Chapter 1

Demand Side Energy Management

Energy efficiency, electricity supply and sustainability are important research topics in society [1]. The provisioning of energy is subject to increasing resource usage, scarcity and environmental concerns. Next to a slightly increasing energy usage in the Western world, developing countries like China and India show growth figures up to 25%. Since the production capacity of fossil energy sources, especially crude oil, cannot keep up with this growth, the oil reserves are diminishing and energy is becoming scarce and expensive. Furthermore, a lot of fossil energy sources are obtained from politically less stable regions. This, in combination with the growing awareness of the greenhouse effect, drives the search to renewable energy sources.

Other effects of the above mentioned problems can already be seen in the *electricity supply chain*. The electricity supply chain consists of electricity generation, transportation, distribution and consumption. In this supply chain a lot of changes are ongoing or expected.Within these changes four trends can be identified:

an electrification of the energy distribution: a growing part of the consumed energy is transported and consumed as electricity,

an increase in energy consumption: the energy consumption, and the electricity consumption in particular, increases,

more dynamic electrical loads are occurring: electricity consumption does not only increase, it also becomes more fluctuating and sometimes even uncontrollable,

an increase in distributed electricity generation: nowadays more and more electricity is generated on a relatively small scale lower in the grid, where in the past all electricity was generated in a few large power plants and was transported via the grid to the consumers.

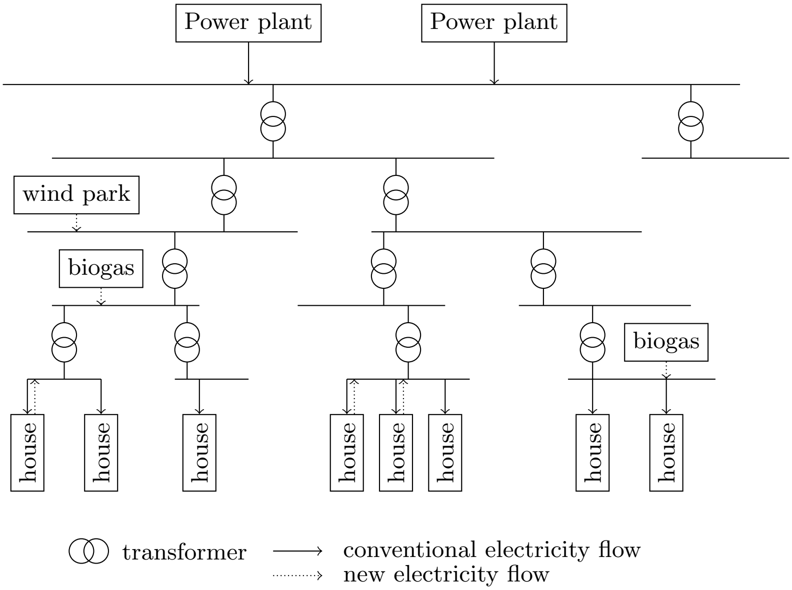

Figure 1.1: Sketch of the (changes in the) electricity grid structure

The most important change in the electricity supply chain is a shift from centrally produced electricity flowing downwards through the grid to the consumers, towards a distributed electricity generation on different levels in the grid. These trends and changes result in challenges to maintain a reliable and stable supply, but it also opens opportunities. Using wide-spread ICT to monitor and manage this distributed generation and other (domestic) technologies allows the grid to become more efficient and more sustainable.

The electricity supply chain is sketched in Figure 1.1. The shift toward sustainable generation and the addition of small-scale distributed electricity generation may look rather harmless in first instance, but it has severe consequences on the electricity supply chain. The electricity grid is no longer a matter of one way traffic, for which it was built and designed for many years. This changes the process of decision making in electricity management completely. New concepts for managing/controlling the electricity supply chain are needed. Demand Side Management in the broad sense can be seen as such a concept to treat the supply chain management problem.

In this chapter we give an overview of demand side developments, forthcoming challenges to integrate these new technologies in the concept of a Smart Grid, and control methodologies that are proposed for Demand Side Management.

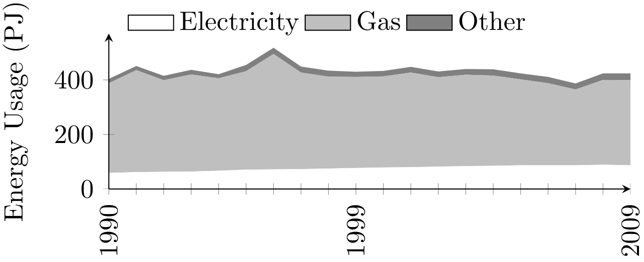

Figure 1.2: Energy usage per household for Dutch households (CBS)

1.1 Demand Side Developments

In the last decades, more and more stress is put on the electricity supply and infrastructure. As shown in Figure 1.2 the still ongoing electrification of the energy demand caused a significantly increase in electricity demand. Furthermore, the electricity demand became very fluctuating, caused by the stochastic nature of demand; people switch on the dishwasher or washing machine whenever they like. The electricity supply chain is designed decades ago and is completely demand driven; consumers just switch on devices when they want to and the generation side has to deal with this fluctuating and hard to predict demand. In the 'old-fashioned' supply chain the base load of the total system is supplied by large-scale, inflexible but quite efficient generation, whereas fast-reacting (and relatively inefficient) peak capacity has to be reserved to serve the peak loads. Demand peaks result in peaks in generation and transmission, which define the requirements in the supply chain. Thus, due to the fluctuating demand, grid requirements have increased. When electricity demand rises and becomes more fluctuating, for example with a large scale introduction of electrical cars without charge time optimization, the efficiency of conventional power plants drops [2] and large investments in grid capacity are required to be able to transport all electricity (peaks) from the power plants to the consumers.

On the other hand, the reduction in the CO_2 emissions and the introduction of generation based on renewable sources become important topics today. The current rate of natural resources consumption will lead to a depletion of these resources, urging for alternative methods to provide the required energy demand. However, renewable resources are mainly 'fueled' by very fluctuating and uncontrollable sun-, water- and wind power. To maintain grid stability, all generated electricity must be consumed. Therefore, the peaks in renewable generation should be lower than the electricity consumption. A consequence is that within the current demand-supply philosophy only a limited percentage of the conventional generation can be replaced with renewable generation. Supplemental peak generation capacity is required to keep the demand and supply in balance, resulting in an even more fluctuating generation pattern for the conventional power plants.

So, the demand side of the original supply chain has to deal with *more fluctuating and increasing consumption* and it faces the introduction of *(renewable) small-scale generation* at the demand side (or between the original consumption and generation).

While a lot of research is ongoing to enable the possibility to supply our energy needs with renewable sources, still a lot of improvements can be achieved on the efficiency of current systems as long as not all energy needs can be supplied sustainably, for example by preventing the usage of peak power plants.

Therefore, the challenges we face are 1) to increase the efficiency of current power plants, 2) to reduce the stress on the grid resulting from higher demand peaks and prevent investments in grid capacity and 3) to facilitate a large percentage of renewable sources for electricity generation in the grid while maintaining a stable grid and a reliable supply.

In the next three subsections the implications of the current trends on consumption, the transmission and the generation is discussed. Next, in the last subsection of this section the optimization potential of new technologies are introduced.

1.1.1 Implications on consumers

The current trends in the energy supply decrease the flexibility on the generation side, urging for more flexibility on the consumer side of the supply chain. At the moment, especially increasing energy prices and a growing awareness of the greenhouse effect drive consumers to adopt new domestic technologies to save money and energy.

An example of these technologies is a *microgenerator*. Micro-generators generate electricity at kilowatt level in or nearby buildings, resulting in less transport losses. Often microgenerators are more energy efficient than conventional power plants and some are based on renewable energy sources [2, 3].

Other new technologies are energy buffers and smart devices. Energy buffers can (temporarily) store energy. Heat buffers are already common in current buildings, but more and more electricity buffers are introduced. These energy buffers make it possible to shift electricity consumption in time, e.g. shift consumption to earlier times by filling the buffer and supply the demand with the stored energy. Smart devices are defined as devices with the ability to temporarily switch off (parts of) the device or devices that can shift the demand in time. A smart fridge is an example of a device that can shift load in time; the cooling temperature of the fridge should stay between certain bounds; within these bounds there is freedom to start cooling earlier. This is sketched in Figure 1.3.

Unfortunately, some of these technologies may introduce more fluctuations on the electricity grid. For example, if due to human behavior, all microgenerators start producing simultaneously the generated energy must be either consumed locally, more likely, by the grid. However, these new domestic technologies also introduce freedom in the electricity consumption patterns. These

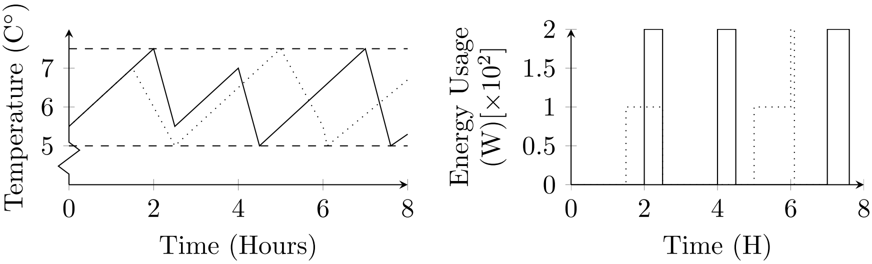

Figure 1.3: Shift the load of a fridge in time

devices can be monitored and managed to change their consumption profile resulting in more flexibility of the consumers.

1.1.2 Implications on transmission/distribution

The increasing demand and peaks lead to an increase of required grid capacity and therefore large investments. However, to reduce fluctuations and to incorporate more renewable sources, generation and consumption need to be matched. To make this possible, significant improvements in the grid infrastructure and more intelligence in the grid are required.

The foreseen changes in production and consumption will increase the stress on the grid while at the same time stability, reliability and fault-tolerance of the grid becomes more important since the community more and more depends on electricity. Therefore, the streams through the grid should be monitored and managed.

Demand Side Management plays a key role in allowing a larger share of renewable electricity generation. However, there is also a geographical aspect on the possibilities for this generation. Large scale sustainable electricity generation is often only possible on remote places with a low density of population and therefore a low electricity demand (e.g. large wind power farms offshore or solar panels in the desert). It is expected that the renewable potential in Europe is large enough to supply all electricity [4]. But this electricity needs to be transported to the customers, requiring a large transmission capacity. The large distance between areas with high potential for generating renewable electricity and areas where the electricity is consumed puts additional pressure on the grid. To transport the sustainable electricity from the generation site towards the customers in Europe for example, a European wide interconnected high capacity electricity grid is required, in combination with a European wide electricity market.

1.1.3 Implications on generation

A shift towards a sustainable energy supply has large consequences for the electricity generation. Today, coal is the main source of electricity generation. A future without electricity generation using coal is almost unthinkable since coal is cheap, abundant and can be harvested up in more stable countries [5]. Unfortunately, coal is one of the most polluting fossil fuels concerning the amount of CO_2 emission. A better option is sustainable electricity generation using renewable sources (sun, wind, tides, etc). However, this requires profound changes and improvements of the electricity grid and the electricity supply.

Large scale sustainable electricity generation has large differences with conventional power plants, both in generation capacity and controllability. Especially sun and wind are very fluctuating in strength, for example a cloud blocking the sun, which needs to be handled properly to ensure a stable supply of electricity. It is, in general, agreed that it is both desirable and necessary to manage this new type of generation and adapt the rest of the grid infrastructure to facilitate the sustainable, unmanageable generation.

So, next to high capacity lines for long-distance transportation of electricity, a sustainable electricity supply also requires more and better monitoring and control capabilities of all types of generation on different levels of the grid.

1.1.4 Optimization potential

The current trends in the electricity supply chain have implications for all parts of the grid. Furthermore, a number of challenges mentioned in the introduction of this section should be solved to maintain a reliable and dependable supply. A solution for these challenges may be to transform customers from static consumer into active participants in the production/consumption process. Consumers can exploit the potential of the new technologies, by shifting load and/or generation to the most beneficial times, where beneficial depends on the optimization objective. More can be reached when a large group of consumers together work towards objectives, but this requires coordination and consumers lose (a part of) the control over their devices.

The low flexibility at the generation side of the electricity supply chain is compensated by an increase of flexibility on the consumer side. However, this transformation of consumers into active participants also requires a change in the state of mind of people, i.e. consumers for whom the availability of energy was always evident should cooperate in keeping the quality and reliability of supply at a high level. A start of this transformation is awareness of the energy consumption. Just this awareness already leads to a decrease of electricity usage of up to 20% [6]. Furthermore, it requires readiness from politics and policy makers.

1.2 Technical challenges

In this paragraph the foreseen transition towards a better monitored and managed grid, a so-called *Smart Grid*, is studied in more detail. First, a definition of the concept of Smart Grids is given and the technical challenges are derived. These comprise the technical requirements that are necessary elements in the development of management methodologies for the future electricity supply chain. The technical challenges for the Smart Grid boil down to requirements for Demand Side Management.

The improved version of the grid is often called a Smart Grid. It is hard to give a definition of a Smart Grid, different parties have their own definition. In [7] is stated that the Smart Grid is not a "thing" but rather a "vision": "*The Smart Grid vision generally describes a power system that is more intelligent, more decentralized and resilient, more controllable, and better protected than today's grid*". The definition given in [8] is rather common:

> *"A Smart Grid generates and distributes electricity more effectively, economically, securely, and sustainably. It integrates innovative tools and technologies, products and services, from generation, transmission and distribution all the way to customer devices and equipment using advanced sensing, communication, and control technologies. It enables a two-way exchange with customers, providing greater information and choice, power export capability, demand participation and enhanced energy efficiency."*

For a successful introduction of a Smart Grid we face a number of technical challenges. In [9] five key technologies required for the Smart Grid are identified:

1. sensing and measurement,
2. integrated communications,
3. advanced components,
4. improved interfaces and decision support,
5. advanced control.

Since you can only manage what you measure, sensing and measuring are an important part of the Smart Grid. The health parameters of the transmission lines and substations should be monitored to prevent the grid from outages. Monitoring and forecasting of the weather can be used for forecasting load and potential output of renewable sources. This can subsequently be correlated with transmission line capacity. Next to the grid, also the generation, storage and consumptions sites and devices need to be monitored to be capable of balancing generation and usage and respecting transmission limitations.

To transport all information, a high speed communication infrastructure is required. This integrated communications infrastructure moves the information between sensing and measurement devices towards the operators and management information back to the actuators. Creating a homogeneous infrastructure requires standards respected by all stakeholders, from home networks and all devices connected to it via the smart meters and the distribution companies to the overall network operators. The National Institute for Standardization and Technology (NIST) addressed this problem and is working together with IEEE to create Smart Grid standards [10]. The integrated communications infrastructure should be designed with future in mind, meaning that capacity, security and performance should be sufficient to facilitate also future applications. A fast, reliable and well designed integrated communications infrastructure glues all the parts of the Smart Grid together.

A Smart Grid is built up by a network of advanced components. The grid itself should consist of efficient transmission elements connected by advanced flow control devices. On domestic level a lot of technologies are in development. The technologies can be subdivided in three groups:

Distributed Generation (DG): the local electricity production,

Distributed Storage (DS): the local energy storage,

Demand Side (Load) Management (DSM) in the narrow sense: the control of the load of specific appliances (c.q. flexible fridges).

New tools are required to assist the grid operators. The grid operators' job became much more challenging in the last years, from respond times of minutes some years ago they have to react in seconds nowadays. To have enough information to take decisions, data mining is very important. An improved interface is required to visualize the large amount of data on such a way it can be understood at a glance. Furthermore, decision support tools help taking decision, for example fast simulations to forecast consequences of decisions.

To make use of all control capabilities and to exploit all optimization potential, advanced control systems need to be developed. Advanced protection systems can adjust relay settings in time for better protection of the grid and even increased power flows in some cases [9]. Controlling flows can for example increase stability, increase damping of oscillations, operate transmission networks as efficiently as possible and assure maximum utilization of transmission assets. The growing share of technologies on a lower voltage level that can influence real and reactive flow, can enhance operators' ability to influence grid conditions significantly. Furthermore, coordination of (renewable) generation, storage and consumption is fundamental to reach all targets of a Smart Grid.

1.2.1 Requirements on Demand Side Management

As shown in the previous subsection Demand Side Management is already incorporated in some emerging advanced components in the Smart Grid. However, the intelligence of these components mainly focuses on the component itself and extends its focus atmost to its local environment. We want to refer to this kind of DSM as Demand Side Management in the narrow sense. Demand Side Management *in the broad sense* asks for management tools (on prediction, on planning, on control) that, besides focus on DSM in the narrow sense, also include intelligence to reliably integrate all parts of the Smart Grid.

The optimization objective can differ, depending on the stakeholder of the control systems, the system state and the rest of the electricity infrastructure. Therefore, a control methodology for DSM in the broad sense should be able to work towards different objectives. Next to different objectives, control methodologies can have different scopes for optimization: a local scope (within the building), a scope of a group of buildings e.g. a neighborhood (micro-grid) or a global scope (Virtual Power Plant). Finally, there are a lot of different (future) domestic technologies and building configurations and it should be possible to incorporate new technologies. As a consequence, the control methodology needs to be very *flexible and generic.*

The goal of the control methodology is to monitor, control and optimize the import/export pattern of electricity and to reach objectives which may incorporate *local but also global goals.* In this context, local objectives concern energy streams within the building, e.g. lowering electricity import peaks and using locally (in or around the building) produced electricity in the building. Global objectives on the other hand concern energy streams of multiple buildings, e.g. on a neighborhood, city or even (parts of) a country level. These objectives can be on different levels, e.g. on a neighborhood level to consume local generated electricity locally or on a national level to optimize production patterns of large power plants. Thus, the control methodology optimizes the runtime of individual devices to work towards local and global objectives.

Furthermore, the control methodology should be able to optimize for a single building up to a large group of buildings. Thus, the algorithms used in the control system should be *scalable* and the *amount of required communication should be limited.* The control methodology should try to exploit the potential of the devices as much as possible while *respecting the comfort constraints of the residents* and the technical constraints of the devices. Furthermore, the control system should consume significant less electricity than it saves.

Furthermore, *limitations on the communication links* should be taken into account. Due to the latency of communication links, sending information between system elements about system state and taken decisions require a certain amount of time. However, deciding whether it is profitable/required to switch on a large consuming device (e.g. a washing machine) or reacting on fluctuation in generation need to be done virtually instantaneously. Thus, a local control system has to be able to make these *realtime decisions* or these decisions need to be taken on beforehand.

1.2.2 Pitfalls of large scale control

The technical challenges lead to several requirements for DSM as mentioned in the previous section. The complexity of the used methods in DSM is of more importance in the Smart Grid. Especially for realtime control low complexity management tools should be available, since the possible decisions to choose from have increased significantly. This problem is noticed in the requirement for scalable methods, but we would like to stress out that scalability should not be achieved by neglecting the cooperation between all elements of the Smart Grid. For example, *turn-based* decision making, in which each level (domestic, neighborhood, city) makes its own decisions based on global information from the past, could lead to an unstable electricity grid, so coordination between different components should not be neglected.

The control methodology should prevent oscillating behavior caused by oversteering and large fluctuations (peaks), e.g. when a lot of buildings react on the same steering signal. This is called *damage control.* Damage is often caused by prediction errors and/or using more potential then available (e.g. maximum electricity import is too low) or synchronous behavior (all buildings reacting at the same time).

1.3 Control methodologies

In this section the characteristics of control methodologies for DSM are discussed.

Control methodologies for DSM in the broad sense can work towards objectives on different levels. On a high level, a large group of buildings is combined to improve efficiency of power plants by reducing fluctuations in demand or the flexibility is used to compensate for fluctuating renewable generation to allow a higher penetration rate of renewable energy. On a medium level the electricity streams through the grid are managed to optimally use the available grid capacity. On a low level the locally generated electricity is kept within the neighborhood and peaks in consumption are lowered (*peak shaving*). We have mentioned before that a control methodology should focus on:

1. improving the efficiency of existing power plants,
2. facilitating the large scale introduction of renewable generation,
3. allowing large scale introduction of new domestic technologies, both producing and consuming, using the current grid capacity,

while at the same time maintaining grid stability and reliability of supply.

Based on the way how the control methodology is used, extra requirements may arise. One possible application of the control methodology is to act actively on an electricity market for a group of buildings. To trade on such a market, an electricity profile must be specified one day in advance. Therefore, it should be possible to determine a forecast of the net electricity profile of the managed group of buildings one day in advance. Another application can be to react on fluctuations in the grid, for example caused by renewable generation, asking for a realtime management. Reacting on fluctuations requires a realtime control and the availability of sufficient generation capacity at every moment in time to be able to increase or decrease the consumption. To achieve sufficient capacity, again a planning must be determined in advance, in combination with realtime control to react on the fluctuations. Thus, a combination of *prediction* of demand and generation of devices, a *planning* of the use of these devices and *realtime control* is needed.

To create a successful Smart Grid solution and exploit all optimization potential the introduced technologies need to be monitored and synchronized to each other. Based on the measured data during monitoring, prediction and trends can be generated which can be used during planning and the realtime control.

1.3.1 Objectives and stakeholders

An important issue is the large number of stake holders involved in the transition towards a Smart Grid: governments, regulators, consumers, generators, traders, power exchanges, transmission companies, distribution companies, power equipment manufacturers and ICT providers [5]. These stake holders need an incentive to cooperate, whereas in first instance it seems to be unattractive for some stakeholders to change their view on the supply chain. However, distribution companies can decrease operating and maintenance costs and reduce capital costs. Production companies can introduce new types of generation and increase generation by relatively cheap base-load plants [11]. The consumers can reduce their costs and increase power quality and finally society will benefit from a stimulated economy and improved environmental conditions [11]. For the electricity retailers, demand side developments open new possibilities to act on the electricity market. Based on the (partial) control over local (renewable) generation capacity, retailers can remodel their strategies on the electricity market, forcing the original generation and transportation side to adapt to the emerging technologies.

Both [8] and [12] indicate that commercial attainability and legislation are important issues for the success of the introduction of DG. The opinions for the investments and profits differ strongly. On the one hand, the European Climate Forum states that large investments are required while it is unknown what the actual benefits and profits are [4]. On the other hand, the U.S. department of energy states that the transition towards a Smart Grid already started and that profits are higher than the investments [11]. They even claim that due to all benefits (e.g. improve safety and efficiency, better use of existing assets) the transition towards a Smart Grid will be market driven.

1.3.2 Level of optimization

The optimizations can be performed on different levels in the grid, all with their advantages and disadvantages. Roughly the levels can be divided into three groups:

Local scope On a local scope the import from and export into the grid can be optimized, without cooperation with other buildings. Possible optimization objectives are shifting electricity demand to more beneficial periods (e.g. nights) and peak shaving. The ultimate goal can be to create an independent building. This can be done in two forms: *energy neutral* or *islanded.* Energy neutral implies that there is no net import from or net export into the grid. A building that is physically isolated from the grid is called an islanded building.

The advantages of a local scope is that it is, besides the technical challenge, relatively easy to realize; there is no communication with others (less privacy intrusion) and there is no external entity deciding which devices are switched on or off (better social acceptance). The disadvantage is that it might result in high investment costs, e.g. in storage capacity and micro-generation.

Micro-grid In a micro-grid a group of buildings together optimize their combined import from and export into the grid, optionally combined with larger scale DG (e.g. wind turbines). The objectives of a micro-grid can be shifting loads and shaving peaks such that demand and supply can be matched better internally. The ultimate goal can be perfect matching within the micro-grid, resulting in a neutral or islanded micro-grid. The advantage of a group of buildings is that their joint optimization potential is higher than that of individual buildings since the load profile is less dynamic (e.g. startup peaks of devices disappear in the combined load). Furthermore, multiple micro-generators working together can match more demand than individual micro-generators since better distribution in time of the production is possible [13]. Finally, within a micro-grid the locally produced electricity can be used locally, saving transmission costs and preventing streams from lower to higher voltage levels. However, for a micro-grid a more complex control methodology is required.

Virtual Power Plant (VPP) The original VPP concept is to manage a large group of micro-generators with a total capacity comparable to a conventional power plant. Such a VPP can replace a power plant while having a higher efficiency, and moreover, it is much more flexible than a normal power plant. Especially this last point is interesting since it expresses the usability to react on fluctuations. This original idea of a VPP can of course be extended to other domestic technologies. Again, for a VPP a complex control methodology is required. Furthermore, communication with every individual building is required and privacy and acceptance issues may occur.

The three above mentioned groups mainly differ and where the decisions are made. This is tightly coupled in who is responsible for both the control systems as the techniques used. For example, in case of a local scope, house owners can invest in their on house, reaping the profits made locally. In case of a VPP, retailers or utilities might invest in domestic generators to be placed in houses, using them to make money on an energy market.

1.3.3 Optimization tool-chain approaches

There are many research projects investigating energy efficiency optimization. From the studied research, simulations and field tests it can be concluded that the efficiency can be improved significantly, especially when all three types of technologies (consuming, buffering and generating) are combined.

Several *control methodologies* for DG, energy storage, demand side load management or a combination of these can be found in literature. Roughly these control methodologies can be divided into two groups: 1) *agent-based mar-*

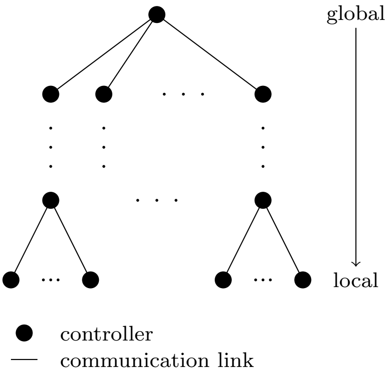

Figure 1.4: Hierarchical control architecture

ket mechanisms and 2) *discrete mathematical optimizations*. The advantage of agent-based market mechanisms is that no knowledge of the local situation is required on higher levels, only (aggregated) biddings for generation/consumption are communicated. The advantage of mathematical optimizations is that the steering is more direct and transparent, the effect of steering signals is better predictable. Another important difference is that in an agent based approach often every building works towards its own objectives where in a mathematical approach the buildings can work together to reach a global objective.

To overcome the scalability and communication issues the structure of the control system is important. A hierarchical structure with data aggregation on the different levels is an often proposed scheme. Such a structure is scalable while the amount of communication can be limited. However, when data is aggregated, information gets lost, so it is a trade-off between precision and the amount communication. An example of such a hierarchical structure is shown in Figure 1.4.

All control methodologies split the control into a local and a global part, most of them using a hierarchical structure for scalability. Furthermore, most control methodologies use an online algorithm deciding on device level and some control methodologies use prediction to adapt the production and demand patterns. However, this prediction data is often only used on a local level and, therefore, on a global level hardly any prediction knowledge is available. What is lacking most control methodologies is the predictability on a global level which is required for electricity market trading, i.e. insight in the effect of choices. This is also related to dependability.

Several control methodologies are based on cost functions for every devices, which is a nice abstraction mechanism from device specific characteristics. These cost functions define the normal behavior of the device and express options to deviate from the normal behavior with the desirability (costs to deviate). The cost functions for devices are a very flexible way to express the status of the device and desirability of different options. Since the cost functions are similar for every type of device, new devices can be incorporated in this approach. Furthermore, the control methodologies act on an homogeneous set of cost functions that keeps the algorithms much easier and less computationally intensive. Finally, cost functions of multiple devices can be combined into one cost function to study the effects of a single steering signal on a group of (different) devices.

1.3.4 Current research

Most of the current research considers agent based control methodologies. These agent based control methodologies propose an agent per device [14]. The agents give their price for energy production (switching an appliance off is seen as production); via a market principle it is decided which agents are allowed to produce. Since there are a lot of agents, the information is aggregated on different levels in a hierarchical way. The research described in [15] combines domestic generation, consumption and buffering of both heat and electricity. They propose an agent based system where buildings are divided into groups (microgrids) which are loosely connected to the conventional large-scale power grid. In first instance the goal is to maintain balance within the microgrid without using the large-scale power grid. Furthermore, agents use predictions to determine their cost function. Their field studies show that 50% of the domestic electricity demand can potentially follow a planned schedule (within certain boundaries). To reach this potential, there have to be incentives for the residents to allow some discomfort.

The PowerMatcher described in [16] and [17] additionally takes the network capacities into account. This control methodology is rather mature; it is a product capable of being used in field tests [18]. In this field tests, a peak reduction of 30% is reached when a temperature deviation of one degree of the thermostat in the buildings is allowed. To be able to reach objectives, business agents can be added that influence the biddings in the auction market.

In [19] the authors compare the results of individual (local) and overall (global) optimizations. They conclude that global optimizations lead to better results. Next, they claim that agent based control methodologies outperform non-agent based control methodologies since agent based control methodologies take more (domestic) information into account.

In literature, also some mathematical control methodologies are proposed. The research described in [20] proposes a methodology that is capable to aim for different objectives. For every device a cost function is determined for both heat and electricity. Using a Non Linear Problem definition the optimal on/off switch pattern is found. The authors of [21] address the problems of both agent and non-agent based solutions: non-agent based solution are less scalable and agent based solutions need local intelligence and are not transparent. Therefore, they propose a combination: aggregate data on multiple levels, while these levels contain some intelligence. The aggregation is done with a database, the control methodology is rule based. In [22] a control methodology is proposed using Stochastic Dynamic Programming (SDP). The stochastic part of the control methodology considers the uncertainty in predictions and the stochastic nature of (renewable) production and demand. The authors of [23] propose a control methodology based on Time Of Use (TOU) pricing, where electricity is cheaper during off-peak periods. They combine this approach with a domestic wireless sensor network: when a Smart Appliance would like to switch on, it has to send a request to a controller. This controller decides, based on the electricity price and the status of the other devices, whether the appliance is allowed to switch on. The TOU pricing can be seen as global steering signals, however it is a rough steering signal which is equal for a large group of buildings. Furthermore, it is not known in advance what the impact of the steering signals is.

In [24] a combination of existing tools together with a new developed platform is used. The electricity consumption and production per device is forecasted and using genetic algorithm the best runtime for every device is determined. The platform exists of two levels, a global level for global optimizations sends steering signals to the local level and a local level control which uses the global steering signals as input and determines the runtimes based on the steering signals while respecting local constraints.

Most control methodologies use some sort of prediction of demand and/or production. These predictions can be done rather good with neural networks, as described in [25] and [26]. The predictions follow the trend rather well.

At the University of Twente a methodology is developed that uses mathematical optimization techniques and a combination of prediction, offline global planning based on the predictions and online realtime control based on the global planning [27]. The base of the control methodology is 1) using local information, 2) communication using multiple levels and 3) scalability. The goal of the control methodology is to work towards (global) objectives and the performance of the control control methodology is measured by the extend the objectives are reached. The methodology uses 1) predictions on a device level to be able to predict the overall result, 2) planning to estimate the energy streams in the building and the grid and 3) realtime control to respond on changes (e.g. fluctuations in renewable generation) and work around predictions errors.

Based on the above considerations, the control methodology uses three steps and is split up into a local and a global part: 1) local offline prediction, 2) global offline planning and 3) local online control. Because of scalability reasons, the global planning has a hierarchical structure and can aggregate data and plannings on different levels, e.g. within a neighborhood or city.

Due to the predictions and planning on beforehand, the predictability of the global electricity streams is improved. The combination of planning (aggregated knowledge on higher levels) and mathematical optimization result in better dependability and combination of planning and realtime control improves the damage control. Furthermore, the amount of communication can be limited due to the hierarchical structure. Finally, the requirements on the communication medium is low since the local controller can work independently and a lot of information can be sent on beforehand without high latency requirements.

The combination of prediction, planning and realtime control exploits the potential of the overall system at the most beneficial times. The hierarchical structure with intelligence on the different levels ensures scalability, reduces the amount of communication and decreases the computation time of the planning.

1.4 Conclusion

Concerns about climate change, increasing energy prices and dependability of energy supply ask for drastic changes in the energy supply chain, but also in the current demand-supply philosophy. Current trends in energy consumptions result in an increasing and more fluctuating electricity usage, causing a decreasing efficiency of conventional power plants and increasing requirements on the grid and generation capacity. Furthermore, in order to meet the CO_2 emission reductions aimed for in the 20-20-20 agreements, at least a large part of the electricity should be generated by renewable sources which are to a large extent uncontrollable. This introduces even more challenges to maintain a reliable, dependable and affordable electricity supply. Therefore, new ways 1) to achieve a more efficient use of the generated electricity of existing power plants, 2) to facilitate the large scale introduction of renewable sources and 3) to allow a large scale introduction of new technologies for consumption and storage of energy, is required, while maintaining grid stability and ensuring a reliable and affordable supply.

The current grid is developed based on a demand-supply philosophy in which all electricity is generated in a few large central power plants and is transported top-down and one-way to the consumers. The consumers' side of the supply chain is static, consumers switch on devices and the generation side has to supply the demand. However, to increase the efficiency of current power plants and to allow the introduction of uncontrollable renewable sources, the consumer side of the supply chain should become more flexible; i.e. consumption should be adjusted to generation. To achieve this, the current electricity grid should be transformed into a Smart Grid and domestic customers should be transformed from static consumers into active participants in the energy supply chain. The main goals of a Smart Grid are to support the introduction of renewable generation and to keep up with the growing electricity demand and at the same time maintaining a stable, reliable and affordable electricity supply. The consumption can be adjusted to the generation: the decrease in flexibility on the generation side can be compensated by a more flexible electricity grid and a more flexible consumer side. Essential in a Smart Grid is a monitoring and management system that monitors and manages all parts of the grid. The emergence of smartening the grid and updating the electricity supply chain is emphasized by the numerous initiatives worldwide from the European Union, from governments, from industrial as well as from the academic world. However, to reach a smarter grid, a number of technical (e.g. scalability and dependability), economical (e.g. who has to invest/profit), political (e.g. is it allowed) and ethical (e.g. privacy issues) challenges have to be addressed. To tackle the technical challenges and to realize a monitoring and management system, ICT is seen as one of the key enabling technologies.

An important component of monitoring and management systems for Smart Grids is, next to sensors and actuators, a control methodology consisting of algorithms to gather information, process this information and optimize the overall electricity streams. Such a control methodology, capable of exploiting all potentials in a reliable and dependable way, should meet a number of requirements. The control methodology should work with both local and global objectives and should be very generic and flexible. Furthermore, since a large number of buildings is involved, the control methodology needs to be scalable. To be acceptable for the residents, it should also respect the comfort level of the residents. Furthermore, to get a dependable and reliable control methodology capable of damage control, a combination of prediction, planning and control is required. Finally, the requirements on the communication links should be limited and in case of failing communication links the local controller needs to be capable of working independently.

An hierarchical tree structure ensures scalability and limits the required communication. Furthermore, the optimizations based on cost functions result in a flexible and generic control methodology. The separation in local and global controllers distributes the required computational power and ensures the comfort and privacy of the end-users. The combination of offline prediction, offline planning and online control results in a flexible, dependable and predictable solution.

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