Chapter 1

Problem Statement

Renewable energy use has been increasing significantly during last years, and forecasts say that this trend will continue and even develop in the future [1]. Private households are participating in the renewable boom, e.g. with roof-mounted PV plants, small combined heat and power (CHP) plants or heat pumps in residential buildings. Owners are interested in best exploiting their renewable resources to minimize energy costs, to decrease emissions or to reduce their dependence on fossil fuels or energy suppliers.

Energy storage and the change of load demand, also called *demand response*, are two possibilities to increase the exploitation of locally available renewable resources [2]. The application of both depends on the general conditions defined by:

- renewable energy generation,
- load demand,
- energy prices,
- compensation payments for renewable grid feed,
- storage parameters,
- maximum demand response flexibility,
- available energy supply technologies.

Demand response and energy storage are used differently subject to these conditions and the objective the household pursues with its energy supply strategy. Consequently, the impact on the objective, e.g. minimum costs, also varies. The benefits the household can gain from demand response or energy storage are the improvements related to the objective compared to the case without the two applications, e.g. an additional energy cost reduction.

The installation of an energy storage device is generally costly [3], and demand response could decrease the living comfort due to necessary adaptations in the consumption behavior [4]. Hence, for the private consumer the question arises whether the use of energy storage or demand response brings any benefits, and if so, under which circumstances? This issue is accompanied by the question if a combination of both applications results in further advantages, or if either demand response or energy storage would be sufficient?

The exploitation of renewable energy can also be increased if the household affiliates with its vicinity and shares excess energy. Here, the question arises whether the cooperation can notably increase the collective welfare. It is also of interest if energy storage and demand response can account for further benefits in this setting.

The aim of this thesis is to contribute to the questions presented above resulting from the utilization of demand response and energy storage in residential applications, especially in the presence of renewable energy resources.

Chapter 2

State of the Art

This chapter presents the main principles and necessary information about demand response and energy storage with regard to the problem statement described in chapter 1. Also, state of the art models for a residential building and its energy supply infrastructure as well as an overview about related research are given.

2.1 Technical Background and Modeling of a Residential Building and its Energy Supply

In this section, the basics of demand response (section 2.1.1) and energy storage (section 2.1.2) are introduced, followed by the model of a residential building and the energy hub concept for its supply infrastructure (section 2.1.3).

2.1.1 Demand Response

Already in the 1980's, C. Gellings suggested to cause desirable changes in a utility's load shape by influencing the behavior of customers [5, 6]. Six objectives for load adjustment were presented (figure 2.1):

1. peak clipping,

2. valley filling,

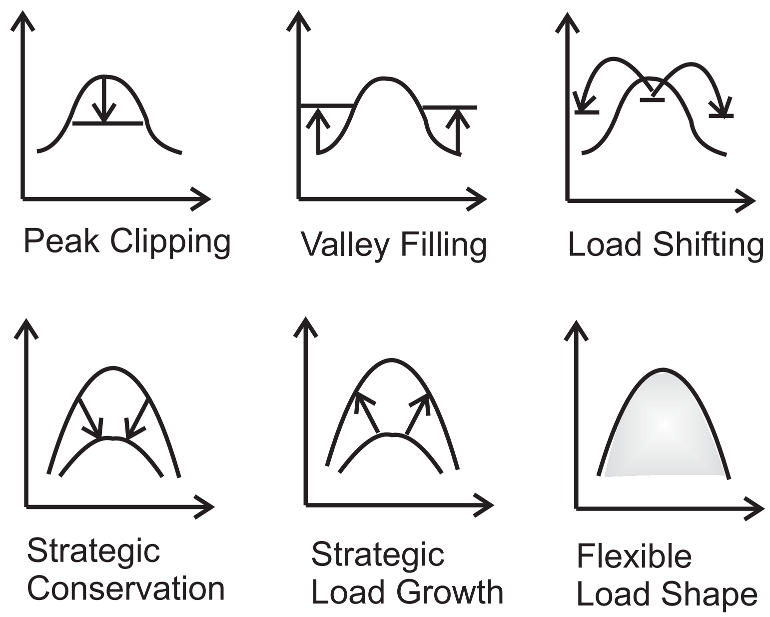

Figure 2.1: Demand-side management options [6]

3. load shifting,
4. strategic conservation,
5. strategic load growth,
6. flexible load shape.

Peak clipping, valley filling and load shifting are classic forms of load management. The first two aim at reducing peak and increasing off-peak loads, respectively. The third possibility aims at shifting load from on- to off-peak periods, e.g. using energy storage devices. Strategic load conservation and growth intend to decrease and raise the general load level, respectively. Finally, flexible load shape targets the supply reliability at the customer's. In exchange for various incentives, the utilities may temporarily curtail loads and apply service constraints or other limitations to energy supply quality.

These load management activities are driven by the utilities and are denoted *demand-side management* (DSM) [6]. Demand-side management is defined as "the planning and implementation of those electric utility activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape" ([6], p. 1468). But load modification can also be driven by the customer himself, e.g. to save energy costs or to increase independence from fossil fuels or energy suppliers. *Demand response* (DR) denotes all changes from nominal consumption patterns that are made by the customer voluntarily with an inherent objective [4]. The clear distinction between utility's and customer's aims using the definitions of *demand-side management* and *demand response* can also be found in [7] and is valid for this thesis. The focus, nevertheless, lies on demand response, as a customer's perspective is taken rather than a utility's.

Customers can influence their load demand by shifting loads from high- to low-tariff times or by reducing the overall load demand. Additionally, they can locally produce electricity (and heat) using *distributed generation* [4]. With local generation, e.g. a combined heat and power (CHP) or a photovoltaic (PV) plant, the consumption behavior of the customer does not have to change a lot, but the load demand pattern seen from the utility changes significantly.

The benefits for the customers are mainly reductions of the energy bill [4, 8]. But customers have to change their consumption habits and as a consequence their living comfort may be decreased [4, 9]. On-site generation needs maintenance which may result in inconvenient additional effort, both temporal and financial. Also, investment in enabling technologies for load shifting and optionally also in distributed generation technologies is necessary.

2.1.2 Energy Storage

Storage devices are one way to increase demand in off-peak and decrease it in on-peak times [10]. But energy storage can be applied for many other objectives, too [3]. In private households, storage can be used as a buffer directly coupled to a power plant or a renewable generation unit to decouple electric and thermal load or to increase the exploitation of locally available renewable energy. It also allows to profit from price variations. Storage devices and (renewable) generation can guarantee a reliable stand-alone energy supply. Finally, with the emerging technology of electric and hybrid vehicles, energy storage devices also find their way into the mobility sector [11].

Energy can be stored in four different ways [11]:

1. mechanically,
2. thermally,
3. electrically/electromagnetically,
4. chemically.

Mechanic storage devices include compressed air and pumped hydro energy storage, flywheels, and stationary and mobile fuel storage. Heat can be stored in sensitive and latent heat accumulators. Electricity can be directly stored in electrochemical capacitors and superconductive magnetic storage devices. Indirectly, it can be stored in chemical storage devices comprising accumulators, hydrogen, thermochemical storage devices and substantial energy carriers.

The current variety of technical storage possibilities covers a broad range of required power and energy [11] (fig. 2.2). In the range appropriate for residential use (rated power $\leq$ 10 kW), only chemical storage devices such as lead-acid or metal-air batteries are available. Also, flywheels (long time) could be used. The other existing technologies are applied for voltage stability and uninterruptible power supply (UPS), emergency power supply or energy management.

The manifold kinds and operation areas of storage devices and the associated benefits go together with significant financial investment and sometimes ecological impacts, both for construction and operation [3]. Depending on the kind of energy storage and its operation mode, costs per stored kilowatt hour vary significantly. Large-scale pumped hydro is assumed to be the least expensive alternative, with prices down to $\approx$ 5 € ct/kWh [3, 12]. General statements about costs are not possible, however, as the costs do not only depend on the storage itself, but also on its use, the building location, the efficiency, the life time, and various other parameters [3]. The costs per stored kilowatt hour have to be compensated by the savings resulting from the storage process to run the system economically viable.

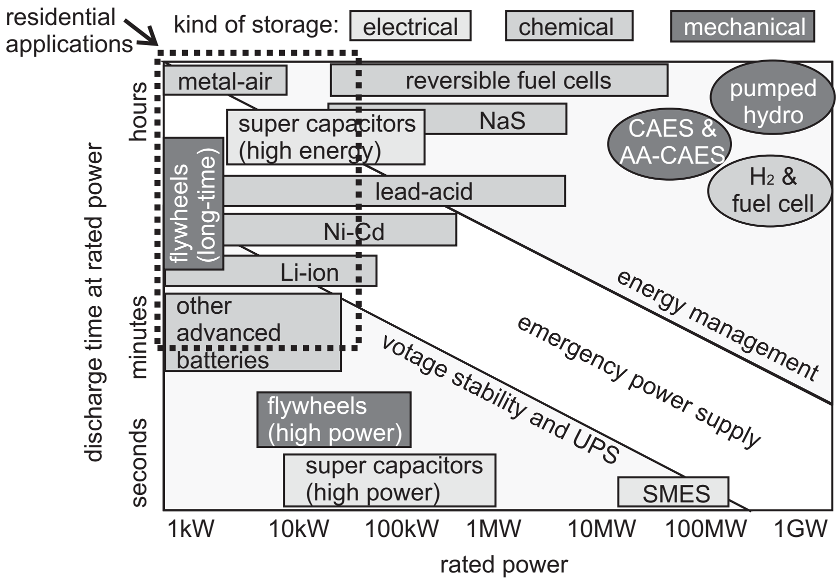

Figure 2.2: Energy storage systems for stationary applications [11]

2.1.3 Residential Building and Energy Supply System

Residential energy supply, e.g. for a single-family house, is in the scope of the study at hand. The following sections present state of the art models for residential buildings and their energy supply systems.

House Model

Various models of (residential) buildings exist. They range from simple models to predict a building's overheat [13] to complex models with third-order differential equations describing the behavior of the house [14]. In this thesis, a relatively simple model of the building is chosen to keep the computational effort reasonable. Nevertheless, the model reflects the main heat exchange and gain/loss mechanisms, as well as space heating and cooling.

The equations of the models hold true for each instant of time, t. However, the time dependency, $\bullet(t)$, is omitted whenever possible for better legibility. The models are time-discrete.

Space Heating and Cooling

The considered single-family house is a detached house. It consists of a cellar, several rooms on different levels, and a roof (fig. 2.3). The cellar is considered not to be heated. The other rooms all have to be conditioned to the nominal room temperature ϑ_{nom}.

To keep the model of the house simple, all conditioned rooms are grouped and modeled as one big room (fig. 2.4). This cube has the following parameters:

$$\begin{aligned} A_{\text{base}} &= l \cdot w \\ A_{\text{wall}} + A_{\text{window}} &= 2 \cdot (l + w) \cdot h \\ A_{\text{roof}} &= A_{\text{base}} \\ V_{\text{DH}} &= A_{\text{base}} \cdot h, \end{aligned}$$

where l, w and h are length, width and height of the building, respectively. The area of the outer walls excluding windows is denoted A_{wall}, and the area covered by windows is A_{window}. The roof area A_{roof} is assumed to be the same as the base area A_{base}. The volume of the resulting cube is V_{DH}.

Within the house, the room temperature has to be kept at a comfortable temperature level ϑ_{nom}. It is assumed that the nominal temperature ϑ_{nom} is the same for all rooms, although this simplification generally does not hold true for single-family houses [15].

Heat is exchanged between the interior and the ambient due to temperature differences. The heat flow $\dot{Q}$ can be calculated using the heat transfer coefficient U [16]:

$$\begin{aligned} \dot{Q} = & (U_{\text{wall}} \cdot A_{\text{wall}} + U_{\text{window}} \cdot A_{\text{window}} + \\ & + U_{\text{roof}} \cdot A_{\text{roof}}) \cdot (\vartheta_{\text{out}} - \vartheta_{\text{in}}) + U_{\text{cellar}} \cdot A_{\text{base}} \cdot (\vartheta_{\text{ground}} - \vartheta_{\text{in}}), \end{aligned} \tag{2.1}$$

where ϑ_{out} and $\vartheta_{\text{ground}}$ denote the ambient and the ground temperature, respectively. The actual temperature within the house is denoted ϑ_{in}. Heat is exchanged via the outer walls (U_{walls}), the windows