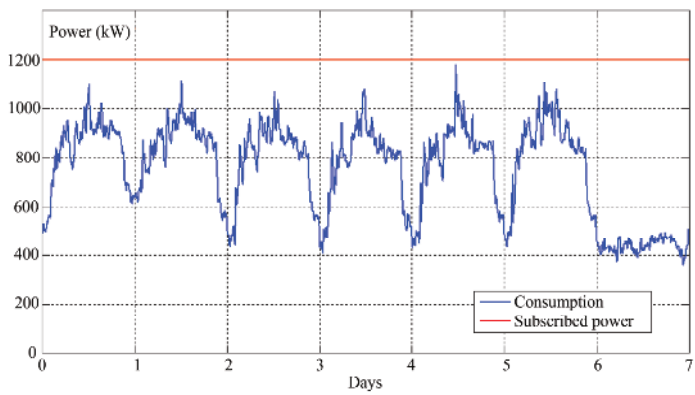

Figure 1.5. *Power consumption profile for a large supermarket over the course of a week*

In a supermarket, positive and negative cold storage may account for between one-third and half of electrical consumption. Negative cold storage can be adjusted within the limits imposed for food conservation, and this may be exploited as part of an energy management approach. Figure 1.6 shows a possible evolution of freezer temperature:

– phase 1, descending temperature, corresponds to positive consumption, and is equivalent to a cold storage system absorbing electrical energy;

– phase 2, increasing temperature, corresponds to zero consumption, but cold is being lost.

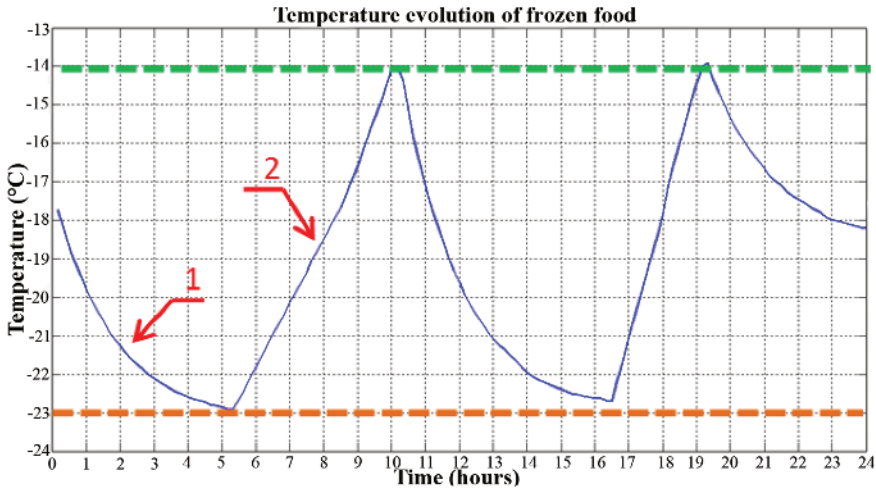

Figure 1.6. *Cold storage*

Load consumption management is nothing new. As early as the 1970s, a system was implemented to manage hot water sanitation tanks in order to avoid electrical peaks every morning and evening. Two approaches were used to achieve this: first, a pricing incentive with different tariffs for peak and off-peak production, and second, the option to control hot water tanks remotely at times of low consumption. Figure 1.7 shows the positive impact of these measures on the power profile for hot water tanks over several years. Note that these solutions were only possible because the tanks possess the capacity to retain heat over a 24-hour period.

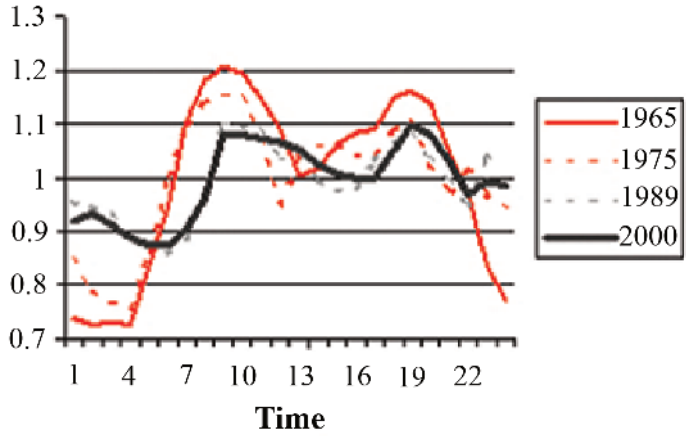

Figure 1.7. *Influence of power consumption of electric water heaters on power profiles (normalized) for mainland France [DOB 13]*

These examples highlight the variability of power demands made on the network by different types of loads and show the value of smoothing these variations, using an optimized pricing strategy and exploiting the existing storage capacity of charges (particularly water heaters, in this case), or, now, using additional storage systems for electrical energy. The integration of fluctuating renewable energy, which is difficult to predict at a local level, also justifies the use of storage systems. Storage capacity may be further exploited to provide additional services to electricity distribution or transmission grids, increasing their potential to generate profit [ROB 15]. Charging electrical vehicles using a building's electrical network offers another means of load modulation, storage and service provision for the electrical grid [BOU 15, BOU 16, ROB 16].

1.4.2. *Self-production and self-consumption*

The development of renewable energy sources has encouraged local production of electricity in proximity to the power-consuming load, i.e. local consumption. This is particularly true for energy obtained from a primary source which varies independently of demand and does not have a natural form of storage (hydraulics or combustible, for instance), and for which production is difficult to predict – particularly solar and wind power. In this context, self-production and

self-consumption of renewable energy are defined as follows, with reference to the illustration in Figure 1.8:

– self-production is the portion of total consumption which is supplied by local renewable energy sources, for example over the course of the day, i.e. surface C/surface B (generally calculated over the course of a year);

– self-consumption is the portion of renewable production which is consumed in real–time, for example over the course of a day, i.e. surface C/surface A (generally calculated over the course of a year).

Using Figure 1.8, we can also define the conditions for zero-energy or positive-energy buildings, extending our calculations over a full year:

– a building can be considered zero-energy if surface B is equivalent to surface A, calculated over the whole year;

– a building can be considered positive-energy if surface B is smaller than surface A, calculated over the whole year.

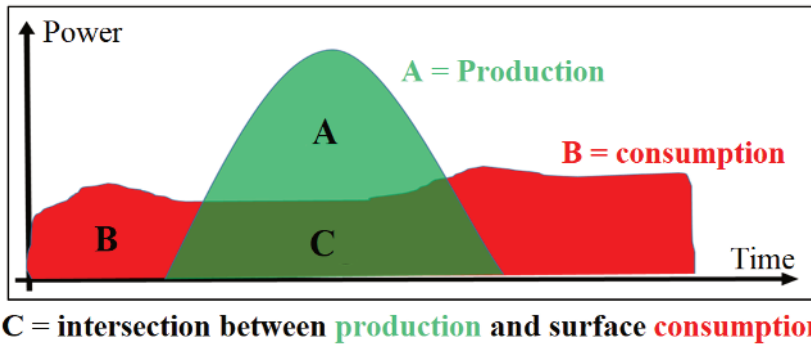

Figure 1.8. *Self-production and self-consumption over a 24-hour day*

In the absence of an energy storage system, a local network can function autonomously, or in isolation from the main grid, only if production A is greater than or equal to consumption C at all times.

1.4.3. *Micro-grids*

Micro smart grids are small-scale electrical networks designed to provide a reliable and high-quality power supply to a small number of consumers. An example of a micro-grid structure is presented in Figure 1.9. Micro-grids operate by

aggregating multiple local production systems of varying types (gas micro-turbines, fuel cells, diesel generators, solar generators, wind turbines, small hydraulic systems, etc.), consumer installations, storage systems and supervisory and demand management tools. They may be directly connected to the distribution grid or operate as an island. This concept is now being extended to heating and gas networks. The micro-grid concept can also be applied to multi-fluid systems and on differing scales (building, neighborhood, industrial or manufacturing group, village, etc.) [CRE].

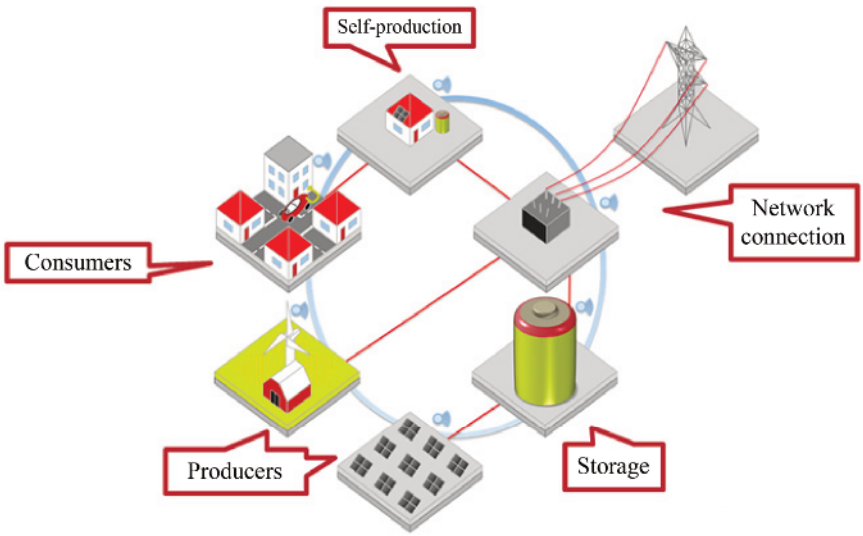

Figure 1.9. *Example of a micro-grid structure [CRE]*

Electric micro-grids may be categorized by size, as well as by utility (reliability, resilience and effectiveness of the network, difficulty of access to energy, operation in poor weather conditions, emergence of eco-neighborhoods, multi-energy possibilities, energy saving, etc.), falling into five main categories [CRE]:

– micro-grids for commercial, small manufacturing or industrial zones: these zones consume large amounts of electricity and include companies and industries carrying out a variety of different activities, all with different energy requirements. The aim is to optimize energy management to maximize control of the zone profile in relation to the distribution grid;

– university campus micro-grids: the aim in this case is to improve energy management on campus in order to reduce energy consumption;

– micro-grids for isolated zones with little or no connection to the grid, or which are temporarily cut off due to poor weather conditions: micro-grids are a way of exploiting local renewable energy and avoiding dependence on polluting, costly diesel generators. Micro-grids can also prevent a total loss of electrical power in towns affected by severe weather events;

– eco-neighborhoods: operating along very similar lines to micro-grids for commercial or industrial zones;

– “life base” micro-grids (military bases or hospitals), with their own means of production and storage and their own distribution infrastructure: the micro-grid model guarantees energy autonomy, enabling continued operation even during power outages in the main grid. This is essential for installations such as military bases or hospital, which must be able to fulfill their functions even though the main supply is down.

Micro-grids present several advantages [CRE]:

– in technical terms, micro-grids allow optimal management of renewably produced electricity at the local level. They may act as an ancillary service alongside the public distribution grid, assisting in maintaining a stable voltage and “lightening” the load in cases where they are cut off from the distribution grid;

– in economic terms, depending on size, a micro-grid may be used as an aggregator, adjusting to markets (spot market, adjustment market and capacity market). Micro-grids also make it possible to delay network investment, as the proximity between production and consumption sites enables the optimization of energy transportation. They also reduce the volume of technical losses;

– in social terms, micro-grids provide a response to evolutions in the basic energy needs of a territory. They are notably more secure and more reliable in case of incident. As local projects, they also promote initiatives and the development of new partnerships between local actors;

– in environmental terms, they permit better integration of renewable energy sources into networks and avoid the need to build thermal power stations in zones which are only weakly interconnected [ROB 12c].

Moreover, the infrastructure needed for a smart electrical grid is complex and can take several years to install; micro-grids are simpler in terms of implementation, and can act as a catalyst to the creation of smart grids. Responding to many of the issues associated with smart grids and the integration of renewable energy sources on a smaller scale, they provide an illustration of the ways in which larger grids may operate.

An example of a micro-grid can be found on the island of Kythnos, in the Cyclades archipelago in the Aegean Sea (Figure 1.10). Installed as part of the European "More Micro-Grids" program, it provides power to 12 houses. It is made up of photovoltaic solar panels with a power of 10 kWc, a 5 kW diesel generator, battery banks with a capacity of 53 kWh, and monitoring and communication systems, powered by a 2 kWc photovoltaic system. This micro-grid has been used to test both centralized and decentralized control strategies in island mode and to test communication protocols.

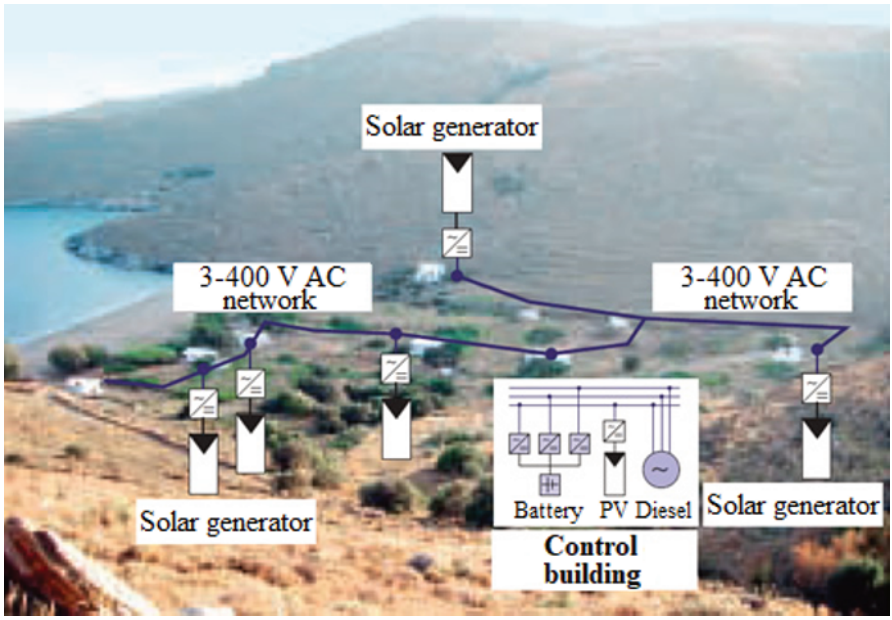

Figure 1.10. *Micro-grid on the island of Kythnos (source: ABB)*

1.5. Smart buildings

Buildings have a key role to play in the development of smart energy grids, micro-grids, eco-neighborhoods and smart cities. Figure 1.11 shows different characteristics of a smart building, including local energy production and storage and controllable loads with modulable consumption (lighting, heating, electric vehicles, etc.), which may be connected to the electricity distribution grid and to external sources or in islanded mode, i.e. cut off from the main grid.

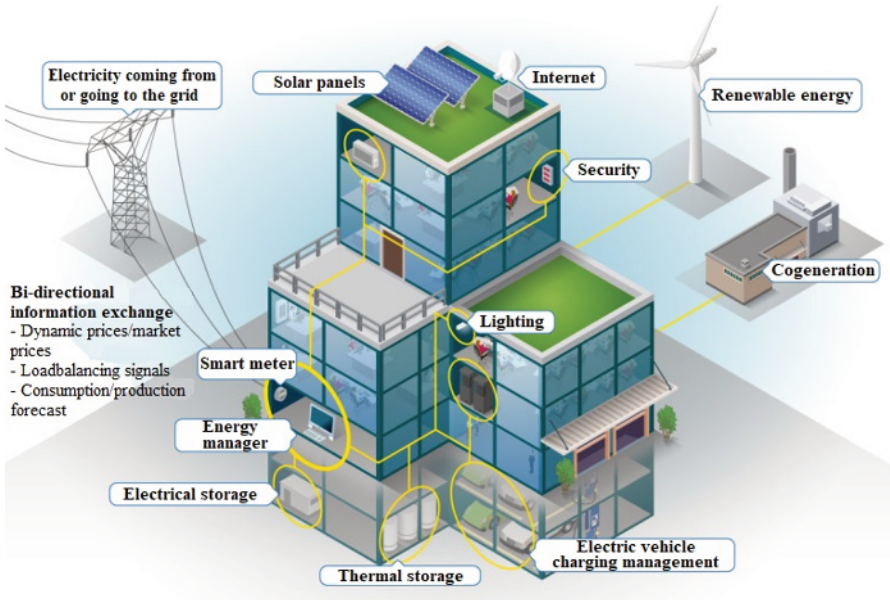

Figure 1.11. *Smart building [http://www.objetconnecte.com/batiments-intelligents-marche-iot/]*

Smart buildings include a variety of technical equipment, providing an interface between:

– some or all weather conditions (heat, luminosity, air quality, wind);

– some or all of the energy-consuming equipment needed for the building to function (heating, air conditioning, ventilation, lighting, electric vehicles, etc.), for production and for storage of local energy;

– some or all areas of the building and some or all periods of use, whether the building is residential or used for other commercial purposes.

The “smartness” of a building can vary according to the range of services provided by technical equipment. This “smartness” involves a number of different aspects, and will ideally aim to maximize energy efficiency and user comfort. These may be grouped into four areas:

– **Automation**: typically, following a measurement or time setting, a technical tool (such as a captor) triggers an adjustment process (e.g. variations in temperature,

lighting or ventilation). For example, luminosity sensors may trigger the activation of lighting or of blinds, depending on the strength of the sun and the time of day. In a domestic setting, automation of this type is generally known as domotics. Actions may be triggered by dialog between devices, with or without human intervention.

– **Centralization**: some or all of the devices present are controlled by a single system, for example a thermostat for home heating. Systems are often in place to override the centralized system, for example thermostatic regulation on radiators.

– **Regulation**: a generic term covering all actions intended to adjust energy consumption and/or user comfort in accordance with requirements, technical or otherwise, automatic or manual. For example, a window that can be opened is a regulation device in its own right. Similarly, rules, consumption information or raising awareness of green behaviors are all means of regulating (or, to use a different term, modifying) the sociotechnical conditions of energy usage.

– **Information**: consumption must be closely monitored, over the course of the year, month, week, day, hour, by device, etc. The aim here is to identify connections between technical devices, consuming devices, periods of use and effective consumption. This information is not sufficient to develop a full picture of energy usage practices, but provides information regarding timing and, in some cases, the intensity of use (e.g. oven temperature settings).

Connected electric meters, such as the Linky meter in France, play an essential role in smart buildings, acting as a communication interface between the electricity grid and the consumer's equipment. A concentrator installed in a distribution station collects information from connected meters using power-line communication (PLC), acquiring data from the electrical devices in the local environment (transformers, switches, etc.) and sending it to the grid operator. The grid operator's computer system can then be accessed by energy suppliers, who use regular metering data for their clients to calculate bills. Figure 1.12 shows the relationships between consumers, suppliers and grid operators which will develop over the coming years. Smart meters provide consumers with precise and frequent updates regarding their electricity consumption via a dedicated site. They improve the quality of service offered by grid operators by generalizing remote meter reading, enabling bills to be systematically established on the basis of real consumption, and encouraging the development of varied offers tailored to specific requirements in order to improve the response to demand in periods of high consumption [CRE]. Connected meters are also being developed for use in gas networks (e.g. Gazpar in France).

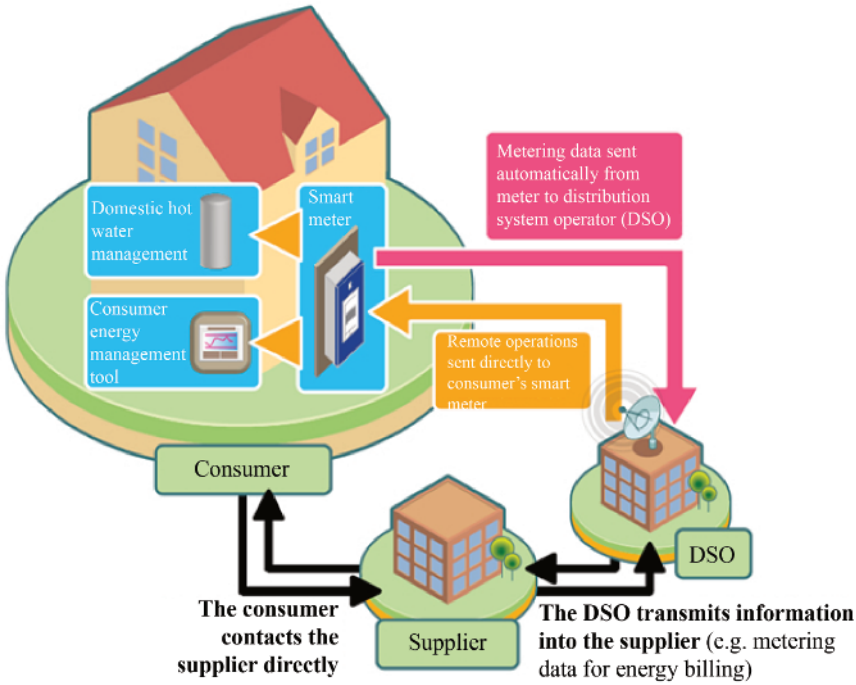

Figure 1.12. *Connected meter principle [CRE]*

The final consumer is thus at the heart of these future electric grids. Their behavior contributes to maintaining the balance between supply and demand at all times and to limiting peaks in consumption. To this end, consumers may adopt two different behavior types; these individuals are known as flexi-consumers [CRE]:

– downward modulation (balancing): in response to a specific request, the consumer temporarily reduces their electricity consumption below the usual level. This may notably include temporarily cutting off power to some of the most powerful electrical equipment (heating, washing machine, an electric vehicle being charged), by delaying consumption (the washing machine or vehicle charging may start a few minutes or a few hours later than usual, activated manually or automatically) or by stopping certain uses entirely (e.g. acting on a domestic water heater or on production machines in an industrial setting);

– upward modulation (consumption shift): in response to a request from actors in the electric system, a consumer temporarily delays consumption, either manually or automatically. This may be carried out in anticipation of the use of certain equipment. The modulation does not increase electricity consumption, but

encourages the user to use power at more helpful times (e.g. when renewable power sources are producing large amounts of electricity or to exploit dedicated or pre-existing storage capacity which may be present in certain loads).

1.6. Smart cities

Towns and cities account for barely 2% of the Earth's surface, but they are home to 50% of the global population, consume 75% of all energy produced and are responsible for 80% of CO_2 emissions. Urban centers need to develop new, energy efficient services in a range of domains [CRE]:

– Smart transportation and mobility: different individual modes of transport (cars, motorcycles, bicycles, walking) and collective modes of transport (buses, metro systems, trams, taxis, etc.) must be integrated into a single, efficient, accessible, affordable, safe and environmentally friendly system. This will reduce the environmental footprint of the city, optimize the use of urban space and provide citizens with a varied range of mobility options to respond to all of their needs. The cities and towns of tomorrow will also make use of the latest public transportation and electric mobility technologies [ROB 16].

– Development of a sustainable environment: towns and cities will become increasingly involved in waste and energy management, for example via the construction of eco-neighborhoods. With regard to waste, towns and cities will aim to reduce or even eliminate waste production, and will implement efficient systems for retrieving and exploiting garbage. In terms of energy, towns and cities will make greater efforts to increase energy efficiency (developing low-energy public lighting, higher-performance transportation solution, etc.) and will implement local energy production systems (solar panels on the roofs of public buildings, producing energy through waste processing, etc.).

– Development of responsible urbanization and smart habitat: the high value of real estate in city centers combined with limited availability of land means that urbanization is a complex issue. The urban spread model which has dominated up to the present day is costly in terms of space, public amenities and energy, and is no longer tenable. Towns and cities will move toward solutions which respect the essential need for privacy, ensure sufficient sunlight, are able to evolve easily and facilitate community life. Buildings will need to become "smarter" to facilitate and improve energy management, and, potentially, to reduce consumption.

Citizens will have a central role to play in the towns and cities of tomorrow. No longer simply consumers of services, they will be seen as partners and stakeholders in urban development. They will be able to take on this role due to a democratization of the means of information, enabling enhanced participation.

The implementation of smart cities will be a progressive process. Demonstrators will be used to test different functions made possible by smart grids and smart buildings, to identify the new economic models essential to the viability of these functions, and to examine questions of acceptability and the implication of different actors (producers, consumers, energy grid operators, aggregators, etc.). In Lille, France, for example, demonstrator programs have already been established, including Live Tree (Lille Vauban en Transition Energétique, Ecologique et Economique: Energy, Environmental and Economic Transition in the Vauban neighborhood of Lille) [LIV] and “So MEL, So Connected” (supported by the ADEME, Agence de l’Environnement et de Maîtrise de l’Energie en France: the French Environment and Energy Management Agency) [SOM].

1.7. Socio-economic questions

1.7.1. *Toward new economic models*

The notion of an economic model includes multiple dimensions: a macroscopic (top-down) dimension, whereby public authorities may establish frameworks to encourage the development of smart electricity grids, and a microscopic (bottom-up) dimension, which relates to companies’ ability to establish business models specific to their activities. Company business models describe the distribution of activities and, notably, the source of revenues, highlighting profitability. To develop a business model, actors need access to a number of basic elements [CRE]:

– identification of the actors in question and an understanding of their interest/risk in relation to smart electricity grids;

– cost–benefit analysis within a coherent framework. For example, the conclusions drawn from cost–benefit analysis of connected meters are different depending on the perspective taken, which may be limited to the distributor or take account of all costs and benefits from producers to final consumers;

– once a calculation framework has been defined, expenditure items and sources of profit should be defined along the new value chain;

– an estimation of the financial values associated with these profit and expenditure items;

– identification of possible funding sources.

In order to develop these business models, we need to identify the way in which smart electric grids modify the value chain. In the new value chain, final users will take on a particularly important role, as the balance of the electrical system will be managed primarily by directing consumption; in the existing system, balance is based on controlling production. The integration of renewable and intermittent

energy sources makes electricity production harder to control and to manage. Final users will thus play an active role in the energy system, and will become the central focus for other actors in the value chain.

For final users to take an active part in the definition of future economic models for smart grids, a certain number of crucial steps need to be taken [CRE]:

– provide better information regarding the economic and environmental benefits to consumers and communities obtained through the use of new ICT technologies in managing the electrical system (improved public electricity system, increased quality and frequency of consumption information to enable greater control, etc.);

– provide easy access to information via a variety of simple interfaces (smartphones, computers, etc.), enabling reactivity and normalizing the use of services linked to smart networks;

– guarantee the protection of personal data and manage the way in which individuals' information is shared.

The increasing interdependence between different actors (producers, consumers, storers, network operators, aggregators, etc.) inherent in the development of smart grids makes the development of new economic models increasingly complex, while offering new economic possibilities.

1.7.2. *Social acceptability*

The introduction of technical developments which are seen as overwhelmingly positive in terms of problem-solving or progress may be met with resistance from the intended users. Innovations are slow to take root and can face opposition for reasons other than price. These forms of resistance are always baffling as they contradict the presupposition that progress (improvements, solutions, additional services) will always be welcome in a rationale based on utility and profit maximization (cost–benefit approach). Sociology can cast some light on the issues of resistance and on the conditions of overcoming this resistance to reach the level of support needed for a change which is *a priori* beneficial to be adopted.

Social acceptability refers to the set of individual judgments relating to the acceptance (or non-acceptance) of a practice or condition, whereby individuals compare this solution with possible alternatives in order to determine desirability. It is expressed by groups, active in the political life of a society, who share a judgment with regard to the practice in question [YEL 13].

This constitutes a collective process insofar as acceptability becomes "social" once a minimum level of support is attained. This minimum reflects a threshold

which varies from subject to subject, and which results in the diffusion of acceptance throughout the target social group via a number of different mechanisms (conformity, normality, innovation, etc.).

Acceptability is the result of a reasoning or rationality which structures the mode of comparison between different possible scenarios. Rationality may be modeled as the interaction between four notions:

– an objective, i.e. the aims of the actor (money, pleasure, recognition, distinction, information, conservation, comfort, etc.);

– resources, i.e. which is required for the objective to be attained (skills, information, allies, money, network, etc.);

– constraints, i.e. which acts against the achievement of the objective (rivals, competition, lack of skills, isolation, weaknesses, etc.);

– strategy, i.e. the use of resources with regard to the objective and the constraints to overcome. Rationality is thus an interplay between cognitive and reflexive elements, resulting in a way of thinking and acting in relation to a short-, medium- or long-term goal.

Acceptability becomes a social and influential concern when an opinion is shared by a sufficient number of individuals (threshold effect) and/or by a group with sufficient weight within the social milieu. Not all social groups have the same influence within their social environment. Groups with the highest capital (economic, cultural or relational) have more influence in prescriptive terms and their opinions may have a knock-on effect.

The reasoning involved in acceptability develops within a multi-layered context. This explains the systemic nature of the social acceptability process: as the issue is not limited to personal preference, it is useful to understand social psychology.

In terms of context, the parameters to consider include:

– individual reasoning, following the structure described above (objective, resources, constraints, strategy);

– social context, which is made up of three aspects:

- macro: regulations, market, price, incentives, social culture, national politics, etc.,

- meso: geography, territory, operators, technical constraints in the immediate area, etc.,

- micro: organization, operation, requirements, resources, values and image of the actor, etc.

In this context, values, image and attitudes carry a heavy weight. Beliefs, worldviews and preconceived ideas all contribute to the formulation of a positive or negative attitude toward a proposition which may or may not be accepted. The meso and macro levels are equally important; however, their influence is subtler in that it is less immediately obvious and more debatable.

1.8. Storage management

Different time frames need to be taken into account when establishing an energy system management strategy, with or without one or more energy storage solutions (Figure 1.13):

– long-term supervision, over the course of a day or more;

– medium-term supervision, corresponding to durations from approximately 30 min to 1 hour;

– real-time supervision, which corresponds to the shortest timescale used in ensuring the system functions correctly, ensuring stability, goal attainment, hazard response, etc. This timescale may be anywhere from a few hundredths of a second to several minutes.

Longer-term planning (for storage over several days, weeks, months or years) may also be needed to ensure efficient storage management and to guarantee economic viability.

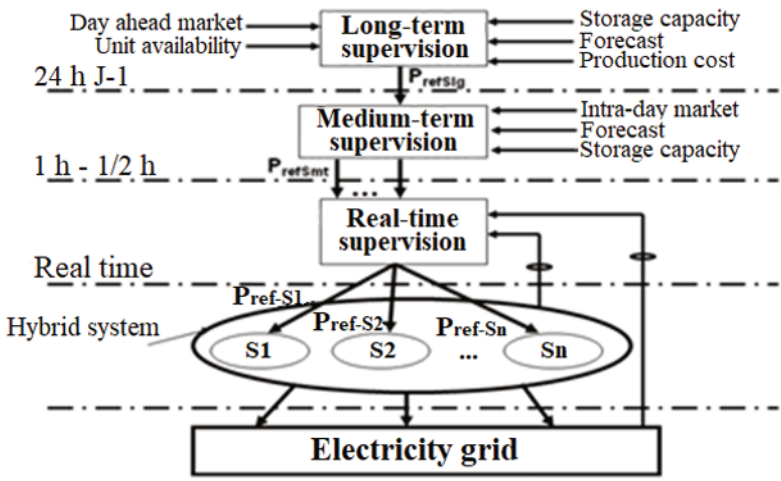

Figure 1.13. *Different timescales to consider when managing an energy system, with or without energy storage systems*

Managing energy storage represents a significant challenge due to the complexity of the problems involved, the economic and ecological objectives, and the fact that there is no single solution for achieving these goals [NEH 11, ROB 12b, ROB 13a, ROB 13b, ROB 15, ROB 16]. Three broad groups of tools for supervising hybrid systems with storage have been proposed in the literature:

– **causal formalization tools** [ALL 10, FAK 11, ZHO 11, DEL 12]. This approach consists of identifying power flows which may be inverted in order to identify reference power values. It requires the use of a detailed mathematical model of sources and storage systems, alongside excellent real-time data concerning different flows and the associated losses;

– **explicit optimization tools** with objective functions [ROB 12a, SAR 13, SAR 16, ROB 16]. This approach is necessary to guarantee that optimal choices have been made to ensure maximization, for example of energy produced from renewable sources. However, minimization of a well-formulated cost function is no easy matter, particularly in real-time;

– **implicit optimization tools**, for example using fuzzy logic [CHE 00, LEC 03, LAG 09, COU 10, ZHA 12, MAR 12, KAD 13, ROB 13a, ROB 13b, ROB 15, BOU 15, BOU 16, ROB 16]. This type of tool is eminently suitable for the management of complex systems, involving quantities or states which are difficult to predict and not particularly well known in real-time (wind, sunshine, network frequency and state, variation in consumption, etc.).

A variety of approaches may be considered and combined for storage management purposes, including filters, correctors and artificial intelligence tools.

A methodology for the design of supervisors for managing hybrid energy production systems including storage is developed in this book [ROB 13a, ROB 13b, ROB 15, ROB 16]. Our method is an extension of those commonly used in designing control systems for industrial processes: Petri networks [ZUR 94, LU 10] and GRAFCET [GUI 99]. These approaches allow a graphical and “step by step” approach to the construction of system control, making analysis and implantation considerably easier. They are particularly well suited to sequential logic systems. However, in the case of hybrid production units including random variables and continuous states, tools of this type encounter certain limits. The method we propose is an extension of this graphical approach to include fuzzy and poorly known quantities.

This methodology does not require the use of mathematical models, as it is based on system expertise, represented by fuzzy rules. Input may be random, and supervision may aim to achieve several objectives simultaneously. Transitions between operating modes are progressive as they are determined by fuzzy variables.

Finally, our methodology enables storage management by convergence toward a load level, along with control of complexity for the purposes of real-time processing.

It is made up of eight stages, each assisting in supervisor design (discussed at length in Chapter 1 of [ROB 16] and implemented in several chapters of the present book):

– determination of a system specification, with objectives, constraints and resources clearly laid out;

– definition of a supervisor structure, including determination of the required input and output;

– determination of operating modes using functional graphs, with a graphical representation of modes of operation developed based on knowledge of the system. These modes are expressed verbally, which makes it easier to integrate socio-economic considerations;

– definition of the membership functions of fuzzy variables;

– determination of fuzzy modes using operational graphs;

– extraction of fuzzy rules, characteristics of the fuzzy supervisor, from operational graphs;

– definition of indicators to use in assessing whether or not objectives have been met. For example, these may include an indication of power, energy, voltage quality, yield, or concern economic or environmental aspects;

– optimization of supervisor parameters using design of experiments (DoE) and/or genetic algorithms, for example.

This methodology will be developed progressively over the course of this book, considering energy storage based on one or more technologies in the context of different buildings (supermarkets, tertiary sector buildings, micro-grids, residential neighborhoods, and with regard to the integration of reversible-charge electric vehicles). Causal and explicit optimization methods will also be used.

1.9. Methodologies used in developing energy management for storage systems

In this book, we will progressively implement several different methods which may be used to develop a management approach for storage systems, based on one or more storage technologies and in different building-related contexts. Table 1.1 shows a summary of the different contexts which will be considered, along with our objectives, the tools and disciplines used, and the methods to design an energy management system which will be discussed in later chapters.

Chapter/theme	Objectives	Methods, tools and disciplines used in designing an energy management system
2. Commercial buildings consuming and producing electricity	Reduce the electricity bill Reduce CO_2 emissions	Fuzzy logic
3. Tertiary buildings consuming and producing electricity. Implementation of a dedicated DC electrical architecture	Promote self-consumption of local production Reduce CO_2 emissions	Fuzzy logic
4. Photovoltaic solar producer with hybrid storage in the context of a non-interconnected grid	Production injected into an electricity grid according to a planned profile. Participate in grid frequency control Increase life expectancy of storage systems	Fuzzy logic Electrochemical battery degradation model Economic analysis
5. System including multiple tertiary or residential actors within a smart grid	Economic and sociological conditions to promote energy load balancing	Economic openness to contract theory Openness to the notion of social acceptability
6. Energy pooling between buildings of varying natures, consumers and producers	Promote self-consumption of local production and load balancing with respect to the public distribution grid. Reduce electricity bill and CO_2 emissions	Fuzzy logic Integration of an acceptability coefficient
7. Residential community, e.g. eco-neighborhood	Promote self-consumption of local production of renewable energy	Hierarchical and causal control
8. Reversible charge electric vehicles	Minimize cost of transporting electrical energy through the distribution grid. Maximize local consumption of renewable energy	Fuzzy logic with optimization via genetic algorithm

Table 1.1. *Different aims and construction methods for energy management systems described later in this book*