Franziska Adamek

Demand Response and Energy Storage for a Cost Optimal Residential Energy Supply with Renewable Generation

Cuvillier Verlag Göttingen
Internationaler wissenschaftlicher Fachverlag

DISS. ETH Nr. 19784

Demand Response and Energy Storage for a Cost Optimal Residential Energy Supply with Renewable Generation

A dissertation submitted to

ETH Zurich

for the degree of
Doctor of Sciences

presented by

FRANZISKA ADAMEK

Dipl.-Ing. Univ., B.Sc.
born April 21, 1983
citizen of Germany

accepted on the recommendation of
Prof. Dr. K. Fröhlich, examiner
Prof. Dr. L. van der Sluis, co-examiner
Prof. Dr. C. Franck, co-examiner

2011

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

1. Aufl. - Göttingen: Cuvillier, 2011
Zugl.: (ETH) Zürich, Univ., Diss., 2011

978-3-86955-939-1

Nonnenstieg 8, 37075 Göttingen
Telefon: 0551-54724-0
Telefax: 0551-54724-21
www.cuvillier.de

1. Auflage, 2011
Gedruckt auf säurefreiem Papier

978-3-86955-939-1

AMDG

Acknowledgement

Detours let you know the place better.
Umwege erweitern die Ortskenntnis.
Kurt Tucholsky

During the past three years I have been working on my PhD thesis at the High Voltage Laboratory at ETH Zurich. During this time I took many detours, walked into blind alleys, found direct and roundabout ways, and thereby explored my research area and adjacent topics. Finally, after a long walk, the destination was reached: the written thesis at hand. This would not have been possible without the support of various people.

First of all, I would like to thank my supervisor, Prof. Dr. Klaus Fröhlich, for his confidence in my scientific abilities, for his valuable comments and advice, and the many things I was fortunate to learn during the past three years. I am also grateful to Prof. Dr. Lou van der Sluis, the co-examiner, for carefully reading and evaluating my thesis within a short period of time, and for his helpful remarks. My thanks also go to Prof. Dr. Christian Franck for providing a second expertise on my thesis.

With my office mates Peter Ahcin, Michael Schüller and Josep Aniceto I have had a great time at work. Intensive conversations, professional discussions and a lot of fun and companionship characterized our days. Thanks a lot!

I would also like to thank my other colleagues of the High Voltage Laboratory, namely Dr. Andreas Bitschi, Dave Brühlmann, Dominik

Dahl, Felix Hug, Hans-Jürg Weber, Henry Kienast, Lukas Graber, Matthias Schulze, Michael Strobach, Michael Walter, Myriam Koch, Philipp Simka, Sedat Adili, Thomas Brügger and Dr. Ueli Straumann for the pleasurable working atmosphere, the good times at lunch, coffee breaks and other occasions, and valuable discussions about anything. Special thanks go to Claudia Stucki and Karin Sonderegger for IT and administrative support and the nice chats we had.

Thanks go to the colleagues from the Power Systems Laboratory for uncounted cakes and chats. All diploma and semester thesis workers and the IAESTE students deserve thanks for the professional discussions and inputs to my work. I am also obliged to Noemi Deak for proof-reading my thesis.

I thank my parents, Monika and Prof. Dr. Gerd Becker, for their support on both private and professional levels, and my sister, Dr. med. Katrin Werth with her husband Tobias Werth, as well as my brother Bernhard Becker, for enduring four PhDs at one time and nevertheless having a good time.

I am especially grateful to Dr. Beat Altenbach SJ, without whom this work would never have been finished.

Last but not least I cordially thank my husband, Dr. Lars Adamek, for being at my side on all detours and paths I have walked during the past years.

Zurich, July 31, 2011

Abstract

Renewable energy generation has been increasing for years, and is likely to increase even more in the future. Private households contribute to the renewable boom, e.g. with the installation of roof-mounted photovoltaic plants. Owners are interested in making the most of their local resources to keep energy costs as low as possible. To reach this aim, a household can apply energy storage and the change of load demand, also called *demand response*, or cooperate with other neighbors in the vicinity by sharing renewable generation and coordinating load demand to minimize the collective energy costs.

The aim of this thesis is to examine the influence of energy storage and demand response on domestic energy costs in the residential sector. Special focus is put on the influence of both on the energy supply strategy and the resulting energy costs. It is also examined whether additional benefits arise from a combination of demand response and energy storage, and if a cooperation of a group of houses can actually increase the overall welfare compared to individual energy supply.

The application of demand response and energy storage to exploit price variations and intermittent renewable generation has been widely treated in literature. First research has been carried out with respect to a cooperation of several residential customers. However, the benefits of demand response and energy storage for a private household have not yet been investigated in detail. Also, advantages and limits of combining both possibilities have not been studied. The combined effort of a group of houses has been subject of few studies, but no analysis of potential benefits for the individual actors has been carried out.

This thesis considers a single-family house in moderate climate and one in hot climate as well as a group of houses in moderate climate in order to examine the topics presented above. Heat exchange between the interior and the ambient due to temperature differences and artificial ventilation, and heat gain by solar irradiation cause a temperature change in the house. Space heating or cooling have to compensate this change to keep the inner temperature at a comfortable level. The required heating or cooling power and energy as well as warm water and electricity have to be provided by a number of conversion and storage technologies. The devices are aggregated in a multi-energy hub and coordinated so that they best exploit the available renewable resources and variable energy prices to minimize the household's energy costs. An energy hub is a device that models the processing (conversion and storage) of various energy carriers, both conventional and renewable, to determine the optimal power supply for a given load demand. The energy hub is extended with demand response to be suitable for the study at hand. A sensitivity analysis is carried out to determine the impacts of the system parameters. The storage parameters *cycle efficiency* and *storage capacity*, the demand response parameters *maximum shiftable power* and *maximum shiftable energy*, and the amount of *local renewable electricity generation* are varied. Also, the cases without/with energy storage and without/with demand response are examined to assess their respective impacts and the benefits of a combination of both. As frame conditions, seven price constellations for gas and electricity are evaluated.

For a group of six houses, a multiple-level approach is proposed to model the interdependencies and the cooperation of the actors. The two cases of *coexistence* and *cooperation* are compared for the group of houses. In the first case, each actor defines its own energy supply strategy, in the latter case the houses share excess electricity and information about demand response and energy storage use to increase common benefits.

The results show that in moderate climate electric demand response does not significantly influence the energy costs. Also, an electrical domestic hot water tank allows larger for cost savings than an electric storage device. In hot climate, it is the other way around. Electric demand response is well suited to reduce costs, as well as an electric storage device. In both climate zones, the combination of demand response and energy storage is only beneficial if sufficient renewable excess electricity is available and load demand is high enough. A co-operation of a number of households is only beneficial and expedient if the renewable generation sites are concentrated in few places. As a consequence of the obtained results, single-family houses in moderate climate are recommended to use excess electricity for thermal load demand, while houses in hot climate should invest in small electric storage devices. In a group of houses, energy storage is best installed in such a way that it supplies a number of houses, while renewable resources should be exploited individually.

Zusammenfassung

Erneuerbare Energieerzeugung nimmt seit Jahren zu. Hierbei leisten private Haushalte ihren Beitrag beispielsweise durch die Installation von Aufdach-Photovoltaikanlagen. Die Besitzer dieser Anlagen möchten ihre lokalen Ressourcen optimal nutzen, um die Energiekosten so gering wie möglich zu halten. Zur Erreichung dieses Ziels kann ein Haushalt Energiespeicher oder Lastverschiebung, auch *Demand Response* genannt, anwenden, oder sich mit Häusern aus der Nachbarschaft zusammenschliessen, um durch die gemeinsame Nutzung lokaler erneuerbarer Energien und die Koordination des Verbrauchs die gemeinschaftlichen Energiekosten zu minimieren.

Ziel dieser Arbeit ist es, den Einfluss von Energiespeichern und Demand Response auf die Energiekosten privater Verbraucher zu untersuchen. Dabei sind die Auswirkungen beider Möglichkeiten auf die Energieversorgung sowie die resultierenden Energiekosten von besonderem Interesse. Ausserdem wird untersucht, inwieweit die Kombination von Demand Response und Energiespeichern weitere Vorteile mit sich bringt, und ob ein Zusammenschluss von Häusern zur Senkung der gemeinsamen Energiekosten dient.

In der Literatur wurden Demand Response und Energiespeicher zur Nutzung von Preisschwankungen und intermittierenden erneuerbaren Energiequellen bereits häufig behandelt. Es gibt auch erste Untersuchungen über die Zusammenarbeit mehrerer privater Verbraucher. Jedoch wurden die Vorteile von Demand Response und Energiespeichern für einen privaten Haushalt bisher noch nicht genauer untersucht. Zudem wurden der Nutzen und die Grenzen einer Kombination beider nicht analysiert. Der Zusammenschluss mehrerer Häuser

zu einer gemeinsam agierenden Gruppe wurde zwar in wenigen Studien behandelt, jedoch wurden mögliche resultierende Vorteile für die einzelnen Beteiligten nicht beleuchtet.

In der vorliegenden Arbeit werden die oben genannten Punkte für je ein Einfamilienhaus in gemässigtem und in heissem Klima sowie für eine Häusergruppe in gemässigtem Klima untersucht. Wärmeeinträge durch Solarstrahlung sowie Wärmeflüsse zwischen dem Hausinneren und der Umgebung aufgrund von Temperaturdifferenzen und Belüftung bewirken eine Temperaturänderung im Haus. Diese muss durch Raumheizung oder -kühlung ausgeglichen werden, um die Innentemperatur auf einem angenehmen Niveau zu halten. Die benötigte Wärme- oder Kühlleistung und -energie muss, ebenso wie Warmwasser und Elektrizität, durch Energiewandler und -speicher zur Verfügung gestellt werden. Diese Geräte werden in einem "Multi-Energy Hub" zusammengefasst und derart koordiniert, dass Preisschwankungen und die vorhandene erneuerbare Energie bestmöglich genutzt werden, um die Energiekosten zu minimieren. Der "Multi-Energy Hub" ist ein Konzept, das die Umwandlung und Speicherung verschiedener konventioneller und erneuerbarer Energieträger modelliert und deren Verwendung zur Lastdeckung optimiert. Der Energy Hub wird mit Demand Response erweitert, um für die vorliegende Arbeit verwendet werden zu können. Es wird eine Sensitivitätsanalyse durchgeführt, um die Einflüsse der verschiedenen Parameter auf die Energiekosten und -versorgung zu untersuchen. Dabei werden die Speicherparameter *Zyklenwirkungsgrad* und *Speicherkapazität*, die Demand Response-Parameter *maximal verschiebbare Leistung* und *maximal verschiebbare Energie*, sowie die Menge *lokal erzeugter erneuerbarer Elektrizität* variiert. Zudem werden die Fälle ohne und mit Energiespeicher und ohne und mit Demand Response verglichen, um die Einflüsse und Vorteile beider sowie deren Kombination bestimmen zu können. Sieben Preiskonstellationen für Gas- und Strompreis sind als Rahmenbedingungen definiert.

Zur Untersuchung einer Gruppe von sechs Häusern wird ein Multiple-Level-Ansatz vorgestellt, der die Abhängigkeiten und die Zusammenarbeit der Beteiligten modelliert. Die zwei Fälle *Nebeneinander* und *Miteinander* werden verglichen. Im ersten Fall handelt jedes Haus für sich allein, wohingegen im zweiten Fall überschüssige erneuerbare

Energie sowie Informationen über Demand Response- und Energiespeichernutzung ausgetauscht werden.

Die Ergebnisse zeigen, dass elektrisches Demand Response in gemässigtem Klima nur geringen Einfluss auf die Energiekosten hat. Zudem erlaubt ein elektrischer Boiler höhere Kosteneinsparungen als ein elektrischer Speicher. In heissem Klima ist es genau umgekehrt. Elektrisches Demand Response ist ebenso wie ein elektrischer Speicher geeignet, um die Energiekosten zu senken. In beiden Klimazonen lohnt sich die Kombination von Demand Response und Speicher nur, wenn genügend überschüssige erneuerbare Energie vorhanden und die Lastnachfrage hoch genug ist. Ein Zusammenschluss mehrerer Haushalte ist nur sinnvoll, wenn die erneuerbare Energieerzeugung auf wenige Stellen konzentriert ist. Aufgrund der Ergebnisse kann man Einfamilienhäusern in gemässigtem Klima raten, erneuerbare Elektrizität auch zur Deckung der thermischen Last einzusetzen. Häuser in heissem Klima hingegen investieren besser in kleine elektrische Energiespeicher. In einer Häusergruppe werden Energiespeicher am besten so installiert, dass sie zur Lastdeckung mehrerer Häuser beitragen können, wohingegen erneuerbare Energien besser dezentral und individuell verwendet werden.

Contents

1 Problem Statement **1**

2 State of the Art **3**
2.1 Technical Background and Modeling of a Residential Building and its Energy Supply . . . 3
2.1.1 Demand Response . . . 3
2.1.2 Energy Storage . . . 5
2.1.3 Residential Building and Energy Supply System 7
2.2 Research Overview . . . 21
2.2.1 Cost-Driven Use of Demand Response . . . 21
2.2.2 Theoretical Potential and Practical Application of Demand Response . . . 24
2.2.3 Cost-Driven Use of Energy Storage . . . 25
2.2.4 Intermittent Renewable Generation and Energy Storage . . . 26
2.2.5 Cooperation of Consumers . . . 27
2.2.6 Summary of the Research Overview . . . 28

3 Research Goal **29**
3.1 Research Questions . . . 29
3.2 Locations of Influence of Demand Response and Energy Storage . . . 30
3.3 Methodology to Assess the Research Questions . . . 31
3.4 Thesis Outline . . . 34

4 Modeling and Examined Cases 35
4.1 Modeling of the Single-Family House 35
4.1.1 Parameters of the Single-Family House 36
4.1.2 Extension of the Energy Hub Model with Demand Response 38
4.1.3 Conversion and Storage Technologies of the Houses in Moderate and Hot Climate 39
4.1.4 Load Demand Curves of the Houses 42
4.1.5 Determination of the Optimal Energy Supply Strategy for the Single-Family House 45
4.2 Modeling of a Group of Houses 47
4.2.1 Model Description 47
4.2.2 Examined Groups of Swiss Houses 49
4.2.3 Determination of the Optimal Energy Supply Strategy for a Group of Houses 51
4.3 Cost Optimization and Energy Prices 52
4.4 Parameters of the Sensitivity Analysis 55
4.5 Optimization Interval and Parameters 57

5 Case Studies 61
5.1 Influence of the Parameters on Energy Costs and Supply Strategy (House in Moderate Climate) 61
5.1.1 Influence of the Electric Demand Response Parameters 61
5.1.2 Influence of the Cycle Efficiency (Electric Storage) 71
5.1.3 Influence of the Available Storage Capacity (Electric Storage) 79
5.1.4 Influence of the Optimization Horizon and the Solution Horizon 82
5.1.5 Influence of the Amount of Local Photovoltaic Electricity 84
5.1.6 Verification of the Results for One Year 92
5.2 Influence of the Parameters on Energy Costs and Supply Strategy (House in Hot Climate) 95
5.2.1 Influence of the Electric Demand Response Parameters 95
5.2.2 Influence of the Cycle Efficiency (Electric Storage) 101

5.2.3 Influence of the Available Storage Capacity (Electric Storage) 103
5.2.4 Influence of the Amount of Local Photovoltaic Electricity 106
5.2.5 Verification of the Results for One Year 112
5.3 Influence of Cooperation, Demand Response and Energy Storage on the Energy Costs for a Group of Houses in Moderate Climate 114

6 Discussion 119
6.1 Energy Storage Utilization 119
6.2 Demand Response Application 121
6.3 Impact of the Combination of Demand Response and Energy Storage 121
6.4 Cooperation of Consumers 122
6.5 Influence of Energy Prices and Renewable Generation 123
6.6 Data Availability and Exchange 125
6.7 Socio-Economic Issues 125

7 Summary of Key Results 127

8 Conclusions 131

List of Figures 133

List of Tables 137

Bibliography 139

A Nomenclature 147
A.1 Latin Symbols 147
A.2 Greek Symbols 152
A.3 Abbreviations 154

B Assumptions and Simplifications of the Applied House Model 155

C Comments on the Matlab Implementation 157
C.1 Constraints on Heating and Cooling Power 157
C.2 Interval for Demand Response Balance 159

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,

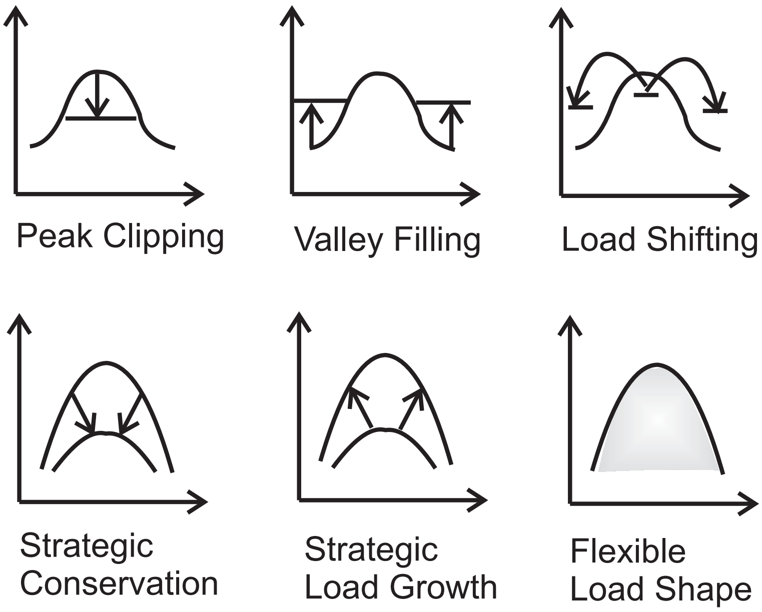


Figure 2.1: Demand-side management options [6]

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.

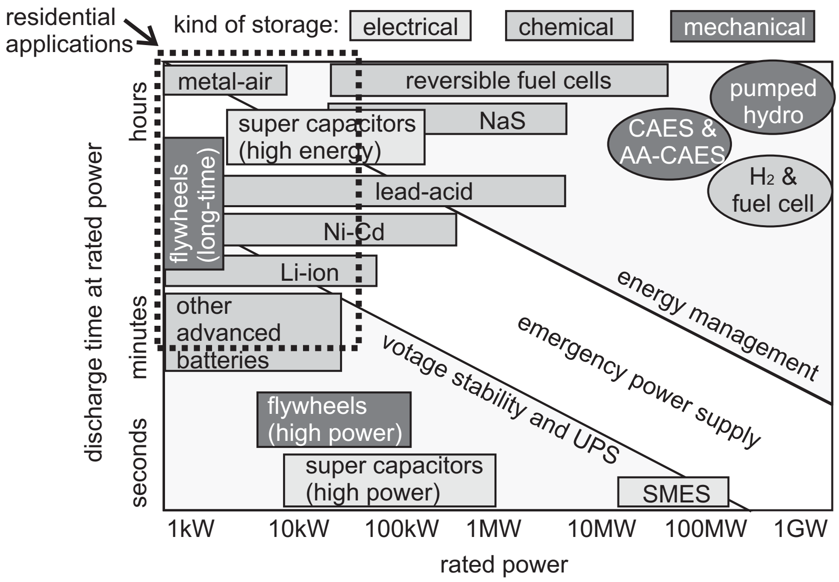


Figure 2.2: Energy storage systems for stationary applications [11]

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:

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

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]:

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

where ϑ_{out} and $\vartheta_{\mathrm{ground}}$ 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

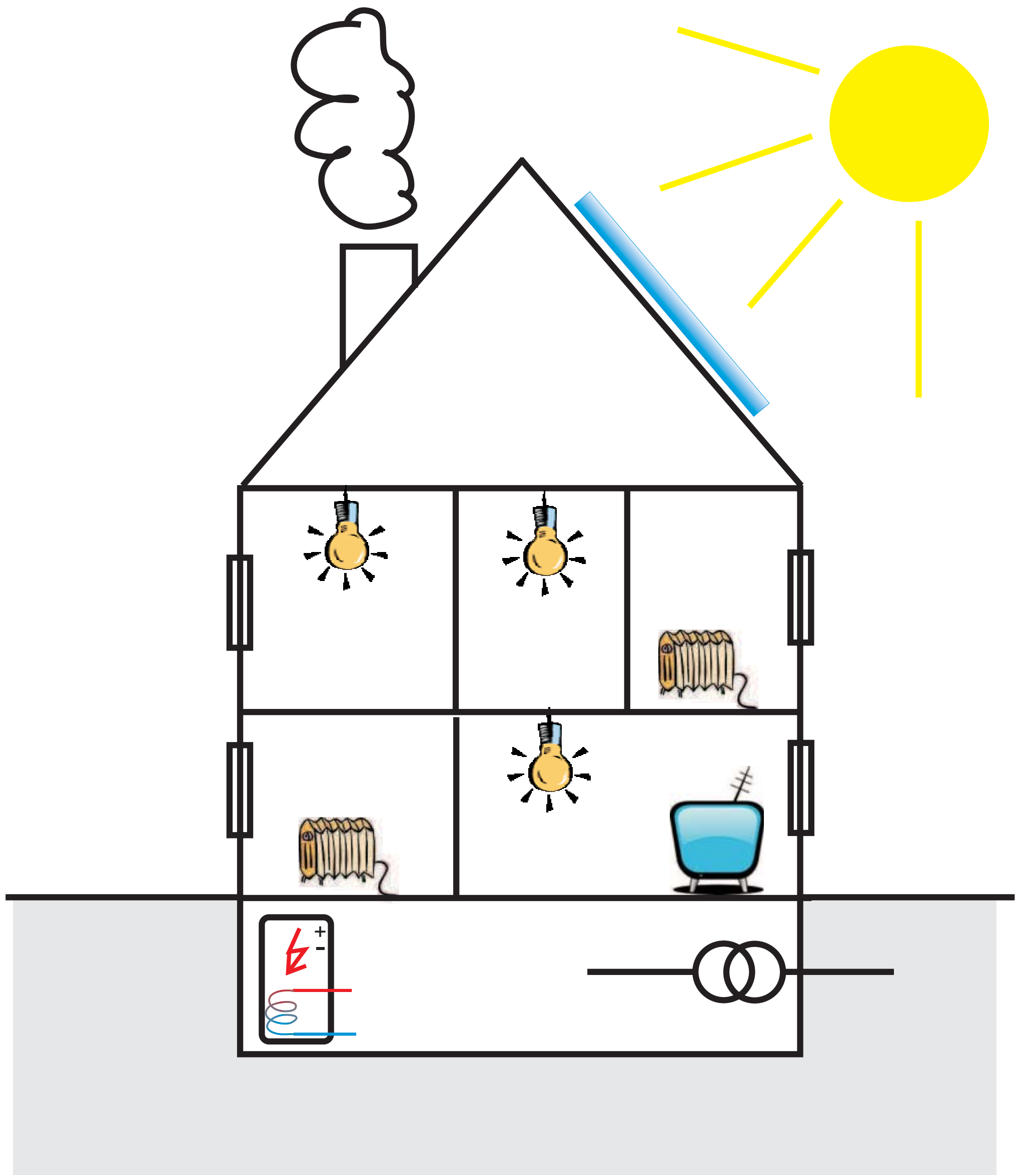


Figure 2.3: Detached house with different rooms, load demand and power supply

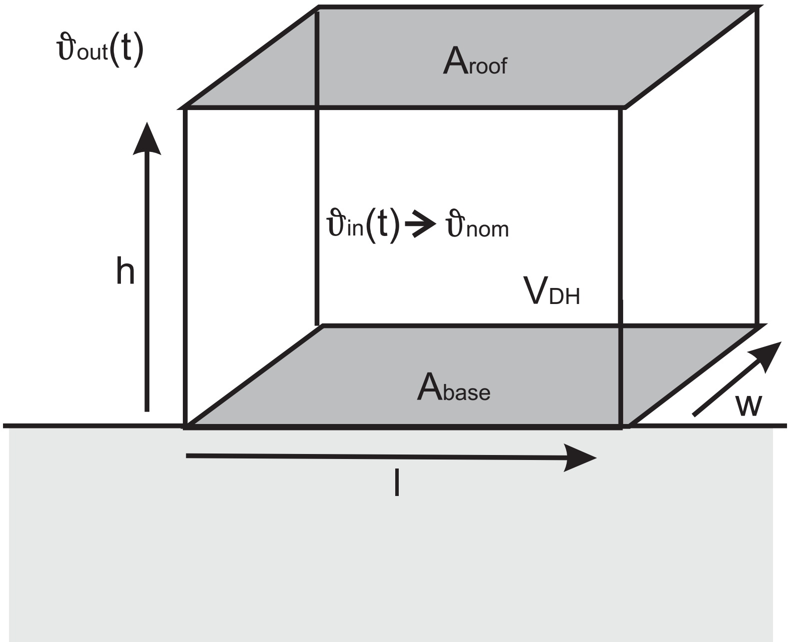


Figure 2.4: Cubic model for the detached house

(U_{window}), the roof (U_{roof}) and the cellar (U_{cellar}). For simplicity, the heat transfer between ground and cellar is not considered, assuming a very good insulation between the house and the ground ($U_{\text{cellar}} = 0$). The roof is regarded as an additional outer wall. The heat exchange via the walls can thus be stated as:

$$\begin{aligned} \dot{Q} &= U_{\text{wall}} \cdot (A_{\text{wall}} + A_{\text{roof}}) \cdot (\vartheta_{\text{out}} - \vartheta_{\text{in}}) + \\ &\quad + U_{\text{window}} \cdot A_{\text{window}} \cdot (\vartheta_{\text{out}} - \vartheta_{\text{in}}). \end{aligned} \tag{2.2}$$

Heat is also exchanged due to artificial ventilation [13, 17]. Each n_{air} hours, the air within the house is completely replaced by ambient air. The ambient air has to be adjusted to the inner temperature requiring the power $\dot{Q}_{\text{air}}$:

$$\dot{Q}_{\text{air}} = (1 - p_{\text{recov}}) \cdot \frac{1}{n_{\text{air}}} \cdot V_{\text{DH}} \cdot \rho_{\text{air}} \cdot c_{\text{air}} \cdot (\vartheta_{\text{out}} - \vartheta_{\text{in}}), \tag{2.3}$$

where V_{DH} is the volume of the detached house, ρ_{air} is the density and c_{air} the heat capacity of air. The percentage of heat recovered within the ventilation system is denoted p_{recov}.

The inner temperature ϑ_{in} of the house also rises due to solar irradiation. The heat inserted by the sun can be estimated using the global irradiation G, the energy transmission value g of the windows, and the conversion factor α for determining the global irradiance on a vertical surface from the horizontal value [18]:

$$\dot{Q}_{\text{sol}} = \alpha \cdot g \cdot G \cdot A_{\text{window}}. \tag{2.4}$$

The resulting heat flow $\dot{Q}_{\text{res}}$ between the house and the ambient is the sum of solar heating $\dot{Q}_{\text{sol}}$, ventilation losses $\dot{Q}_{\text{air}}$ and heat exchange via the walls $\dot{Q}$:

$$\dot{Q}^{(\text{sum})} = \dot{Q}_{\text{sol}} + \dot{Q}_{\text{air}} + \dot{Q}. \tag{2.5}$$

The heat flow causes a temperature change $\Delta\vartheta$ within the house:

$$\Delta\vartheta = \frac{\dot{Q}^{(\text{sum})} \cdot \Delta t}{m \cdot c}, \tag{2.6}$$

where Δt is the time interval, m the heat storing mass of the house, and c the heat capacity of the material. The parameters m and c depend on the building characteristics. Space heating or cooling have to balance the temperature change to keep the room at a constant temperature level ϑ_{nom}:

$$\dot{Q}^{\text{sh}}_{\text{fur}} = \frac{\dot{Q}^{(\text{sum})}}{\eta_{\text{heat}}}, \quad \text{if } \dot{Q}^{(\text{sum})} \leq 0, \tag{2.7}$$

$$\dot{Q}_{\text{cool}} = \frac{\dot{Q}^{(\text{sum})}}{\eta_{\text{cool}}}, \quad \text{if } \dot{Q}^{(\text{sum})} > 0, \tag{2.8}$$

where η_{heat} and η_{cool} denote the efficiencies of the space heating and cooling system, respectively.

Instead of keeping a constant temperature, the room temperature ϑ_{in} can also vary within a temperature band $\vartheta_{\text{nom}} \pm \Delta\vartheta_{\text{nom}}$. Then, the inserted heat flow either from the furnace, $\dot{Q}^{\text{sh}}_{\text{fur}}$, or the cooling system, $\dot{Q}_{\text{cool}}$, has to ensure an admissible temperature change within the room:

$$\begin{aligned}
\vartheta_{\text{nom}} - \Delta\vartheta_{\text{nom}} &\leq \vartheta_{\text{in}}(t) \leq \vartheta_{\text{nom}} + \Delta\vartheta_{\text{nom}} \\
\dot{Q}_{\text{res}} &= \dot{Q} + \dot{Q}_{\text{Sol}} + \dot{Q}_{\text{air}} + \begin{cases} \dot{Q}^{\text{sh}}_{\text{fur}} \cdot \eta_{\text{heat}} \\ \dot{Q}_{\text{cool}} \cdot \eta_{\text{cool}} \end{cases} \\
\Delta\vartheta &= \frac{\dot{Q}_{\text{res}} \cdot \Delta t}{m \cdot c} \qquad (2.9) \\
\vartheta_{\text{in}}(t+1) &= \vartheta_{\text{in}}(t) + \Delta\vartheta \\
\vartheta_{\text{nom}} - \Delta\vartheta_{\text{nom}} &\leq \vartheta_{\text{in}}(t+1) \leq \vartheta_{\text{nom}} + \Delta\vartheta_{\text{nom}}.
\end{aligned}$$

For a house, a small part of the heat is stored within the air, while the main part is stored within the walls, as the heat capacity of the construction materials is much higher than that of air [13, 19]. The outer layer of the walls, however, is (nearly) on the same temperature level as the ambient, while the inner layer is on the level of the room temperature. Consequently, not the complete mass of the wall can be considered as effective for heat conservation. Reverted, it can be said that the effective heat capacity C_{eff} of the wall will be smaller than the heat capacity c_{mat} of the wall material, due to the temperature gradient within the walls [16]. Extensive studies have been carried out to determine the effective heat capacity of different walls depending on their type and thickness [13]. For the thesis at hand, the values for light, medium and heavy construction will be used [13]:

$$\begin{aligned}
C_{\text{eff,light}} &= 25 \frac{\text{kJ}}{m^2 \cdot K} = 6.95 \frac{\text{Wh}}{m^2 \cdot K} \\
C_{\text{eff,medium}} &= 65 \frac{\text{kJ}}{m^2 \cdot K} = 18.07 \frac{\text{Wh}}{m^2 \cdot K} \\
C_{\text{eff,heavy}} &= 105 \frac{\text{kJ}}{m^2 \cdot K} = 29.19 \frac{\text{Wh}}{m^2 \cdot K}.
\end{aligned}$$

Consequently, the product of heat storing mass and heat capacity, $m \cdot c$, can be calculated as

$$\begin{aligned}
m \cdot c &= m_{\text{air}} \cdot c_{\text{air}} + (A_{\text{wall}} + A_{\text{floor}}) \cdot C_{\text{eff}} + m_{\text{in}} \cdot c_{\text{in}} \qquad (2.10) \\
m_{\text{in}} &= (A_{\text{floor}} + A_{\text{innerwalls}}) \cdot d_{\text{in}} \cdot \rho_{\text{in}} \\
m_{\text{air}} &= l \cdot w \cdot h \cdot \rho_{\text{air}},
\end{aligned}$$

with A_{floor} and $A_{\text{innerwalls}}$ being the area of interior floors and walls, d_{in} the thickness of the inner walls and floors, ρ_{in} the inner wall density, ρ_{air} the air density, and c_{air} and c_{in} the heat capacities of air and the inner walls, respectively.

Resulting, the thermal load curve of the house is defined by the heating or cooling demand, $\dot{Q}^{\text{sh}}_{\text{fur}}(t)$ or $\dot{Q}_{\text{cool}}(t)$, respectively, based on the processes and parameters described above.

Warm Water

The power

$$\dot{Q}_{\text{ww}} = \frac{m}{\Delta t} \cdot c \cdot (\vartheta_{\text{hot}} - \vartheta_{\text{cold}}) \tag{2.11}$$

is needed to heat up a mass m of cold water at temperature ϑ_{cold} to the hot water temperature ϑ_{hot} within the time interval Δt [16].

Hence, the necessary furnace power resulting from warm water demand is

$$\dot{Q}^{\text{ww}}_{\text{fur}} = \frac{\dot{Q}_{\text{ww}}}{\eta_{\text{ww}}}, \tag{2.12}$$

where η_{ww} is the efficiency of the warm water system.

Multi-Energy Hub Model

An appropriate possibility to model the energy supply system of a single-family house is the *energy hub concept* [20, 21]. An energy hub (figure 2.5) aggregates all conversion and storage technologies available to fulfil a given multi-energy load demand and coordinates the operation of the devices. Subsequently, the energy hub model will be explained. A more detailed description can be found in [22].

Conversion Technologies

The energy hub (fig. 2.5) processes a number of different input energy carriers P to supply the multi-energy load L. The set of energy carriers $\mathcal{E}$ is denoted with small Greek letters:

$$\alpha, \beta, \gamma, ..., \omega \in \mathcal{E} = \{\text{electricity, gas, heat,...}\}.$$

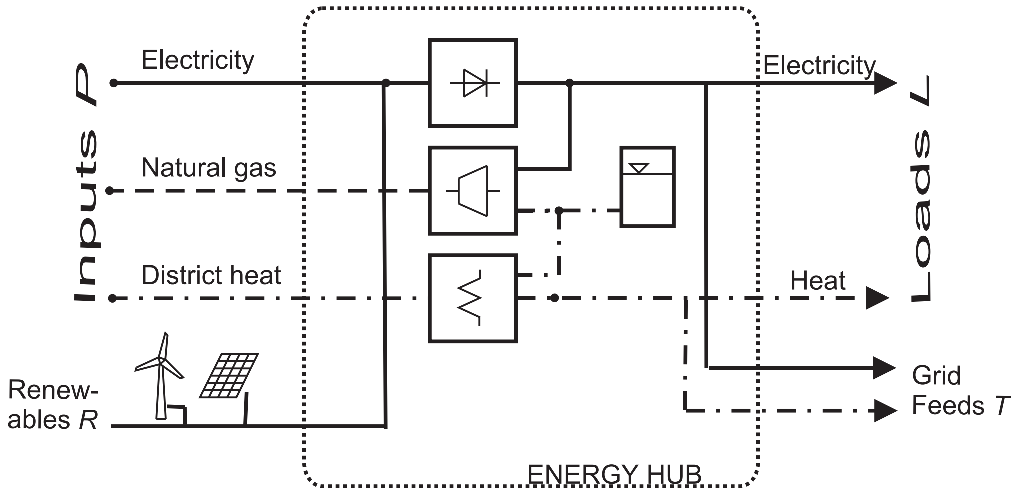


Figure 2.5: Exemplary energy hub: electric and thermal load are supplied by an electricity transformer, a gas-fueled combined heat and power plant, a heat exchanger for district heat, a heat storage device and wind and solar power.

The required load demand L consists of the load curves for all energy carriers of interest:

$$L = \begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix}. \tag{2.13}$$

By analogy, external energy, e.g. grid electricity or fuel, is comprised in the input vector P:

$$P = \begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix}. \tag{2.14}$$

The renewable vector R contains all locally available, non-dispatchable renewable resources like photovoltaic or wind. Excess electricity can be fed to the grid via T. The vectors R and T are formed analogue to the input and load vector, respectively.

A number of technologies, e.g. a grid connection, a CHP and a heat exchanger, processes the input carriers P and the renewable resources R. The conversion of input P_α to supply load L_β is defined by the efficiency of the converting technology:

$$L_\beta = \eta_{\alpha\beta} \cdot P_\alpha. \tag{2.15}$$

Additionally, a dispatch factor $\nu_{\alpha\beta}$ has to be introduced if P_α is split to be processed by various technologies (fig. 2.6):

$$P_\alpha^{(\beta)} = \nu_{\alpha\beta} \cdot P_\alpha. \tag{2.16}$$

Consequently, (2.15) and (2.16) result in

$$L_\beta = \nu_{\alpha\beta} \cdot \eta_{\alpha\beta} \cdot P_\alpha = c_{\alpha\beta} \cdot P_\alpha. \tag{2.17}$$

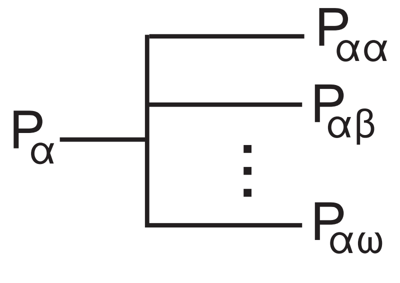


Figure 2.6: Dispatch of input carrier P_α: the input carrier P_α is split into several parts to be converted to different energy carriers $\alpha ... \omega$

The dispatch factors $\nu_{\alpha k}$ are constrained to be less than 1, and the sum of all dispatch factors of one input carrier has to be equal to 1, due to energy conservation:

$$0 \leq \nu_{\alpha k} \quad \leq \quad 1, \quad \forall \alpha \in \mathcal{E}, \ \forall k = \alpha ... \omega \tag{2.18}$$

$$\sum_{k=\alpha}^{\omega} \nu_{\alpha k} \quad = \quad 1, \quad \forall \alpha \in \mathcal{E}. \tag{2.19}$$

The conversion matrix C contains the coupling factors of input and output carriers as defined in (2.17):

$$\begin{aligned} \begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix} &= \begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \dots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \dots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \dots & c_{\omega\omega} \end{bmatrix} \cdot \begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix} \\ L &= C \cdot P \end{aligned} \tag{2.20}$$

Including the grid feed T and the renewable resources R results in [23]:

$$L + T = C \cdot (P + R) \tag{2.21}$$

The power balance (2.21) of the system has to hold true $\forall t \in [0, T_{\text{end}}]$. Additionally, the input power P may not exceed a threshold given by the associated conversion technology:

$$P_{\text{min},\alpha} \leq P_\alpha(t) \leq P_{\text{max},\alpha}(t), \quad \forall t, \forall \alpha \in \mathcal{E}. \tag{2.22}$$

Only renewable energy can be fed into the grid, i.e. energy produced by an intermittent source like wind or sun, or energy produced by a combined heat and power plant. Consequently:

$$0 \leq T_\alpha(t) \leq \sum_m R_{\alpha,\text{m}}(t), \quad \forall t, \forall \alpha \in \mathcal{E}, \tag{2.23}$$

where m counts all available renewable sources of carrier α.

Energy Storage

Energy storage can also be modeled in the energy hub [21]. The storage device (fig. 2.7) exchanges the power M with the system. The energy flow into the storage is defined to be positive, i.e.

- $M_\alpha > 0 \;\rightarrow$ charging: $M_\alpha = M_{\text{char},\alpha}$
- $M_\alpha \leq 0 \;\rightarrow$ discharging: $M_\alpha = M_{\text{dis},\alpha}$

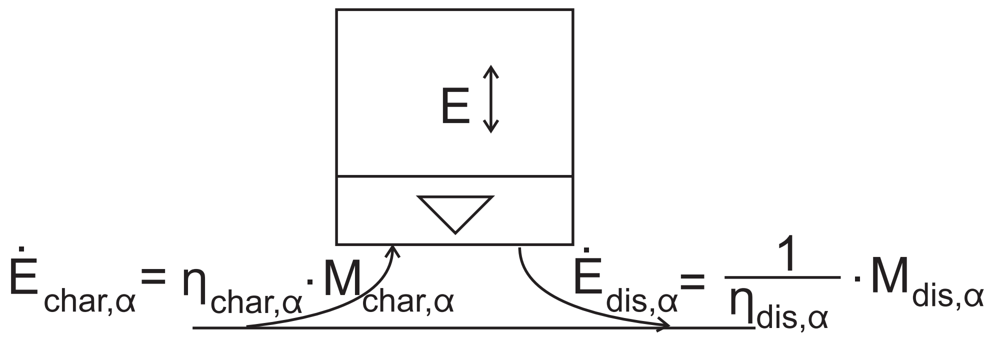


Figure 2.7: Power flow of a storage device: The power $M_{\text{char},\alpha}$ released from the system charges the energy storage of carrier α during the time interval Δt with the power $\dot{E}_{\text{char},\alpha}$. As a consequence, the energy E within the storage device increases by $\dot{E}_{\text{char},\alpha} \cdot \Delta t$. The reverse case happens for discharge.

The state of charge, $E_\alpha(t)$, of the storage for energy carrier α changes according to the power withdrawn from or charged into the device within the time period Δt:

$$\frac{E_\alpha(t+1) - E_\alpha(t)}{\Delta t} = \begin{cases} \dot{E}_{\text{char},\alpha} = \eta_{\text{char},\alpha} \cdot M_{\text{char},\alpha}, & \text{if } M_\alpha > 0, \\ \dot{E}_{\text{dis},\alpha} = \frac{1}{\eta_{\text{dis},\alpha}} \cdot M_{\text{dis},\alpha}, & \text{if } M_\alpha \leq 0, \end{cases} \tag{2.24}$$

where $\eta_{\text{char},\alpha}$ and $\eta_{\text{dis},\alpha}$ are the charge and discharge efficiencies, respectively.

The storage device can be installed on the load or the input side of the conversion technologies (see fig. 2.5, where a load-side device is depicted). By analogy to P and R, the power exchange $M^{(\mathrm{in})}$ of an input-side device has to be processed by the conversion technologies to supply the load, while a load-side storage ($M^{(\mathrm{load})}$) can be included directly. For simplicity of explanation, only load-side storage devices will be considered in the following with $M^{(\mathrm{load})} = M$. See [22] for a more general description.

Consequently, the hub equation (2.21) can be extended with energy storage to

$$L + T + M = C \cdot (P + R)\,. \tag{2.25}$$

Applying (2.24), (2.25) can be reformulated as

$$L + T = C \cdot (P + R) - S \cdot \dot{E}, \tag{2.26}$$

where $\dot{E} = [\dot{E}_\alpha \; ... \; \dot{E}_\omega]^T$ is the vector of changes in the state of charge of the devices, and

$$S = \begin{bmatrix} s_{\alpha\alpha} & s_{\beta\alpha} & \dots & s_{\omega\alpha} \\ s_{\alpha\beta} & s_{\beta\beta} & \dots & s_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ s_{\alpha\omega} & s_{\beta\omega} & \dots & s_{\omega\omega} \end{bmatrix}$$

is the storage matrix containing the charge and discharge efficiencies according to

$$s_{ik} = \begin{cases} \frac{1}{\eta_{\mathrm{char},\alpha}}, & \text{if } \dot{E}_i > 0, \\ \eta_{\mathrm{dis},\alpha}, & \text{if } \dot{E}_i \leq 0. \end{cases} \tag{2.27}$$

The cycle efficiency η_{cycle} of the storage is determined by the multiplication of charge and discharge efficiency

$$\eta_{\mathrm{cycle}} = \eta_{\mathrm{char}} \cdot \eta_{\mathrm{dis}} \tag{2.28}$$

and defines the performance of the storage. The higher the cycle efficiency, the lower are the losses and the more economically can the storage be operated.

The operation of the storage devices is also constrained by technological limits. The state of charge, E, must not exceed the storage capacity $E_{\max}$, and the charge and discharge power, $\dot{E}_{\text{char}}(t)$ and $\dot{E}_{\text{dis}}(t)$, respectively, must be within their admissible range:

$$E_{\min} \leq E(t) \leq E_{\max} \quad \forall t, \tag{2.29}$$

$$0 \leq \dot{E}_{\text{char,min}} \leq \dot{E}_{\text{char}}(t) \leq \dot{E}_{\text{char,max}} \quad \forall t, \tag{2.30}$$

$$\dot{E}_{\text{dis,min}} \leq \dot{E}_{\text{dis}}(t) \leq \dot{E}_{\text{dis,max}} \leq 0 \quad \forall t, \tag{2.31}$$

with

$$\dot{E} = \begin{cases} \dot{E}_{\text{char}}, & \text{if } \dot{E} > 0, \\ \dot{E}_{\text{dis}}, & \text{if } \dot{E} \leq 0. \end{cases} \tag{2.32}$$

The upper and lower boundary of the state of charge, $E_{\max}$ and $E_{\min}$, respectively, define the available storage capacity E_{serv}:

$$E_{\text{serv}} = E_{\max} - E_{\min}. \tag{2.33}$$

The storage utilization is characterized by four different values (figure 2.7):

1. energy charged to the storage, $\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t$.
2. energy released by the storage device, $\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t$,
3. energy, $\sum_{t=1}^{T_{\text{end}}} M_{\text{char}}(t) \cdot \Delta t$, the system has to supply to charge the storage with $\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t$,
4. energy, $\sum_{t=1}^{T_{\text{end}}} M_{\text{dis}}(t) \cdot \Delta t$, the system effectively uses when discharging the storage with $\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t$.

These values are related by the following formulae:

$$M_{\text{char}}(t) \cdot \eta_{\text{char}} = \dot{E}_{\text{char}}(t) \tag{2.34}$$

$$\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t - \sum_{t=1}^{T_{\text{end}}} V_{\text{Stby}}(t) \cdot \Delta t = \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t \tag{2.35}$$

$$\eta_{\text{dis}} \cdot \dot{E}_{\text{dis}}(t) = M_{\text{dis}}(t) \tag{2.36}$$

The difference between M_{char} and M_{dis} are the losses of the storage device. Assuming small standby losses V_{Stby}, (2.35) simplifies to

$$\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t \approx \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t, \tag{2.37}$$

and (2.34) and (2.36) can be combined to

$$\begin{aligned} \sum_{t=1}^{T_{\text{end}}} M_{\text{char}}(t) \cdot \Delta t \cdot \eta_{\text{char}} &= \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t \approx \\ &\approx \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t = \sum_{t=1}^{T_{\text{end}}} \frac{M_{\text{dis}}(t) \cdot \Delta t}{\eta_{\text{dis}}}. \end{aligned} \tag{2.38}$$

The utilization of the energy storage can thus be characterized by the amount of energy charged to or discharged from the device,

$$U_{\text{stor}} = \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t \approx \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t, \tag{2.39}$$

or by the amount of stored energy used by the system,

$$U_{\text{sys,stor}} = \sum_{t=1}^{T_{\text{end}}} M_{\text{dis}}(t) \cdot \Delta t. \tag{2.40}$$

Optimization of the Energy Hub

With the presented hub model, the operation of the available devices can be determined to be optimal with respect to a given objective function $\mathcal{F}$. The optimization is carried out for a number of T_{end} time steps and takes into account the technical constraints of the system:

$$\min \mathcal{F} = \sum_{t=1}^{T_{\text{end}}} \mathcal{F}^{(t)} \Big(P(t), T(t), \dot{E}(t), \nu(t) \Big) \tag{2.41a}$$

s.t.

$$L(t) + T(t) - C \cdot (P(t) + R(t)) - S \cdot \dot{E}(t) = 0 \qquad \forall t \tag{2.41b}$$

$$P_{\min} \leq P(t) \leq P_{\max} \qquad \forall t \tag{2.41c}$$

$$0 \leq \nu_{\alpha k}(t) \leq 1 \qquad \forall t \tag{2.41d}$$

$$\sum_{k=\alpha}^{\omega} \nu_{\alpha k}(t) = 1 \qquad \forall t \tag{2.41e}$$

$$T_{\min} \leq T(t) \leq T_{\max} \qquad \forall t \tag{2.41f}$$

$$E_{\min} \leq E(t) \leq E_{\max} \qquad \forall t \tag{2.41g}$$

$$0 \leq \dot{E}_{\text{char,min}} \leq \dot{E}_{\text{char}}(t) \leq \dot{E}_{\text{char,max}} \qquad \forall t \tag{2.41h}$$

$$\dot{E}_{\text{dis,min}} \leq \dot{E}_{\text{dis}}(t) \leq \dot{E}_{\text{dis,max}} \leq 0 \qquad \forall t \tag{2.41i}$$

(2.41j)

The result of (2.41) are the optimal values for the input vector, P^*, the grid feed, T^*, the storage charge and discharge power, $\dot{E}^*$, and the dispatch factors, ν^*, for each time step $t \in [1, T_{\text{end}}]$.

2.2 Research Overview

The application of demand response, demand-side management and energy storage is widely treated within literature. This section presents the main work related to the problem statement introduced in chapter 1.

2.2.1 Cost-Driven Use of Demand Response

Residential customers are mainly motivated financially to carry out demand response actions. The aim is to reduce the energy bill due to less consumption in high-tariff times and increased demand in off-peak periods. Reference [24] examines how the customers' willingness to save costs can be used to reduce the peak power demand a utility has to supply. Four different pricing schemes are evaluated, one with a constant energy price, and the others with on- and off-peak tariffs. Also, summer and winter prices are considered. The investigation showed that the on-peak load of the grid can be reduced to about the half. The benefit for the customer is a monthly reduction of the energy bill of around 10 % to 45 %.

The effects of critical-peak pricing (CPP) were analyzed in an experiment conducted in a U.S. city [25]. On some days during a three months testing period, customers were asked to reduce their electricity consumption during several peak hours to save energy costs. During CPP days, customers were rewarded for each kWh they did not consume compared to their typical consumption. The compensation was about 3 to 5 times the electricity costs. Compared to the control group, the CPP customers consumed about 12 % less electricity during peak hours, while the mean electricity demand stayed about the same.

The impacts of demand response from a private household's perspective are examined in [26]. Three different pricing schemes are available:

1. constant electricity price,
2. day-ahead market prices of the Dutch Amsterdam Power Exchange,
3. and real-time pricing based on national load data and marginal costs of Dutch generation facilities.

The considered household has a yearly electricity consumption of 3400 kWh, and a heat demand of 12500 kWh. It is equipped with a fuel cell micro CHP and a thermal energy storage. The energy storage is used to buffer the heat generation of the CHP, while electric load is shifted from high- to low-tariff times. A model-predictive control strategy manages the devices and the load shift. As a result of the demand response application, the energy costs of the household can be decreased by 1 % to 14 % compared to standard heat-led operation. The largest savings are possible for pricing scheme 2 due to its large price variations. However, the authors conclude that the achievable savings are no strong incentives for residential customers to apply demand response with their micro CHP because of the low magnitude of potential savings.

In [27], a photovoltaic plant (4 kW), a grid connection (6 kW) and an electricity storage (15 kWh) cooperate to best exploit the renewable energy and to minimize energy costs of a single residential house of about 105 m^2. Load scheduling is possible, but no curtailment is allowed. Two different control mechanisms are applied. First, the optimal control strategy is anticipated based on load and generation predictions. Then, reactive management recalculates the operation plan according to the real values which might deviate from the forecasts due to unpredicted events. In the examined scenario, the combination of PV plant, demand response and grid supply reduces the costs to around 38 % compared to the case with only grid electricity consumption.

The thermal inertia of domestic water heaters can also be used to enforce demand response. In [28], a thermal storage device is used to decouple warm water consumption from heating up the water. The objective is to minimize energy costs while keeping the technical constraints of the system. The storage devices are either controlled centrally from the utility or decentralized at the customer's. The utility can buy its electricity demand in two pricing schemes:

1. high and standard tariff times (time of use tariff),
2. billing of the highest demand of each month (demand and energy charge tariff).

The customer either pays a constant price for the electricity received from the utility, or prices vary between off and on-peak period and standard prices (off-peak: 65.1 % of standard price, on-peak: 279.8 %). The authors conclude that the variable prices allow savings around 2.5 - 3 times higher than for constant prices. Additionally, the household's energy bill is reduced most if heaters are controlled locally (26 % energy costs compared to the base case). For centralized control it is important that the utility is charged with the time of use tariff instead of the demand and energy charge tariff to save more costs (34 % of base case energy costs compared to 36 %, respectively).

2.2.2 Theoretical Potential and Practical Application of Demand Response

The sum of demand response activities carried out by individual households impacts on the load demand of a utility. Reference [9] examines the potential of private, commercial and industrial customers. A major result is that a full participation in the demand-side management program could lower the peak demand by up to 20 %.

Although the estimated potential of demand response is quite high with 20 % of peak load reduction, the acceptance of load shift and its application at the customers' is still low. This can be concluded from the results of a case study concerning the demand response behavior of single-family homes [29]. The study, carried out in a U.S.-American municipality, had two aims:

1. to increase demand response participation by means of real-time consumption feedback and enhanced information of the customer
2. to better understand the effects of time-of-use energy prices on the customers' behavior.

The time-of-use energy rates included seasonal, weekly and diurnal changes of the electricity price. They were designed to enforce load shifting to off-peak hours and to reward low overall consumption. Customers were provided with different information material. One part was informed by mail, the other part was equipped with a real-time electricity-use feedback monitor. Also, a randomly selected set of participants from both groups was additionally informed in detail via letter and provided with a graphical presentation of the electricity tariffs. The behavior of the demand response participants was compared to the behavior of a control group in which the regular power supply contract was valid. The study found that only two statistically significant behavioral changes occurred due to the transition from fixed to time-of-use energy prices:

1. During off-peak weekday late evenings (10pm - 7am), the consumption decreased by about 3 %.
2. During off-peak weekend mornings (7am to 12am) the demand slightly increased by around 3 %.

The behavior during the rest of the time was not changed in a statistically significant manner. The information available to the customers only had a small influence on the consumption behavior. The study clearly showed that although price incentives are offered by the utilities, the observable changes in customers' consumption behavior are small with only 3 % load increase or decrease.

2.2.3 Cost-Driven Use of Energy Storage

By analogy to demand response, energy storage is applied for arbitrage, i.e. the exploitation of price differences. In [30], an electric thermal storage is used to shift electricity consumption from higher to lower price periods. The effect of the storage size on the utility's cost of service is examined for time-of-use rates and real-time pricing. The results show that the costs can be reduced with increasing storage size if real time pricing applies. For the time-of-use tariff nearly no influence of the storage size could be observed.

The financial attractiveness of energy storage in a private household is examined in [31]. The household has an electricity demand of 4000 kWh/a which is supplied by the grid and either a 4.5 kW PV system, a 1 kW_{el} Stirling engine or a 15 kW_{el} fuel cell CHP. The electricity price varies according to the day-ahead market of the Amsterdam Power Exchange. The objective of the household is to minimize energy costs by load shifting or a reduction of feed-in of own generated electricity. The energy storage can be applied for both possibilities. The analysis of the two cases shows that storage is best applied for a reduction of grid feed. Here, the savings on the yearly electricity bill are around two to three times higher than for load shift.

Reference [32] investigates the impacts of electricity and hot water storage devices on the yearly energy costs of a household. A number of households is considered, whereof 10 % are equipped with a 15 kWh battery storage, and 7.5 % use a 18.5 kWh electrically heated hot water tank. The electricity price is modeled according to U.K. wholesale price behavior. The simulations show that the electricity storage can save up to £105 per year, resulting in a payback period of around 8 - 10 years when assuming investment costs of £100 per kWh. This is economically not viable as the devices have to be replaced after some years. The situation is different for thermal storage. The hot water tank accounts for £183 of cost savings compared to £785 of energy costs without the thermal storage. With initial costs of £1000 and a life time significantly larger than 6 years, thermal storage is well suited for domestic applications.

In [33], a control algorithm is presented to minimize the electricity and heat costs of domestic appliances of a single household. The household consumes 12.5 kWh_{el} and 42 kWh_{th} per day. The load is supplied by a micro CHP, a heat buffer (10 kWh) and a battery (1 kWh). The controller does not take into account predictions of future load and generation, and no smart appliances (demand response) are available. The simulations show that the controller is able to supply the system without energy shortage or surplus. The amount of possible cost savings resulting from the controller use is not quantified.

2.2.4 Intermittent Renewable Generation and Energy Storage

Energy storage can be used to match intermittent renewable generation to load demand. In [34], a hydrogen energy storage is combined with a wind turbine to supply a University's energy demand of around 27 GWh/a. Both devices are selected such that the electricity demand can be supplied entirely with local resources. The optimum capacity is determined by the wind generation and the load curve. In the considered case, a hydrogen storage of 2000 m^3 capacity is required in combination with a 48.4 m radius wind turbine.

A battery energy storage device, a gas turbine and a wind energy plant are combined in [35] to provide baseload power. A significant share of that power has to be generated by wind, while still keeping the costs reasonable. The battery size is determined as the minimum capacity that allows for a constant power output of the system. A scenario analysis shows that the system can provide power with a 30 % wind share and a deviation from the required output power of less than 0.5 %.

Energy storage can also be used to bridge seasonal gaps in generation and consumption. In [36], a phase change material heat storage is used to provide summer solar energy during winter time. A solar collector of 40 m^2 was coupled with a storage tank of 456 m^3 to supply space heating for a 325 m^2 Chinese villa building. The simulations indicated that the gained solar heat is able to provide space heating throughout the year using the phase change material storage device. The storage losses accounted for 17 % of the total collected energy.

2.2.5 Cooperation of Consumers

In [37], a concept to analyze the socio-technical complexity and characteristics of an energy infrastructure with various participants and a high penetration of decentralized generation is presented. Several heat and electricity consuming households are aggregated to clusters. Each cluster is assigned with an energy supplier and a network manager. The behavior of the cluster is defined by the sum of the individual household actions. The households in each cluster, the clusters and the other grid participants exchange energy and/or control information. Different options to operate the distributed generation devices such as minimum costs or minimum emissions can be examined with the proposed hierarchical system structure. However, an analysis of the system behavior and the interaction of the players is not presented.

The conflicting objectives of energy suppliers and households are subject of [38]. The households decide about the amounts of bought and produced energy by determining the power level of their micro-CHP and the amount of heat to be blown off. The supplier influences the behavior of his costumers by adjusting the prices for grid electricity and the compensation for renewable energy fed into the grid. The customers are provided with information about prices and reimbursement, and the utility knows the technology characteristics and energy use data of households and market. Each actor tries to maximize its profit while depending on the decisions of the other actors. The solution of the multi-level decision problem defines the prices and compensation payments optimal from the perspective of the utility.

A multi-level control algorithm for household appliances and their implications on the electricity grid is presented in [39]. The aim of the control algorithm is to adapt residential load consumption of a group of houses to real-time energy price variations while simultaneously keeping the energy consumption limits imposed by the residents. The *home automation layer* is responsible for allocating electricity based on predictions of load and available resources. The underlying *device layer* manages the residential appliances such as an oven or the air conditioning. The *load management layer* controls a set of houses by means of the information of the home automation layer. A detailed analysis of the control scheme and the interaction of the players is not given, but the proposed control algorithm allows private households to participate in demand-side management systems. Concrete case studies or examples are not presented.

2.2.6 Summary of the Research Overview

The literature review showed that energy storage and demand response are investigated in various applications and with different objectives. Their utilization in the residential environment is also subject to research.

However, the case study [29] showed that demand response is not widely accepted by private households. To increase the motivation for participation, the customers' benefits of demand response have to be examined carefully. This has not yet been done sufficiently.

Energy storage is already applied to increase the exploitation of renewable generation, but its employment in private households and the resulting benefits for the inhabitants have not yet been studied. Also, no publications about the advantages and limits of a combination of demand response and energy storage and the influences of their respective parameters could be found.

The cooperation of a group of houses has been subject of few studies. Methodologies to coordinate the various actors have been presented, but no analysis of potential benefits of the joint action has been carried out. Also, the interaction of energy storage, demand response and the households' cooperation has not yet been studied extensively.

Chapter 3

Research Goal

The literature review of the previous chapter clearly showed that the combination and coordination of demand response and energy storage in the residential sector has not yet been sufficiently studied. Although clusters of residential customers have been a research subject, no investigation about benefits or drawbacks of the cooperation could be found.

3.1 Research Questions

The aim of this thesis is to contribute to the research topics introduced in chapter 1. According to the literature review (chapter 2), the following questions remain open:

1. When applied individually, how do demand response and energy storage in households influence the energy supply strategy and consequently the objective function value?
2. Does the combination of both achieve additional benefits?
3. Which parameters are decisive for the operation and cost reduction potential of demand response and energy storage?
4. How do renewable generation and energy prices influence the utilization of demand response and energy storage?
5. Can a combined effort of several private households increase the individual and overall welfare?

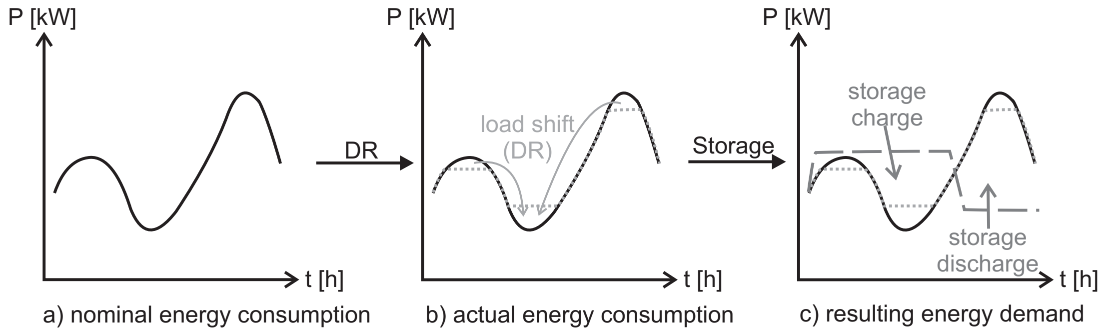


Figure 3.1: Influence of demand response and storage on load and demand curves: demand response alters the nominal energy consumption profile (a) of the customers, while energy storage influences the actual energy consumption profile (b); the resulting curve is the customer's energy demand (c).

The study at hand is motivated by examining these questions for residential customers. The central point is to analyze the expedient and optimal utilization of demand response and energy storage and to assess the impacts of parameter changes.

3.2 Locations of Influence of Demand Response and Energy Storage

In literature, energy storage is widely treated as one means to enforce demand response (DR). However, demand response in compliance with its definition stated in section 2.1 and [4] alters the consumption profile of the household, while an energy storage device changes the energy demand profile that has to be supplied internally or externally (fig. 3.1).

Three profiles have to be distinguished within the house:

1. *Nominal energy consumption*: basic energy requirements of the household; initial energy consumption profile before demand response options.

2. *Actual energy consumption*: consumption of all appliances running in parallel at each instant of time after application of demand response options.

3. *Resulting energy demand*: energy demand that has to be supplied externally or by locally available resources, including charge and discharge of the storage device.

The people living within the house have a certain *nominal energy consumption* profile. For example, they are used to doing the laundry in the evenings or during the weekends and they prefer a distinct room temperature. The nominal consumption curve can be altered to the *actual energy consumption* curve by changing the consumption patterns due to demand response incentives. For example, laundry can be shifted to off-peak periods. The *resulting energy demand* to be satisfied by locally available resources or an external supplier can differ from the actual consumption when a storage device is available. The device is charged and discharged according to the objectives of the household, the available local energy sources and the actual energy consumption, and consequently changes the consumption profile to the resulting energy demand curve.

3.3 Methodology to Assess the Research Questions

The energy demand of the inhabitants has to be supplied by a number of conversion and storage technologies. Also, demand response can be applied. The electricity and heat demand curves of the house are defined by the mean power $L(t)$ required for the time interval of $\Delta t = 1\,\text{h}$. Both power and energy demand have to be met by the supply technologies.

The application of demand response and the operation of a storage device depend on the general conditions valid for the household, such as the electric and thermal load profiles, the pricing and refunding schemes, and the available amount of renewable energy. Also, the objective of the energy supply strategy, e.g. minimum operation costs or minimum emissions, effect the solution. However, the principle of the utilization scheme is always the same: Storage and demand response allow to alter the consumption and demand profiles according to incentives and the frame conditions to minimize the objective function. Both locally available renewable resources and changes in the frame conditions (e.g. price variations) can be exploited. To assess the research questions presented in section 3.1, the effects of system changes on the objective function have to be estimated, i.e. the impacts of

- the introduction of demand response and the increase of demand response flexibility,
- the installation of a storage device and a variation of its characteristics,
- different price structures,
- the amount of locally available renewable generation.

In the system, however, there are several interdependencies (fig. 3.2):

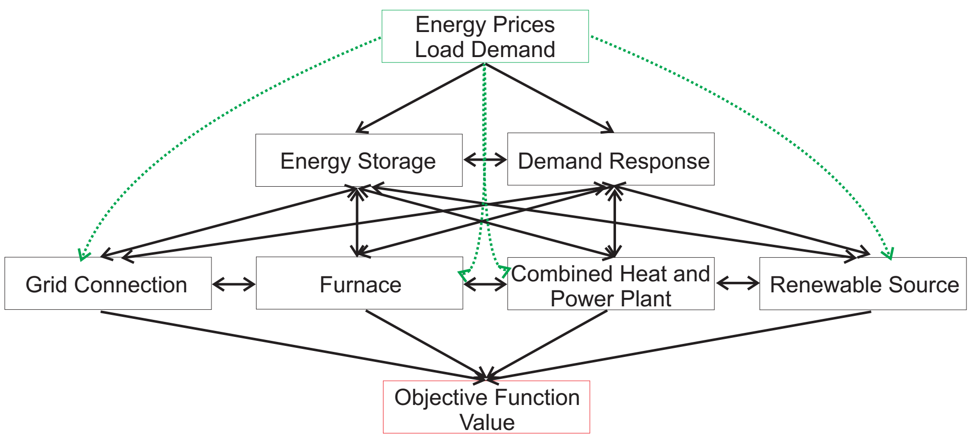


Figure 3.2: Interdependencies in the energy supply system of a household (example): load demand and energy prices influence the application of energy storage, demand response and the conversion technologies; the devices all have to cooperate to minimize the objective function value, resulting in dependencies among each other and also in time via energy storage and demand response.

- The utilization of the different technologies is coupled via the load demand and the price constellation.

- DR and energy storage couple the time steps and influence the operation of the technologies.

- The available energy sources have to cooperate to best supply the load demand. Additionally, they interact with DR and energy storage.

- The CHP couples electric and thermal load.

- Renewable energy sources and price variations compete for storage utilization and load shifting.

The objective function value is the result of the coordination and synergy of all devices. The impact of a change of a single parameter cannot be easily estimated due to the interrelations shown in figure 3.2. For example, without demand response and energy storage, the effect of the introduction of a renewable energy source can be easily estimated by subtracting the renewable generation curve from load demand. The remaining load curve has to be supplied, and the difference between the objective function without and with renewable source is the impact of the change. Contrarily, for example with a storage device, load is not simply reduced by the renewable source, but the energy can be stored according to aspects such as price conditions and the optimal operation policy of the technologies. Consequently, the charge/discharge curve of the storage device cannot be analytically approximated with appropriate effort. But the multiplication of this curve with the price curve, for example, is necessary to assess the impact on the objective function. Thus, the effects of demand response and energy storage and changes of the system parameters are evaluated using numerical simulations.

In this thesis, the model of a single-family house is coupled with a model for multi-energy load supply, including demand response and storage. The objective function is exerted to the system, and changes in the value of the function resulting from changes in the system are assessed.

3.4 Thesis Outline

The thesis is divided into three parts:

1. Presentation of the applied models and the examined scenarios.
2. Evaluation of the simulation results.
3. Discussion of the results and conclusions.

Chapter 4 combines the model of a single-family house and the energy hub concept extended with demand response to determine the optimal energy supply for one single-family house. Also, a model for a group of houses and its respective supply strategy is presented. Chapter 4 introduces the scenarios studied within this thesis, too.

The results of the sensitivity analysis are described and explained in chapter 5, separated into the results of the parameter studies (sections 5.1 and 5.2) and the results for a cooperation of customers (section 5.3).

These results are finally discussed and related in chapter 6. The key results of the thesis are stated in chapter 7 and conclusions are derived in chapter 8.

Chapter 4

Modeling and Examined Cases

Chapter 3 presented the research aims of this thesis. In chapter 2, the behavior of a building as well as the energy hub concept to model multi-energy supply systems have been described. Here, these models are adapted and extended to application within this thesis. Also, a multiple-level model to examine the grouping of houses is presented. Furthermore, the chapter introduces the examined scenarios.

4.1 Modeling of the Single-Family House

The research questions (section 3.1) will be examined for a single-family house once located in moderate climate and once in hot climate in order to assess the different influences of heating and cooling demand. In the first case, space heating is required, but no air conditioning is considered. In the latter case it is vice versa. Switzerland is selected to represent the moderate climate due to its central location in Middle Europe. A single-family house located in the south of Spain is examined as an opposite example to the Swiss case, as the ambient conditions are completely different [40].

The heat exchange with the environment and the resulting furnace or cooling power $\dot{Q}_{\mathrm{fur/cool}}$ of the cube are determined using (2.1) - (2.10). Waste heat of electric appliances is not considered.

4.1.1 Parameters of the Single-Family House

The building itself and the number of residents are the same in both countries to keep comparability as high as possible. The values are selected according to Swiss statistics and data sheets relevant for Swiss buildings. They are listed in table 4.1. The global irradiance, the ambient temperature profile and the generation curves of the photovoltaic plants are adapted from measurement data available for Switzerland and southern Spain.

Switzerland is appropriate for the analysis of residential energy supply using single-family houses, as the majority of inhabited buildings in Switzerland are single-family houses (54.9 % in 2000) [41]. Apartment buildings account for 17.0 %, and only 9.2 % are semidetached houses. 18.8 % of inhabited buildings are of other kind. In 2000, 36 % of all private households were single-person households, followed by 32 % two-person households [42]. Households with three or four persons account for approximately 13 % each. Only 6 % comprise five (or more) residents. In rural areas, single-person households are more common (38 %) than in urban areas (28 %) [43].

In 2000, an average of 2.3 persons lived together in one flat [44]. However, there were differences in the occupancy of accommodations of different sizes. In flats smaller than $30\,m^2$ lived an average of only 1.2 persons lived, while on more than $160\,m^2$ generally lived 3.1 persons together. In flats with footpoints in between, the average of residents increases approximately in linear proportions.

In 2000, 5.2 % of the first residential habitations were one-room and 12.8 % two-room flats [41]. The majority were four-room habitations (28.1 %), whereas three-room habitations were very rare (2.2 %). About 27 % of the first residential habitations had more than five rooms.

The living space of only 4.5 % of all first residential habitations in 2000 was smaller than $39\,m^2$ [41]. In contrast, more than double (11.2 %) were larger than $160\,m^2$. The average living space per person varies between $22\,m^2$ and $68\,m^2$, depending on the number of persons living in the same household. The Swiss average is $39\,m^2$ p.P.

Table 4.1: Parameters of the building

Parameter	Acronym	Unit	Value
Number of residents			3
Living area per person		m^2	44
Width	w	m	6
Length	l	m	8.8
Height	h	m	6.4
Inner wall thickness	d_{in}	m	0.256
Inner wall density	ρ_{in}	$\frac{\text{kg}}{m^3}$	900
Heat capacity inner walls	c_{in}	$\frac{\text{Wh}}{\text{kg}\cdot K}$	0.278
Heat capacity air	c_{air}	$\frac{\text{Wh}}{\text{kg}\cdot K}$	0.278
Heat transfer coefficient walls	U_{wall}	$\frac{\text{W}}{m^2\cdot K}$	0.4
Effective heat capacity	C_{eff}	$\frac{\text{Wh}}{m^2\cdot K}$	18.07
Window area	A_{window}	m^2	20
Heat transfer coefficient windows	U_{window}	$\frac{\text{W}}{m^2\cdot K}$	0.8
Air exchange	n_{air}	h	5
Conversion factor	α		0.36
Energy transmission value	g		0.57
Cold water temperature	ϑ_{cold}	$°C$	30
Hot water temperature	ϑ_{hot}	$°C$	50
Efficiency space heating	η_{heat}		0.95
Efficiency warm water	η_{ww}		0.95
Nominal inner temperature	ϑ_{nom}	$°C$	21
Temperature bandwidth	$\Delta\vartheta_{\text{nom}}$	$°C$	0

4.1.2 Extension of the Energy Hub Model with Demand Response

The conversion and storage technologies of the house are modeled with the energy hub concept (section 2.1.3). However, demand response has to be included for the application of the hub within this thesis.

Demand response changes the nominal energy consumption curves $L^{(\mathrm{nom})}$ to the actual consumption $L^{(\mathrm{act})}$ (fig. 3.1). In doing so, load can be shifted forward and backward in time. At time instant t_1, the load $L^{(\mathrm{nom})}(t_1)$ is decreased by the power $H(t_1) > 0$, which is shifted to the time instant t_2:

$$L^{(\mathrm{act})}(t_1) = L^{(\mathrm{nom})}(t_1) - H(t_1) \quad (4.1)$$

$$L^{(\mathrm{act})}(t_2) = L^{(\mathrm{nom})}(t_2) + H(t_1). \quad (4.2)$$

Time instant t_2 can be either before or after t_1:

$$t_2 = t_1 \pm T_{\mathrm{DR}}, \quad T_{\mathrm{DR}} \neq 0. \quad (4.3)$$

The boundaries $H_{\max}$ and $H_{\min}$ of power that may be added or subtracted at each instant of time are not fixed by technological constraints, but can be defined by the residents:

$$H_{\min} \leq H(t) \leq H_{\max}, \quad \forall t. \quad (4.4)$$

The load demand of the house must be supplied at some instant of time, as no energy saving activities are examined. Consequently,

$$\sum_{t=0}^{T_{\mathrm{end}}} H(t) \cdot \Delta t = 0. \quad (4.5)$$

Additionally, the residents can define a maximum amount of energy, J, that may be shifted within the time interval ΔT:

$$-J \leq \sum_{t_{\mathrm{i}}}^{t_{\mathrm{i}}+\Delta T} H(t) \cdot \Delta t \leq J \quad \forall t_i \in [1, T_{\mathrm{end}}]. \quad (4.6)$$

The demand response matrix D with

$$D = \begin{bmatrix} d_{\alpha\alpha} & & \underset{\sim}{0} \\ & \ddots & \\ \underset{\sim}{0} & & d_{\omega\omega} \end{bmatrix}$$

states whether load L_α may be shifted or not:

$$d_{\alpha\alpha} = \begin{cases} 1, & \text{load } L_\alpha \text{ adjustable,} \\ 0, & \text{load } L_\alpha \text{ fixed.} \end{cases} \tag{4.7}$$

Demand response can be added to the hub equation(2.26) using the matrix D and the vector of shifted load, H:

$$L - D \cdot H + T = C \cdot (P + R) - S \cdot \dot{E}. \tag{4.8}$$

In the study at hand, only electric demand response is possible. The utilization of the demand response, U_{DR}, by the residents of the house is defined as the sum of electricity that is subtracted from the load at one instant of time and added at another:

$$U_{\mathrm{DR}} = \sum_{t=1}^{T_{\mathrm{end}}} H_{+}^{(\mathrm{el})}(t), \text{ with } \begin{cases} H_{+}^{(\mathrm{el})}(t) = H^{(\mathrm{el})}(t), & H^{(\mathrm{el})}(t) > 0 \\ H_{+}^{(\mathrm{el})}(t) = 0, & H^{(\mathrm{el})}(t) < 0. \end{cases} \tag{4.9}$$

The presented demand response model does not allow to consider the shift of distinct appliances (e.g. a washing machine), but it is appropriate and adequate to examine the demand response flexibility in the residential sector and its impact on the energy supply strategy.

4.1.3 Conversion and Storage Technologies of the Houses in Moderate and Hot Climate

The load demand of the single-family houses in Switzerland and Spain is supplied by a number of conversion and storage technologies aggregated in an energy hub. In moderate climate (Switzerland), electricity, warm water and space heating are required, whereas in hot climate (Spain) cooling is demanded together with electricity and warm water. The conversion technologies are selected accordingly and will be introduced in the following paragraphs.

Demand response (section 4.1.2) and energy storage can be applied in addition to the conversion technologies to optimally supply the demand. The storage devices considered within this study will be presented in the last part of this section.

In 2000, a central heating for one or more buildings was the most common type of heating in Swiss habitations, with 69 % and 19 %, respectively [41]. Stand-alone furnaces (6 %), self-contained central heating (3 %) and public district heating (3 %) were not widely used.

Oil (63.4 %) and gas (18.6 %) were the most common fuels for space heating in 2006 (fig. 4.1), followed by wood (9.0 %) [41, 45]. Other energy carriers are of minor importance. In warm water supply, oil (47.9 % in 2006) and gas (17.0 %) are also dominant, but electricity is also significant with 26.5 % [45].

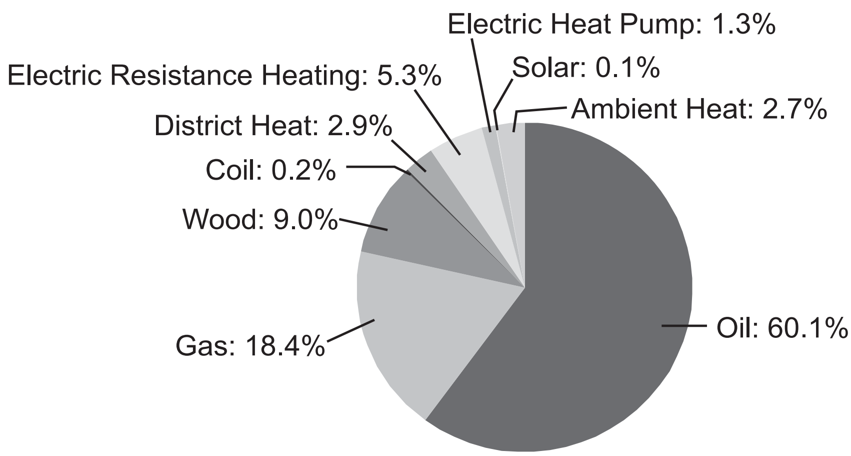


Figure 4.1: Shares of energy carriers at heat energy consumption in private accommodations in 2006 [45]

Consequently, in the Swiss house heat and electricity demand are supplied by a grid connection, a gas furnace, and a gas-fueled CHP. Oil is not considered despite its significant share in heat supply (60.1 %), as its use is assumed to decrease in coming years for ecologic reasons. The CHP has been chosen although this technology is currently not widely used, but its utilization is considered to increase in coming years. Also, it couples electric and thermal load and allows the exploitation of synergy effects. In hot climate, cooling is required instead of space heating. Thus, the CHP is replaced by an electrically driven air conditioning. The other technologies are the same as for the Swiss house. The parameters of the technologies are stated in table 4.2.

Table 4.2: Parameters of the conversion technologies for the Swiss and Spanish single-family houses.

Parameter	Acronym	Unit	Value
Grid connection			
minimum input power	$P_{\mathrm{min}}^{\mathrm{grid}}$	kW	0
maximum input power	$P_{\mathrm{max}}^{\mathrm{grid}}$	kW	30
efficiency	$\eta_{\mathrm{el,el}}^{\mathrm{grid}}$		1
Furnace			
minimum input power	$P_{\mathrm{min}}^{\mathrm{fur}}$	kW	0
maximum input power	$P_{\mathrm{max}}^{\mathrm{fur}}$	kW	36
efficiency	$\eta_{\mathrm{gas,th}}^{\mathrm{fur}}$		1
CHP			
minimum input power	$P_{\mathrm{min}}^{\mathrm{CHP}}$	kW	0
maximum input power	$P_{\mathrm{max}}^{\mathrm{CHP}}$	kW	12
electric efficiency	$\eta_{\mathrm{gas,el}}^{\mathrm{CHP}}$		0.25
thermal efficiency	$\eta_{\mathrm{gas,th}}^{\mathrm{CHP}}$		0.65
Air conditioning			
minimum input power	$P_{\mathrm{min}}^{\mathrm{ac}}$	kW	0
maximum input power	$P_{\mathrm{max}}^{\mathrm{ac}}$	kW	1.5
coefficient of performance	$\mathrm{COP}_{\mathrm{el,cool}}^{\mathrm{ac}}$		2.6

Two different storage devices are examined:

1. an electrically heated domestic hot water tank that is charged with electricity heats up water and discharges heat,

2. an electric storage device, e.g. a battery, that is charged and discharged electrically.

The storage parameters as introduced in section 2.1.2 are given in table 4.3. The application of these two devices allows the study of the impacts of demand response, energy storage and renewable resources on both electric and thermal load demand and supply.

Table 4.3: Parameters of the thermal hot water tank and the electric storage device considered in the analysis.

		Thermal	Electric
Parameter	Unit	Value	Value
E_{min}	kWh	2	1
E_{max}	kWh	10	5
$\dot{E}_{\text{char,min}}$	kW	0	0
$\dot{E}_{\text{char,max}}$	kW	6	0.8
$\dot{E}_{\text{dis,min}}$	kW	-6	-0.5
$\dot{E}_{\text{dis,max}}$	kW	0	0
η_{cycle}		0.98	0.81
V_{Stby}	%/h	4e-3	4e-3

4.1.4 Load Demand Curves of the Houses

The residents of the single-family house have an electric and a thermal load demand to be supplied. Electricity consumption within the house mainly consists of cooking, washing and drying, cooling and freezing, lighting, and other electric devices [45]. Data about the total electricity consumption of an average household vary quite significantly. Reference [46] states a consumption between 1100 kWh/a and 7300 kWh/a according to the electrification level (e.g. electric heating) and the number of residents. An average household needs around 6500 kWh/a according to [47], while a modern household only consumes 2200 kWh/a. The electricity demand of a passive house is in about the same range (3000 kWh/a) [48].

In the study at hand, electric heating is not considered, consequently the yearly electricity consumption (without cooling) of the three residents amounts to 4500 kWh/a. The electricity consumption of the house is modeled using a standardized load profile [49] (fig. 4.2).

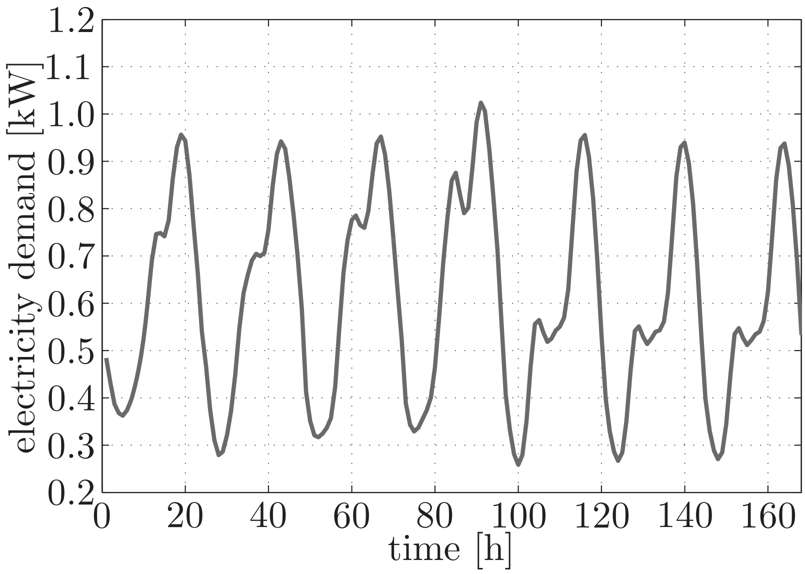


Figure 4.2: Electricity demand of the single-family house (example: first week in January).

The people living in the house also consume warm water. The warm water use only covers service water and no water necessary for space heating. The warm water demand is given as a fixed curve of needed hot water per time interval, $\frac{m}{\Delta t}$ (fig. 4.3). It is assumed that the required water temperature is constant at ϑ_{hot}. The water can either be heated instantaneously when needed, e.g. with a flow heater, or hot water from a heat storage can be used. The resulting furnace power is defined by (2.11).

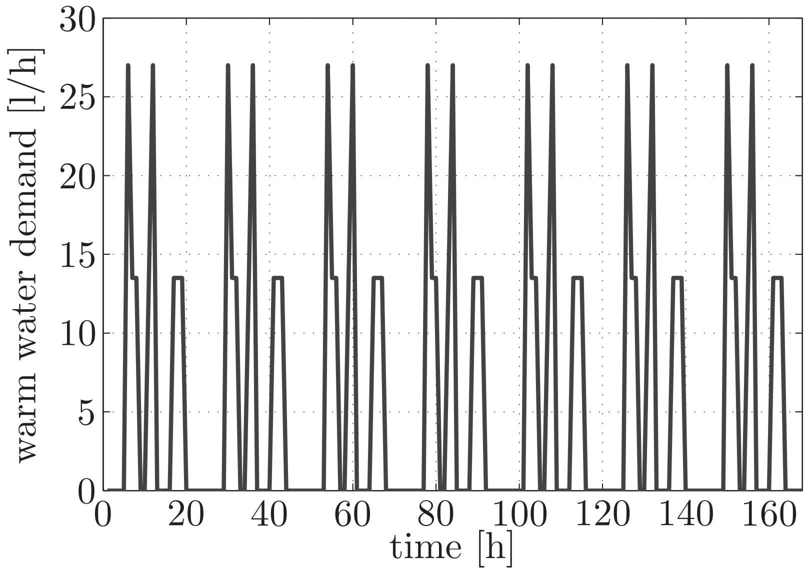


Figure 4.3: Warm water demand of the single-family house (example: first week in January).

Both in Switzerland and in Spain warm water has to be provided by the furnace requiring the power $\dot{Q}_{\text{fur}}^{\text{ww}}$ (2.12). In Switzerland, the space heating demand $\dot{Q}_{\text{fur}}^{\text{sh}}$ (2.7) also has to be supplied by the furnace. Consequently, the Swiss thermal load demand $L_{\text{th}}^{(\text{CH})}$ is defined as:

$$L_{\text{th}}^{(\text{CH})} = \dot{Q}_{\text{fur}}^{\text{ww}} + \dot{Q}_{\text{fur}}^{\text{sh}}, \tag{4.10}$$

while the electricity demand is

$$L_{\text{el}}^{(\text{CH})} = L_{\text{el}}^{\text{el}}. \tag{4.11}$$

Contrary, the cooling demand $\dot{Q}_{\text{cool}}$ of the Spanish house increases the electric load demand, as an electric air conditioning is considered:

$$L_{\text{el}}^{(\text{E})} = L_{\text{el}}^{\text{el}} + \dot{Q}_{\text{cool}}, \tag{4.12}$$

and the thermal load demand only comprises warm water:

$$L_{\text{th}}^{(\text{E})} = \dot{Q}_{\text{fur}}^{\text{ww}}. \tag{4.13}$$

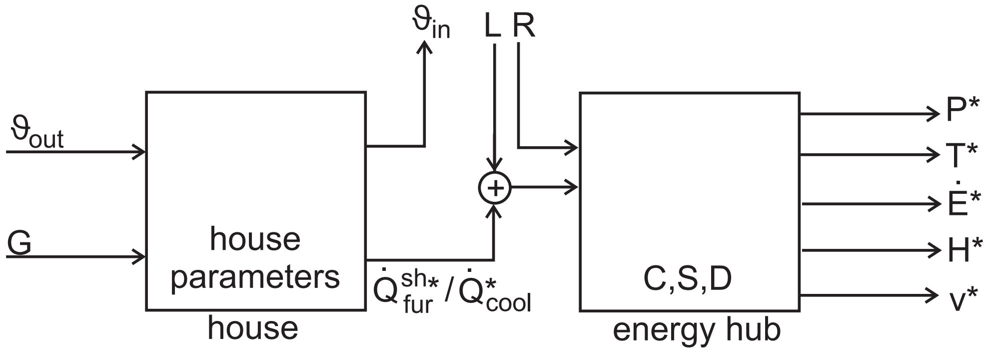


Figure 4.4: Flow chart of the single-family house optimization: The ambient parameters ϑ_{out} and G determine with the house parameters the inner temperature ϑ_{in} and the optimal space heating or cooling power, $\dot{Q}_{\text{fur}}^{\text{sh}*}$ or $\dot{Q}_{\text{cool}}^{*}$, respectively. Then, with the energy hub matrices and the load and renewable generation curves, the optimal input vector, P^*, grid feed, T^*, storage power, $\dot{E}^*$, demand response, H^*, and dispatch factors, ν^*, are defined.

4.1.5 Determination of the Optimal Energy Supply Strategy for the Single-Family House

The house model and the multi-energy hub are in the following combined to determine the optimal power supply strategy for the single-family house (fig. 4.4). The ambient temperature ϑ_{out} and the global irradiance G determine together with the house parameters (table 4.1) the inner temperature ϑ_{in} and the necessary heating or cooling demand, $\dot{Q}_{\text{fur}}^{\text{sh}}$ or $\dot{Q}_{\text{cool}}$, respectively. The resulting thermal and electric load demand is calculated according to (4.10) - (4.13).

The load curves L as well as the renewable generation R enter the energy hub. The optimal power supply strategy is then determined according to (2.41), but extended with demand response (section 4.1.2) and coupled with the constraints for space heating or cooling. Consequently, the optimization procedure for the single-family house results in (4.14a) - (4.14m).

$$\min \sum_{t=1}^{T_{\text{end}}} \mathcal{F}^{(t)} \left(P(t), T(t), \dot{E}(t), H(t), \left[\dot{Q}_{\text{fur}}^{\text{sh}}(t); \dot{Q}\text{cool}(t) \right], \nu(t) \right) \tag{4.14a}$$

$$\text{s.t.}$$

$$L(t) + T(t) - C \cdot (P(t) + R(t)) - S \cdot \dot{E}(t) - D \cdot H(t) = 0 \qquad \forall t \tag{4.14b}$$

$$P_{\min} \leq P(t) \leq P_{\max} \qquad \forall t \tag{4.14c}$$

$$0 \leq \nu_{\alpha k}(t) \leq 1 \qquad \forall t \tag{4.14d}$$

$$\sum_{k=\alpha}^{\omega} \nu_{\alpha k}(t) = 1 \qquad \forall t \tag{4.14e}$$

$$T_{\min} \leq T(t) \leq T_{\max} \qquad \forall t \tag{4.14f}$$

$$E_{\min} \leq E(t) \leq E_{\max} \qquad \forall t \tag{4.14g}$$

$$0 \leq \dot{E}_{\text{char},\min} \leq \dot{E}_{\text{char}}(t) \leq \dot{E}_{\text{char},\max} \qquad \forall t \tag{4.14h}$$

$$\dot{E}_{\text{dis},\min} \leq \dot{E}_{\text{dis}}(t) \leq \dot{E}_{\text{dis},\max} \leq 0 \qquad \forall t \tag{4.14i}$$

$$H_{\min} \leq H(t) \leq H_{\max} \qquad \forall t \tag{4.14j}$$

$$-J \leq \sum_{t_{\text{n}}}^{t_{\text{n}}+\Delta T} H(t) \cdot \Delta t \leq J \qquad \forall t \tag{4.14k}$$

$$\sum_{t=0}^{T_{\text{end}}} H(t) \cdot \Delta t = 0 \tag{4.14l}$$

$$\vartheta_{\text{nom}} - \Delta\vartheta_{\text{nom}} \leq \vartheta_{\text{in}}(t) \leq \vartheta_{\text{nom}} + \Delta\vartheta_{\text{nom}} \qquad \forall t. \tag{4.14m}$$

4.2 Modeling of a Group of Houses

The single-family house can also cooperate with its vicinity such as other single-family houses nearby to increase the common welfare. The group of houses is modeled with a multiple-level approach. The model itself, the scenarios examined within this thesis, and the optimization procedure for the group of houses are presented in the following sections.

4.2.1 Model Description

The multiple-level model (fig. 4.5) structures a number of actors according to their hierarchical level. Each actor is modeled as an energy hub $h_i \in \mathcal{H}$, $i = 1, ..., N_{\mathcal{H}}$, where $\mathcal{H}$ denotes the set of all hubs within the multiple-level model, and $N_{\mathcal{H}} := |\mathcal{H}|$ is the number of hubs. The subset $\mathcal{H}_{\text{house}} \subseteq \mathcal{H}$ contains all hubs that model a single-family house and are consequently coupled with a house model. The multiple-level model consists of $N_{\mathcal{L}}$ levels, and each level l_j, $j = 1, ..., N_{\mathcal{L}}$, contains the subset $\mathcal{H}_{l_j} \subseteq \mathcal{H}$ hubs, with

$$\bigcup_{j=1}^{N_{\mathcal{L}}} \mathcal{H}_{l_j} = \mathcal{H} \tag{4.15}$$

and $N_{l_j} := \left|\mathcal{H}_{l_j}\right|$. The set of subordinate hubs $h_i \in \mathcal{H}$, $i = 1, ..., N_{\mathcal{H}}$, is denoted $\mathcal{H}_{h_i}$, with

$$\mathcal{H}_{h_i} \subseteq \mathcal{H}; \tag{4.16}$$

$$h_k \in \mathcal{H}_{h_i} \quad \rightarrow \quad h_k \notin \mathcal{H}_{h_j}, \text{ if } i \neq j, \quad \forall k = 1, ..., N_{\mathcal{H}}. \tag{4.17}$$

For the hubs $h_i \in \mathcal{H}_{l_1}$ on the lowest level, the sets of subordinate hubs are empty:

$$\mathcal{H}_{h_i} = \emptyset. \tag{4.18}$$

Each hub $h_i \in \mathcal{H}$, $i = 1, ..., N_{\mathcal{H}}$ contains a number of conversion and storage technologies to supply its load. Additionally, hubs in the same set $\mathcal{H}_{h_j}$ can exchange energy if the infrastructure is available. Energy can also be supplied by the superimposed level l_{j+1}. Consequently, the actors and levels interact by exchanging energy.

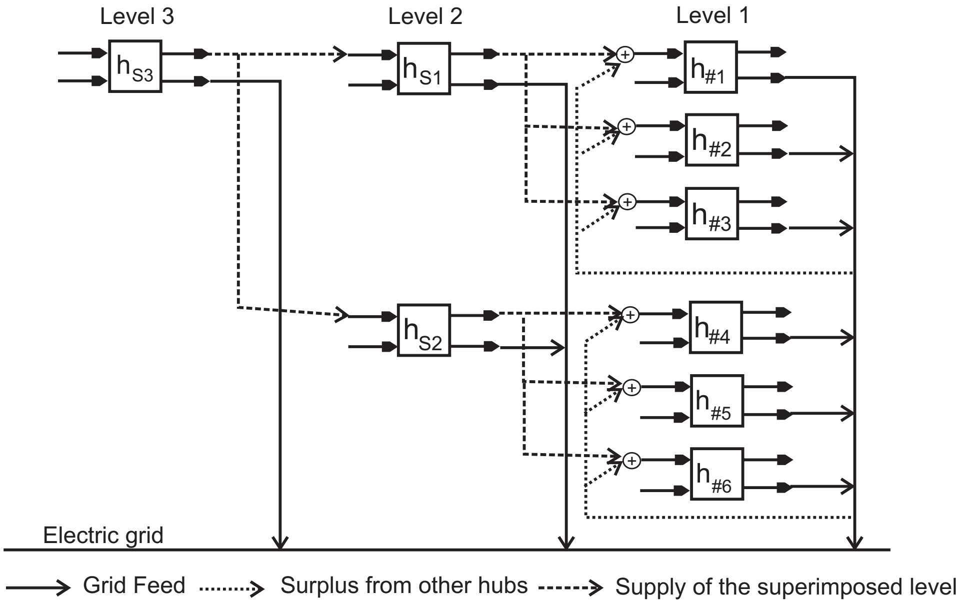


Figure 4.5: Schematic representation of a group of houses with a multiple-level model: Two groups of houses with two superimposed supply levels.

Generally, the actors and levels can be selected in any reasonable way. However, the choice should be made such that levels and actors can be clearly distinguished. Thus, the level selection according to political units (e.g. houses, villages or districts) is proposed (fig. 4.6). These units are unique, straightforward and comprehensible. Also, their hierarchy is clear. The political units can be selected according to the examined group of actors.

The assignment of conversion and storage technologies to a certain actor may be ambiguous in some cases, as political units superimpose (e.g. a city is formed by a number of districts). Consequently, the following hub rule is suggested:

> A technology is assigned to that actor where the main part of its (generated or stored) energy is consumed. If a number of actors is supplied, the technology is assigned to that hub that superimposes the level of these actors.

The application of this hub rule results in a consistent layout of the hubs and the levels.

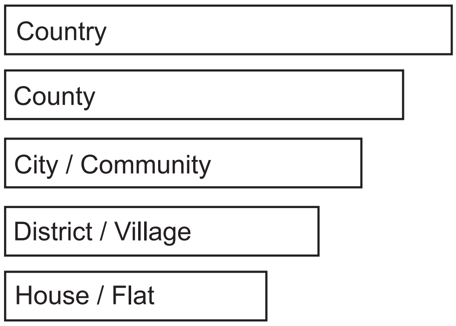


Figure 4.6: Political units and their hierarchical structure (example).

4.2.2 Examined Groups of Swiss Houses

A pool of six houses is considered. The buildings are assumed to be identical (table 4.1), but the supply technologies, the amount of electric load and the availability of photovoltaic electricity are distinct (table 4.4). The parameters of the conversion technologies are defined in table 4.2. Different nominal consumption patterns are implied by shifting in time the standard load curve relative to house #1. The remaining input curves for ambient temperature, global irradiance and PV generation are the same as for the individual house.

Table 4.4: Characteristics of the group of Swiss houses.

house #	$\lvert L_{\mathrm{el}}\rvert$ [kWh/a]	$\lvert\sum_{t=1}^{8760} R_{\mathrm{el}}\rvert$ [kWh/a]	technologies	Δt [h]
1/4	4500	2500	Grid, CHP, Furnace	0
2	3500	0	Grid, Furnace	+2
3	4000	0	Grid, CHP	+1
5	4500	3500	Grid, Furnace	-2
6	3500	3500	Grid, Furnace	-1

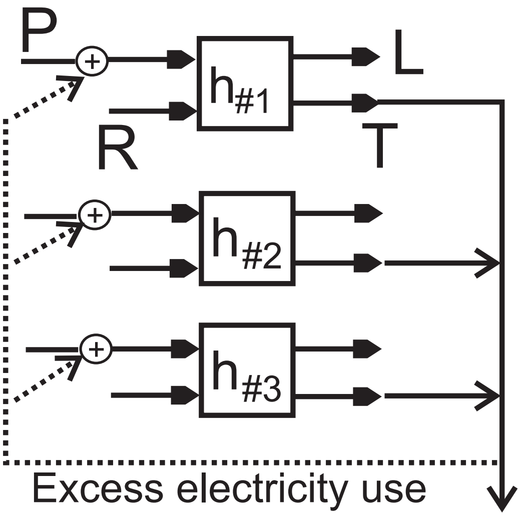


Figure 4.7: Groups of actors within the multiple-level model for the Swiss case.

For the group houses, two cases are considered:

a. An assembly of three houses (houses #1 - #3) on one level, without superimposed supply levels (fig. 4.7).

b. An assembly of twice three houses on one level (houses #1 - #3, and #4 - #6, respectively), with two superimposed supply levels (fig. 4.5).

The two superimposed levels l_2 and l_3 in case b supply the electric load demand of their respective set of subordinate hubs, $\mathcal{H}_{h_{S1}}$, $\mathcal{H}_{h_{S2}}$ and $\mathcal{H}_{h_{S3}}$. The levels exchange information about their respective electric load demand, L_{el}, but not about renewable generation, demand response application and storage use. Thermal load can only be supplied locally. Consequently, the supply hubs h_{S1}, h_{S2} and h_{S3} only contain a transformer for grid connection ($\eta_{\text{el,el}}^{\text{grid}} = 1$). However, the application of energy storage devices and renewable energy sources is possible, too.

Both for the group of houses and the association of houses with superimposed supply levels, the two cases of “coexistence” and “cooperation” are considered:

1. *Coexistence*: Each house determines its own energy supply strategy without interaction with the neighbors. Excess electricity of one house cannot be consumed by another house.

2. *Cooperation*: The houses within the subsets $\mathcal{H}_{h_{S1}}$ and $\mathcal{H}_{h_{S2}}$, respectively, exchange information about their load demand, the available renewable resources, demand response application and storage application. Excess electricity of one house can be used by another house. Nevertheless, each house tries to consume as much of its own renewable electricity as possible to avoid high network load.

These two cases reflect the individual and joint action of a vicinity of single-family houses, respectively.

4.2.3 Determination of the Optimal Energy Supply Strategy for a Group of Houses

The energy supply strategy of the group of houses is determined in analogy with the two cases *coexistence* and *cooperation.*

Optimization in the Case of Coexistence

The coexistence optimization procedure determines the optimal power supply strategy for each hub $h_i \in \mathcal{H}_{l_1}$ of the lowest level according to (4.14). The resulting load demand of the superimposed level l_{j+1} is determined by adding up the individual input demands:

$$L^{(l_{j+1})} = \sum_{k=1}^{N_{l_j}} P_k^{(l_j)} - \sum_{k=1}^{N_{l_j}} T_k^{(l_j)}. \tag{4.19}$$

Energy fed into the grid, $T_k^{(l_j)}$, can be consumed by other actors and hence lowers the load demand of the superimposed level. However, no coordination of excess energy use is possible. The optimization procedure continues until reaching the highest level $l_{N_\mathcal{L}}$. The result is an individually optimal power supply strategy for the region, including all levels of energy supply. The direction from decentralized to centralized power generation is contrary to the common procedure to start at the highest, most centralized, level [50], taking into account the perspective of the end customer.

Optimization in the Case of Cooperation

The cooperation optimization enforces one power supply strategy for the whole system by applying a global objective function $\mathcal{F}$. The actors consequently do not only exchange excess energy, but they coordinate their individual behaviors with the others'. For example, it is possible that one hub $h_i \in \mathcal{H}_{h_x}$ generates more electricity than it would need to supply another hub $h_j \in \mathcal{H}_{h_x}$ at the same level, if this is advantageous for the global objective. The load of the upper levels is calculated as for coexistence optimization (4.19), but the hub can interact with the subordinate actors instead of only optimally supplying the required load demand.

The cooperation optimization problem can be stated as:

$$\min \mathcal{F} = \sum_{t=1}^{T_{\text{end}}} \mathcal{F}^{(t)} \Big(P(t), T(t), \dot{E}(t), H(t), \dot{Q}_{\text{fur/cool}}(t), \nu(t) \Big) \tag{4.20}$$

$$\begin{aligned} &\text{s.t.} \\ (4.14\text{b}) - (4.14\text{i}) \quad & \forall h_i \in \mathcal{H} \\ (4.14\text{j}) - (4.14\text{m}) \quad & \forall h_j \in \mathcal{H}_{\text{house}} \\ (4.19) \quad & \forall h_k \in \mathcal{H}_{l_m},\ m = 2, ..., N_{\mathcal{L}}. \end{aligned}$$

The result is a collectively optimal power supply strategy for the whole system.

4.3 Cost Optimization and Energy Prices

With their energy supply policy, the residents of an individual house or an association of houses can persue different objectives. They can for example minimize the energy costs, maximize their independence of fossil fuels or external suppliers, maximize the exploitation of local renewable resources or minimize emissions.

In the thesis at hand, cost optimization is selected due to the following reasons:

1. The other objectives presented above all result in the maximum possible use of renewable resources and are consequently alike.

2. The emissions of energy carriers are not subject to market fluctuations as are the prices. Consequently, no or only little variations in the emissions due to changes in the electricity mix could be exploited in the optimization.

3. The emissions are indirectly included in the energy prices via the costs for emission permits.

The costs for each energy carrier $\alpha, \beta, ..., \omega \in \mathcal{E}$ are collected in the corresponding price vector π_α, π_β, etc. The vectors are summarized in the price matrix Π_P:

$$\Pi_\text{P} = \begin{bmatrix} \pi_\alpha \\ \pi_\beta \\ \vdots \\ \pi_\omega \end{bmatrix}. \tag{4.22}$$

The overall energy costs $\pi^{(\text{sum})}$ are determined as the sum of costs of all energy carriers:

$$\pi^{(\text{sum})} = \Pi_\text{P}^T \cdot P. \tag{4.23}$$

Consequently, the objective function $\mathcal{F}$ for minimum costs is defined as

$$\mathcal{F} = \sum_{t=1}^{T_\text{end}} \Pi_\text{P}^T(t) \cdot P(t). \tag{4.24}$$

Within this study, no compensation payments for renewable grid feed are considered, as with increasing renewable generation subsidies are going to decrease and even vanish within the next years and decades.

For the energy prices, five different combinations are considered (table 4.5). The prices are either constant throughout the week ("const."), or they vary between low- and high-tariff times ("LT/HT") or with intermediate medium-tariff period ("LT/MT/HT"). The intervals for the price categories are chosen in analogy with current Swiss tariffs:

Table 4.5: Constellations for gas and electricity prices; the category indicates when the different prices are active (LT: low-tariff; MT: medium-tariff; HT: high-tariff).

#	π_{el} $\left[\frac{\text{Rp.}}{\text{kWh}}\right]$	π_{gas} $\left[\frac{\text{Rp.}}{\text{kWh}}\right]$	category	line style in plots
1	8/17	6/12.75	LT/HT - LT/HT	
2	8/19	6/12.75	LT/HT - LT/HT	
3	8/17	8	LT/HT - const.	solid
4	8/19	8	LT/HT - const.	dashed
5	8/12/19	8	LT/MT/HT - const.	dotted
6	10	6/12.75	const. - LT/HT	dash-dotted
7	8/12/19	6/12.75	LT/MT/HT - LT/HT	diamonds

- Low/high-tariff (LT/HT): high-tariff times Mon-Fri 8-19h, Sat 8-12h;
- Low/medium/high-tariff (LT/MT/HT):
  - low-tariff times 22-5h,
  - medium-tariff 6-8h & 14-17h.

The price combinations are selected in such a way that the influences of price variations and different ratios between the input carrier prices can be examined. The price variations motivate the utilization of demand response and energy storage, in addition to excess renewable energy. The ratio of the costs for electricity and gas is decisive for the utilization of the technologies (e.g. CHP vs. grid). The absolute prices are crucial for investment decisions as they strongly influence the amortization time of the technologies. But investment costs are not considered in this study, as they are only important when deciding on a certain technology or when comparing two or more alternatives. The scope of this study, however, is the application of demand response and its combination with renewable resources and energy storage, which is independent of investment costs.

4.4 Parameters of the Sensitivity Analysis

The previous sections defined the models for a single-family house and a group of houses as well as the general conditions (prices, technologies, building parameters, climatic situation) valid for this thesis. Within these settings, the electric demand response and storage parameters as well as the amount of renewable electricity (table 4.6) are varied. With the sensitivity analysis, the influences of the respective parameters on the energy costs will be studied.

Table 4.6: Parameters varied within the sensitivity analysis.

Description	Acronym	Unit
Maximum shiftable electric power	$H^{(\mathrm{el})}_{\max}$	kW
Maximum shiftable electric energy	$J^{(\mathrm{el})}$	kWh
Time interval for load shift	$\Delta T^{(\mathrm{el})}$	h
Electric cycle efficiency	η_{cycle}	
Available electric storage capacity	E_{serv}	kWh
Amount of renewable electricity	$\sum_{t=1}^{8760} R_{\mathrm{el}}(t)$	kWh

The values are varied both in the presence and absence of demand response and energy storage, respectively (fig. 4.8):

- the demand response parameters $H^{(\mathrm{el})}_{\max}$, $J^{(\mathrm{el})}$ and $\Delta T^{(\mathrm{el})}$ with and without energy storage,
- the storage parameters η_{cycle} and E_{serv} with and without demand response,
- and the amount of renewable electricity, $\sum_{t=1}^{8760} R_{\mathrm{el}}(t)$, with and without energy storage and with and without demand response.

With this procedure, the specific influences of demand response and energy storage and their combination can be examined.

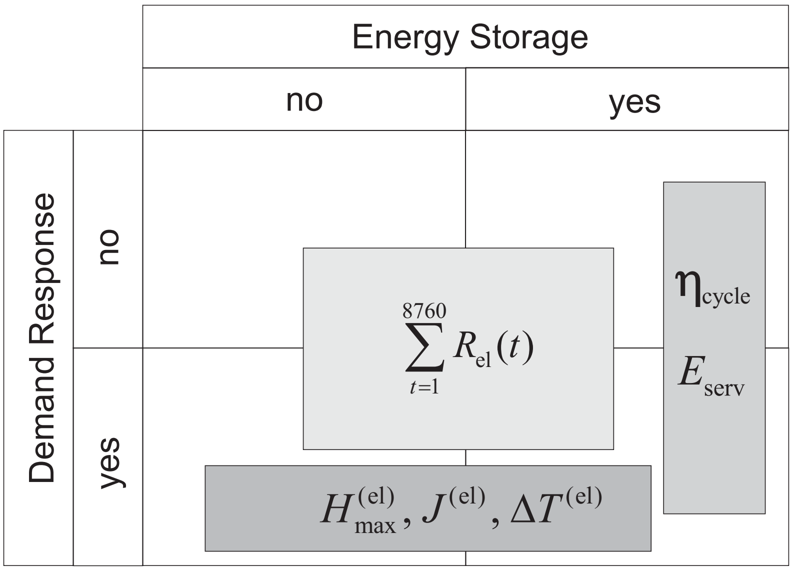


Figure 4.8: Combination of demand response and energy storage with the parameters varied within the sensitivity analysis: storage parameters (η_{cycle}, E_{serv}) are varied without and with demand response; DR parameters ($H_{\text{max}}^{(\text{el})}$, $J^{(\text{el})}$ and $\Delta T^{(\text{el})}$) without and with energy storage, and the amount of renewable electricity ($\sum_{t=1}^{8760} R_{\text{el}}(t)$) without and with both DR and storage.

In the case "with demand response", both electric storage device and electrically heated domestic hot water tank are considered. The hot water tank parameters are not varied, but the results with thermal and with electric storage are compared to see the distinct impacts of each storage type.

Additionally, the two cases

1. $\sum_{t=1}^{8760} R_{\text{el}}(t) = 500\,\text{kWh/a}$
2. $\sum_{t=1}^{8760} R_{\text{el}}(t) = 4500\,\text{kWh/a}$

are compared for the variation of demand response and storage parameters to assess the impacts of renewable generation.

The amount of renewable electricity produced in one year is denoted by $\sum_{t=1}^{8760} R_{\text{el}}(t)$. In the following, the abbreviation "PVxxx" will be used as an equivalent to this term, where e.g. "PV4500" indicates a yearly generation of 4500 kWh. Hence:

$$\text{PV4500} \mathrel{\widehat{=}} \sum_{t=1}^{8760} R_{\text{el}}(t) = 4500\,\text{kWh}.$$

In the same way, the sum of electric load consumed within the considered time period, $|L_{\text{el}}|$, the amount of electricity supplied from the grid, $|P_{\text{el}}|$, and the sum of gas consumed by the CHP, $|P_{\text{CHP}}|$, are defined as:

$$\begin{aligned}
|L_{\text{el}}| &\mathrel{\widehat{=}} \sum_{t=1}^{T_{\text{end}}} L_{\text{el}}(t), \\
|P_{\text{el}}| &\mathrel{\widehat{=}} \sum_{t=1}^{T_{\text{end}}} P_{\text{el}}(t) \\
|P_{\text{CHP}}| &\mathrel{\widehat{=}} \sum_{t=1}^{T_{\text{end}}} P_{\text{CHP}}(t).
\end{aligned}$$

These values will be used in the evaluation of the case studies with the parameter variations introduced above.

4.5 Optimization Interval and Parameters

The models and scenarios presented above are implemented in Matlab® (versions R2009a - R2010a). The `fmincon`-algorithm of the optimization toolbox is used to determine the solutions for the optimization problems stated in (2.41) and (4.20) with the objective function defined in (4.24).

Two periods of 1000 time steps are considered for one single-family house, one in winter and the other in summer:

$$\begin{aligned}
t \in [1, 8760]: &\quad \text{year (01.01. - 31.12.)}, \\
t \in [1, 1000]: &\quad \text{winter (01.01. - 10.02.)}, \\
t \in [4001, 5000]: &\quad \text{summer (15.06. - 27.07.)}.
\end{aligned} \tag{4.25}$$

The simulations of the groups of houses are run for 30 hours only (winter: 01.01., 1am - 02.01., 8am; summer 15.06., 5pm, to 16.06., 10pm). These two extreme periods are chosen (thermal load dominance in winter, no space heating in summer) to study the research questions at the edges of the spectrum and simultaneously maintain the computing time and effort at a reasonable level. Additionally, several simulations are run for a complete year to generalize the findings made in both season.

Clearly, the chosen settings do not cover the complete range of Swiss residential buildings, ambient conditions and energy supply possibilities, but due to their statistical and exemplary character they allow for general statements about residential energy supply.

Additionally to the reduction to winter and summer period for most simulations, further adaptations where necessary to comply with the numerical simulation software, see also appendix C.

The main adaptation required was the shift from one optimization run for the complete interval $t = 1, ..., T_{\text{end}}$ to several sub-optimizations of less time steps. The objective function (4.24) aims at minimizing the costs for the entire period under consideration. Both summer and winter intervals comprise 1000 time steps and the yearly simulations 8760, consequently

$$T_{\text{end}} = \begin{cases} 1000, & \text{summer/winter}, \\ 8760, & \text{year}. \end{cases} \tag{4.26}$$

All time steps within an optimization period have to be considered at once due to the time interconnection enforced by storage and demand response. Hence, the optimization of 1000 or 8760 time steps results in a significant computational time and effort. Consequently, the interval $t = 1, ..., T_{\text{end}}$ is split into several intervals of length N_{int} (figure 4.9) to decrease the computation time to a reasonable level (from several minutes up to around an hour instead of hours or days). The *optimization horizon* N_{int} can be selected as

$$1 \leq N_{\text{int}} \leq T_{\text{end}}. \tag{4.27}$$

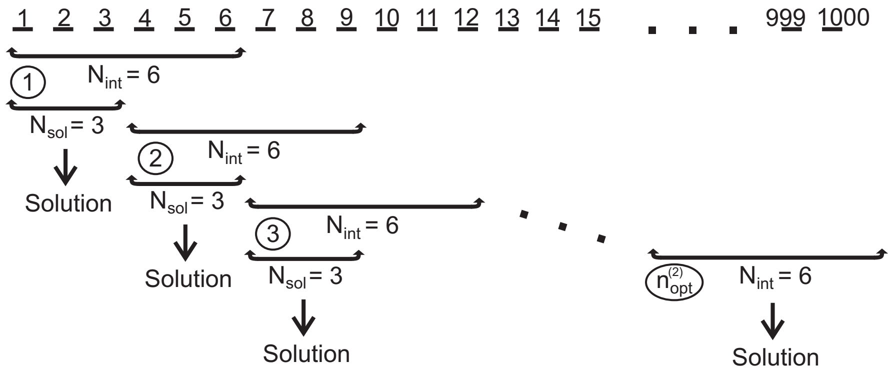


Figure 4.9: Splitting of the optimization interval [1,...,T_{end}] into sub-optimizations of length N_{int}, where N_{sol} steps are taken into the solution.

A number $n_{\text{opt}}^{(1)}$ optimization sub-runs have to be executed to determine the optimal solution for the period $t = 1, ..., T_{\text{end}}$, with

$$n_{\text{opt}}^{(1)} = \left\lceil \frac{T_{\text{end}}}{N_{\text{int}}} \right\rceil, \tag{4.28}$$

when no overlap between the optimization intervals is assumed. However, storage devices need an overlay between two optimization runs n_i and n_{i+1}. At the end of each interval n_i the storage device is discharged entirely, as remaining energy in the device causes costs without benefits. The resulting periodic charge/discharge behavior may be optimal for each sub-optimization, but is not expedient for the complete period $t = 1, ..., T_{\text{end}}$. Consequently, only a number N_{sol} of the optimized N_{int} time steps is taken into the solution. The remaining time steps $N_{\text{sol}} + 1, ..., N_{\text{int}}$ are discarded and optimized anew in the next run. Solely in the last optimization run the complete interval N_{int} is resumed in the solution. The parameter N_{sol} is called *solution horizon* and can be selected as

$$1 \leq N_{\text{sol}} \leq N_{\text{int}}. \tag{4.29}$$

The overlap between the optimization intervals n_i and n_{i+1} smoothes the storage operation and converges the synopsis of the interval solutions to the solution for one comprehensive optimization of $t = 1, ..., T_{\text{end}}$.

A number $n_{\text{opt}}^{(2)}$ of optimization runs results from the approach depicted in figure 4.9, with

$$n_{\text{opt}}^{(2)} = \left\lceil \frac{T_{\text{end}} - N_{\text{int}}}{N_{\text{sol}}} \right\rceil + 1. \tag{4.30}$$

The sub-runs are connected via the initial value x_0 of the optimization run n_{i+1}, as it is determined by the final value of the preceding run n_i:

$$x_0^{(n_{i+1})} = x_{\text{end}}^{(n_i)}. \tag{4.31}$$

The procedure described above is applied to calculate the optimal solution for the year and the summer and winter periods according to (4.24) and (2.41) for the single-family houses. The same methodology is implemented for the multiple-level model, although only $T_{\text{end}} = 24$ time steps are considered. But the complex interaction of actors takes much computational effort and consequently also a reduction of the optimization interval. If not stated differently, the optimization parameters are selected as

$$N_{\text{int}} = 12, \quad N_{\text{sol}} = 4$$

for the single-family house, and

$$N_{\text{int}} = 4, \quad N_{\text{sol}} = 1$$

for the multiple-level model.

Chapter 5

Case Studies

The models and scenarios examined in this thesis were presented in the previous chapter. Also, the parameters of the sensitivity analysis and the optimization interval and procedure were introduced. In this chapter it will be examined and explained how these parameters influence the energy supply strategy and energy costs, both for the Swiss house in moderate climate (section 5.1), the Spanish house in hot climate (section 5.2) and the Swiss groups of houses (section 5.3). In chapter 6, the results will be discussed and related.

5.1 Influence of the Parameters on Energy Costs and Supply Strategy (House in Moderate Climate)

First, the results for the Swiss single-family house as defined in tables 4.1 and 4.2 are presented. The varied parameters and the examined cases are listed in table 4.6 and fig. 4.8

5.1.1 Influence of the Electric Demand Response Parameters

The inhabitants can change their electricity consumption profile to benefit from price variations and renewable electricity. There, they can change two values: the maximum power that may be added or subtracted at each time instant, $H_{\max}^{(\mathrm{el})}$, and the maximum energy $J^{(\mathrm{el})}$ that may be shifted within the time interval $\Delta T^{(\mathrm{el})}$. Each of these parameters is varied to examine its influence on the costs while the other parameters are kept constant. For simplicity reasons it is assumed that the amount of power that may be added or subtracted at any instant of time is of the same magnitude according to amount:

$$H_{\min}^{(\mathrm{el})} = -H_{\max}^{(\mathrm{el})}. \tag{5.1}$$

Without storage device

First, scenarios #1 and #2 (table 4.5) are examined. In scenario #1 the CHP is not running due to the price constellations, but in #2 it is used in high-tariff times. The optimization parameters are $N_{\mathrm{int}} = 8$ and $N_{\mathrm{sol}} = 4$, and the complete year is considered. In both scenarios, an increase of $H_{\max}^{(\mathrm{el})}$ reduces the overall costs $\pi^{(\mathrm{sum})}$ by around $7 - 9\,\%$ (table 5.1). Without CHP, the costs for electricity, $\pi^{(\mathrm{el})}$, decrease by around $14\,\%$ when $H_{\max}^{(\mathrm{el})}$ increases from $0.2\,\mathrm{kW}$ to $1.2\,\mathrm{kW}$. With CHP, the electric costs nearly remain constant, while the grid electricity consumption increases by $\approx 12\,\%$. At the same time, the CHP use decreases by $\approx 65\,\%$, as more load is shifted to times where heat and electricity are supplied separately.

Contrary to $H_{\max}^{(\mathrm{el})}$, the parameters $J^{(\mathrm{el})}$ and $\Delta T^{(\mathrm{el})}$ have almost no influence on the costs in the considered scenarios. This can be explained by taking a look at the parameter selection. Demand response is constrained by two inequalities (4.14j) and (4.14k), and one equality (4.14l). As long as $\Delta T^{(\mathrm{el})} \cdot H_{\max}^{(\mathrm{el})} < J^{(\mathrm{el})}$, limitation (4.14j) is stricter than (4.14k), so the variable ΔT has no influence on the result. In the scenarios here, this is the case for $\Delta T^{(\mathrm{el})} \leq 6$. Additionally, equality (4.14l) ensures that all shifted load is supplied at some time during the considered time interval. Here, the time interval T_{end} is set to N_{int} (appendix C.2). Consequently, the following two constraints apply:

Table 5.1: Variation of the demand response parameters $H^{(el)}_{max}$, $\Delta T^{(el)}$ and $J^{(el)}$; percentage values related to the values without electric demand response ($H^{(el)}_{max} = 0\,kW$); ($N_{int} = 8$, $N_{sol} = 4$); year, PV4500.

$J^{(el)} = 5\,kWh$, $\Delta T^{(el)} = 8\,h$

	$H^{(el)}_{max}$	0.2	0.4	0.6	0.8	1.0	1.2	[kW]
#1	$\pi^{(sum)}$	98.2	97.1	96.2	95.2	94.1	93.2	[%]
	$\pi^{(el)}$	95.0	92.0	89.5	86.7	83.9	81.4	[%]
#2	$\pi^{(sum)}$	97.2	95.4	93.9		92.0	91.5	[%]
	$\pi^{(el)}$	93.8	93.5	94.4		94.4	93.5	[%]
	$\lvert P_{el}\rvert$	101.3	105.0	108.6		112.7	113.4	[%]
	$\lvert P_{CHP}\rvert$	89.3	72.2	55.9		37.5	34.4	[%]

$J^{(el)} = 5\,kWh$, $H^{(el)}_{max} = 0.8\,kWh$

	$\Delta T^{(el)}$	1	4	8	10	12		[h]
#1	$\pi^{(sum)}$	95.2	95.2	95.2	95.2	95.2		[%]
	$\pi^{(el)}$	86.7	86.7	86.7	86.7	86.7		[%]
#2	$\pi^{(sum)}$	92.7	92.8		92.7	92.8		[%]
	$\pi^{(el)}$	94.8	94.8		94.7	94.7		[%]
	$\lvert P_{el}\rvert$	111.3	111.3		111.3	111.3		[%]
	$\lvert P_{CHP}\rvert$	43.7	43.8		44.0	44.0		[%]

$H^{(el)}_{max} = 0.8\,kW$, $\Delta T^{(el)} = 8\,h$

	$J^{(el)}$	3	5	8	10			[kW]
#1	$\pi^{(sum)}$	95.3	95.2	95.2	95.2			[%]
	$\pi^{(el)}$	86.9	86.7	86.7	86.7			[%]

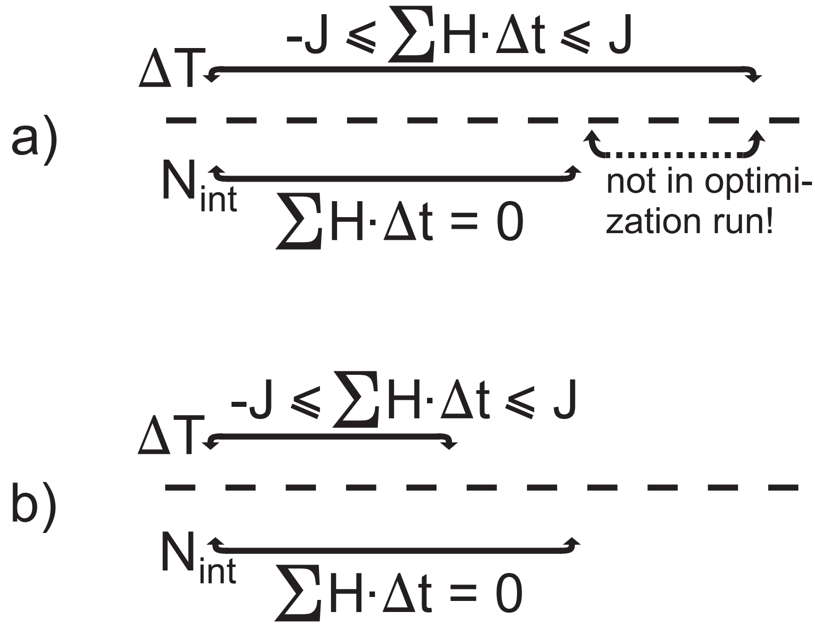


Figure 5.1: Superposition and interference of constraints (5.2) and (5.3); a) $\Delta T > N_{\text{int}}$, b) $\Delta T < N_{\text{int}}$.

$$\sum_{t=1}^{N_{\text{int}}} H_{\max}^{(\text{el})}(t) \cdot \Delta t = 0, \tag{5.2}$$

$$\left| \sum_{t=1}^{\Delta T^{(\text{el})}} H_{\max}^{(\text{el})}(t) \cdot \Delta t \right| \leq J^{(\text{el})}. \tag{5.3}$$

Constraint (5.2) dominates (5.3) if $\Delta T^{(\text{el})} > N_{\text{int}}$ (fig. 5.1a). Also, if $\Delta T^{(\text{el})} \approx N_{\text{int}}$, the first constraint limits the exploitation of the flexibility of the second one. For scenarios #1 and #2 presented in table 5.1 the value of $\Delta T^{(\text{el})}$ is near to the optimization horizon N_{int} or higher. Consequently, it has only little impact.

The parameter $\Delta T^{(\text{el})}$ effects the optimization outcome for a larger optimization horizon $N_{\text{int}} = 16$ (fig. 5.1b and table 5.2 scenario #2). The CHP use is decreased due to the increased optimization horizon and its influence on the thermal load. Nevertheless, it can be seen that an increase of $\Delta T^{(\text{el})}$ decreases the electric costs while increas-

Table 5.2: Energy costs depending on the parameter $\Delta T^{(\mathrm{el})}$ with $J^{(\mathrm{el})} = 5\,\mathrm{kWh}$ and $H^{(\mathrm{el})}_{\mathrm{max}} = 0.8\,\mathrm{kW}$; percentage values related to the values without electric demand response ($H^{(\mathrm{el})}_{\mathrm{max}} = 0\,\mathrm{kW}$); ($N_{\mathrm{int}} = 16$, $N_{\mathrm{sol}} = 8$); year, PV1000, #2).

$\Delta T^{(\mathrm{el})}$	2	4	6	8	10	12	20	[h]
$\pi^{(\mathrm{sum})}$	87.8	87.8	88.0	88.0	88.3	88.4	88.1	[%]
$\pi^{(\mathrm{el})}$	84.0	84.0	84.0	83.8	83.3	83.0	84.0	[%]
$\lvert P_{\mathrm{el}}\rvert$	112.8	112.8	112.6	112.4	111.6	111.2	112.2	[%]
$\lvert P_{\mathrm{CHP}}\rvert$	8.8	9.0	10.6	11.3	17.0	19.5	12.7	[%]

ing the overall costs and the CHP use. This trend is in analogy with $H^{(\mathrm{el})}$ and $J^{(\mathrm{el})}$: the higher the flexibility (H and J large, ΔT small), the lower the costs and, for this scenario, the lower the CHP use.

The results presented above show that the power boundary $H^{(\mathrm{el})}_{\mathrm{max}}$ influences the costs more significantly than the energy boundary implied by $J^{(\mathrm{el})}$ and $\Delta T^{(\mathrm{el})}$. Consequently, the latter two parameters are fixed at

$$J^{(\mathrm{el})} = 15\,\mathrm{kWh}, \quad \Delta T^{(\mathrm{el})} = 12\,\mathrm{h} \tag{5.4}$$

to allow demand response without notably constraining the load shift, while the influence of $H^{(\mathrm{el})}_{\mathrm{max}}$ will be examined in further detail.

The summer/winter analysis of price configurations #3 - #7 confirms the results of the yearly analysis that an increasing $H^{(\mathrm{el})}_{\mathrm{max}}$ reduces the costs (fig. 5.2). However, there is a strong difference between summer (red) and winter (blue). In winter, thermal load dominates, consequently savings in the electricity costs do not have much impact on the overall costs. Contrarily, demand response has a huge influence in summer with only warm water as thermal load. In summer, a saturation in the cost savings potential can be noticed for $H^{(\mathrm{el})}_{\mathrm{max}} \geq 0.6\,\mathrm{kW}$, while in winter and for one year (table 5.1) the saturation is not notably pronounced.

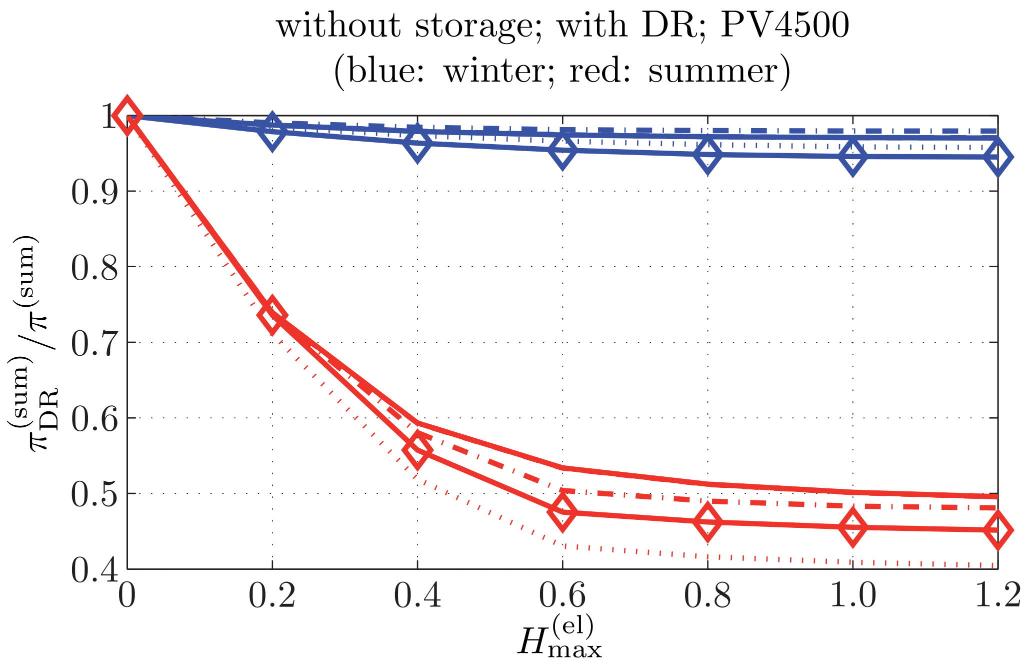


Figure 5.2: Energy costs with demand response, $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$, related to costs without demand response, $\pi^{(\mathrm{sum})}$.

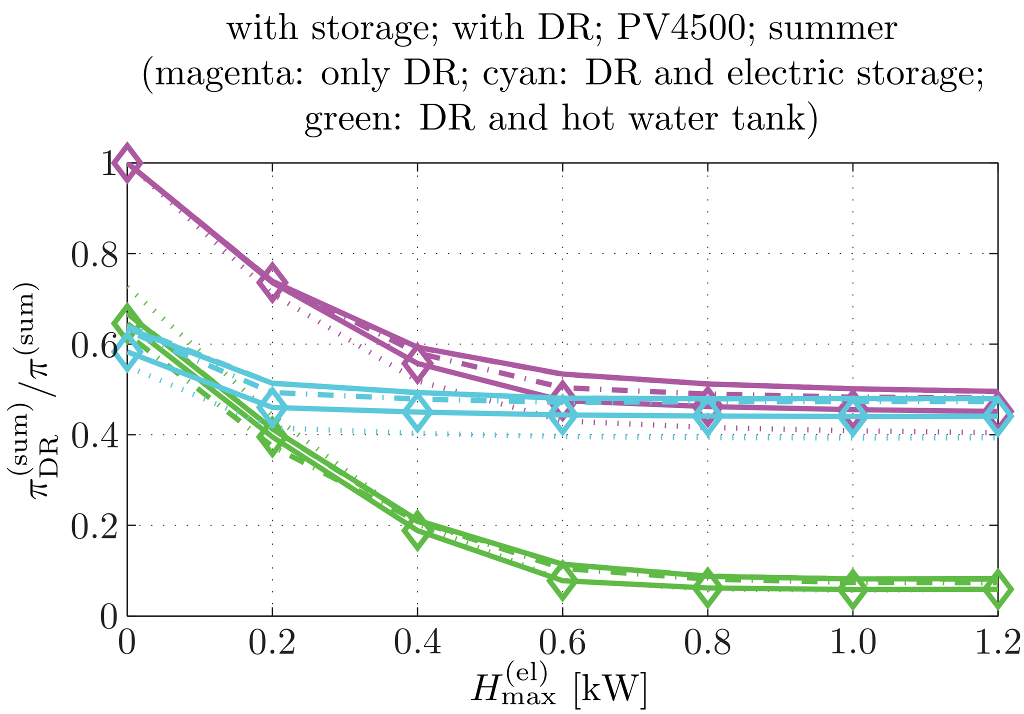


Figure 5.3: Energy costs $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$ related to costs without demand response and without storage, $\pi^{(\mathrm{sum})}$.

With storage device

The electrically heated domestic hot water tank (table 4.3) significantly increases the cost savings potential (fig. 5.3, green lines). Over 90 % of cost reductions are possible in summer, while only around 50 % were achievable purely with demand response (fig. 5.3, magenta lines). The thermal storage device itself accounts for around 35 % reduction (at $H_{\max}^{(\mathrm{el})} = 0$), but by increasing $H_{\max}^{(\mathrm{el})}$ its cost savings potential slightly grows to around 40 %. The significant cost reduction results from the possibility to use (excess) renewable electricity both for electric and thermal load. However, in winter (not depicted) differences are much smaller as no or only little excess electricity is available.

In summer, demand response increases the thermal storage utilization (fig. 5.4). At $H_{\max}^{(\mathrm{el})} = 0.6\,\mathrm{kW}$ the storage use saturates. A higher demand response flexibility cannot further increase the thermal storage use or even decreases it, as the potential of a cooperation between storage and demand response is exhausted. In winter, the price scenarios partly differ in a significant extent.

- In price constellation #6, demand response has no influence on the thermal storage utilization. Here, the hot water tank is used extensively to exploit the renewable electricity for differences in the gas price.

- In price constellations #3 - #5, the thermal storage is nearly not used at all, as all renewable electricity is either consumed directly or exploited via demand response to benefit from electricity price variations.

- For price constellation #7, the thermal storage use increases by about 13 % as the demand response flexibility reaches $H_{\max}^{(\mathrm{el})} = 1.2\,\mathrm{kW}$. Price variations exist both for electricity and gas prices. Consequently, demand response and thermal storage can cooperate to benefit from both variations, resulting in an increased storage utilization as more electric load may be shifted. Thereby, changes in the electricity price can also be made available for exploitation at thermal load supply.

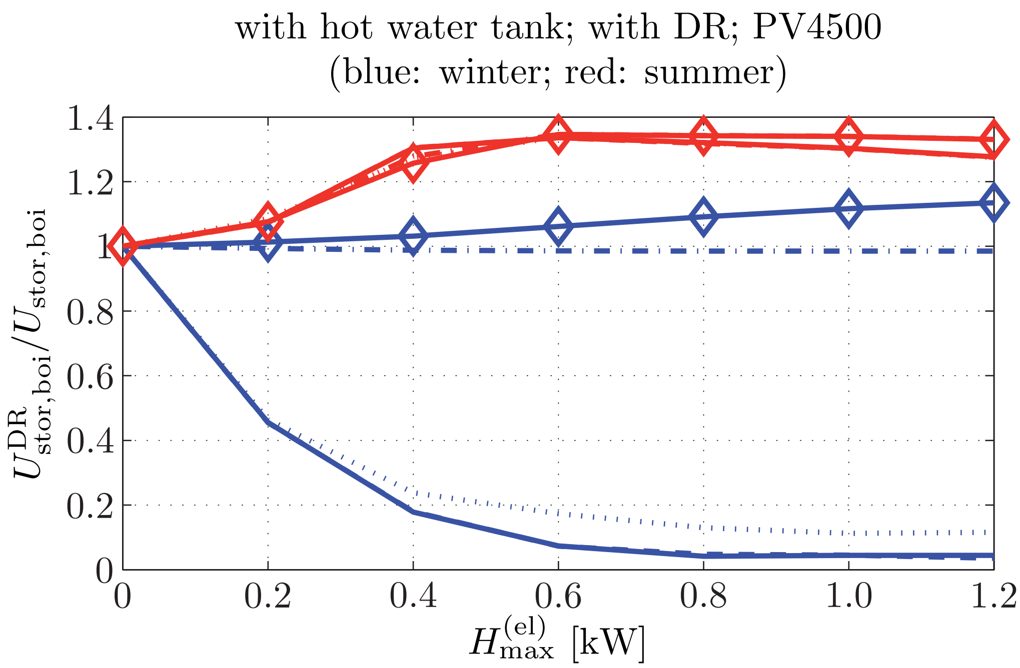


Figure 5.4: Utilization of the hot water tank with demand response, $U^{DR}_{stor,boi}$, related to utilization of the hot water tank without demand response, $U_{stor,boi}$.

The savings potential of the electric storage device (table 4.3) is approximately as high as that of the thermal storage device with no demand response available ($H^{(el)}_{max} = 0$; fig. 5.3, cyan lines). However, the additional benefit is not lasting for increasing $H^{(el)}_{max}$, as electric demand response and electric storage device compete for load shifting and price variations in electric load.

The decreasing influence of the electric storage device can also be seen in figure 5.5. As $H^{(el)}_{max}$ increases, the relation between costs with electric storage device and demand response compared to only demand response decreases significantly, showing that an additional storage does not result in benefits. In winter, the amount of load shifted by demand response application is about the same with or without an electric storage device (fig. 5.6). In summer, the presence of the storage reduces the shifted load by around $7 - 10\,\%$ of the electric load (fig. 5.7). Also, both in summer and in winter, the amount of energy charged to the storage, U_{stor}, decreases with increasing $H^{(el)}_{max}$ (fig. 5.8), as there is not enough load to be shifted. Consequently, no further electricity needs to be stored to fulfill the load demand.

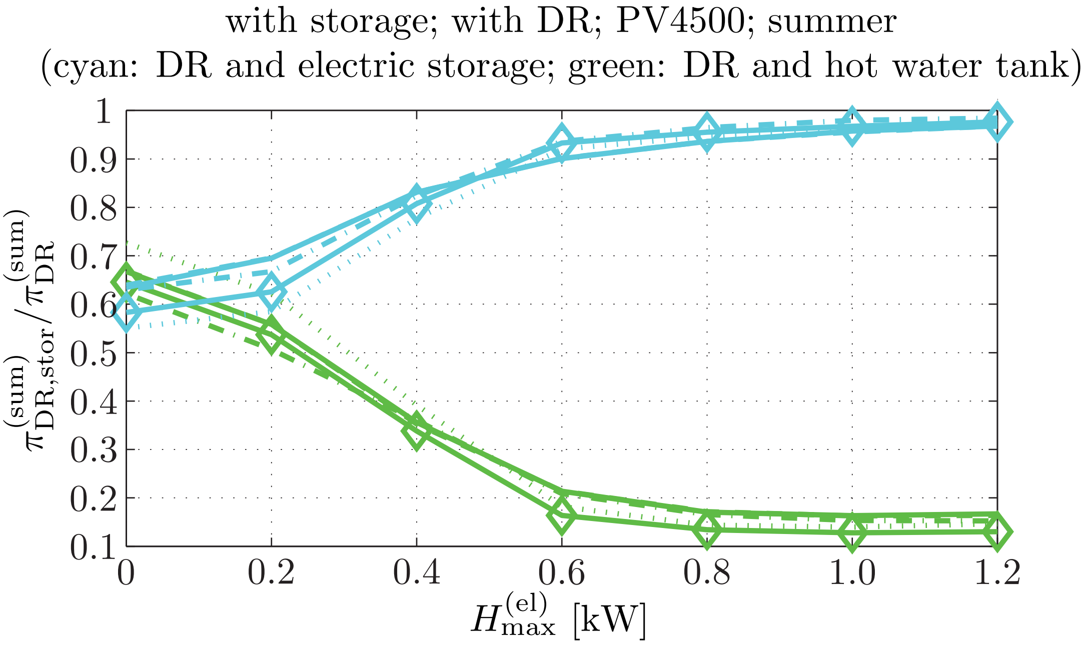


Figure 5.5: Energy costs with demand response and storage device, $\pi^{(sum)}_{DR,stor}$, related to energy costs with only demand response, $\pi^{(sum)}_{DR}$.

For PV500, the combination of electric storage device and demand response has no benefit compared to only demand response (table 5.3). Renewable energy can be consumed immediately anyway and either demand response or an electric storage device is sufficient to exploit price variations. The hot water tank, in contrast, can achieve an additional cost saving of around $4\,\% - 7\,\%$.

Table 5.3: Energy costs depending on the parameter $H^{(el)}_{max}$; percentage values related to the values without storage device and electric demand response ($H^{(el)}_{max} = 0\,\text{kW}$); only summer, PV1000, #7.

$H^{(el)}_{max}$ [kW]	0	0.2	0.4	0.6	0.8	1.0	1.2
$\pi^{(sum)}_{DR}/\pi^{(sum)}$	1.0	0.88	0.79	0.73	0.71	0.71	0.71
$\pi^{(sum)}_{DR,stor,el}/\pi^{(sum)}$	1.0	0.88	0.79	0.73	0.71	0.71	0.71
$\pi^{(sum)}_{DR,stor,boi}/\pi^{(sum)}$	0.96	0.83	0.74	0.68	0.66	0.65	0.64

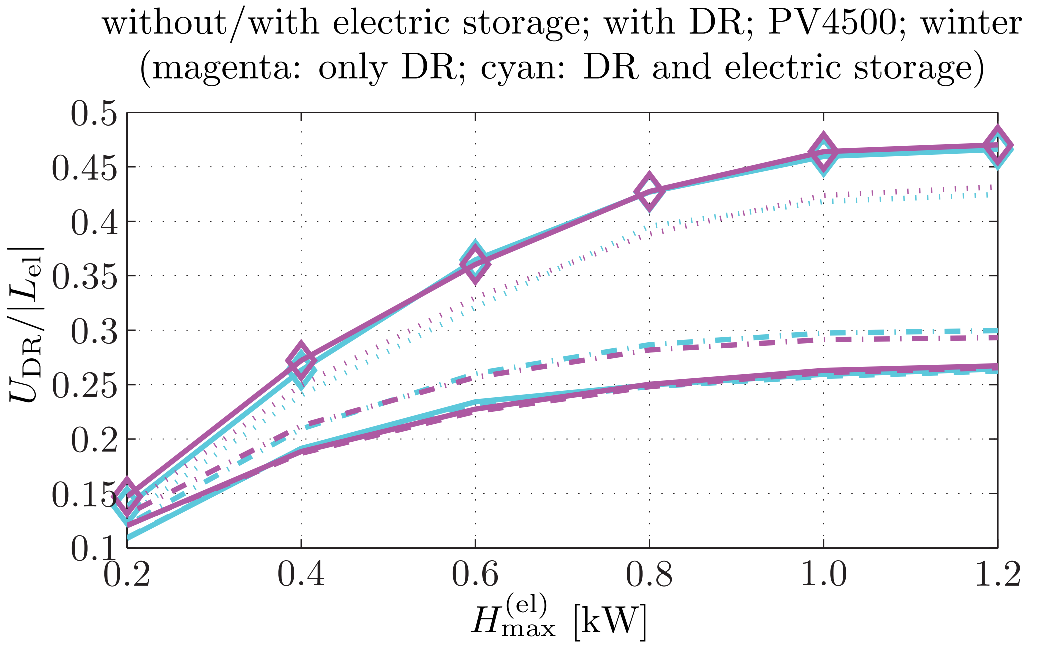


Figure 5.6: Demand response use U_{DR} related to the sum of electric load, $|L_{\mathrm{el}}|$.

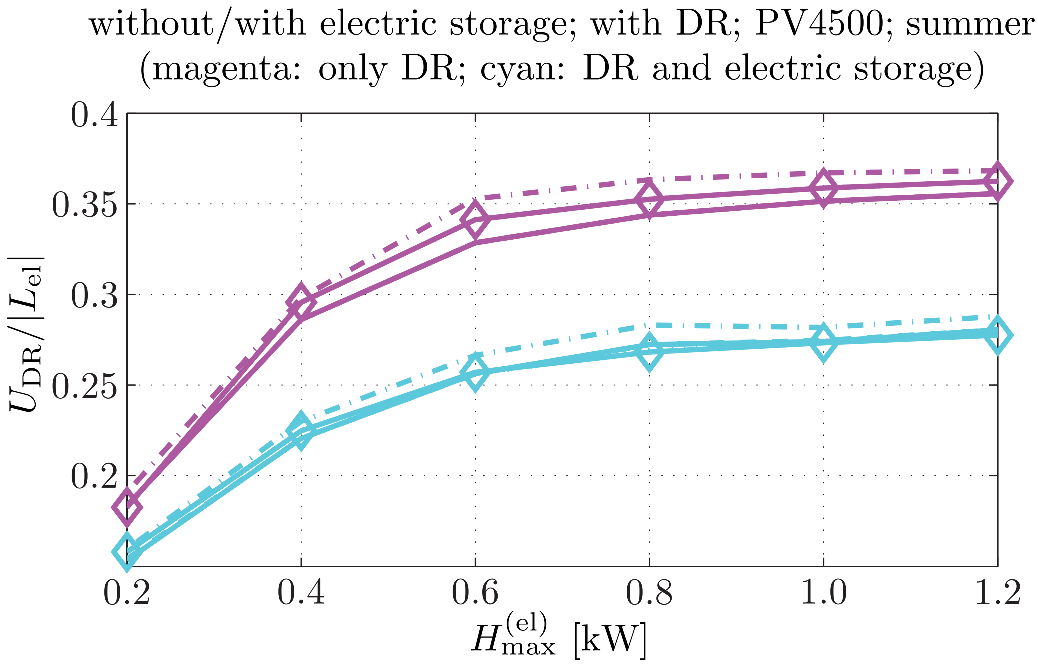


Figure 5.7: Demand response use U_{DR} related to the sum of electric load, $|L_{\mathrm{el}}|$.

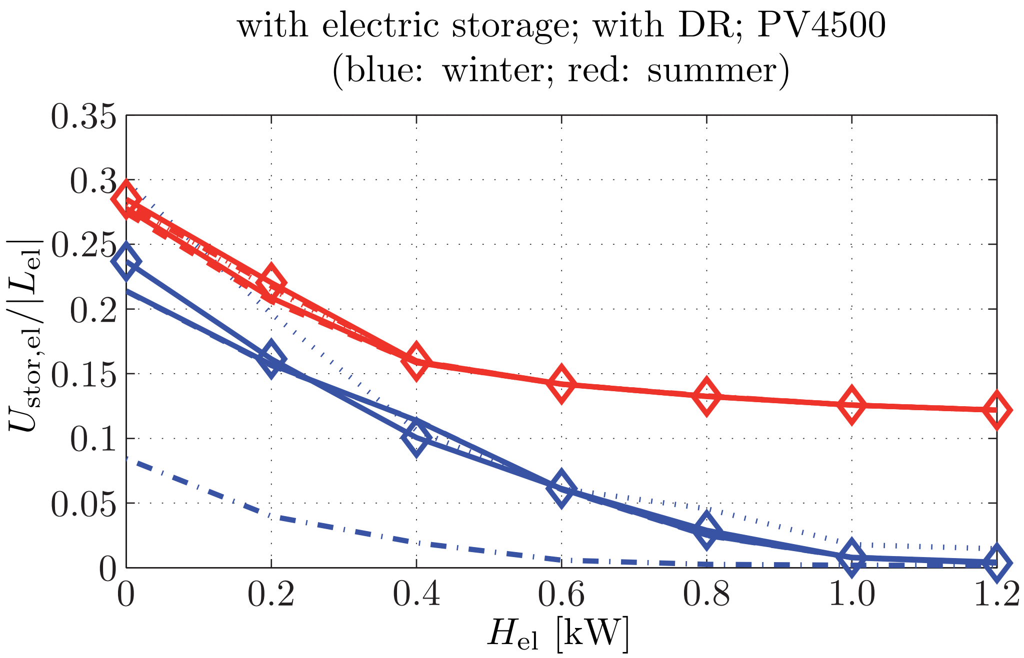


Figure 5.8: Energy charged into the electric storage, $U_{\text{stor,el}}$, related to the sum of electric load, $|L_{\text{el}}|$.

5.1.2 Influence of the Cycle Efficiency (Electric Storage)

The influence of the cycle efficiency η_{cycle} on the usage of the storage device and its competitiveness to demand response are analyzed for an electric storage device (table 4.3). The efficiency is increased from $\eta_{\text{cycle}} = 0.5$ to $\eta_{\text{cycle}} = 1.0$. Price configurations #3, #6 and #7 are considered (table 4.5).

Equation (2.38) showed that the amounts of input and output energy of the storage, $\sum_{t=1}^{T_{\text{end}}} M_{\text{char}}(t) \cdot \Delta t$ and $\sum_{t=1}^{T_{\text{end}}} M_{\text{dis}}(t) \cdot \Delta t$, respectively, as well as the stored energy, $\sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{char}}(t) \cdot \Delta t \approx \sum_{t=1}^{T_{\text{end}}} \dot{E}_{\text{dis}}(t) \cdot \Delta t$, only differ by a multiplication with the charge and discharge efficiencies. The comparison of different scenarios can consequently be performed with each of these values as long as the efficiencies are the same for all scenarios. However, for cases with distinct efficiencies the influence of the cycle efficiency on the relations between the variables has to be considered to be able to correctly interpret the simulation outcome. Thus, the impact of the cycle efficiency η_{cycle} of the storage device is taken into account in the results subsequently presented.

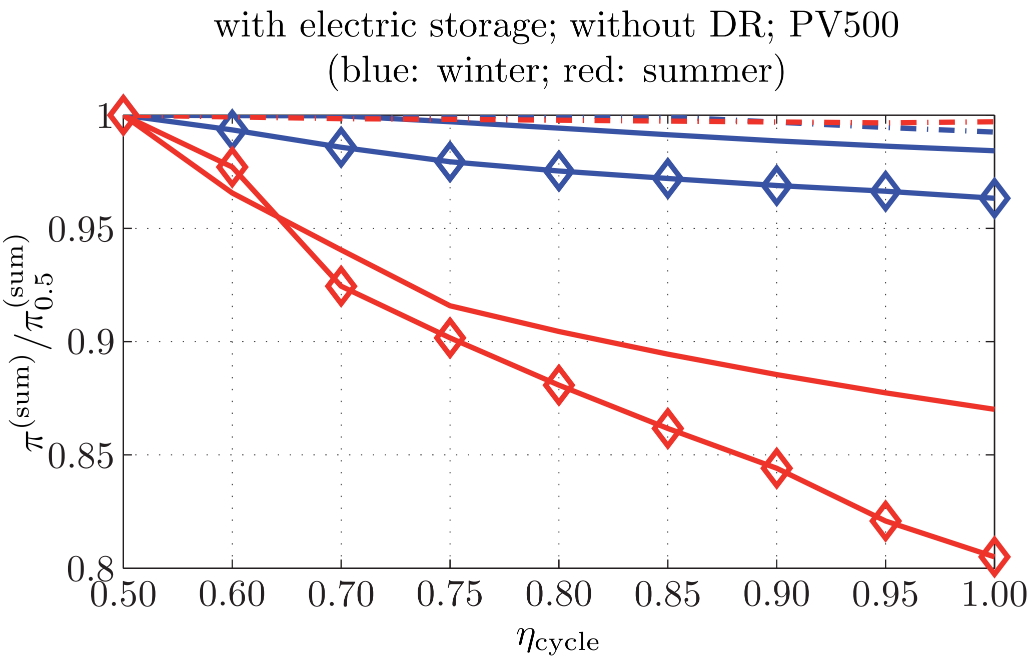


Figure 5.9: Energy costs $\pi^{(\mathrm{sum})}$ related to costs at $\eta_{\mathrm{cycle}} = 0.5$, $\pi_{0.5}^{(\mathrm{sum})}$.

Without Demand Response

Without demand response, in summer the costs decrease about linearly with increasing cycle efficiency for small amounts of photovoltaic energy (PV500) (figure 5.9), as less losses have to be compensated. For PV4500, also excess PV electricity can be stored, resulting in an increased savings potential of rising η_{cycle} (fig. 5.10), as generally more costs can be saved by renewable energy use than by price variation exploitation.

In winter, the storage use for $\eta_{\mathrm{cycle}} = 1$ lies between 22 % and 27 % of the electric load for PV500, and between 19 % and 25 % for PV4500, depending on the price configuration. Consequently, the storage utilization in winter is not negligible. Nevertheless, its influence on the costs is little (figures 5.9 and 5.10) as thermal load is decisive for the overall costs. The influence of an increasing cycle efficiency is slightly higher for PV500 than for PV4500. Contrary to summer, no excess PV electricity is available in both cases. For PV500, the resulting load $L^{'}$ (5.9) is larger, and more electricity has to be stored from low to high tariff times, resulting in higher storage losses. Consequently, an efficiency increase in η_{cycle} saves more energy and hence more costs.

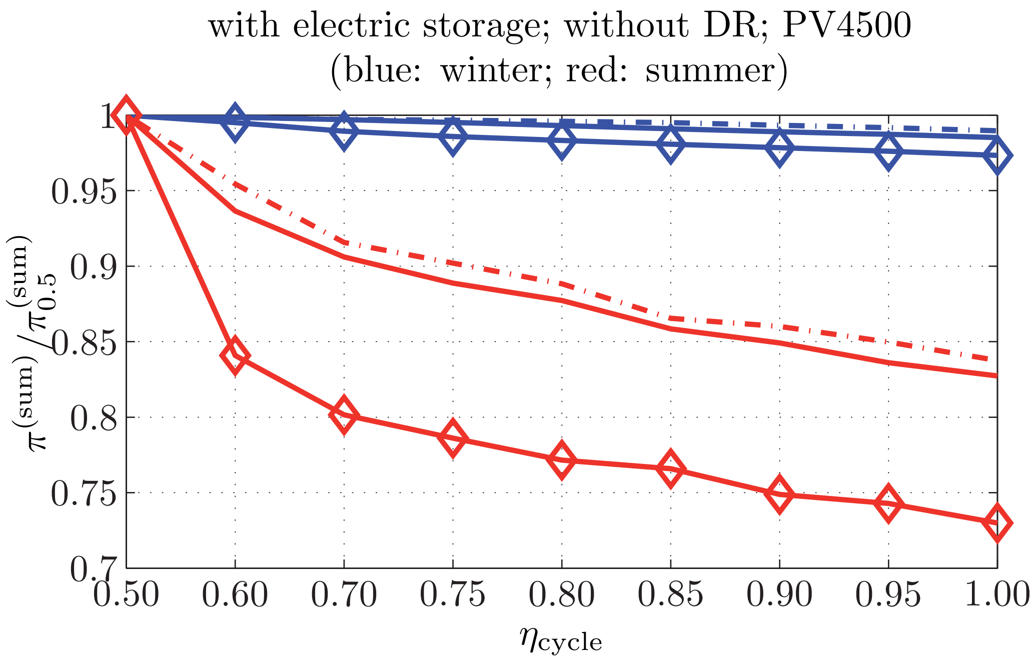


Figure 5.10: Energy costs $\pi^{(sum)}$ related to costs at $\eta_{cycle} = 0.5$, $\pi_{0.5}^{(sum)}$.

In summer (PV4500), the energy discharged from the storage increases about linearly with increasing efficiency (fig. 5.11), with a steeper rise between $\eta_{cycle} = 0.5$ and $\eta_{cycle} = 0.7$. The curve shape follows the same trend as the price curve (fig. 5.10). In winter (PV4500) and for PV500 generally (fig. 5.12), however, the amount of released storage energy jumps at certain efficiency values. This can be explained by having a look at the price constellations and the utilization of the renewable energy. In the following paragraphs, the utilization of the electric storage device will be explained for PV4500 in winter (fig. 5.11) and for PV500 in winter and summer (fig. 5.12). In these cases, the renewable energy can generally be consumed immediately without any load shift or storage application, as load exceeds PV generation. Consequently, the storage device is almost exclusively used to exploit price variations.

Price constellation #3

In summer only little heat is required, mainly for warm water supply. So electricity is predominantly supplied via the grid due to missing thermal load. Charging of the storage device during low-tariff times

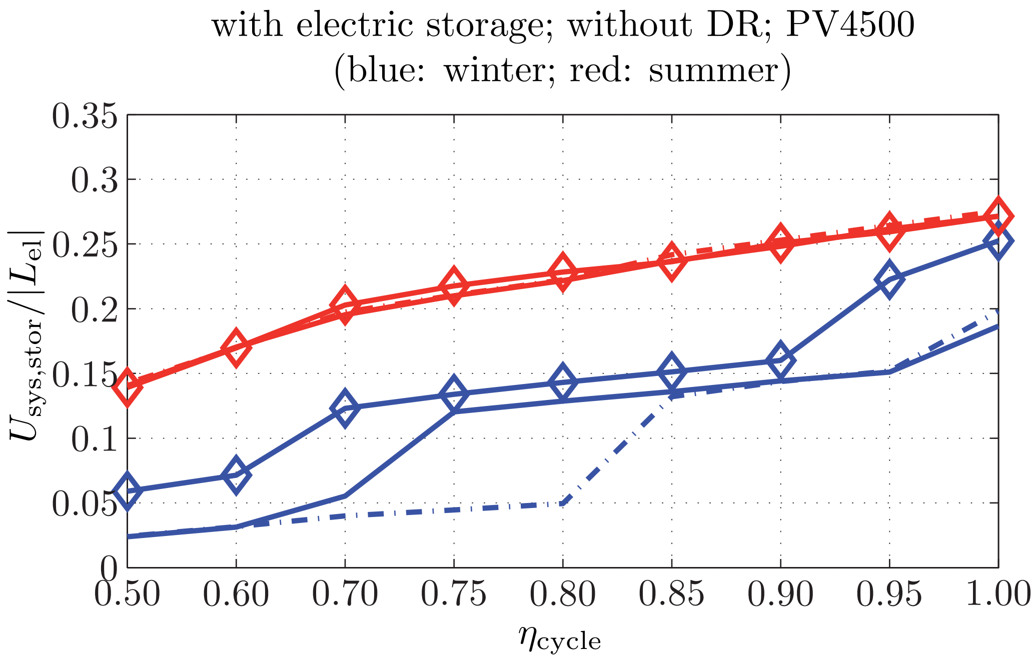


Figure 5.11: Stored energy used by the system, $U_{\text{sys,stor}}$, related to sum of electric load, $|L_{\text{el}}|$.

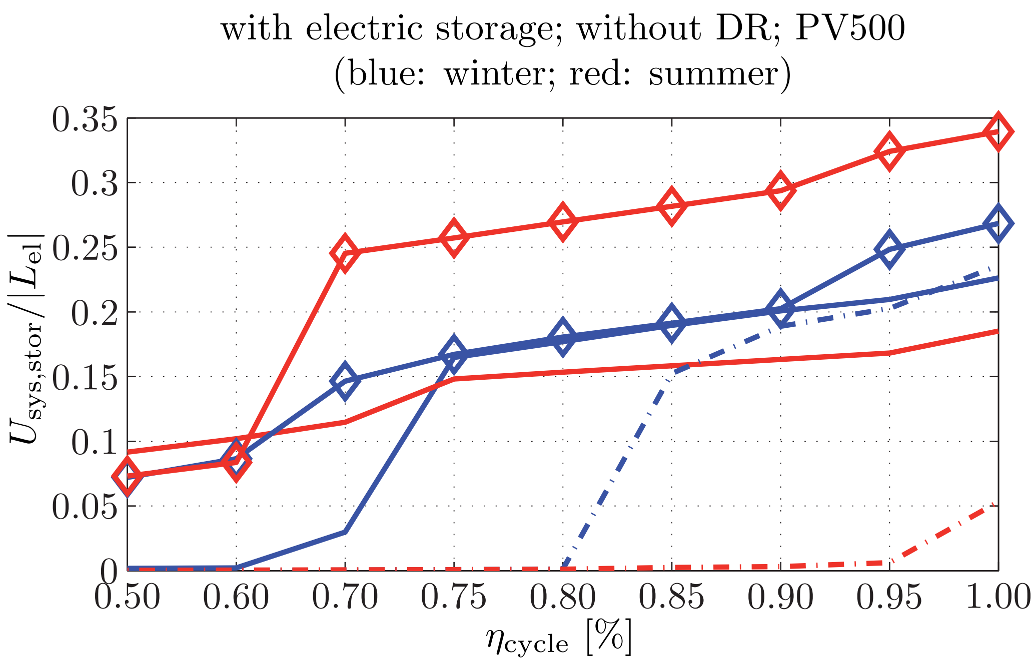


Figure 5.12: Stored energy used by the system, $U_{\text{sys,stor}}$, related to sum of electric load, $|L_{\text{el}}|$.

and discharging during high-tariff times is economic when the withdrawn kilowatt hour is cheaper than one bought during high-tariff times:

$$\frac{8\,\text{Rp./kWh}}{\eta_{\text{cycle}}} \leq 17\,\text{Rp./kWh} \tag{5.5a}$$

$$\eta_{\text{cycle}} \geq \frac{8}{17} = 0.47 \tag{5.5b}$$

Consequently, using the storage device is economically viable for all considered efficiencies within price constellation #3 and summer. So the storage utilization increases about linearly with increasing efficiency (figs. 5.11 and 5.12).

In winter, the CHP also has to be considered. The CHP use decreases significantly between $\eta_{\text{cycle}} = 0.7$ and $\eta_{\text{cycle}} = 0.75$ (fig. 5.13). Without storage device, the CHP is running for electricity prices higher than 11.2 Rp./kWh[1]. Consequently, the CHP is not running in electricity low-tariff times. With storage device, the CHP additionally has to compete with the prices for the withdrawn storage energy. The price for a withdrawn kilowatt hour has to fall below the boundary value of 11.2 Rp./kWh such that the CHP use is less economic than charging the storage in electricity low-tariff times. This is the case for $\eta_{\text{cycle}} \geq 0.71$, explaining the jump in the curve for price constellation #3 in winter.

Price constellation #6

In price constellation #6, the electricity price is constant. In summer nearly no heat is required, consequently the gas price variations cannot be exploited by the CHP. So the storage device is nearly not used (fig. 5.12).

In winter, the storage device can exploit variations in the gas price via the electricity generation of the CHP. Depending on the prices for

[1] break even point: $\pi(\text{CHP}) = \pi(\text{grid}) + \pi(\text{fur})$.

$$\frac{\pi_{\text{gas}}}{\eta^{\text{CHP}}_{\text{gas,th}}} = \pi_{\text{gas}} + \frac{\eta^{\text{CHP}}_{\text{gas,el}}}{\eta^{\text{CHP}}_{\text{gas,th}}} \cdot \pi_{\text{el}}$$

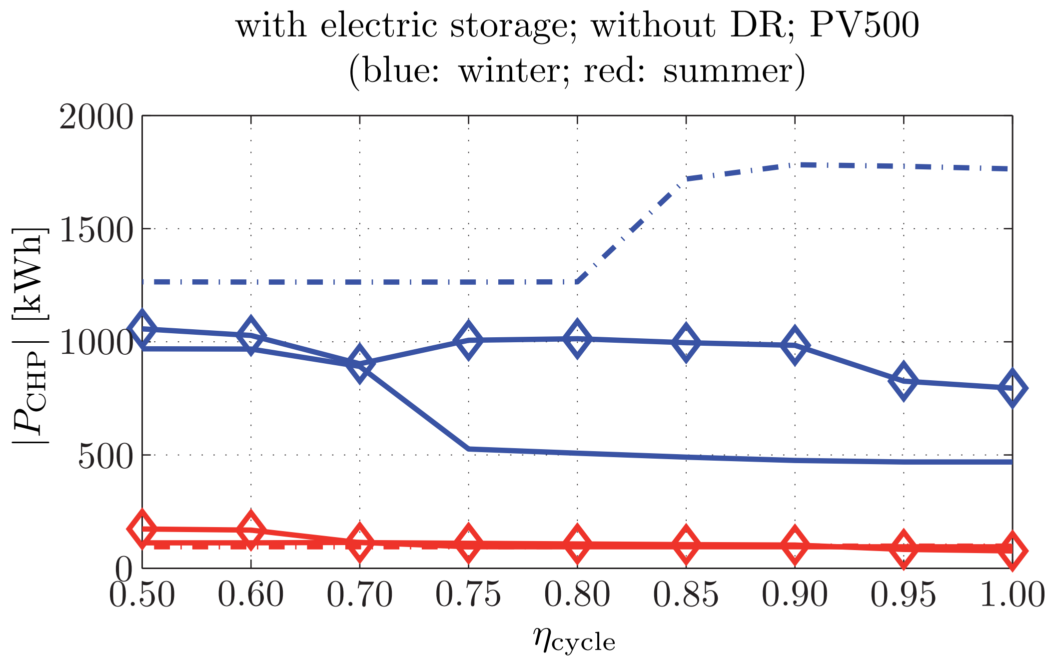


Figure 5.13: Utilization of the CHP, $|P_{\text{CHP}}|$.

electricity and gas, electric and thermal load can either be completely supplied via the grid and the furnace (in this case during high gas-tariff times), or via the CHP (here for low gas-tariff times), as long as both heat and electricity can be consumed. Remaining energy is supplied either by the grid or the furnace. The storage device admits to increase the CHP use above the limit given by electric load demand by storing the excess electricity. The price difference Δ_{p} that has to be paid additionally when applying the CHP instead of the furnace has to be compensated by the benefits resulting from stored electricity. This is only the case when the cycle efficiency is high enough:

$$\Delta_{\text{p}} = \frac{\pi_{\text{gas}}}{\eta_{\text{th}}^{\text{CHP}}} - \pi_{\text{gas}} \quad (5.6a)$$

$$\Delta_{\text{p}} = \frac{6\,\text{Rp./kWh}}{\eta_{\text{th}}^{\text{CHP}}} - 6\,\text{Rp./kWh} = 3.23\,\text{Rp./kWh} \quad (5.6b)$$

$$\text{Break even point:} \quad \frac{\Delta_{\text{p}}}{\frac{\eta_{\text{el}}^{\text{CHP}}}{\eta_{\text{th}}^{\text{CHP}}} \cdot \eta_{\text{cycle}}} \leq 10\,\text{Rp./kWh} \quad (5.6c)$$

$$\eta_{\text{cycle}} \geq 0.84 \quad (5.6d)$$

Consequently, the CHP utilization and accordingly the storage application increase significantly when the efficiency exceeds $\eta_{\text{cycle}} = 84\,\%$ (fig. 5.13).

Price constellation #7
Exploiting the grid electricity price variations, the storage utilization begins when the cycle efficiency exceeds the values determined by (5.5):

$$\eta_{\text{cycle}} \geq 0.42 \text{ for shift from 8 to 19 Rp./kWh,} \quad (5.7a)$$
$$\eta_{\text{cycle}} \geq 0.63 \text{ for shift from 12 to 19 Rp./kWh,} \quad (5.7b)$$
$$\eta_{\text{cycle}} \geq 0.67 \text{ for shift from 8 to 12 Rp./kWh.} \quad (5.7c)$$

This explains the jumps between $\eta_{\text{cycle}} = 0.60$ and $\eta_{\text{cycle}} = 0.70$ in figure 5.12, both in summer and in winter.

In winter, the CHP is running in gas low-tariff times for an electricity price $\pi_{\text{el}} \geq 8.4\,\text{Rp./kWh}$, and in gas high-tariff times for $\pi_{\text{el}} \geq 17.9\,\text{Rp./kWh}$, when no storage is available[2]. With storage, competition and interaction starts. Grid electricity storage will be preferred to CHP electricity when the prices for the stored kilowatt hour are lower than the electricity prices indicated above. For the different electricity price levels, this is the case for the cycle efficiencies stated in table 5.4.

Table 5.4: Efficiency thresholds of the cycle efficiency η_{cycle} for the use of either CHP electricity or storage discharge; #7.

π_{el} [Rp./kWh]	$\pi_{\text{CHP}} = 8.4\,\text{Rp./kWh}$	$\pi_{\text{CHP}} = 17.9\,\text{Rp./kWh}$
8	$\eta_{\text{cycle}} \geq \frac{8}{8.4} = 0.95$	$\eta_{\text{cycle}} \geq \frac{8}{17.9} = 0.45$
12	$\eta_{\text{cycle}} \geq 1.43$	$\eta_{\text{cycle}} \geq 0.67$
19	$\eta_{\text{cycle}} \geq 2.26$	$\eta_{\text{cycle}} \geq 1.06$

[2] Calculation see footnote 1

Hence, exceeding $\eta_{\text{cycle}} = 0.67$ and $\eta_{\text{cycle}} = 0.95$ the CHP use decreases (fig. 5.13) and storage use augments (fig. 5.11 winter and 5.12), as grid electricity is stored increasingly.

However, the CHP can also be used to charge the storage device and exploit both electricity and gas price variations as it also is in price configuration #6. Applying (5.6) in the same way results in the thresholds listed in table 5.5. Storage is hence charged by the CHP instead of by grid electricity in $\text{LT}_{\text{gas}}/\text{HT}_{\text{el}}$ in all considered cases, and additionally in $\text{LT}_{\text{gas}}/\text{MT}_{\text{el}}$ for $\eta_{\text{cycle}} \geq 0.7$, thus increasing the CHP utilization (fig. 5.13) without effects on the storage use (fig. 5.12). In $\text{HT}_{\text{gas}}/\text{HT}_{\text{el}}$ and for $\eta_{\text{cycle}} \geq 0.94$, the increase superimposes with the decrease due to grid electricity storage instead of CHP use (table 5.4).

Table 5.5: Efficiency thresholds of the cycle efficiency η_{cycle} for the use of the CHP to charge the electric storage device; #7.

π_{gas} [Rp./kWh]	π_{el} [Rp./kWh]	$\eta_{\text{cycle}} \geq$
6	8	1.05
6	12	0.70
6	19	0.44
12.75	8	2.23
12.75	12	1.49
12.75	19	0.94

With Demand Response

Demand response is introduced with

$$H_{\max}^{(\text{el})} = 0.2\,\text{kW}, \; J^{(\text{el})} = 1\,\text{kWh}, \; \Delta T^{(\text{el})} = 5\,\text{h}. \tag{5.8}$$

The demand response utilization is approximately constant for all η_{cycle}, with a slight decline towards $\eta_{\text{cycle}} = 1$. Storage use is reduced by 0.02 - 0.07 p.u. (PV4500) and by up to 0.1 p.u. (PV500) in summer and stays about the same in winter, compared to the case without demand response. As a consequence, the efficiency's influence on the

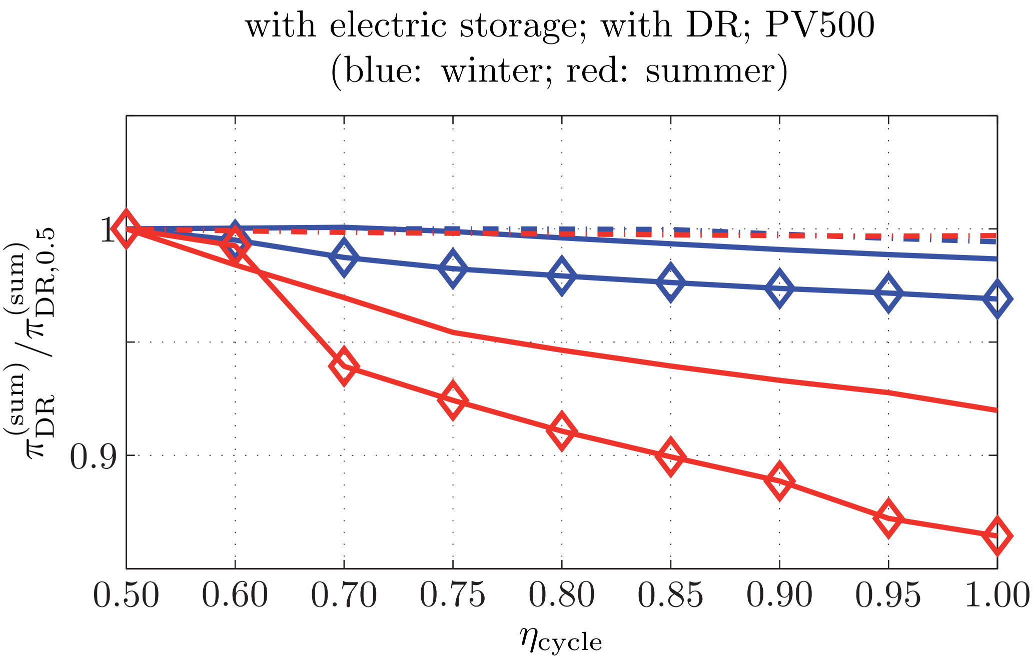


Figure 5.14: Energy costs with demand response, $\pi^{(sum)}_{DR}$, related to costs at $\eta_{cycle} = 0.5$, $\pi^{(sum)}_{DR,0.5}$

overall costs is significantly reduced (compare figures 5.9 and 5.14 for PV500). Again, a competition between electric demand response and electric storage can be seen: demand response reduces the storage utilization and hence its benefit. However, the trends in CHP and storage use observed for the case without demand response can also be made for the case with demand response.

5.1.3 Influence of the Available Storage Capacity (Electric Storage)

Following, the available storage capacity of the electric storage device, $E_{serv} = E_{max} - E_{min}$, is varied. Therefore, E_{max} is kept constant at 15 kWh, and the lower boundary E_{min} is increased from 1 kWh to 14 kWh. The other storage and the demand response parameters are set according to table 4.3 and (5.8). Price constellations #3, #6 and #7 are examined.

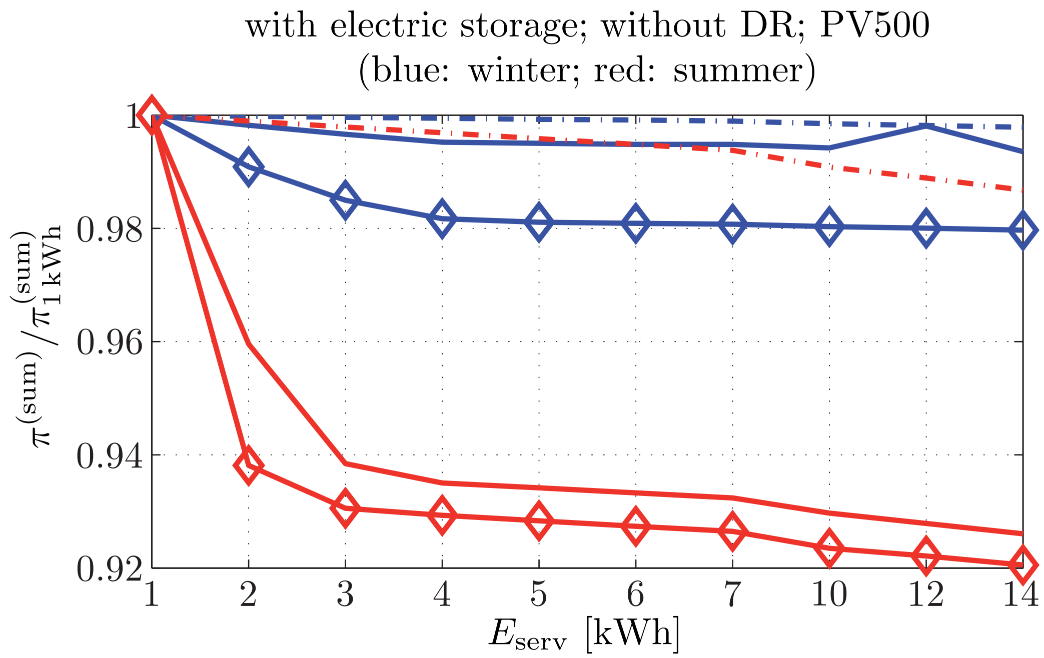


Figure 5.15: Energy costs $\pi^{(\text{sum})}$ related to costs at $E_{\text{serv}} = 1\,\text{kWh}$, $\pi^{(\text{sum})}_{1\,\text{kWh}}$.

Without Demand Response

Fig. 5.15 shows the costs depending on the storage capacity E_{serv} for PV500. In price constellations #3 and #7, the costs in summer are mainly decreased for an increase of E_{serv} from 1 kWh to 3 kWh. Then the costs saturate. This is also the case in winter, but with a smaller impact and a saturation a bit later. In constellation #6, storage is nearly not used due to the constant electricity price. Hence, the influence of the storage capacity on the costs is rather small. The amount of stored power[3] (fig. 5.16) follows the same trends.

For PV4500, the storage device is used also in price constellation #6, as excess renewable electricity can be stored. In analogy with PV500, the costs mainly decrease between $E_{\text{serv}} = 1\,\text{kWh}$ and $E_{\text{serv}} = 3\,\text{kWh}$ and then saturate for the three price constellations in summer. However, the cost savings are much higher ($25 - 30\,\%$) than for PV500 ($6 - 8\,\%$). In winter the influence of the storage device is much lower.

[3] A separate analysis of input and output power of the storage device is not necessary as the cycle efficiency is the same for all compared cases, see section 5.1.2.

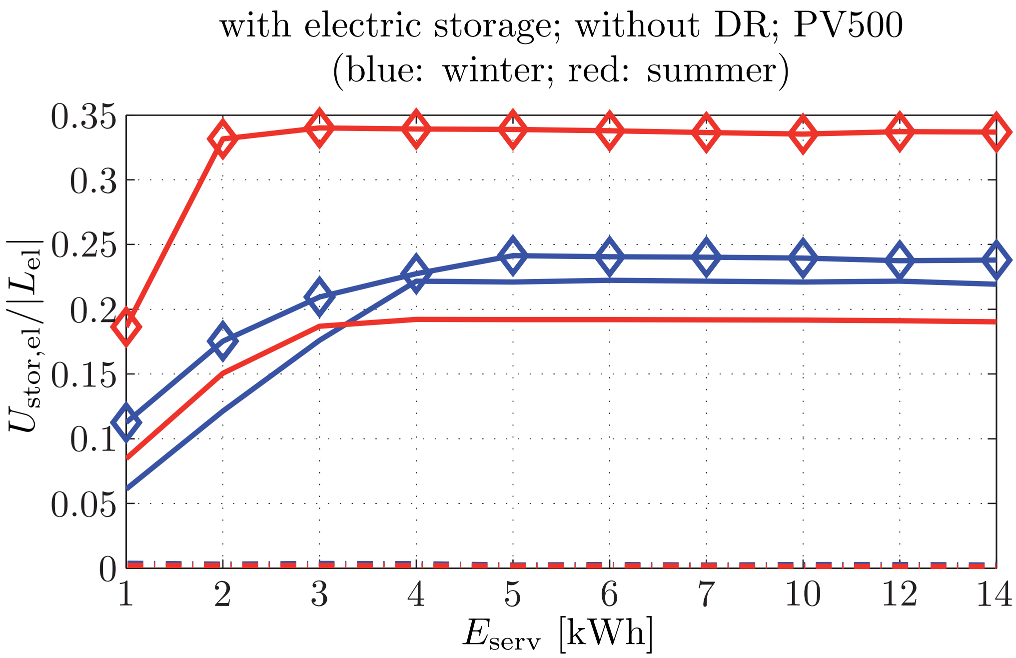


Figure 5.16: Electric storage utilization, $U_{stor,el}$, related to sum of electric load, $|L_{el}|$.

With Demand Response

When demand response is introduced, the potential to save costs with increasing storage capacity declines (compare figures 5.15 and 5.17 for PV500). The application of demand response reduces the storage utilization by up to 0.07 p.u.. As a consequence, the cost savings potential of the device decreases by around 0.04 - 0.05 p.u. (PV500) and 0.05 - 0.06 p.u. (PV4500), respectively.

The amount of shifted load stays approximately constant for all values of E_{serv}. Only for PV4500 and in summer the demand response use decreases slightly by around $0.02 \cdot |L_{el}|$ for an increase from $E_{serv} = 1$ kWh to 3 kWh, where $|L_{el}|$ is the sum of electric load in the considered period. The reduction in demand response use is due to the following: demand response is lossless, but regarding both power and energy its potential is lower than that of the lossy storage device. Renewable electricity generation far exceeds the demand. Consequently, the storage device is more appropriate to handle the PV electricity than is demand response, resulting in a diminution of demand response as soon as enough storage capacity is available.

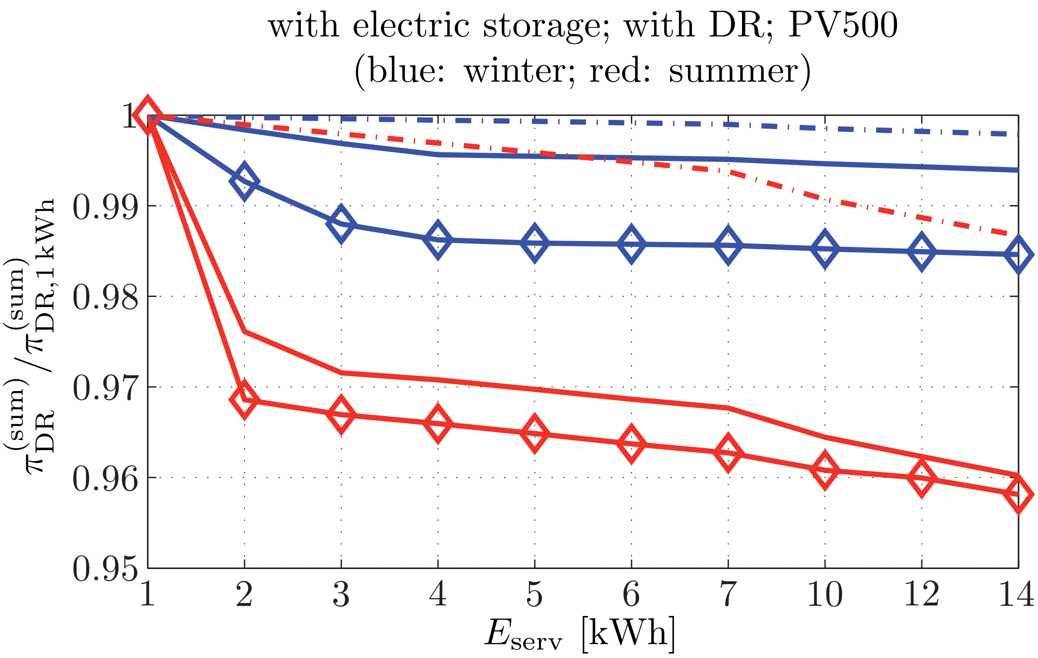


Figure 5.17: Energy costs with demand response, $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$ related to costs at $E_{\mathrm{serv}} = 1\,\mathrm{kWh}$, $\pi_{\mathrm{DR,1\,kWh}}^{(\mathrm{sum})}$.

5.1.4 Influence of the Optimization Horizon and the Solution Horizon

The joint consideration of several time steps allows the exploitation of price variations, thermal and electric demand response and energy storage. The optimization horizon N_{int} defines the number of time steps optimized together. It specifies the data available for the determination of the optimal solution, while the solution horizon N_{sol} influences the flexibility of the optimal result. Consequently, both parameters have to be reasonably set. Their impact on the optimization outcome is examined in the following paragraphs.

Electric demand response can be used to decrease costs. Its applicability, however, is limited by the optimization horizon (appendix C.2, (C.4)). The influence of the optimization parameters is evaluated for PV4500 and for different values of $H_{\max}^{(\mathrm{el})}$. The complete year is simulated for price constellation #1.

Table 5.6 shows the electricity costs $\pi^{(\mathrm{el})}$ depending on the optimization parameters and the DR parameter $H_{\max}^{(\mathrm{el})}$. Generally, the savings

Table 5.6: Electricity costs $\pi^{(el)}$ depending on the optimization parameters N_{int}, N_{sol} and the demand response parameter $H_{\text{max}}^{(el)}$; percentage values related to the value for $H_{\text{max}}^{(el)} = 0.1\,\text{kW}$ and $N_{\text{int}} = 4,\ N_{\text{sol}} = 2$; year; PV4500; #1.

		$H_{\text{max}}^{(el)}$ in [kW]					
		0.1	0.2	0.4	0.8	1.0	1.5
$N_{\text{int}}/N_{\text{sol}}$	4/2	100.0	97.8	89.3	85.0	83.7	81.9
	4/4	102.3	99.9	94.1	90.7	89.7	87.4
	8/4	96.6	94.4	78.2	67.5	68.4	64.9
	12/4	94.4	92.5	69.8	53.7	54.4	50.2
	12/8	94.6	92.9	72.2	60.4	59.8	57.9
	24/12	92.3	91.9	63.4	44.9	46.7	43.5
	24/24	93.5	92.4	64.4	46.2	47.9	43.4

are higher the more flexible the demand response and the larger the optimization horizon is. However, a large $H_{\text{max}}^{(el)}$ in combination with a small optimization horizon N_{int} only helps little to decrease costs. The same holds true for a small $H_{\text{max}}^{(el)}$ and a large N_{int}. Also, a saturation can be noticed for values of $H_{\text{max}}^{(el)} > 1.0\,\text{kW}$, as the maximum required power is around 1.1 kW. Hence, it is neither necessary nor possible to shift more load. The influence of the solution horizon N_{sol} is larger for smaller optimization horizons N_{int} and larger values of $H_{\text{max}}^{(el)}$. Generally, a smaller solution horizon allows larger cost savings due to a better adaptation of the optimization results to future situations.

Unfortunately, the computational time T_{comp} is also strongly dependent on the optimization parameters (table 5.7). It rises with increasing optimization horizon N_{int} and reduces with increasing solution horizon N_{sol}.

It is important to notice that large differences exist between the electric demand response potential in winter and in summer, not only

Table 5.7: Values of the objective function $\mathcal{F}$ (4.24) and computational time T_{comp} depending on the optimization and solution horizons, N_{int} and N_{sol}; objective function values $\mathcal{F}$ related to the value for $N_{\text{int}} = 1$ and $N_{\text{sol}} = 1$.

N_{int}	N_{sol}	$\mathcal{F}$	T_{comp}
1	1	1	4 min
2	1	0.998	11 min
4	1	0.973	52 min
4	2	0.974	26 min
6	3	0.939	40 min
10	2	0.912	3.5 h
10	5	0.924	1.4 h
20	10	0.882	2.5 h

with regard to the costs (table 5.8), but also with regard to the required grid electricity and the exploitation of locally available renewable energy. In summer, increased DR flexibility together with a large optimization horizon allows a proper exploitation of the available PV electricity and hence significant savings on electricity costs. The costs are not dominated by thermal load, so the effects of electric demand response on the overall costs are well noticeable. In winter, the effects are much smaller as less PV electricity is available and thermal load dominates.

5.1.5 Influence of the Amount of Local Photovoltaic Electricity

Locally available renewable electricity supports the load supply. The electricity can be consumed immediately, but exploitation can be increased when storage or demand response are at disposal. The following paragraphs examine the interaction of renewable generation, energy storage and demand response.

Table 5.8: Electricity costs $\pi^{(\mathrm{el})}$ depending on the optimization parameters N_{int} and N_{sol} and the demand response parameter $H^{(\mathrm{el})}_{\mathrm{max}}$; percentage values related to the value for $H_{\mathrm{el}} = 0.1\,\mathrm{kW}$, $N_{\mathrm{int}} = 4$, $N_{\mathrm{sol}} = 2$; PV4500.

		summer		winter	
		H_{el} in [kW]			
		0.1	1.5	0.1	1.5
	4/2	100.0	84.0	100.0	83.0
$N_{\mathrm{int}}/N_{\mathrm{sol}}$	12/4	82.8	3.0	97.2	71.5
	12/8	83.8	14.4	97.4	74.2

Electric storage device

The presence of renewable electricity itself reduces the energy costs because less load has to be supplied by the grid or the CHP. However, the introduction of an electric storage device (table 4.3) significantly increases the PV utilization, especially in summer, as excess electricity can be stored for times with load surplus. Figure 5.18 shows the overall energy costs with storage related to the costs without. In summer, the electric storage device notably reduces the costs to around 60 % − 70 % for a yearly renewable generation of $\sum_{t=1}^{8760} R_{\mathrm{el}}(t) \geq 2000\,\mathrm{kWh}$. Storage utilization only changes little above this value (fig. 5.19), as further storage is not economic within the considered framework. Storage use would most probably increase again when N_{int} increases, or if excess electricity would have to be stored whenever possible.

In summer, the additional introduction of demand response (5.8) allows for a further cost reduction to around 75 − 82 % (fig. 5.20) compared to only storage for $\sum_{t=1}^{T_{\mathrm{end}}} R_{\mathrm{el}}(t) \geq 2500\,\mathrm{kWh/a}$. Nevertheless, demand response reduces the storage utilization by around 5 % (fig. 5.19). The influence of demand response does not continuously increase with rising PV generation, but goes into saturation for $\sum_{t=1}^{T_{\mathrm{end}}} R_{\mathrm{el}}(t) \geq 2500\,\mathrm{kWh/a}$. The amount of shifted load varies by

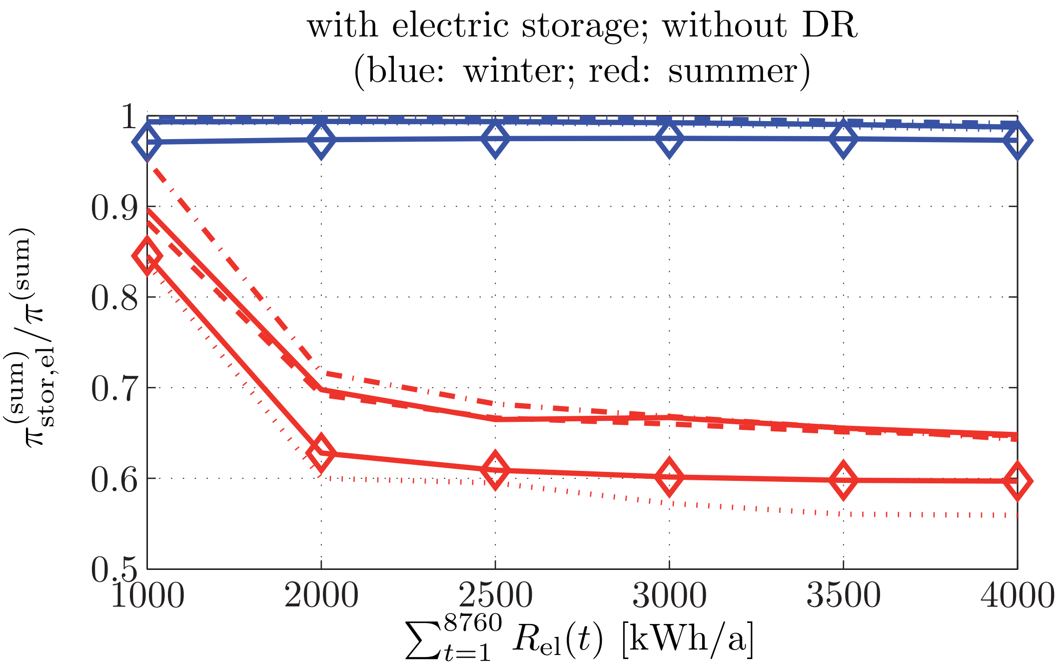


Figure 5.18: Energy costs with electric storage, $\pi_{\mathrm{stor,el}}^{(\mathrm{sum})}$, related to costs without storage, $\pi^{(\mathrm{sum})}$.

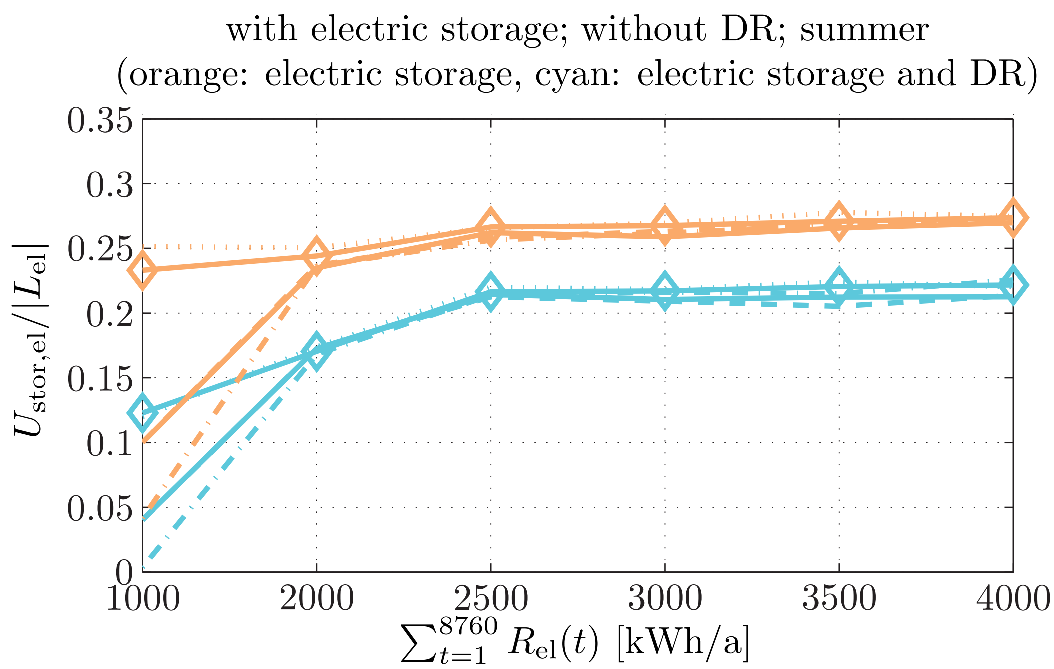


Figure 5.19: Electric storage utilization, $U_{\mathrm{stor,el}}$, related to sum of electric load, $|L_{\mathrm{el}}|$.

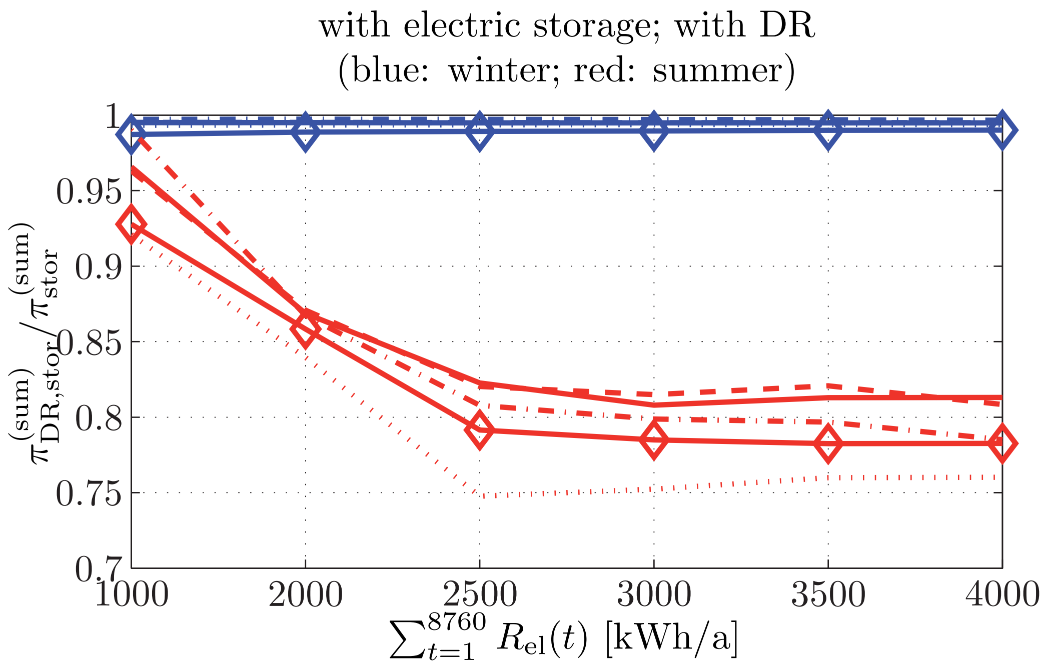


Figure 5.20: Energy costs with demand response and electric storage, $\pi^{(sum)}_{DR,stor}$, related to costs with only electric storage, $\pi^{(sum)}_{stor}$.

around 1 % for $\sum_{t=1}^{T_{end}} R_{el} \geq 2000$ kWh/a (fig. 5.21). Between PV1000 and PV2000, the demand response use reduces notably for price configurations #5 and #7, as less electric load has to be shifted from HT_{el} to MT_{el} or LT_{el}. For price constellations #3, #4 and #6, it is the other way round: more load has to be shifted to better exploit the renewable resources. Exceeding PV2000, all configurations behave similar.

In winter, the influence on the costs of both electric storage device and demand response is low (figures 5.18 and 5.20). Demand response and electric storage device compete, and storage utilization is decreased by demand response (fig. 5.22). Although the amount of shifted electric load is nearly constant at around 10 % to 14 % of the electric load (fig. 5.21), the storage use decreases with increasing PV electricity except for price constellation #6.

- In price constellation #6, no variations exist in the electricity price. Consequently, storage is only applied to fit demand and generation if surplus renewable electricity is available and the demand response potential is exhausted. This is a seldom case, but more frequent with increasing renewable generation.

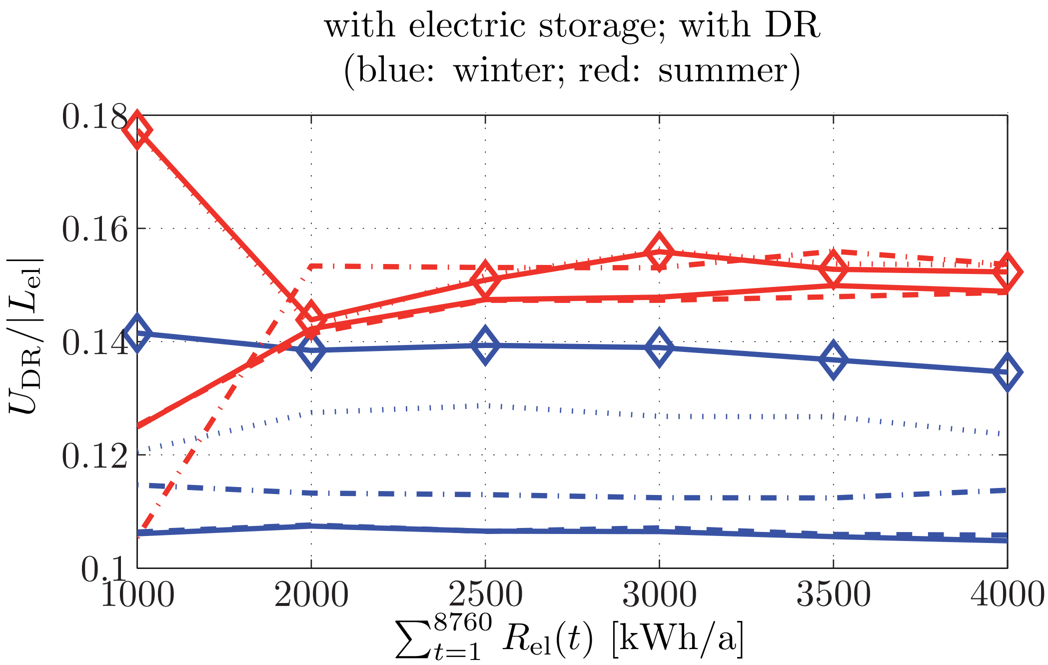


Figure 5.21: Demand response utilization, U_{DR}, related to sum of electric load, $|L_{\mathrm{el}}|$.

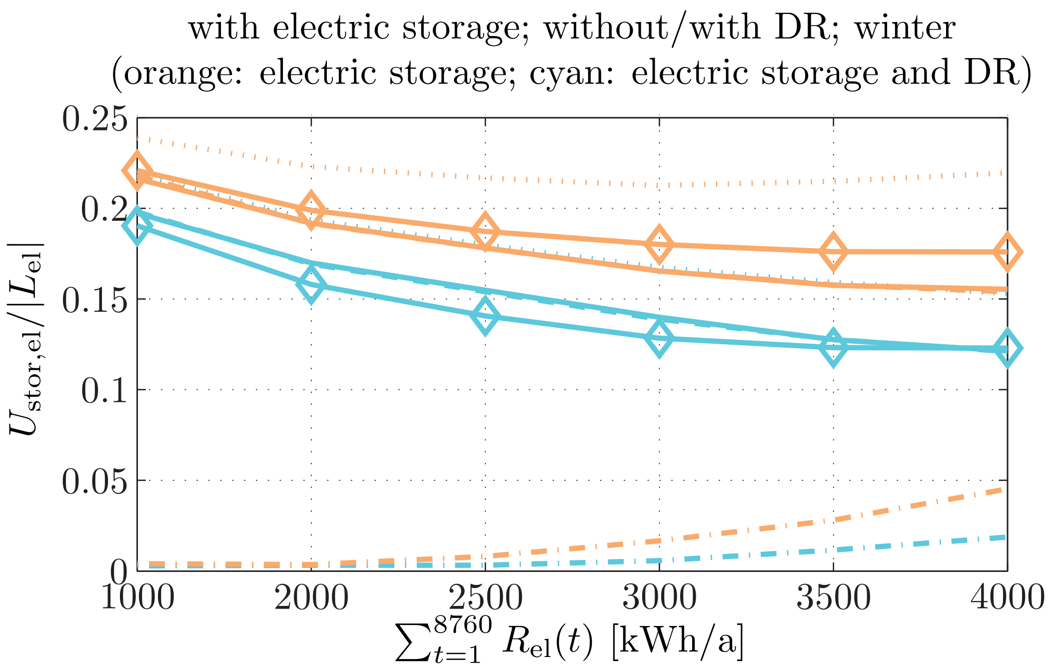


Figure 5.22: Electric storage utilization, $U_{\mathrm{stor,el}}$, related to sum of electric load, $|L_{\mathrm{el}}|$.

(blue: 1000 kWh/a; red: 2000 kWh/a; green: 2500 kWh/a; yellow: 3000 kWh/a; cyan: 3500 kWh/a; magenta: 4000 kWh/a)

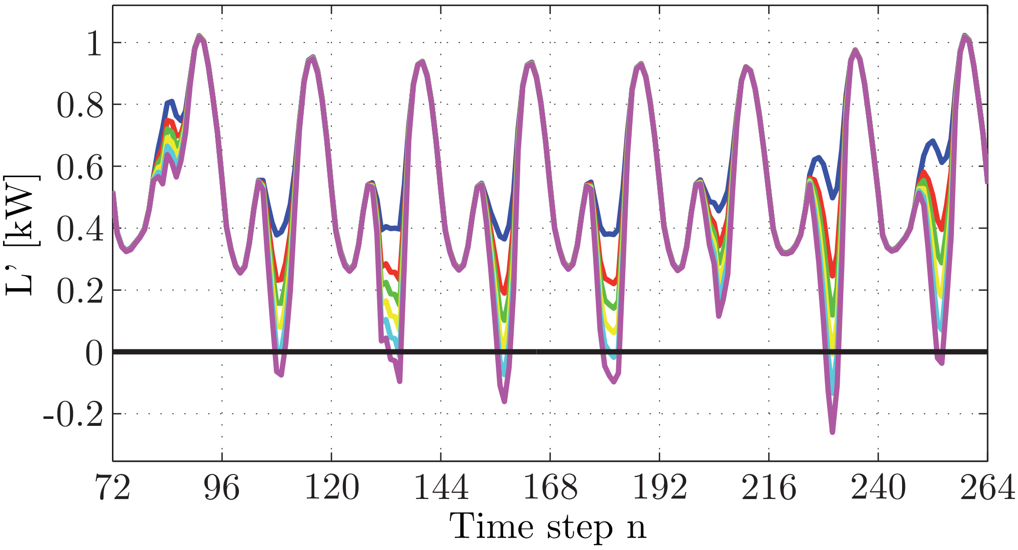


Figure 5.23: Residual load $L' = L_{\mathrm{el}} - R_{\mathrm{el}}$ in winter for increasing amounts of renewable electricity.

- The load curve $L'_{\mathrm{el}}(t)$ that has to be supplied in the presence of PV electricity can be determined as

$$L'_{\mathrm{el}}(t) = L_{\mathrm{el}}(t) - R_{\mathrm{el}}(t). \tag{5.9}$$

  Increasing renewable generation reduces $L'_{\mathrm{el}}(t)$ (fig. 5.23). The evening peak is nearly not affected by the amount of renewable electricity, as sun is setting before. But the midday peak is increasingly reduced for rising renewable generation. Consequently, less electricity has to be stored to cut the peak. Only when excess electricity starts to be available (for $\sum_{t=1}^{T_{\mathrm{end}}} R_{\mathrm{el}} \geq$ 3500 kWh/a), the storage use starts to increase again.

Thermal storage device

The introduction of an electrically heated hot water tank (table 4.3) reduces the overall costs compared to the base case (no storage, no DR) (fig. 5.24). In summer the savings potential is with around 25−37 % smaller than that of the electric storage (30−45 %, fig. 5.18), as thermal load is relatively small. The major cost decrease occurs between PV1000 and PV2000, but also for higher amounts of PV

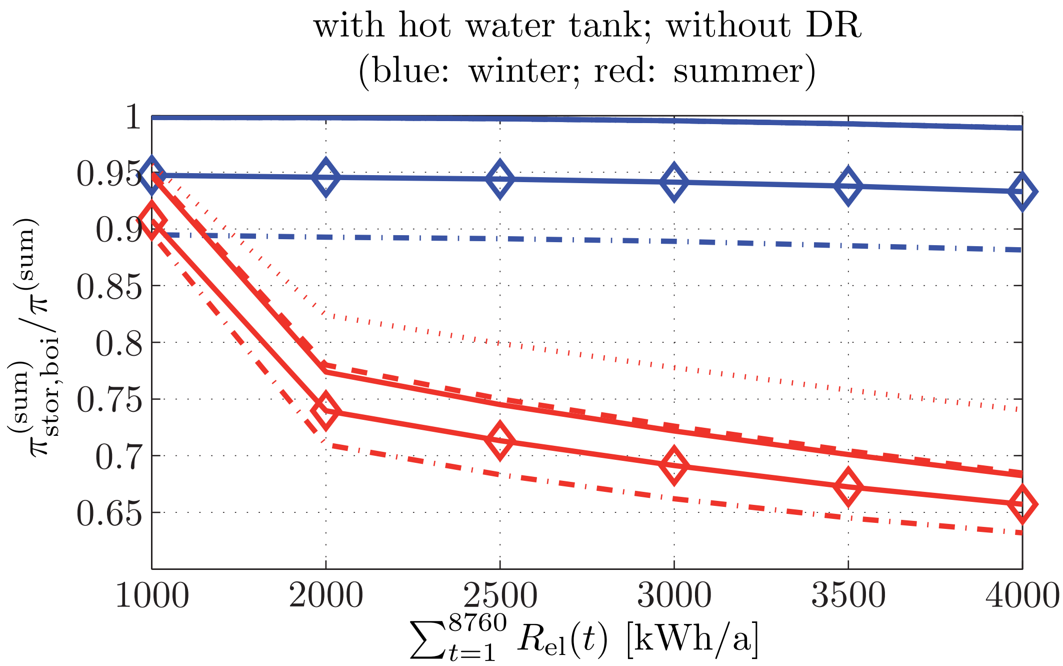


Figure 5.24: Energy costs with hot water tank, $\pi^{(\mathrm{sum})}_{\mathrm{stor,boi}}$, related to costs without storage, $\pi^{(\mathrm{sum})}$.

electricity costs can be decreased further due to the fact that PV electricity can be used both for electric and thermal load supply.

In winter, the hot water tank allows a constant cost reduction of around 6 % to 11 % for price configurations #7 and #6, respectively. The device is used to exploit changes in the electricity price for thermal load supply. Excess electricity is barely available (fig. 5.23) and consequently without major influence on the costs (price configurations #3, #4 and #5).

In summer additional demand response (5.8) significantly reduces the costs compared to only thermal storage (fig. 5.25). The savings potential of demand response in combination with a hot water tank is higher than combined with an electric storage device, namely up to 35 % instead of up to 25 %, respectively. Also, saturation is less abrupt, as electric demand response and thermal storage cooperate by affecting different load curves. In winter, however, the additional demand response flexibility does not alter the costs significantly.

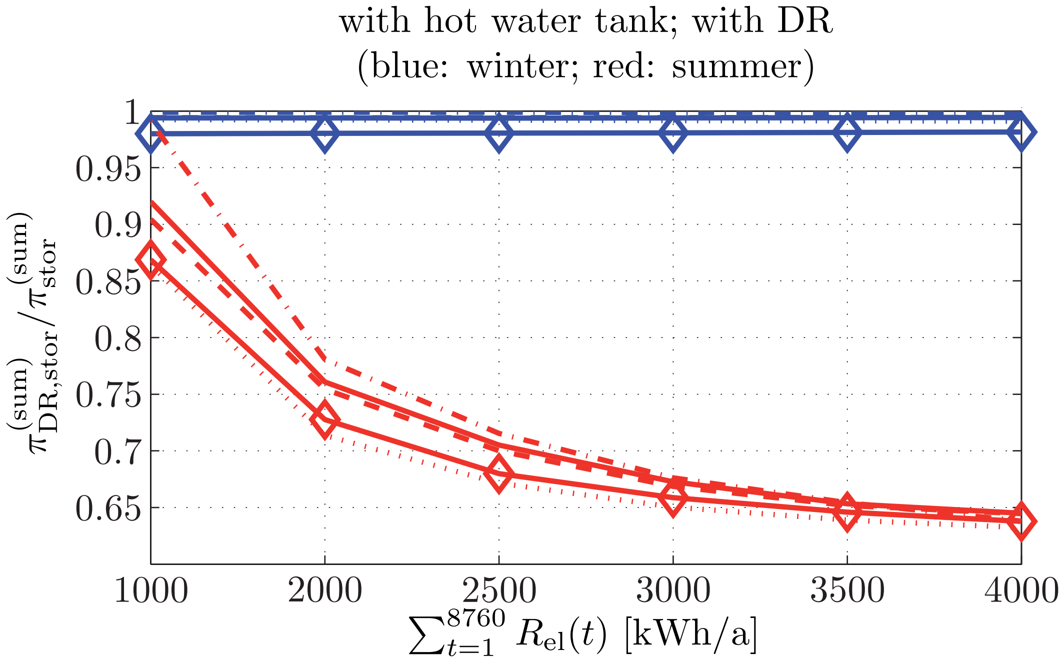


Figure 5.25: Energy costs with demand response and hot water tank, $\pi^{(\mathrm{sum})}_{\mathrm{DR,stor}}$, related to costs with only hot water tank, $\pi^{(\mathrm{sum})}_{\mathrm{stor}}$.

The utilization of thermal storage notably differs from that of an electric storage device:

- In winter and for all examined amounts of renewable electricity, hot water storage is nearly not used at all for price constellations #3, #4 and #5. No excess renewable electricity is available and it is more economic to supply thermal load demand with CHP and furnace instead of via grid electricity and hot water tank. In constellations #6 and #7, however, thermal storage is charged with around 1.4 and 1.7 times the electric load demand, respectively, as in high gas-tariff times it is economically viable to supply thermal load with the hot water tank instead of with furnace or CHP. This is independent of the amount of renewable energy, hence storage utilization is constant for all scenarios.

- In summer, the availability of demand response increases thermal storage use (fig. 5.26), showing a synergy effect for coupling (renewable) electric generation and load with thermal load. But the synergy effects are limited by the amount of renewable energy, the hot water tank and the demand response parameters, resulting in a saturation for $\sum_{t=1}^{T_{\mathrm{end}}} R_{\mathrm{el}} \geq 2000\,\mathrm{kWh/a}$.

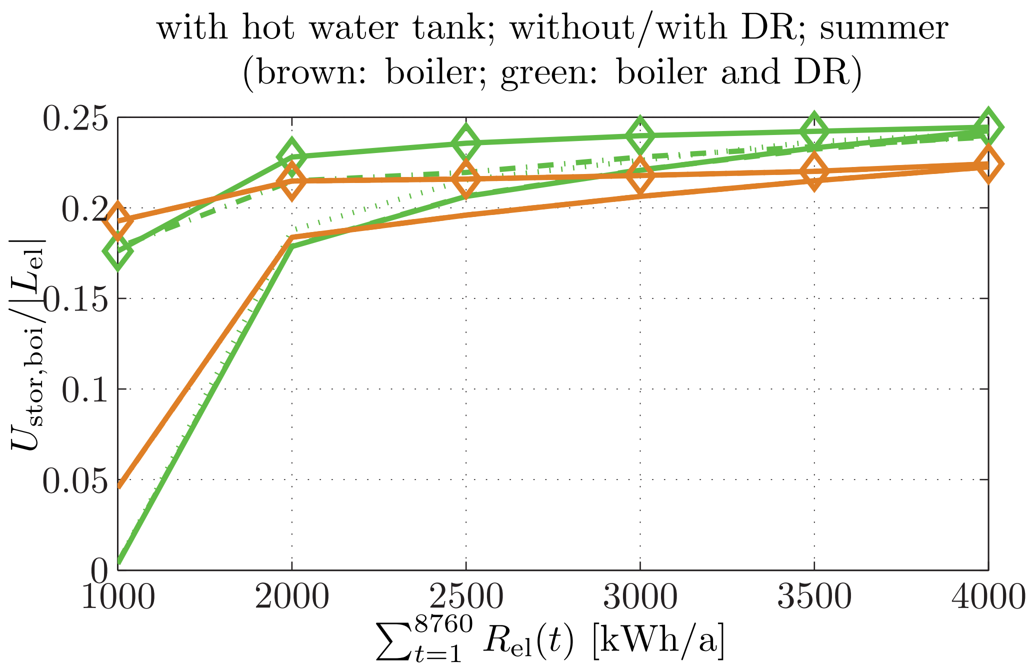


Figure 5.26: Hot water tank utilization, $U_{\mathrm{stor,boi}}$, related to sum of electric load, $|L_{\mathrm{el}}|$.

5.1.6 Verification of the Results for One Year

Parts of the analysis for the Swiss house have been carried out for a complete year, but the larger part was done on the basis of a summer/winter distinction. This allows a sophisticated study of the application of demand response and storage devices under changing conditions. However, the application of both has to prove of value throughout the year, not only in one season. Consequently, a subset of simulations (table 5.9) was carried out to compare the results for the complete year with those of summer and winter.

Generally, the results for the one-year simulations resemble much more the winter than the summer curves (fig. 5.27). The benefits that can be withdrawn both from a storage device and demand response application mainly in summer still exist, but they are dominated by the little savings potential of the winter period and are consequently significantly reduced. This holds true for all simulations carried out (table 5.9).

The dominance of the winter period is caused by the shape of the yearly load profiles (fig. 5.28). Thermal load dominates in most hours

Table 5.9: Overview: Simulations for 8760 time steps, Swiss single-family house.

		price configuration				
variation of		#3	#4	#5	#6	#7
$H^{(el)}_{max}$	PV500					X
	PV4500			X	X	
η_{cycle}	PV500					X
	PV4500					X
E_{serv}	PV500	X				
	PV4500	X				
$\sum_{t=1}^{8760} R_{el}(t)$	el.stor.		X		X	
	therm.stor		X		X	

of the year. Only in the summer period ($t \approx 3800h - 5400h$) when no space heating is required, electric load demand is in about the same range as thermal load. Consequently, the characteristics for the larger part of the year are similar to winter period (4.25), resulting in a significant dominance of the "winter results".

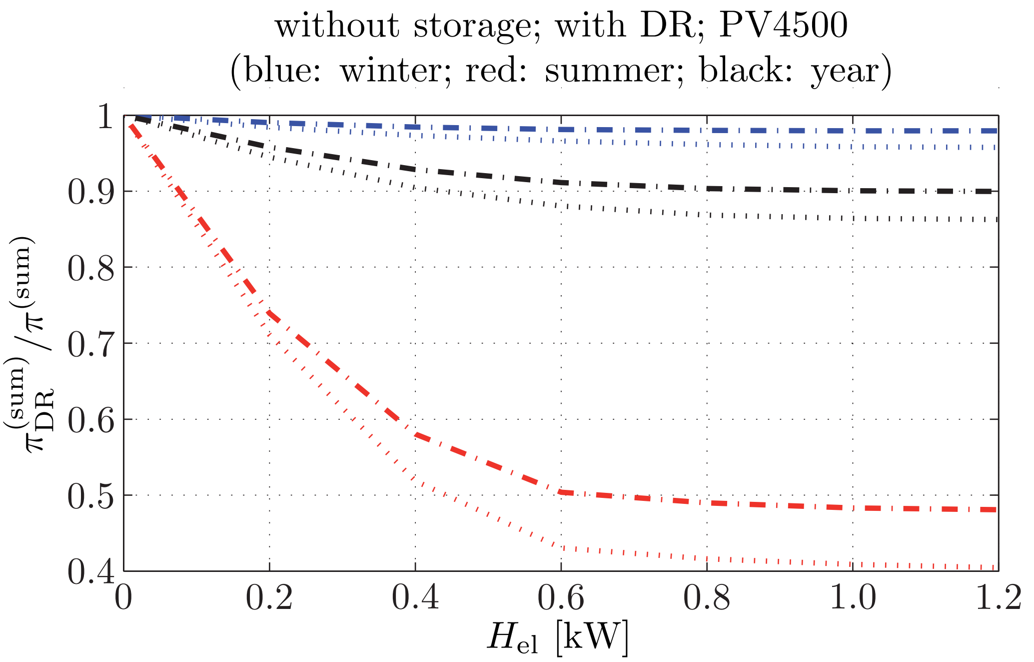


Figure 5.27: Energy costs, $\pi_{DR}^{(sum)}$, related to costs without demand response, $\pi^{(sum)}$.

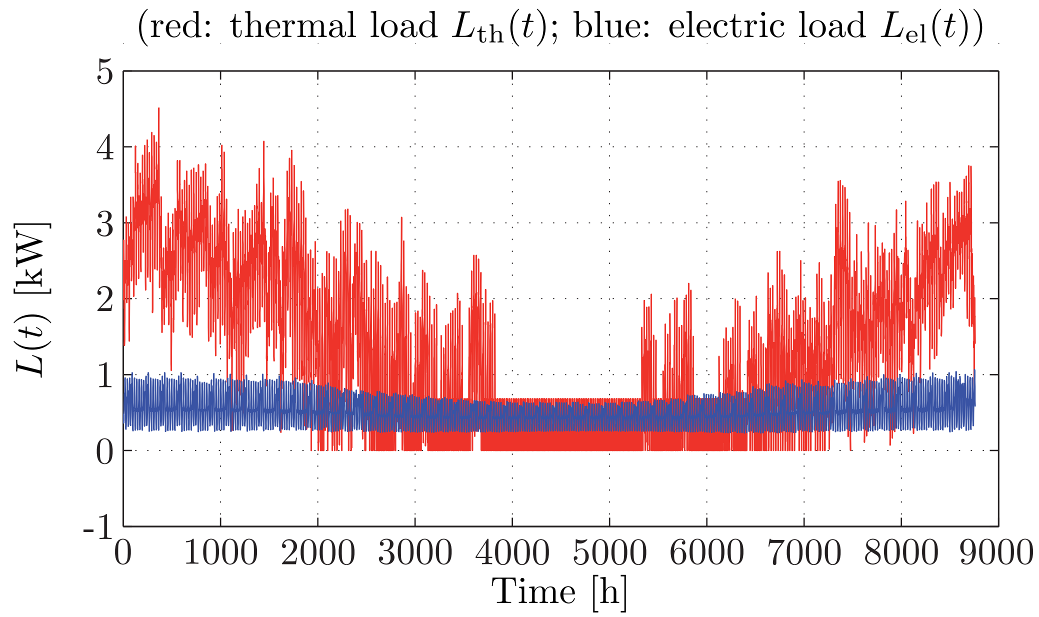


Figure 5.28: Yearly electric and thermal load demand of the Swiss house.

5.2 Influence of the Parameters on Energy Costs and Supply Strategy (House in Hot Climate)

The last section presented the results for the parameter variations of the Swiss house. The same parameters (table 4.6) are now varied for the Spanish single-family house as defined in tables 4.1 and 4.2. The examined cases are depicted in fig. 4.8.

5.2.1 Influence of the Electric Demand Response Parameters

The Swiss simulations showed that the demand response parameter $H_{\max}^{(\mathrm{el})}$ is more influential than $J^{(\mathrm{el})}$ and $\Delta T^{(\mathrm{el})}$. Hence, for the Spanish house only $H_{\max}^{(\mathrm{el})}$ is examined.

Without storage device

For large amounts of renewable electricity (PV4500), the costs constantly decrease with increasing $H_{\max}^{(\mathrm{el})}$, both in summer and winter (fig. 5.29 and 5.30, magenta lines). The demand response utilization increases parallel to the cost decrease. Summer and winter behavior are much more alike than in the Swiss case, as electric load dominates throughout the year. However, load demand differs due to seasonal variations in electricity and cooling requirements and renewable generation (fig. 5.31).

For PV4500, renewable generation far exceeds electric load demand in winter (fig. 5.31(b)). Consequently, a larger $H_{\max}^{(\mathrm{el})}$ can still be exploited, resulting in only a weak saturation in costs (fig. 5.30). Contrarily, load exceeds renewable generation in summer (fig. 5.31(a)). Thus demand response application is limited to price shift exploitation, leading to a saturation of the demand response savings potential. The potential of price configuration #6 is quickly reached ($H_{\max}^{(\mathrm{el})} \geq 0.4\,\mathrm{kW}$) when all excess PV electricity is exploited, while price configurations #5 and #7 have the highest demand response cost decrease capability because of their price structure.

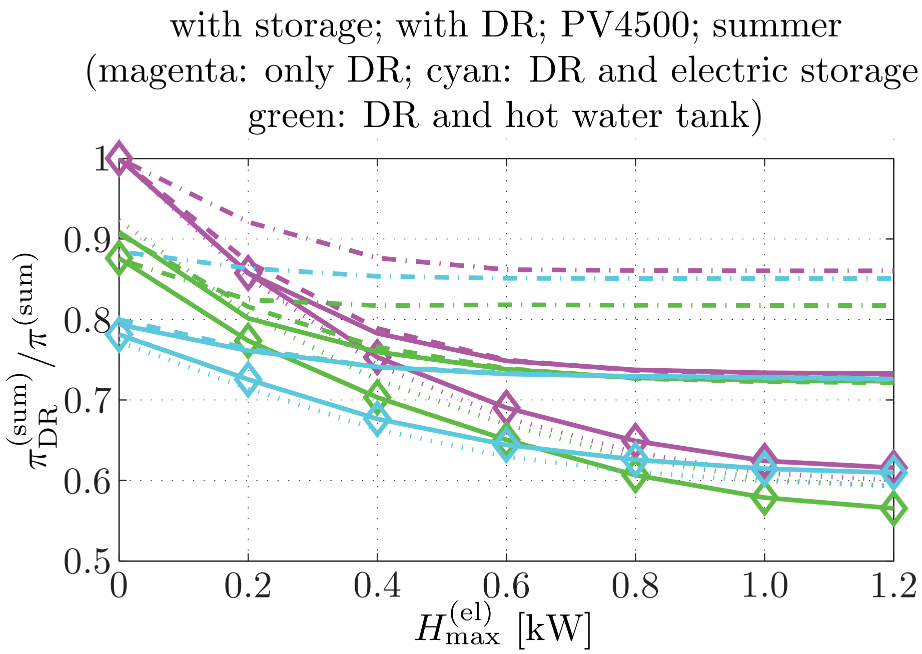


Figure 5.29: Energy costs $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$ related to costs without demand response, $\pi^{(\mathrm{sum})}$.

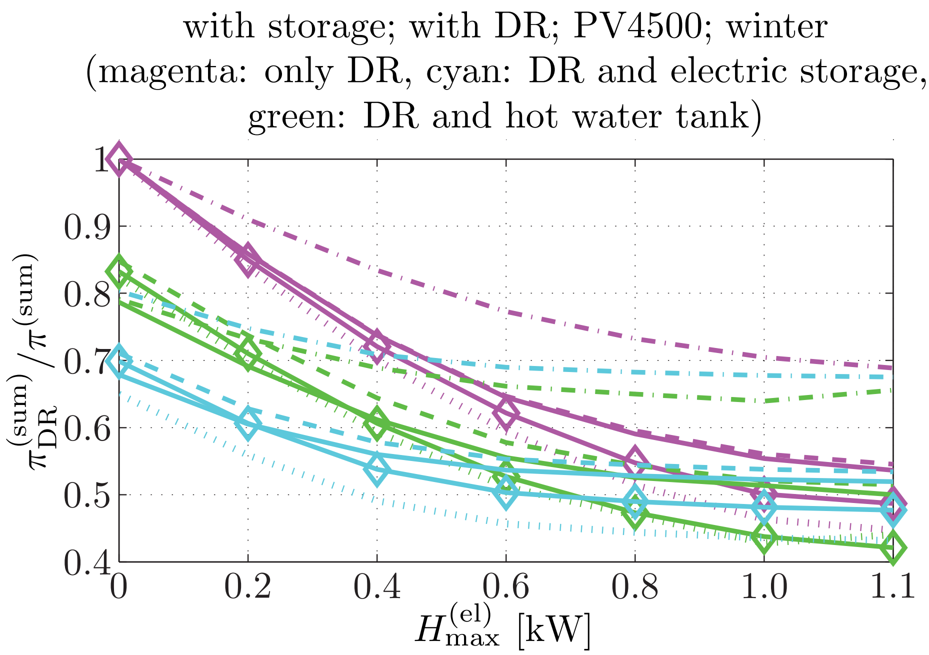
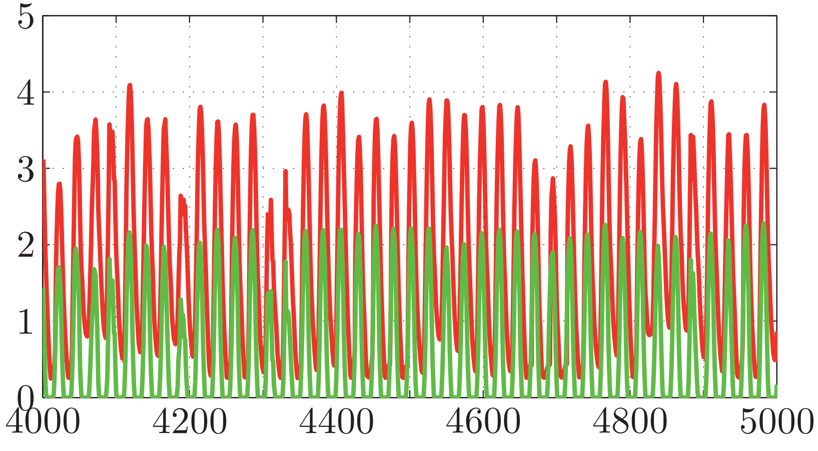
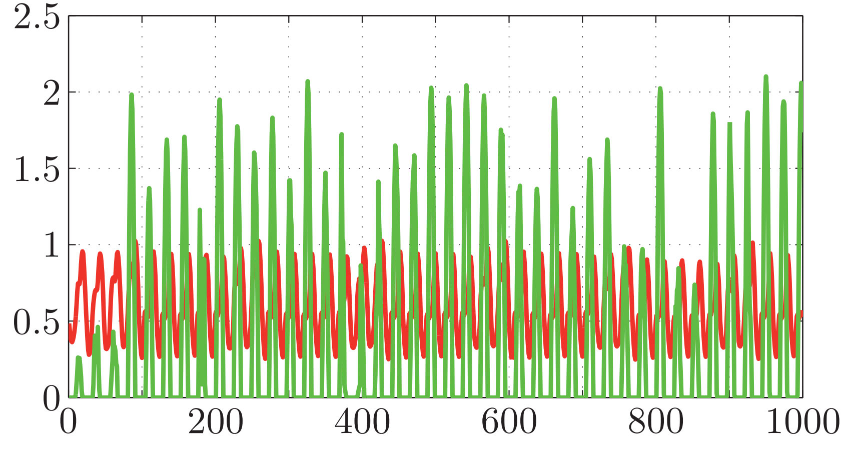


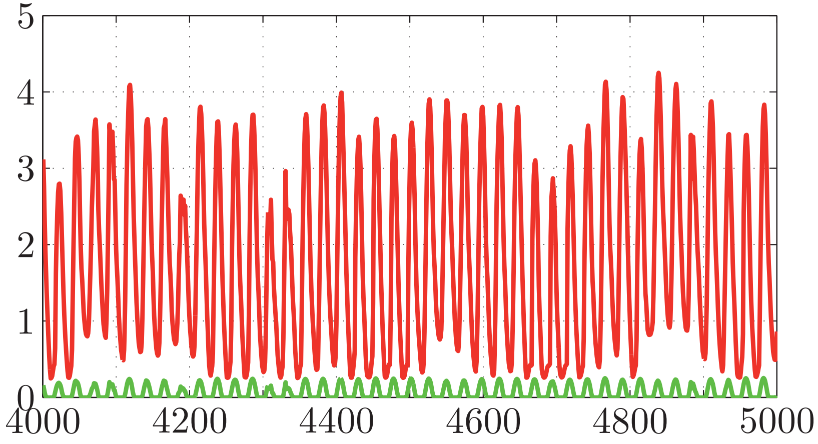
Figure 5.30: Energy costs $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$ related to costs without demand response, $\pi^{(\mathrm{sum})}$.



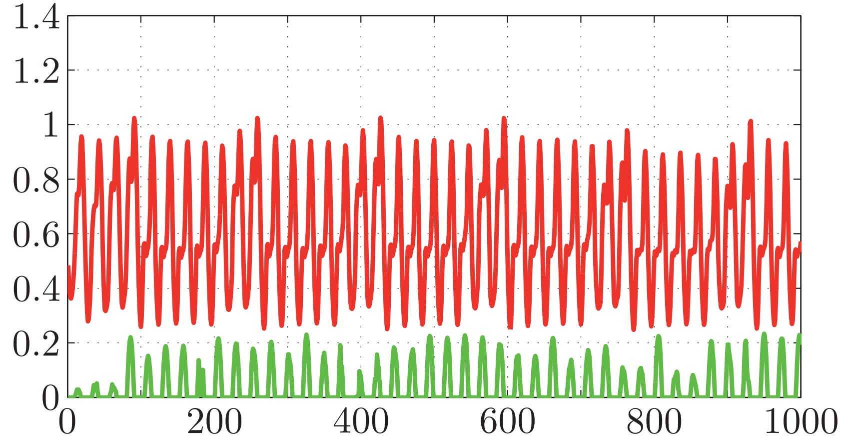
(a) PV4500, summer



(b) PV4500, winter



(c) PV500, summer



(d) PV500, winter

Figure 5.31: Electric load demand $L_{\mathrm{el}}(t)$ and renewable generation $R_{\mathrm{el}}(t)$ (both in [kW]) for the Spanish house for two different amounts of renewable generation, each in summer and in winter (red: $L_{\mathrm{el}}(t)$; green: $R_{\mathrm{el}}(t)$).

For small amounts of renewable electricity (PV500), electric load demand always exceeds renewable generation (figures 5.31(c) and 5.31(d)), but in summer the difference is more pronounced. Consequently, the results are similar to those for PV4500 in summer, but the savings potential of demand response is smaller due to no excess renewable electricity.

With storage device

An electrically heated domestic hot water tank (table 4.3) is introduced into the system. For high amounts of renewable electricity (PV4500), thermal storage (without demand response, $H^{(\mathrm{el})}_{\mathrm{max}} = 0\,\mathrm{kW}$) reduces the costs by around 15 % to 22 % in winter (fig. 5.30, green lines) and 7 % to 12 % in summer (fig. 5.29). The benefit of the hot water tank persists also in the presence of demand response ($H^{(\mathrm{el})}_{\mathrm{max}} > 0\,\mathrm{kW}$), but its cost savings potential reduces.

The presence of the tank slightly increases the utilization of demand response both in winter and in summer (fig. 5.32, PV4500 winter), except for price constellation #6 with no gas price variations. Contrarily, increasing demand response reduces the storage application for price constellations #3, #4 and #5 (fig. 5.33), as demand response and the electrically charged thermal storage compete for the exploitation of electricity price changes. In price constellations #6 and #7, the hot water tank is used at an approximately constant level to economically supply thermal load with grid or renewable electricity.

For small amounts of renewable electricity (PV500), the impact of the hot water storage device on the costs is with $\approx 2\,\%$ (summer) and 3 % (winter) significantly lower than for PV4500, compared to the case with only demand response. Only price variations can be exploited due to a lack of excess renewable electricity, resulting in a constant storage use at around $0.13 \cdot |L_{\mathrm{el}}|$ in winter and $0.18 \cdot |L_{\mathrm{el}}|$ in summer, respectively. As for PV4500, demand response is slightly increased by the hot water tank (fig. 5.34).

The introduction of an electric storage device (table 4.3) reduces the costs more significantly than had thermal storage for $H^{(\mathrm{el})}_{\mathrm{max}} \leq 0.6\,\mathrm{kW}$,

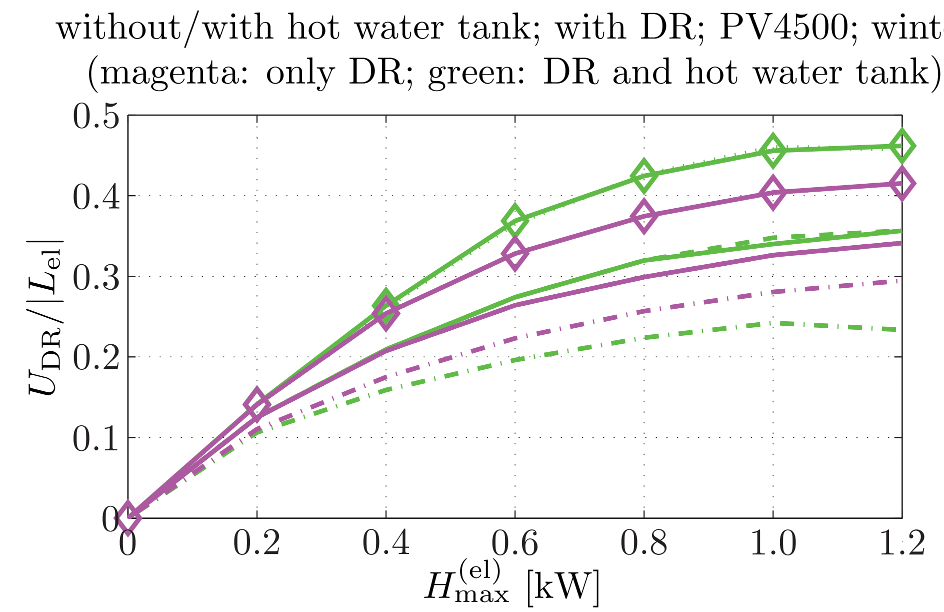


Figure 5.32: Demand response use U_{DR} related to sum of electric load, $|L_{\mathrm{el}}|$.

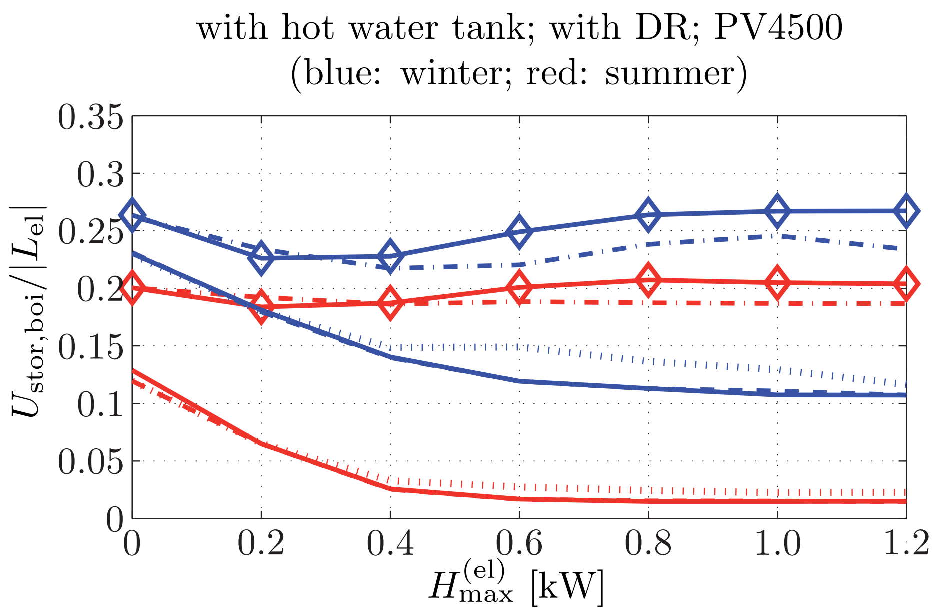


Figure 5.33: Hot water tank use, $U_{\mathrm{stor,boi}}$, related to sum of electric load, $|L_{\mathrm{el}}|$.

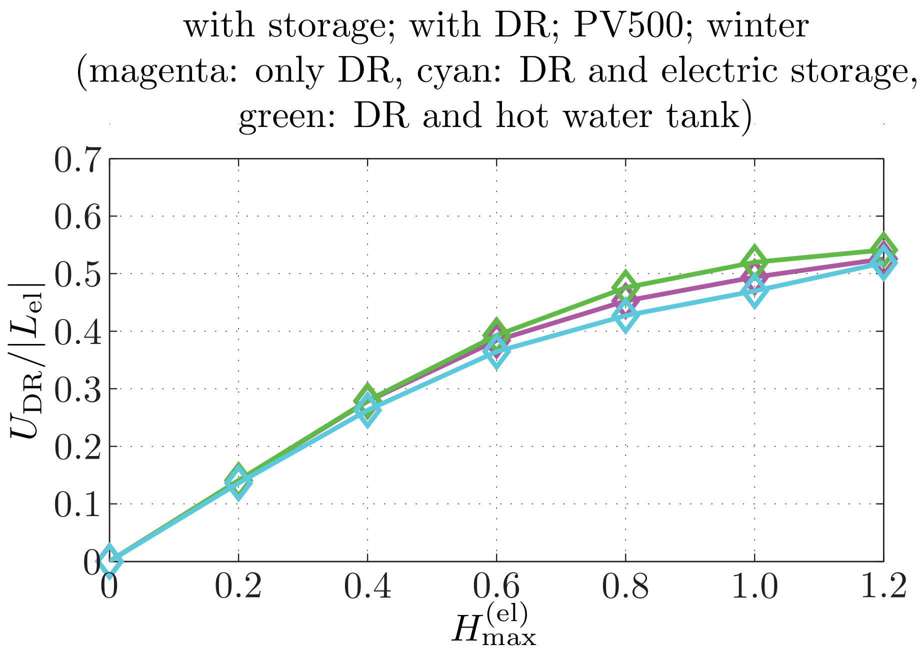


Figure 5.34: Demand response use, U_{DR}, related to sum of electric load, $|L_{\mathrm{el}}|$;price configuration #5.

both for PV500 and PV4500 (fig. 5.29 and 5.30, PV4500). Price constellation #6 is an exception because of the constant electricity price. In the other scenarios, the electric storage device and load shifting cooperate to best exploit the available renewable electricity. However, the cooperation potential is limited by load demand and renewable generation. Consequently, lossy storage application decreases with increasing lossless demand response flexibility (fig. 5.35), resulting in an equalization of energy costs for the cases with (figures 5.29 and 5.30, cyan lines) and without (magenta lines) electric energy storage.

In analogy with the hot water tank, the electric storage device is applied for price shift exploitation only for a low amount of renewable electricity (PV500). Electric storage significantly reduces the costs compared to only demand response with 40 % − 60 % in summer and 1 % − 15 % in winter. Thermal storage only allowed for ≈ 2 % and 4 % reductions, respectively (price configuration #7), as thermal load is much lower than electric load.

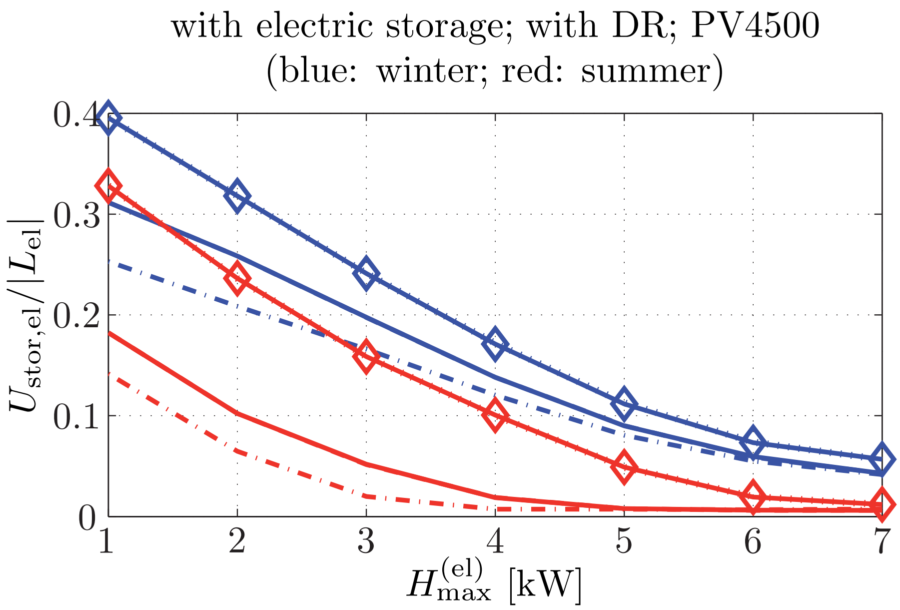


Figure 5.35: Electric storage use, $U_{stor,el}$, related to sum of electric load, $|L_{el}|$.

5.2.2 Influence of the Cycle Efficiency (Electric Storage)

In analogy with the Swiss case, an electric storage device (table 4.3) is introduced to the Spanish house, and the effects of a varying cycle efficiency η_{cycle} are examined.

Without Demand Response

Both for small (PV500) and large (PV4500) amounts of renewable electricity, the costs decrease about linearly for increasing cycle efficiency η_{cycle} (figure 5.36 for PV500). As in the Swiss case, with increasing η_{cycle} costs can be decreased more for PV4500 than for PV500. The cost decline is more pronounced in winter, but the differences between the seasons are smaller than for the Swiss house. A slight bend in the costs can be observed at $\eta_{cycle} = 0.7$ for price constellation #7 (fig. 5.36), as storing low-tariff electricity for consumption during high-tariff times becomes economically viable here (fig. 5.37) (see section 5.1.2). The amount of energy transferred to the storage then decreases due to declining storage losses. In price constellation #6, the storage device is not used for low amounts of renewable electricity (fig. 5.37) and hence is without influence on the costs (fig. 5.36). Storage utilization is generally around 0.1 p.u.

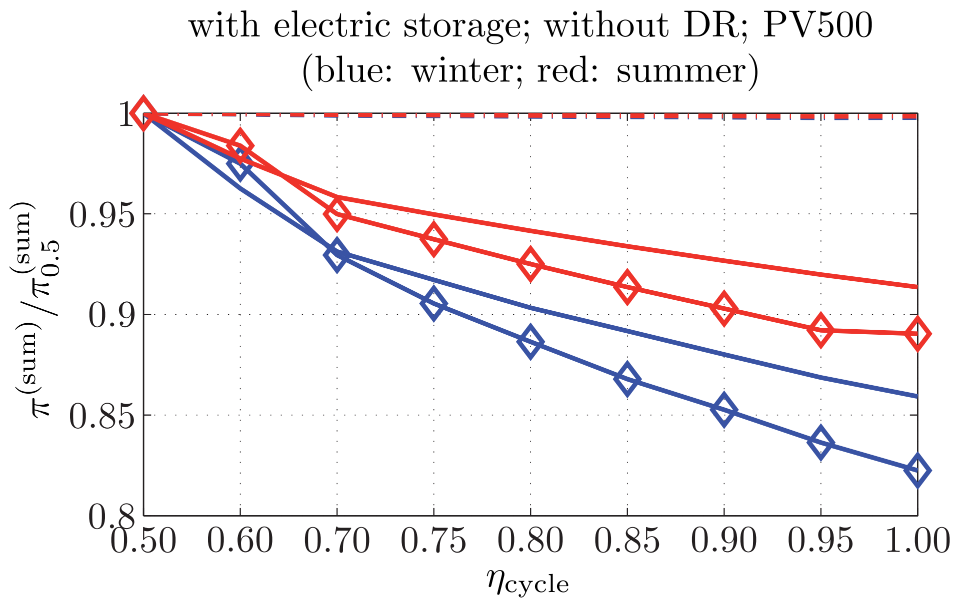


Figure 5.36: Energy costs $\pi^{(\text{sum})}$ related to costs at $\eta_{\text{cycle}} = 0.5$, $\pi^{(\text{sum})}_{0.5}$.

higher for PV500 than for PV4500, as the resulting load $L^{'}$ (5.9) which has to be supplied is smaller for a higher renewable share.

The storage utilization in summer is lower than in winter for PV4500. Figure 5.31(a) shows the electric load demand and the renewable generation in summer. It can be clearly seen that the peaks in load demand correlate with the peaks in PV generation, as the cooling demand depends both on the outside temperature and solar irradiation. Consequently, a large part of the renewable electricity can be consumed immediately without need for storage. In winter, renewable generation exceeds load demand (fig. 5.31(b)) and storage capacity is required. With only little renewable electricity available it is the other way round. The storage device is mainly used to exploit price variations. In winter, less electricity is required due to missing cooling load, and consequently the storage device is used less than in summer.

With Demand Response

Demand response is applied at a constant level independent of η_{cycle}. Its introduction reduces the electric storage utilization. As a consequence, the influence of the cycle efficiency η_{cycle} on the overall

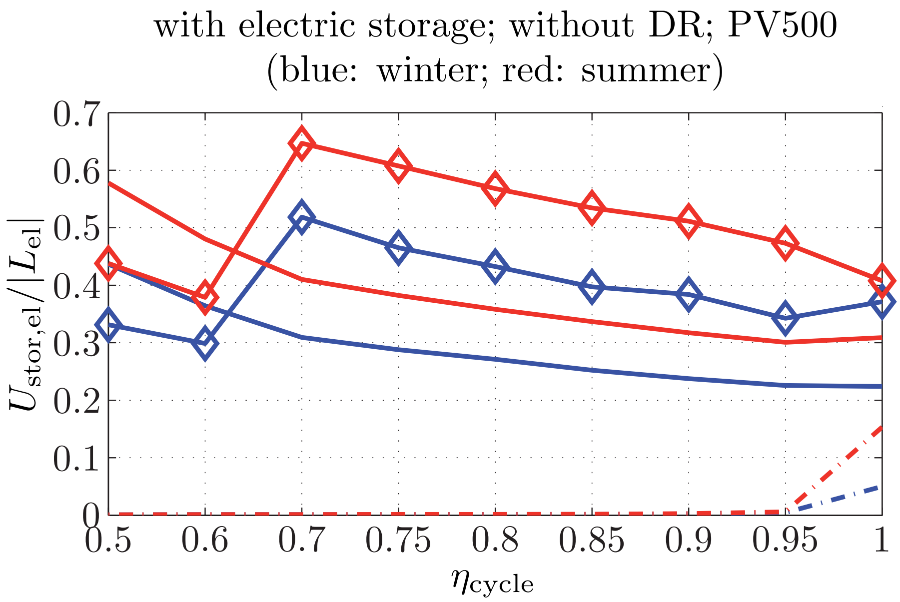


Figure 5.37: Energy charged to the electric storage device, $U_{\text{stor,el}}$ related to sum of electric load, $|L_{\text{el}}|$.

costs is decreased for PV4500 in summer. However, for PV500 and for PV4500 in winter, the reduction resulting from increasing η_{cycle} is about the same as without demand response. For PV4500 summer (fig. 5.31(a)) enough excess electricity is available to exploit both storage and demand response. For PV500, the analogue case holds true with enough load. Only for PV4500 in winter (fig. 5.31(b)), demand response and storage compete as neither excess electricity nor resulting load L' are excessively available.

5.2.3 Influence of the Available Storage Capacity (Electric Storage)

The available storage capacity E_{serv} is increased from $E_{\text{serv}} = 1\,\text{kWh}$ to $E_{\text{serv}} = 14\,\text{kWh}$ for the electric storage device defined in table 4.3.

Without Demand Response

The increase of the available storage capacity from $E_{\text{serv}} = 1\,\text{kWh}$ to around 3 kWh or 4 kWh allows a cost decrease between 5 % and 9 % for PV500 (fig. 5.38), except for price constellation #6, and between 5 % and 18 % for PV4500. The curve shapes for PV4500 are analogue to the curves for PV500, except for price constellation #6.

Its curve for PV4500 is similar to the one for #3, as excess electricity can be stored. However, the savings potential of #6 is approximately 0.01 p.u. less than of #3 due to the absence of electricity price variations. Larger storage capacities only have little additional benefit on the costs. Both for small and large amounts of renewable generation, the savings potential is larger in winter although the electric load demand is smaller there:

- For small amounts of renewable electricity, only price variations can be exploited due to missing renewable excess electricity (figures 5.31(c) and 5.31(d)). In summer, more energy is charged into the storage (fig. 5.39) as the load demand is higher. However, due to the limited prediction and optimization horizon, the amount of energy to be stored expediently is reached rapidly for increasing available storage capacity, resulting in a saturation for $E_{\text{serv}} \geq 4\,\text{kWh}$. As the overall load and hence the costs are smaller in winter, the price reductions from the capacity increase stand out more distinct than in summer.

- For large amounts of renewable generation, the mismatch between renewable generation and electric load demand is (much) larger in winter than in summer (figures 5.31(a) and 5.31(b)). The amount of electricity that can be bought in low-tariff and consumed in high-tariff times is larger in summer, but the exploitation of the excess renewable electricity saves more money. Consequently, the savings potential is higher in winter than in summer.

With Demand Response

With demand response (5.8), the cost savings potential of an increasing storage capacity E_{serv} is generally smaller than without demand response (compare figures 5.38 and 5.40, PV500). The amount of shifted load is approximately constant, independent of the available storage capacity, and the storage utilization is decreased significantly for PV4500 ($2\,\% - 5\,\%$ in winter and $7\,\% - 10\%$ in summer) and only little for PV500 ($< 0.05\,\text{p.u.}$).

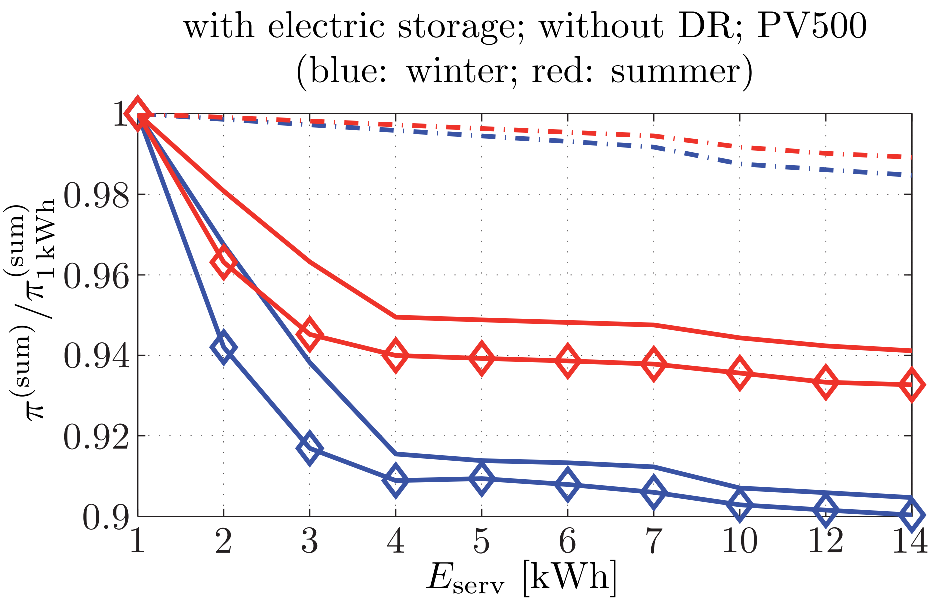


Figure 5.38: Energy costs $\pi^{(\mathrm{sum})}$ related to costs at $E_{\mathrm{serv}} = 1\,\mathrm{kWh}$, $\pi^{(\mathrm{sum})}_{1\,\mathrm{kWh}}$.

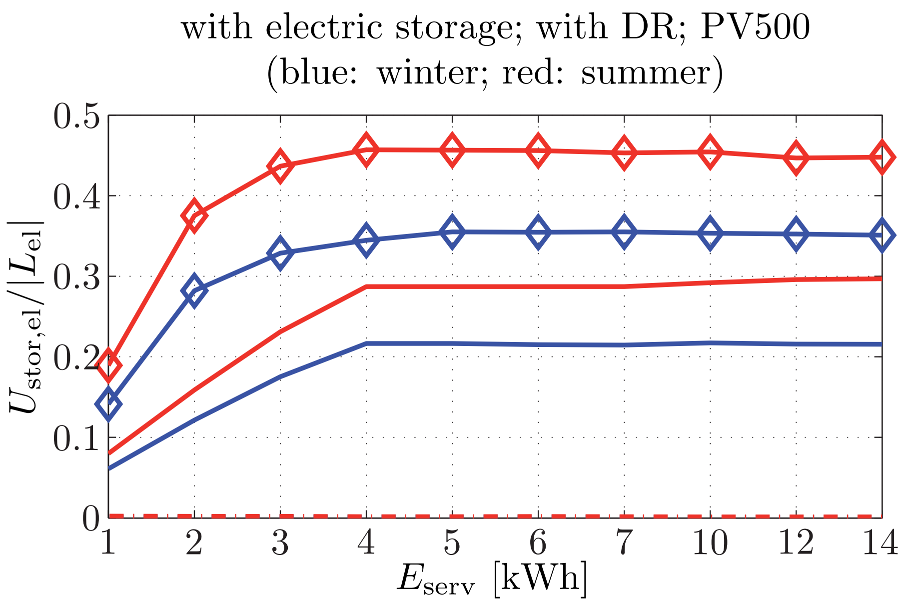


Figure 5.39: Storage use, $U_{\mathrm{stor,el}}$, related to sum of electric load, $|L_{\mathrm{el}}|$.

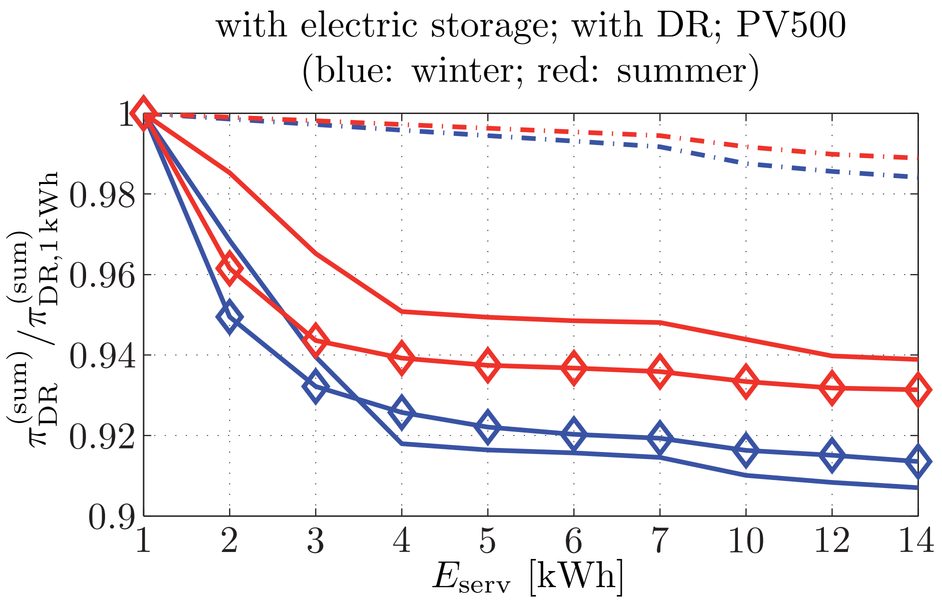


Figure 5.40: Energy costs with demand response $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$ related to costs at $E_{\mathrm{serv}} = 1\,\mathrm{kWh}$, $\pi_{\mathrm{DR,1\,kWh}}^{(\mathrm{sum})}$

5.2.4 Influence of the Amount of Local Photovoltaic Electricity

Photovoltaic resources are of rising interest especially for areas with a long sunshine duration and high global irradiance such as southern Spain. Consequently, the interaction of energy storage, demand response and increasing photovoltaic electricity generation is examined for the Spanish house.

Electric storage device

The increasing amount of renewable electricity results in a significant, continuous cost decrease both in summer and winter, as electric demand can be supplied locally without costs. The introduction of an electric storage device (table 4.3) decreases the costs in summer by a constant amount of around 10 % (price constellations #3 - #5 and #7) (fig. 5.41, red lines), as mainly price variations are exploited. That is why the storage is of nearly no influence in constellation #6. With increasing renewable generation the storage utilization decreases (fig. 5.42). PV electricity does not exceed the electric load demand (fig. 5.43), hence no (or only little) excess electricity has to be saved. Nevertheless, load demand L_{el} is reduced by the locally

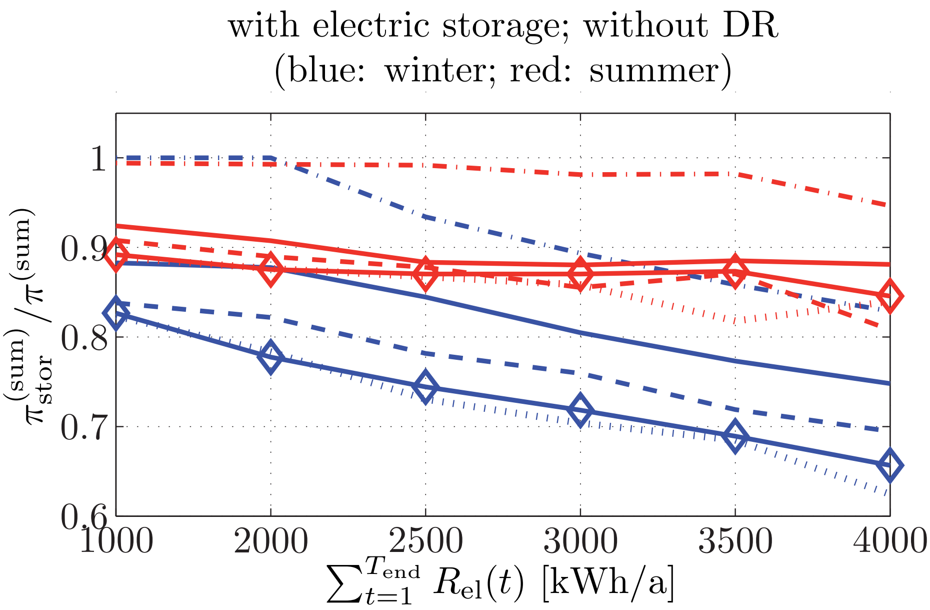


Figure 5.41: Energy costs with electric storage, $\pi_{\text{stor,el}}^{(\text{sum})}$, related to costs without storage, $\pi^{(\text{sum})}$.

available renewable electricity R_{el} (5.9), consequently reducing the amount of electricity that needs to be stored from low- to high-tariff times. The storage utilization decreases.

In winter, renewable generation exceeds electric load demand for around PV2000 and higher (fig. 5.44). An increasing amount of renewable generation reduces the costs, but the influence is less pronounced as in summer because some PV electricity has to be discarded. The introduction of an electric storage device allows a better PV exploitation and hence a cost reduction (fig. 5.41). This can best be seen for price constellation #6 where no electricity price variations superimpose. Storage utilization starts rising continuously for $\sum_{t=1}^{T_{\text{end}}} R_{\text{el}}(t) \geq 2000\,\text{kWh}$ (fig. 5.45). In price configurations #3 and #4, storage utilization first decreases from PV1000 to PV2000 due to a load reduction (5.9), and then continues analogue to #6. In price configurations #5 and #7, the storage utilization is generally at a high level due to low-, medium- and high-tariff times (PV1000: 34 % compared to 20 % in price constellations #3 and #4). Increasing renewable generation decreases the necessity for price motivated storage. With increasing renewable generation and hence excess electricity, the decrease saturates around PV3500/PV4000, and storage

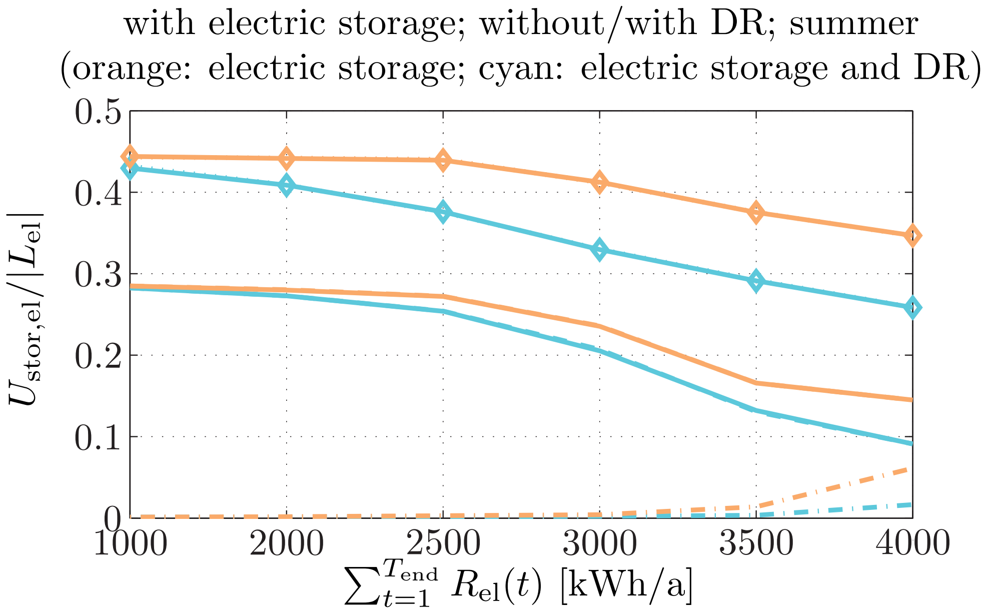


Figure 5.42: Electric storage use, $U_{\text{stor,el}}$, related to sum of electric load, $|L_{\text{el}}|$.

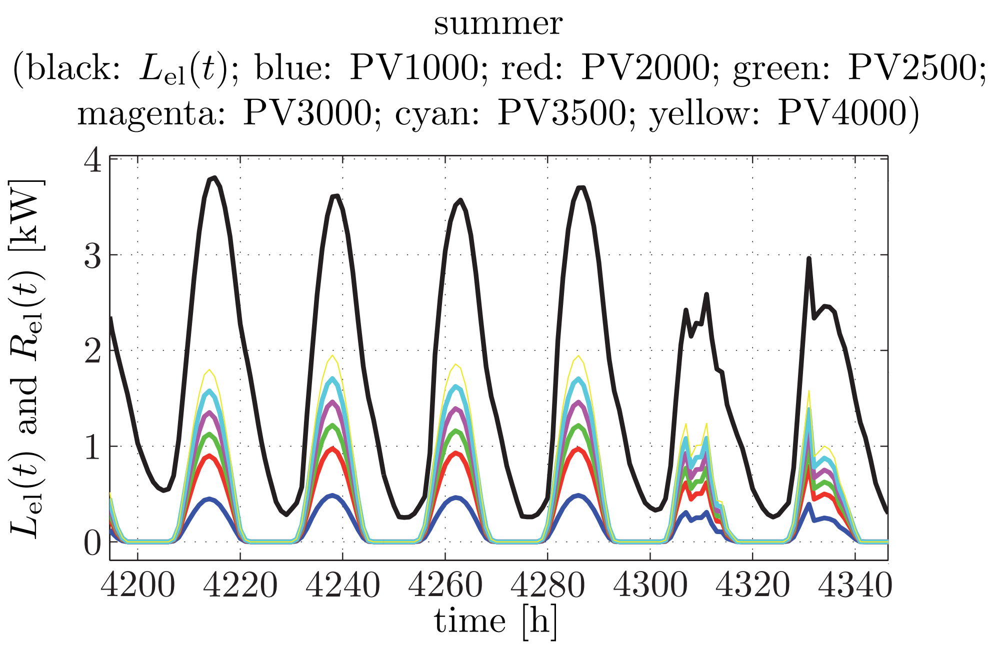


Figure 5.43: Electric load demand, $L_{\text{el}}(t)$, (including cooling) and PV generation, $R_{\text{el}}(t)$, in summer.

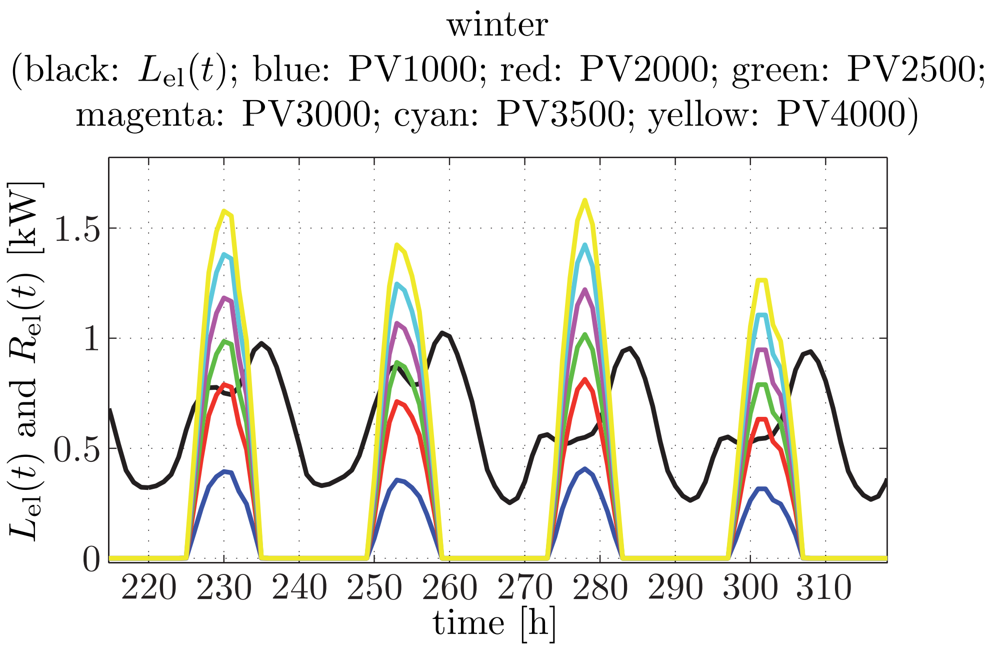


Figure 5.44: Electric load demand, $L_{\mathrm{el}}(t)$, and PV generation, $R_{\mathrm{el}}(t)$, in winter.

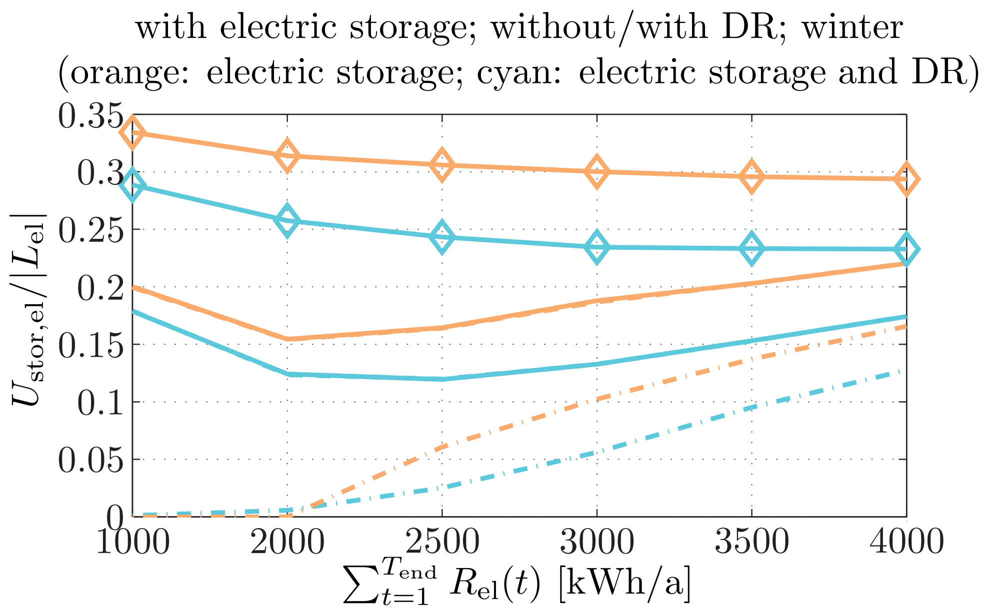


Figure 5.45: Electric storage use, $U_{\mathrm{stor,el}}$, related to sum of electric load, $|L_{\mathrm{el}}|$

utilization increases again. This cannot be seen in figure 5.45, but e.g. for PV6000 the storage use rises to 30 % of the electric load.

In the presence of demand response, storage utilization is reduced by up to 6 % in winter and 9 % in summer (figs. 5.42 and 5.45). The larger the amount of renewable electricity, the higher is the reduction. The reduction is also more pronounced in summer than in winter. In winter, the storage utilization reduction is about constant for $\sum_{t=1}^{T_{\text{end}}} R_{\text{el}}(t) \geq 2000\,\text{kWh}$, where excess electricity starts to be available (fig. 5.44) and the demand response potential is exhausted. In summer, no excess electricity is available (fig. 5.43), but load is increasingly reduced (5.9) with rising $\sum_{t=1}^{T_{\text{end}}} R_{\text{el}}(t)$. Lossless demand response is preferred to lossy storage to exploit price variations (fig. 5.42). The less load $L^{'}$ has to be supplied, the larger is the decrease of storage utilization caused by demand response.

Compared to the sole application of the electric storage, the combination of demand response and electric storage device reduces the costs by around 4 % to 7 % in summer and 6 % to 12 % in winter (both except price constellation #6).

Thermal storage device

The electric storage device is now replaced by an electrically heated domestic hot water tank (table 4.3). In summer, the tank does not have a significant influence on the costs compared to the base case (no DR, no storage) (fig. 5.46), as thermal load is small and few excess electricity exists. Only for high amounts of renewable generation (PV3000 and above), the hot water tank utilization slowly starts to increase with rising excess electricity, resulting in a cost decline.

In winter, the costs decrease constantly (fig. 5.46) as the hot water tank use increases linearly (fig. 5.47) due to increasing excess electricity. In price constellations #6 and #7, the tank utilization is higher than for #3 - #5, as thermal load supply via the thermal storage is economically viable in high gas-tariff times. With increasing excess electricity, however, price exploitations loose significance compared to storage of excess electricity, resulting in an assimilation of all price constellations.

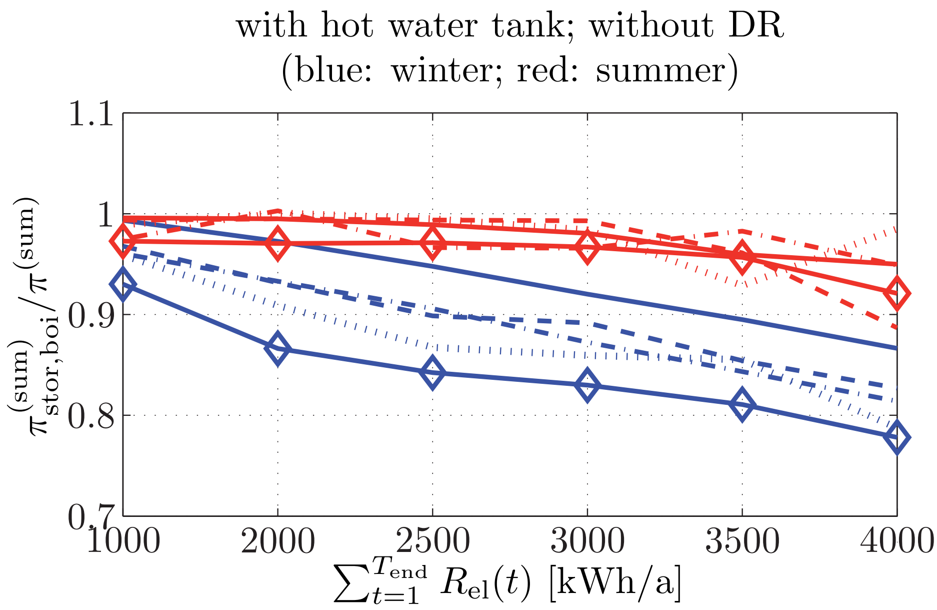


Figure 5.46: Energy costs with hot water tank, $\pi^{(\text{sum})}_{\text{stor,boi}}$, related to costs without hot water tank, $\pi^{(\text{sum})}$.

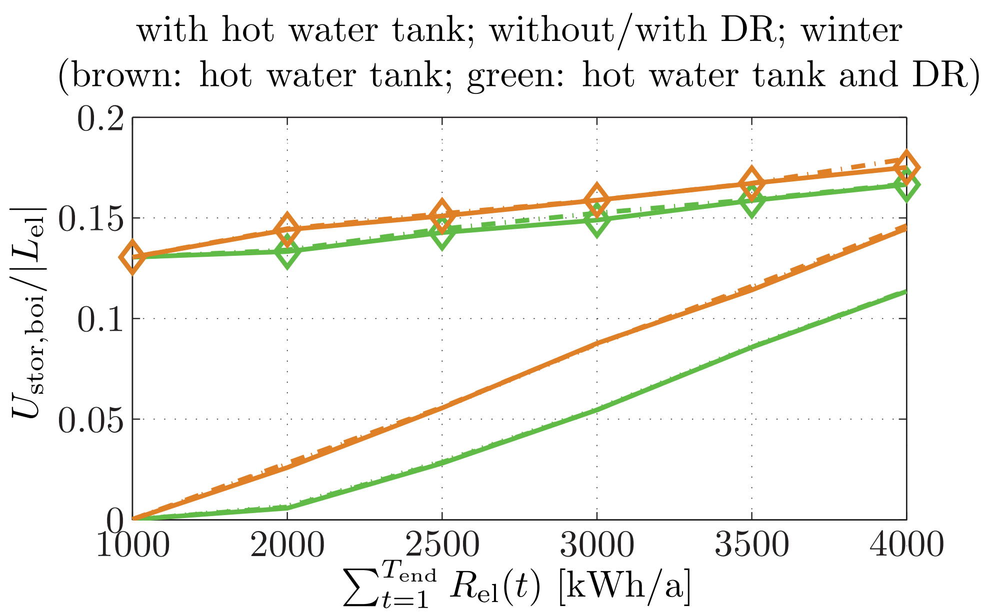


Figure 5.47: Thermal storage use, $U_{\text{stor,boi}}$, related to sum of electric load, $|L_{\text{el}}|$

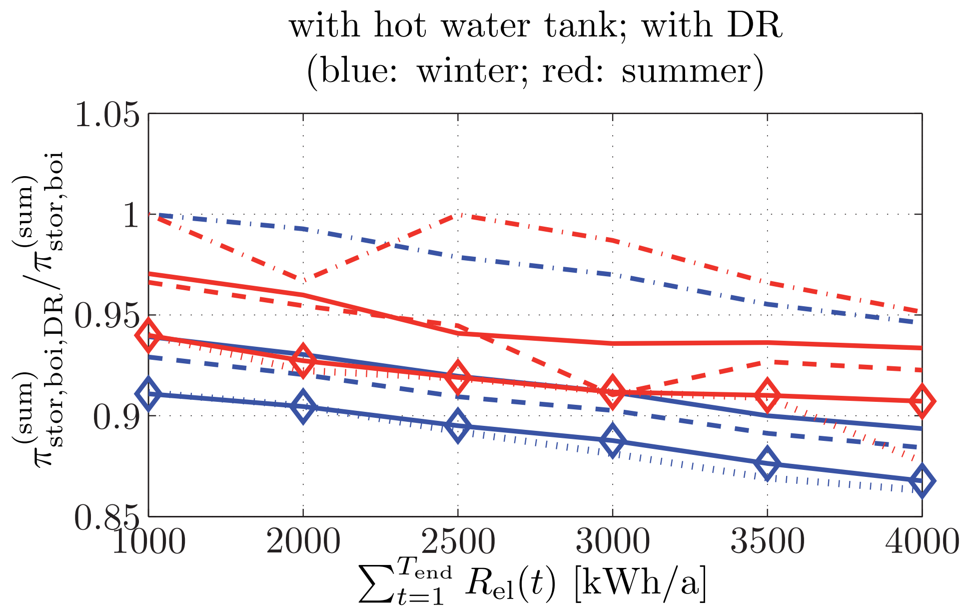


Figure 5.48: Energy costs with demand response and hot water tank, $\pi^{(\mathrm{sum})}_{\mathrm{stor,boi,DR}}$, related to costs with only hot water tank, $\pi^{(\mathrm{sum})}_{\mathrm{stor,boi}}$.

Electric demand response reduces the thermal storage utilization nearly to zero for price configurations #3 - #5 in summer, as excess electricity is better exploited by demand response to benefit from the electric price variations. The utilization of the hot water tank only starts when the amount of excess electricity exceeds the demand response potential. This is the case at around PV3500. In price constellations #6 and #7 demand response decreases the thermal storage use only little, as the price exploitation prevails the competition for excess electricity between thermal storage and demand response.

The cost savings potential of demand response combined with an electrically heated hot water tank is increasing for rising renewable generation both in summer and winter (fig. 5.48). The growing amount of excess electricity can be used both for thermal and electric load supply and consequently reduces costs.

5.2.5 Verification of the Results for One Year

The electric and thermal load demand of the Spanish house differ notably from the Swiss case. Thermal load (warm water) is constant throughout the year (fig. 5.49), while electric load is dominant in

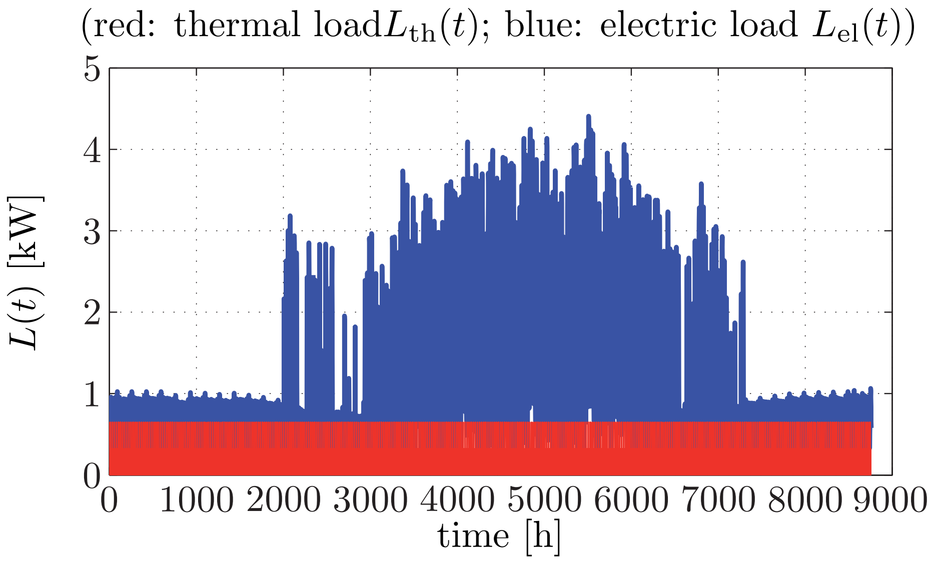


Figure 5.49: Yearly electric and thermal load demand of the standard Spanish house.

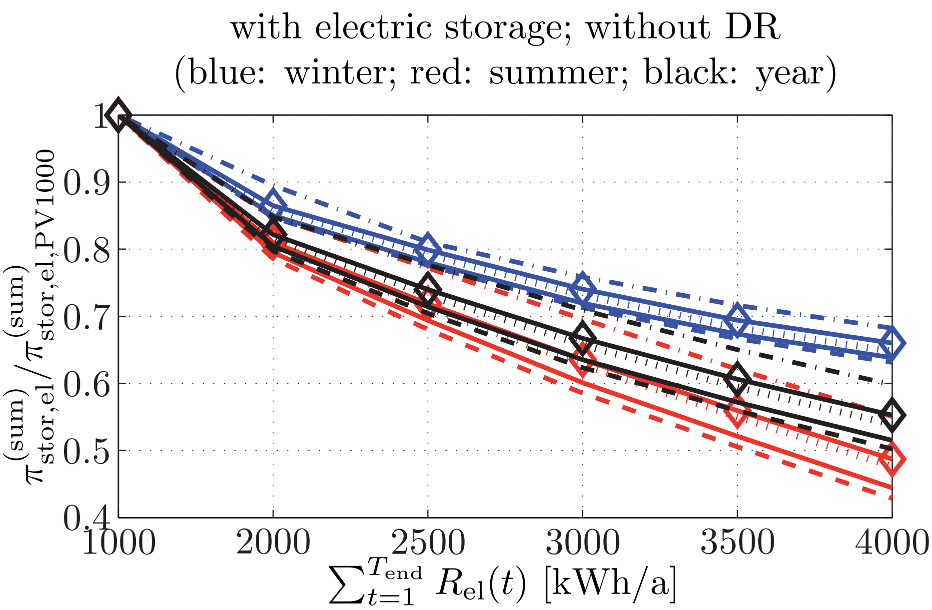


Figure 5.50: Energy costs with electric storage, $\pi^{\rm (sum)}_{\rm stor,el}$, related to costs for PV1000, $\pi^{\rm (sum)}_{\rm stor,el,PV1000}$.

the cooling period (May - September). In the rest of the year it is on about the same level as thermal load. Electric load dominance ("summer") and approximate parity with thermal load ("winter") are about equally frequent within the year, with a slightly larger part for "summer". Consequently, the results for one year range between winter and summer results (fig. 5.50), tending towards summer.

5.3 Influence of Cooperation, Demand Response and Energy Storage on the Energy Costs for a Group of Houses in Moderate Climate

The application of demand response and energy storage within one single-family house has been investigated in the last two sections. However, the residents can also collaborate with the neighbors and coordinate their energy consumption and acquisition. Additionally, they can operate a collective storage on one of the superimposed supply levels. Here the question arises whether these options are beneficial and worth the effort compared to individual power supply. In a first step, this is examined for the agglomeration of Swiss houses presented in section 4.2.2 and for price configuration #4. First, the group of three houses (fig. 4.7) is analyzed, and second the assembly of two sets of houses with superimposed supply levels (fig. 4.5) is examined.

For the group of three houses, coexistence and cooperation are examined for the three cases

1. neither demand response nor storage (base case),
2. electric demand response with $H^{(\mathrm{el})}_{\max} = 0.2\,\mathrm{kW}$,
3. and electric energy storage according to table 4.3.

Demand response is available in all houses, but only houses $h_{\#1}$ and $h_{\#3}$ are equipped with storage. The combination of demand response and electric storage is not considered, as the analysis presented in section 5.1 showed that only little benefit can such be gained.

Table 5.10: Group of houses: energy costs with demand response ($\pi_{\mathrm{DR}}^{(\mathrm{sum})}$) or energy storage ($\pi_{\mathrm{stor,el}}^{(\mathrm{sum})}$) related to costs of the base case, $\pi^{(\mathrm{sum})}$; summer/winter; coexistence and cooperation.

	coexistence		cooperation	
	winter	summer	winter	summer
$\pi_{\mathrm{DR}}^{(\mathrm{sum})}/\pi^{(\mathrm{sum})}$	0.99	0.95	0.99	0.96
$\pi_{\mathrm{stor,el}}^{(\mathrm{sum})}/\pi^{(\mathrm{sum})}$	0.95	0.95	0.95	0.91

Both for coexistence and cooperation, the results match with those for one single-family house. The energy costs with demand response, $\pi_{\mathrm{DR}}^{(\mathrm{sum})}$, and with electric storage, $\pi_{\mathrm{stor,el}}^{(\mathrm{sum})}$, are decreased compared to the base case ($\pi^{(\mathrm{sum})}$) (table 5.10). In winter, the influence of demand response and storage are the same for coexistence and cooperation, as due to missing excess electricity no energy is exchanged. In summer, demand response affects the costs approximately similar in both cases, but energy storage has a larger impact on the costs for combined effort. Here, excess electricity of house $h_{\#1}$ can also be stored by houses $h_{\#2}$ and $h_{\#3}$, consequently further reducing the costs.

The comparison of coexistence and cooperation (table 5.11) shows that in winter the exchange of information and the coordination of load demand and supply does not have a benefit compared to the individual behavior. In summer, however, the cooperation is up to 16 % cheaper than coexistence due to increased renewable exploitation. The application of demand response does not result in additional benefits compared to the base case when used in cooperation (both $\approx 12\,\%$ cost savings), but energy storage profits from the joint action of the neighbors (≈ 0.04 p.u. additional savings).

The influence on the costs of the location of an electric storage device as well as the impact of a neighborhood's combined efforts are examined for the group of houses with superimposed levels. Renewable generation is available on level l_1 according to table 4.4. The storage

Table 5.11: Group of houses: Energy costs of cooperation, $\pi_{\text{coop}}^{(\text{sum})}$, related to energy costs of coexistence, $\pi_{\text{coex}}^{(\text{sum})}$, for base case, demand response and electric storage; summer/winter.

	winter	summer
$\pi_{\text{coop}}^{(\text{sum})}/\pi_{\text{coex}}^{(\text{sum})}$	1.00	0.88
$\pi_{\text{DR,coop}}^{(\text{sum})}/\pi_{\text{DR,coex}}^{(\text{sum})}$	1.00	0.89
$\pi_{\text{stor,coop}}^{(\text{sum})}/\pi_{\text{stor,coex}}^{(\text{sum})}$	1.00	0.84

devices are installed in houses $h_{\#1}$, $h_{\#3}$, $h_{\#4}$ and $h_{\#6}$ on level l_1, in both hubs on level l_2, and in the hub on level l_3.

As for the group of houses, in winter cooperation does not achieve financial benefits compared to coexistence. In summer, cooperation can save between 4 % and 8 % of the costs (table 5.12). The savings potential here is smaller than for the group of houses, as within the subset $\mathcal{H}_{h_{S2}}$ the benefits of energy exchange are small. Each house has its own PV plant, and generation peaks are present at the same time due to alike weather conditions. Consequently, excess electricity cannot be used to a large extent, although available.

Table 5.12: Houses with superimposed supply levels: Energy costs of cooperation, $\pi_{\text{stor,coop.}}^{(\text{sum})}$, related to energy costs of coexistence, $\pi_{\text{stor,coex.}}^{(\text{sum})}$, for the cases with storage on different levels; only summer.

	levels l_i with storage							
i		1	2	3	1,2	1,3	2,3	1,2,3
$\frac{\pi_{\text{stor,coop.}}^{(\text{sum})}}{\pi_{\text{stor,coex.}}^{(\text{sum})}}$	0.93	0.94	0.95	0.92	0.92	0.94	0.96	0.92

Energy storage operated on the three levels of the system effects the overall energy costs differently (table 5.13). Generally, the impacts are similar for coexistence and cooperation. The advantage of a joint action in subset $\mathcal{H}_{h_{S1}}$ is leveled out by the only small benefits in subset $\mathcal{H}_{h_{S2}}$. The introduction of energy storage on only one level is most beneficial on the middle level l_2, with 89 % of the base case costs for coexistence, compared to 92 % (level l_1) and 95 % (level l_3), respectively. The same holds true for cooperation with 91 % (level l_2) compared to 93 % (l_1) and 94 % (l_3).

Table 5.13: Houses with superimposed supply levels: energy costs with energy storage on different levels, $\pi^{(sum)}_{stor}$, related to costs of base case, $\pi^{(sum)}$; only summer; coexistence and cooperation

	levels l_i with storage							
i		1	2	3	1,2	1,3	2,3	1,2,3
$\frac{\pi^{(sum)}_{stor,coex.}}{\pi^{(sum)}_{coex.}}$	1.00	0.92	0.89	0.95	0.82	0.86	0.83	0.77
$\frac{\pi^{(sum)}_{stor,coop.}}{\pi^{(sum)}_{coop.}}$	1.00	0.93	0.91	0.94	0.81	0.87	0.86	0.77

Also, the combination of storage levels is more beneficial if a device is operated on level l_2. The largest cost savings are possible with energy storage on each level.

The last sections 5.1, 5.2 and 5.3 presented and explained the results of the simulations carried out for the Swiss and Spanish single-family houses and the assembly of Swiss houses with superimposed supply levels. These results will be discussed and related in the next chapter 6.

Chapter 6

Discussion

In chapter 5, the influences of demand response and storage parameters, of increasing renewable generation and of a cooperation of a number of single-family houses were investigated. In the following paragraphs, the results of this analysis will be discussed.

6.1 Energy Storage Utilization

The cycle efficiency η_{cycle} of the storage device defines the amount of charge and discharge losses. Consequently, the efficiency η_{cycle} should be as high as possible to keep losses small. Excess electricity can compensate the losses when no refund is paid for grid feed. Although this can be economic from the point of view of the storage and renewable plant operator, it is not reasonable to loose energy at storage charge and discharge instead of consuming it within the system.

The cost decrease with increasing available storage capacity E_{serv} is small compared to the decrease with rising cycle efficiency η_{cycle}. Nevertheless, E_{serv} has to be chosen carefully, as cost savings quickly saturate with rising storage capacity, but investment costs increase further.

Energy storage investment costs play an important role in deciding on the storage capacity [51] and hence influence the overall costs. This effect has not been considered in this thesis, but puts the statement made above into perspective. Nevertheless it can be seen that the cycle efficiency η_{cycle} influences the operating energy costs more significantly than the storage capacity E_{serv}.

However, the utilization of the available storage capacity E_{serv} strongly depends on the optimization horizon N_{int}. Energy is only stored such as it can be used within the optimization interval, surplus excess electricity is fed to the grid. An increase of the optimization horizon N_{int} or a change in the storage operation policy could hence increase the effectiveness of the storage.

The use of electric and thermal storage devices depends on the conditions of operation. Large differences were found between the Swiss and the Spanish single-family house and between summer and winter period. In summer, the use of the electric storage device increased with rising renewable generation in Switzerland, while in Spain the amount of stored energy first decreased and only raised again at very high levels of renewable generation. In winter, the electric storage is of less financial influence in Switzerland than in Spain, but synergy effects between electric and thermal load can be exploited with the combined heat and power plant. The winter dominance in Swiss results and the approximate summer/winter parity in Spain makes the electric storage more adequate for an application in Spain. Contrarily, thermal storage use is significantly more beneficial in Switzerland than in Spain, as electric load is comparatively small with respect to thermal load. Nevertheless, synergy effects can be used in both countries as renewable generation and electricity price variations can be exploited both for thermal and electric load supply.

The CHP use is effected by energy storage, too. Depending on the price constellation and the technology parameters, the storage can be charged with CHP electricity or reduce its operation time. In the considered price constellations, the CHP use is only increased significantly due to storage charge for price constellation #6 and efficiencies $\eta_{\text{cycle}} \geq 0.84$. Else, the storage device diminishes the CHP use and hence its profitability. Grid electricity prices and/or the electric efficiency $\eta_{\text{gas,el}}^{\text{CHP}}$ of the CHP would have to increase significantly to make the CHP competitive to low-tariff grid prices and furnace heat.

6.2 Demand Response Application

The demand response parameter $H_{\max}^{(\mathrm{el})}$ defines the limit for increase or decrease of the residential power demand. It influences the cost savings potential of demand response significantly more than the parameters $J^{(\mathrm{el})}$ and $\Delta T^{(\mathrm{el})}$ that determine the maximum shiftable amount of energy within a certain time interval. Hence, flexibility in power demand is more decisive to decrease costs than an adaptation of energy demand.

Increasing demand response flexibility $H_{\max}^{(\mathrm{el})}$ is well suited to decrease energy costs in all considered price constellations, though its influence in winter in Switzerland is low. A saturation in cost decrease was observed in nearly all calculations. Especially in Switzerland in summer, a flexibility of $H_{\max}^{(\mathrm{el})} \geq 0.6\,\mathrm{kW}$ does not achieve large additional cost savings (fig. 5.2). In the Spanish case, the saturation is not that pronounced and higher flexibility reduces costs more.

A high value of $H_{\max}^{(\mathrm{el})}$ is only effective in combination with a sufficiently large optimization horizon N_{int}. With small optimization intervals, the demand response potential is strongly limited by (4.5) (see appendix C.2). Consequently, the efficient application of demand response necessitates flexibility in time.

By analogy with energy storage, demand response impacts the utilization of the combined heat and power plant. In the scenarios considered in this thesis, the operation of the CHP is mostly reduced by demand response as load is shifted to times of the day where it can be supplied cheaper via the grid and the gas furnace. This declines the energy costs but also the profitability of the CHP.

6.3 Impact of the Combination of Demand Response and Energy Storage

Demand response increases the utilization of the hot water tank both in the Spanish and the Swiss case, as long as sufficient excess renewable generation is available. With little local excess electricity, its use is more economic for electric load supply due to the price constellations. Hence, the hot water tank utilization reduces nearly to zero. The electric storage utilization is generally reduced in the presence of demand response because of the competition for price variations and excess electricity.

Demand response utilization is independent of the storage application. Its use is lossless and consequently preferred to storage.

Although demand response mostly reduces storage utilization, a combination is beneficial when renewable generation is sufficiently exceeding load demand or if price differences are large. As a consequence of the interaction, the energy storage (especially if electric) can be reduced in capacity.

In the calculations carried out, demand response is well suited to match load demand to renewable generation and price variations. The data used are resolved in hourly intervals using mean values. However, renewable generation sometimes changes its amplitude within seconds [52]. Demand response is not able to adapt that quickly, as only complete entities can be switched on or off with certain operation boundaries. Consequently, energy storage would be technically preferred to accommodate renewable electricity, although demand response is preferred to lossy energy storage in the simulations. In contrast, energy storage is expensive [51], thus benefitting demand response from an economic point of view. Further research including investment costs, a more detailed demand response model and a higher time resolution are consequently necessary to weigh advantages and disadvantages of demand response and possible discard of renewable energy compared to storage installation.

6.4 Cooperation of Consumers

The multiple-level considerations showed that a cooperation of several Swiss houses is without impact in winter, but is able to save costs compared to coexistence in summer. The joint action is more advantageous if renewable generation is not widely spread, but concentrated in few places. Otherwise a large surplus of renewable electricity occurring at the same time undoes the advantages of energy exchange. Consequently, increasing private renewable installations are not conducive for joint power supply, while "centralized" plants are in favour for a cooperation.

Joint action is only possible if the groups of houses and supply levels can be accounted and billed together and the costs are divided. Fair division regulations have to be defined to not fleece some participants and privilege others.

Another aspect has to be considered, too. In the multiple-level model, energy exchange between the houses is free of charge and grid use does not have to be paid. However, this is economically not viable both from the perspective of the grid operator and the national economy, as the infrastructure has to be provided nevertheless. Accounting these costs reduces the benefits of cooperation compared to coexistence.

An extension of the joint action of several private customers is presented in [53], where the cooperation of private households and utilities to create a cost-optimal power supply infrastructure has been studied.

6.5 Influence of Energy Prices and Renewable Generation

The prices for electricity and gas determine the operation policies of the conversion technologies, the storage devices and demand response. The results for price configurations #3 and #4 and configurations #5 and #7 were similar. Constellation #7 resembles significantly more to #5 with equal electricity price than to #6 with same gas price. The electric price variations are more dominant for the solution, as both demand response and energy storage operation depend on the electricity price.

The simulations clearly showed that the price constellations effect the costs to different amounts. However, the trends where mostly similar, except for price constellation #6 with constant electricity prices. But further analysis is necessary for more detailed statements about adequate price constellations and their impact on customer behavior. Also, the examination of several price constellations and different scenarios is required to substantiate the results observed for the multiple-level model and price configuration #4.

Reference [31] (see section 2.2.3) concluded that energy storage is best applied to increase the utilization of local renewable generation instead of exploiting price variations. This was also seen in the study at hand. In Switzerland in summer, excess electricity is largely available, and the electric storage impact on the costs with increasing renewable generation is similar for all price configurations (section 5.1.5). Price configuration #6 does not differ significantly as usual. In Spain in winter the situation is similar, but not so pronounced due to less excess electricity. Consequently, (electric) energy storage is more beneficial with a large surplus of excess electricity than with only price variations to be exploited. For the hot water tank, the similar case to electric energy storage holds true. But its influence is more distinct than that of the electric storage device in moderate climate (Switzerland), and less pronounced in hot climate (Spain).

The results of the study also showed that increasing renewable generation countervails the effects of different energy price constellations. With increasing local renewable generation the price variations get less important as savings from renewable energy use exceed savings from price shift exploitation. This observation is important for the investment in energy storage. Price-driven application of energy storage effects the energy prices [32]: the more energy storage is applied, the less pronounced are peaks in energy generation and load demand, hence price variations as incentive to store energy become less important. Price-motivated energy storage withdraws its own basis. But the results of the study at hand suggest that energy storage on a distributed level is motivated by the exploitation of excess electricity rather than price differences. Consequently, decentralized energy storage application will not be stunted by retroactive effects of energy prices.

Although a storage device is beneficial with increasing renewable generation, it cannot accommodate all excess electricity with rising yearly generation. The energy cost reduction saturates for both electricity and hot water storage in Switzerland, while the saturation is more distinct for electricity storage. In Spain, generally more excess electricity can be used due to the higher electric load demand. Consequently, for one single-family house the benefits of excess electricity diminish with rising amounts of surplus electricity. The same effect was observed for a group of houses, where the cooperation advantages were decreased with increasing availability of excess electricity (see also section 6.4).

6.6 Data Availability and Exchange

The optimization horizon N_{int} strongly influences the applicability of demand response and energy storage. The value for N_{int} defines the necessary prediction horizon for the external parameters $T_{\text{out}}(t)$ and $R_{\text{el}}(t)$ and the internal variable $L_{\text{el}}(t)$ to determine the optimal power supply strategy including demand response and storage. Additionally, in the multiple-level model the superimposed supply levels need predictions of demand and generation of the lower levels to adjust their own storage management in the cooperation mode. The predicted data, however, is tainted with uncertainties and errors which are increasing with rising optimization horizon [54]. This deteriorates the reliability of the optimization outcome. Consequently, the need for a long prediction and optimization horizon conflicts with the availability of reliable data. Reference [55] comes to the same conclusion that the prediction horizon is the decisive factor for economic and effective storage application.

In the groups of houses represented in the multiple-level model, the superimposed supply levels are only provided with the resulting energy demand of their respective subsets. No information about renewable generation, storage use and demand response application is exchanged. The availability of this data could further decrease the system costs. This topic still has to be investigated.

6.7 Socio-Economic Issues

Apart from technical details it is important to also account social effects. Demand response may be a technically adequate possibility to adjust demand and generation, but currently it is not widely accepted within the population [29]. Although it allows cost savings, it results in a reduction of comfort and an intervention in privacy. The case study in a US-American municipality [29] clearly showed that a large part of customers is not widely willing to respond to utility's incentives for load alteration. Despite the fact that this thesis showed that demand response does have a potential for cost savings, with a lack of willingness no wide spread will be achieved.

The exchange and processing of demand response data needs additional equipment, hard and software [4], resulting in increased energy demand. This conflicts with the aim of a cost reduction in the energy bill and also with national objectives for consumption reduction like in the EU [56]. Also, data exchange may be restricted by data protection and security laws [57], thus circumventing demand response application.

The issue of social fairness [58] also arises with the promotion of demand response. People who can afford it do not need to adjust their load demand to prices or can invest in energy storage, while others may be forced financially to adapt their consumption appropriately. This contradicts the principle of equality [58].

Chapter 7

Summary of Key Results

The thesis at hand focused on cost-optimal residential multi-energy supply in the presence of local renewable energy sources. Special interest was put on the examination of

- the individual application of demand response and energy storage in the residential sector,
- additional benefits of a combination of both,
- the impacts of their respective parameters,
- the influences of renewable generation, and
- the effects of a cooperation of neighbors.

A combination of a house model and a multi-energy hub (section 4.1.5) and a multiple-level model of a group of houses (section 4.2) were introduced to investigate the topics stated above. The price configurations (table 4.5), the parameters of the system (table 4.6), and the optimization parameters N_{int} and N_{sol} were varied without and with energy storage and demand response for a single-family house both in moderate and hot climate. Also, different amounts of renewable generation and various storage locations were examined for a group of houses in moderate climate. The results were explained in chapter 5 and discussed and related in chapter 6.

The main results of the sensitivity analysis and the comparison of different scenarios can be summarized as follows:

1. In moderate climate,
   - the savings potential on energy costs of electric demand response is only little due to the winter dominance of load demand. The savings potential in thermal load demand is higher.
   - an electrically heated domestic hot water tank is more advantageous than an electric storage device.
   - demand response and energy storage mainly reduce the operation time of the CHP and hence its profitability.
2. In hot climate,
   - the application of electric demand response is beneficial and expedient.
   - an electric storage device should be preferred to thermal storage.
3. The combination of demand response and energy storage is beneficial in two cases:
   (a) sufficient excess renewable energy is available,
   (b) load demand is high enough to exploit price variations.
4. The storage efficiency η_{cycle} is more important to reduce energy costs than the storage capacity E_{serv}. The cost savings potential of E_{serv} quickly saturates.
5. The parameter $H_{\max}^{(\text{el})}$ influences the cost savings potential of demand response significantly more than $J^{(\text{el})}$ and $\Delta T^{(\text{el})}$. Consequently, an adaptation in power demand results in more cost savings than an adaptation in energy demand.
6. The optimization horizon N_{int} reflecting the prediction horizon of the system is a crucial parameter for the application of demand response and energy storage and hence their effectiveness on cost savings.
7. With increasing renewable generation energy price constellations lose influence and importance.

8. A cooperation of a number of households is only beneficial and expedient if the renewable generation sites are concentrated in few places. Electric energy storage devices lose impact if electricity is also exchanged between several actors.

Chapter 8

Conclusions

Based on the main results (chapter 7) and the discussion presented in chapter 6, the following recommendations can be concluded:

1. **For a single-family house in moderate climate:** The focus should be put on thermal load demand and potential savings there (e.g. via insulation), as larger cost reductions are possible. Also, excess renewable electricity should be used for thermal load supply (e.g. via an electrically heated hot water tank).

2. **For a single-family house in hot climate:** In combination with a photovoltaic plant, the investment in a small electric energy storage device ($E_{\text{serv}} \leq 3\,\text{kWh}$) is expedient. For appropriate storage dimensioning, the horizon for reliable prediction data necessarily has to be taken into account. With enough excess renewable electricity, the additional application of demand response is recommended.

3. **For a group of houses in moderate climate:** A cooperation of households results only in small cost reductions and also decreases the benefits of electric energy storage. Consequently, individual energy supply with decentralized renewable generation is advised. Storage devices are best located on the first superimposed level.

The research presented in this thesis carefully examined the application of demand response and energy storage in residential applications, both in a single house and a group of houses. Nevertheless, certain tasks still have to be studied:

- Demand response application has been modeled as a maximum amount of power and energy to be shifted. However, in reality only appliances (like e.g. the washing machine) can be shifted in time. Consequently, the model has to be adapted accordingly and the results have to be verified.
- Operation point dependent efficiencies have to be introduced for the conversion technologies and the energy storage devices to assess the impact of full and part load on the energy costs. Also, ramping constraints have to be considered for enhanced technology models. This comes along with an increase of the time resolution.
- The consideration of investment costs is necessary to weigh advantages and disadvantages of demand response and possible discard of renewable energy compared to storage installation.
- The examination of several price constellations and different scenarios is required to substantiate the results observed for the group of houses in moderate climate.
- In the group of houses, the superimposed supply levels only received information about the accumulated load demand of their subordinate hubs. Details about renewable generation, load shift and storage application may further decrease joint energy costs. Still, this has to be investigated.

In conclusion it can be stated that demand response and energy storage are interesting possibilities to cope with rising renewable generation and price variations. However, their parameters have to be selected carefully to avoid oversizing and unnecessary comfort losses. Also, the current social and technical challenges restrain the ubiquitous use of both technologies. Ongoing research and the further increase of renewable generation may nevertheless foster the application of either demand response or energy storage or both.

List of Figures

2.1 Demand-side management options 4
2.2 Energy storage systems for stationary applications . . 7
2.3 Detached house with different rooms, load demand and power supply 9
2.4 Cubic model for the detached house 10
2.5 Exemplary energy hub 14
2.6 Dispatch of input carrier P_α 15
2.7 Power flow of a storage device 17

3.1 Influence of demand response and storage on load and demand curves 30
3.2 Interdependencies in the energy supply system (example) 32

4.1 Shares of Energy Carriers at Heat Consumption, 2006 40
4.2 Electricity demand of the single-family house 43
4.3 Warm water demand of the single-family house 44
4.4 Flow chart of the single-family house optimization . . 45
4.5 Schematic representation of a group of houses with a multiple-level model 48
4.6 Political units for the multiple-level model 49
4.7 Groups of actors within the multiple-level model for the Swiss case 50
4.8 Combination of demand response and energy storage with the parameter variations 56
4.9 Sub-optimizations defined by the optimization horizon N_{int} and the solution horizon N_{sol} 59

5.1 Superposition and interference of constraints (5.2) and (5.3) on the effectiveness of ΔT 64
5.2 Switzerland: Energy costs related to costs without demand response; summer/winter, PV4500; $H_{\max}^{(el)}$ 66
5.3 Switzerland: Energy costs related to costs without demand response and storage, ; summer, PV4500; $H_{\max}^{(el)}$ 66
5.4 Switzerland: Utilization of the hot water tank with demand response related to utilization of the hot water tank without demand response; summer/winter, PV4500; $H_{\max}^{(el)}$ 68
5.5 Switzerland: Energy costs with demand response and storage device related to energy costs with only demand response; summer, PV4500; $H_{\max}^{(el)}$ 69
5.6 Switzerland: Demand response use U_{DR} related to the sum of electric load; winter, PV4500; $H_{\max}^{(el)}$ 70
5.7 Switzerland: Demand response use U_{DR} related to the sum of electric load; summer, PV4500; $H_{\max}^{(el)}$ 70
5.8 Switzerland: Energy charged into the electric storage related to sum of electric load; summer/winter, PV4500; $H_{\max}^{(el)}$ 71
5.9 Switzerland: Energy costs related to costs at $\eta_{\mathrm{cycle}} = 0.5$; summer/winter, PV500; η_{cycle} 72
5.10 Switzerland: Energy costs related to costs at $\eta_{\mathrm{cycle}} = 0.5$; summer/winter, PV4500; η_{cycle} 73
5.11 Switzerland: Stored energy used by the system related to sum of electric load; summer/winter, PV4500; η_{cycle} 74
5.12 Switzerland: Stored energy used by the system related to sum of electric load; summer/winter, PV500; η_{cycle} 74
5.13 Utilization of the CHP; summer/winter, PV500; η_{cycle} 76
5.14 Switzerland: Energy costs with demand response related to costs at $\eta_{\mathrm{cycle}} = 0.5$; summer/winter, PV500; η_{cycle} 79
5.15 Switzerland: Energy costs related to costs at $E_{\mathrm{serv}} = 1\,\mathrm{kWh}$; E_{serv} 80
5.16 Switzerland: Electric storage utilization related to sum of electric load; summer/winter, PV500; E_{serv} 81
5.17 Switzerland: Energy costs with demand response related to costs at $E_{\mathrm{serv}} = 1\,\mathrm{kWh}$; E_{serv} 82

5.18 Switzerland: Energy costs with electric storage related to costs without storage; summer/winter; PV 86
5.19 Switzerland: Electric storage utilization related to sum of electric load; summer; PV 86
5.20 Switzerland: Energy costs with demand response and electric storage related to costs with only electric storage; summer/winter; PV 87
5.21 Switzerland: Demand response utilization related to sum of electric load; summer/winter; PV 88
5.22 Switzerland: Electric storage utilization related to sum of electric load; winter; PV 88
5.23 Switzerland: Residual load in winter for increasing amounts of renewable electricity; PV 89
5.24 Switzerland: Energy costs with hot water tank related to costs without hot water tank; summer/winter; PV . 90
5.25 Switzerland: Energy costs with demand response and hot water tank related to costs with only hot water tank; summer/winter; PV 91
5.26 Switzerland: Hot water tank utilization related to sum of electric load; summer; PV 92
5.27 Switzerland: Energy costs related to costs without demand response; summer/winter/year, PV4500; $H^{(el)}_{max}$. 94
5.28 Yearly electric and thermal load demand of the Swiss house 94
5.29 Spain: Energy costs related to costs without demand response; summer, PV4500; $H^{(el)}_{max}$ 96
5.30 Spain: Energy costs related to costs without demand response; winter, PV4500; $H^{(el)}_{max}$ 96
5.31 Spain: Electric load demand and renewable generation for the single-family house 97
5.32 Spain: Demand response use related to sum of electric load; winter, PV4500; $H^{(el)}_{max}$ 99
5.33 Spain: Hot water tank use related to sum of electric load; summer/winter, PV4500; $H^{(el)}_{max}$ 99
5.34 Spain: Demand response use related to sum of electric load; winter, PV500, #5; $H^{(el)}_{max}$ 100
5.35 Spain: Electric storage use related to sum of electric load; summer/winter, PV4500; $H^{(el)}_{max}$ 101

5.36 Spain: Energy costs related to costs at $\eta_{\text{cycle}} = 0.5$; summer/winter, PV500; η_{cycle} 102
5.37 Spain: Energy charged to the electric storage device related to sum of electric load; summer/winter, PV500; η_{cycle} 103
5.38 Spain: Energy costs related to costs at $E_{\text{serv}} = 1\,\text{kWh}$; summer/winter, PV500; E_{serv} 105
5.39 Spain: Storage use related to sum of electric load; summer/winter, PV500; E_{serv} 105
5.40 Spain: Energy costs with demand response related to costs at $E_{\text{serv}} = 1\,\text{kWh}$; summer/winter, PV500; E_{serv} 106
5.41 Spain: Energy costs with electric storage related to costs without storage; summer/winter; PV 107
5.42 Spain: Electric storage use related to sum of electric load; summer; PV 108
5.43 Spain: Electric load demand (including cooling) and PV generation in summer 108
5.44 Spain: Electric load demand and PV generation in winter 109
5.45 Spain: Electric storage use related to sum of electric load; winter; PV 109
5.46 Spain: Energy costs with hot water tank related to costs without hot water tank; summer/winter; PV . . 111
5.47 Spain: Thermal storage use related to sum of electric load; winter; PV 111
5.48 Spain: Energy costs with demand response and hot water tank related to costs with only hot water tank; summer/winter; PV 112
5.49 Yearly electric and thermal load demand of the standard Spanish house 113
5.50 Spain: Energy costs with electric storage related to costs for PV1000; summer/winter/year; PV 113

List of Tables

4.1 Building parameters 37
4.2 Technology parameters of the Swiss and Spanish energy supply systems 41
4.3 Parameters of thermal and electric storage 42
4.4 Characteristics of the group of houses 49
4.5 Price Constellations considered in the parameter analysis 54
4.6 Parameters varied within the sensitivity analysis . . . 55

5.1 Switzerland: Variation of the demand response parameters; year, PV4500 63
5.2 Switzerland: Energy costs depending on the parameter $\Delta T^{(\mathrm{el})}$; year, PV1000 65
5.3 Switzerland: Energy costs depending on the parameter $H^{(\mathrm{el})}_{\mathrm{max}}$; summer, PV500 69
5.4 Switzerland: Efficiency threshold for the use of either CHP electricity or storage discharge; #7; η_{cycle} 77
5.5 Switzerland: Efficiency threshold for the use of the CHP electricity to charge the electric storage device; #7; η_{cycle} 78
5.6 Electricity costs depending on the optimization parameters and the demand response parameter; year, PV4500, #1; $H^{(\mathrm{el})}_{\mathrm{max}}$ 83
5.7 Switzerland: Objective function value and the computational time; $N_{\mathrm{int}},\ N_{\mathrm{sol}}$ 84
5.8 Switzerland: Electricity costs depending on the optimization parameters and the demand response parameter; summer/winter, PV4500; $H^{(\mathrm{el})}_{\mathrm{max}}$ 85

5.9 Switzerland: Overview - Simulations for 8760 time steps, single-family house 93
5.10 Group of houses: energy costs with demand response or energy storage related to costs of the base case; summer/winter; coexistence and cooperation 115
5.11 Group of houses: Energy costs of cooperation related to energy costs of coexistence for base case, demand response and electric storage; summer/winter 116
5.12 Houses with superimposed supply levels: Energy costs of cooperation related to energy costs of coexistence for the cases with storage on different levels; only summer 116
5.13 Houses with superimposed supply levels: energy costs with energy storage on different levels related to costs of base case; summer; coexistence and cooperation . . 117

Bibliography

[1] *Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015-2020 mit Ausblick auf 2025.* dena-Netzstudie II, Endbericht, November, 2010.

[2] T. Gül and T. Stenzel. *Variability of Wind Power and Other Renewables - Management options and strategies.* International Energy Agency (IEA), Paris, France, 2005.

[3] ETG Task Force Energiespeicher. *Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger - Bedeutung, Stand der Technik, Handlungsbedarf.* VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., Frankfurt am Main, 2009.

[4] M. Albadi and E. E.-Saadany. Demand Response in Electricity Markets: An Overview. *IEEE Power Engineering Society General Meeting*, 2007.

[5] C. Gellings. Demand-side load management. *IEEE spectrum*, 18:49–52, 12 1981.

[6] C. Gellings. The Concept of Demand-Side Management for Electric Utilities. *Proceedings of the IEEE*, 73(10):1468–1470, 1985.

[7] *Demand side management and demand response in municipalities.* IndEco Strategic Consutling Inc., IndEco report A3238, 2004.

[8] I. Navalón, S. Bañares, L. Moreno, and A. Quijano. DSM in Spain. GAD project. Aims, developments and initial results. In *Cigre Session*, Paris, France, 2010.

[9] *A National Assessment of Demand Response Potential.* Staff Report, Federal Energy Regulatory Commission, USA, 2009.

[10] A. Chuang and C. Gellings. Demand-side Integration for Customer Choice through Variable Service Subscription. *Power and Energy Society General Meeting, Calgary, Canada*, 2009.

[11] D. Oertel. *Energiespeicher - Stand und Perspektiven.* Büro für Technikfolgenabschätzung beim Deutschen Bundestag, Arbeitsbericht Nr. 123, 2008.

[12] S. Schoenung. *Characteristics and Technologies for Long- vs. Short-Term Energy Storage - A Study by the DOE Energy Storage Systems Program.* Sandia Report, Sandia National Laboratories, Albuquerque, New Mexico, USA, 2001.

[13] J. Clemens. *Entwicklung eines einfachen Modells zur Abschätzung der sommerlichen Überwärmung in Gebäuden.* Diplomarbeit, Unversität - Gesamthochschule Siegen, Fachbereich Physik, Siegen, Germany, 2000.

[14] M. Bianchi. *Adaptive Modellbasierte Prädiktive Regelung einer Kleinwärmepumpenanlage.* PhD thesis, ETH Zürich, Zürich, Switzerland, 2006.

[15] H. Böhme. *Berechnung von Warmwasser-Heizungen.* Udo Pfriemer Verlag, München, Germany, 3 edition, 1982.

[16] K. Stephan and F. Mayinger. *Thermodynamik - Einstoffsysteme.* Springer-Verlag, Band 1, Berlin/Heidelberg, Germany, 15 edition, 1998.

[17] A. Bukvic-Schäfer. *Lastmanagement - Nutzung der Thermischen Kapazität von Gebäuden als nichtelektrischer Energiespeicher in elektrischen Versorgungsnetzen.* Erneuerbare Energien und Energieeffizienz, Hrsg. Jürgen Schmid, Universität Kassel, Kassel, Germany, 5 edition, 2007.

[18] G. Becker. *Gebäudeklimatik.* Vorlesungsmanuskript, Hochschule München, München, Germany, 2009.

[19] K. Rapp. *Energiesparende Heizungsregelung - Planung und Aufbau einer witterungsgeführten Vorlauftemperaturregelung.* RPB electronic-taschenbücher, Nr. 177, Franzis-Verlag GmbH, München, Germany, 1984.

[20] M. Geidl and G. Andersson. Optimal Power Flow of Multiple Energy Carriers. *IEEE Transactions on Power Systems*, 22(1), 2007.

[21] M. Geidl and G. Andersson. Optimal Coupling of Energy Infrastructures. In *Proc. of IEEE PES PowerTech*, Lausanne, Switzerland, 2007.

[22] M. Geidl. *Integrated Modeling and Optimization of Multi-Carrier Energy Systems.* PhD thesis, ETH Zürich, Zürich, Switzerland, 2007.

[23] M. Schulze, L. Friedrich, and M. Gautschi. Modeling and Optimization of Renewables: Applying the Energy Hub Approach. In *International Conference on Sustainable Energy Technologies*, pages 83–88, Singapore, 2008.

[24] A. Moholkar, P. Klinkhachorn, and A. Feliachi. Effects of Dynamic Pricing on Residential Electricity Bill. In *IEEE PES Power Systems Conference and Exposition, Vol. 2*, pages 1030–1035, 2004.

[25] F. Wolak. *Residential Customer Response to Real-Time Pricing: The Anaheim Critical Peak Pricing Experiment.* Center for the Study of Energy Markets, University of California Energy Institute, 2006.

[26] M. Houwing, R. Negenborn, and B. De Schutter. Demand Response With Micro-CHP Systems. *Proceedings of the IEEE*, 99, 2010.

[27] T. Ha Pham, F. Wurtz, and S. Bacha. Optimal operation of a PV based multi-source system and energy managment for household application. In *IEEE International Conference on Industrial Technology*, Gippsland, VIC, 2009.

[28] J. vanTonder and I. Lane. A Load Model to Support Demand Management Decisions on Domestic Storage Water Heater Control Strategy. *IEEE Transactions on Power Systems*, 11(4), Nov 1996.

[29] S. Lutzenhiser, J. Peters, M. Moezzi, and J. Woods. Beyond the Price Effect in Time-of-Use Programs: Results from a Municipal Utility Pilot, 2007-2008. In *International Energy Program Evaluation Conference*, Portland, OR, USA, 2009.

[30] B. Daryanian and R. Bohn. Sizing of Electric Thermal Storage Under Real Time Pricing. *IEEE Transactions on Power Systems*, 8(1), Feb 1993.

[31] F. Nieuwenhout, J. Dogger, and R. Kamphuis. Electricity storage for distributed generation in the built environment. In *International Conference on Future Power Systems*, 2005.

[32] C. Foote, A. Roscoe, R. Currie, G. Ault, and J. McDonald. Ubiquitous Energy Storage. In *International Conference on Future Power Systems*, pages 1–6, 2005.

[33] A. Molderink, V. Bakker, M. Bosman, J. Hurink, and G. Smit. Domestic energy management methodology for optimizing efficiency in Smart Grids. In *IEEE Power Tech Conference*, Bucharest, Romania, 2009.

[34] S. Yu, T. Mays, and R. Dunn. A New Method for Designing Hydrogen Energy Storage in Wind Power Systems to Balance Generation and Demand. In *International Conference on Sustainable Power Generation and Supply*, pages 1–6, 2009.

[35] E. Hittinger, J. Whitacre, and Apt J. Compensating for wind variability using co-located natural gas generation and energy. *Energy Systems*, 1(4):417–439, 2010.

[36] Q. Qi, Y. Jiang, and S. Deng. A Simulation Study on Solar Energy Seasonal Storage by Phase Change Material. In *IEEE International Conference on Sustainable Energy Technologies*, pages 106–109, 2008.

[37] M. Houwing, P. Heijnen, and I. Bouwmans. Socio-Technical Complexity in Energy Infrastructures. In *IEEE International Conference on Systems, Man, and Cybernetics*, 2006.

[38] M. Houwing, P. Heijnen, and I. Bouwmans. Deciding on Micro-CHP; A Multi-Level Decision-Making Approach. In *IEEE international Conference on Networking, Sensing and Control*, pages 302–307, Ft. Lauderdale, Florida, USA, 2006.

[39] D. Long Ha, R. de Lamotte, and Quoc Hung Huynh. Real-time dynamic multilevel optimization for Demand-side Load Management. In *IEEE International Conference on Industrial Engineering and Engineering Management*, pages 945–949, 2007.

[40] M. de Castro, J. Martín-Vide, and S. Alonso. *El Clima de España: Pasado, Presente y Escenarios de Clima para el Siglo XXI*. Evaluación preliminar de los impactos en Espana por efecto del cambio climático (ed. Moreno Rodríguez JM), pp. 1-65, Ministerio de Medio Ambiente, Madrid, Spain, 2005.

[41] F. Gerheuser. *Wohnversorgung und Wohnverhältnisse - Entwicklungen 1990-2000*. Eidgenössische Volkszählung 2000, Bundesamt für Statistik, Neuchatel, Switzerland, 2004.

[42] *Haushaltsszenarien - Entwicklung der Privathaushalte zwischen 2005 und 2030*. Bundesamt für Statistik, Neuchatel, Switzerland, 2008.

[43] *Anteil der Einpersonenhaushalte*. Eidgenössische Volkszählung 2000, Bundesamt für Statistik, Neuchatel, Switzerland, 2000.

[44] *Gebäude, Wohnungen und Wohnverhältnisse*. Eidgenössische Volkszählung 2000, Bundesamt für Statistik, Neuchatel, Switzerland, 2004.

[45] *Analyse des schweizerischen Energieverbrauchs 2000-2006 nach Verwendungszwecken*. Bundesamt für Energie (BFE), Bern, Switzerland, 2008.

[46] D. Sauer and M. Kleimaier. Speichertechnologien in dezentralen Versorgungsstrukturen. In *VDE-Kongress*, München, Germany, 2008.

[47] R. Wimmer. Zero CarbO_2n Village. In *Fachtagung am 1.NÖ Klimaaktionstag, Innovative Schritte zur Autarkie*, St. Pölten, Austria, 2008.

[48] T. Loga, M. Grossklos, and W. Feist. Ein Jahr in der "Gartenhofsiedlung Lummerlund" - Messergebnisse aus 22 Passivhäusern in Wiesbaden. In *4. Passivhaustagung in Kassel*, Kassel, Germany, 2000.

[49] O. Kalab. *Standardisierte Lastprofile.* Wirtschaftskammer Oberösterreich, Austria.

[50] P. Konstantin. *Praxisbuch Energiewirtschaft - Energieumwandlung, -transport und -beschaffung im liberalisierten Markt.* Springer-Verlag, Berlin, Germany, 2007.

[51] ETG-Taskforce Dezentrale Energieversorgung 2020. *Dezentrale Energieversorgung 2020.* Energietechnische Gesellschaft im VDE (ETG), Frankfurt, Germany, 2007.

[52] Y.-h. Wan and B. Parsons. *Factors Relevant to Utility Integration of Intermittent Renewable Technologies.* National Renewable Energy Laboratory (NREL), Colorado, USA, 1993.

[53] P. Ahcin. *Planning Energy Systems With Emissions Targets.* PhD thesis, ETH Zürich, Zurich, Switzerland, 2011.

[54] C. Bullard and A. Sebald. Effects of Parametric Uncertainty and Technological Change on Input-Output Models. *The Review of Economics and Statistics*, 59(1), Feb. 1977.

[55] M. Arnold. *On Predictive Control for Coordination in Multi-Carrier Energy Systems.* PhD thesis, ETH Zürich, Zurich, Switzerland, 2011.

[56] M. Jimenez and N. Hatziargyriou. Research activities in Europe on integration of distributed energy resources in the electricity networks of the future. In *IEEE PES General Meeting 2006*, Montreal, Canada, 2006.

[57] M. Lisovich and S. Wicker. Privacy Concerns in Upcoming Residential and Commercial Demand-Response Systems. *IEEE Proceedings on Power Systems*, 1(1), March 2008.

[58] O. Schäfer. *Energieethik - Unterwegs in ein neues Energiezeitalter.* Schweizerischer Evangelischer Kirchenbund SEK, Bern, Switzerland, 2007.

[59] U. Eicker. *Solare Technologien für Gebäude.* B.G. Teubner GmbH, Stuttgart/Leipzig/Wiesbaden, Germany, 1 edition, 2001.

Appendix A

Nomenclature

A.1 Latin Symbols

A_{base}	base area of the cubic house model
A_{floor}	area of the interior floors
$A_{\mathrm{innerwalls}}$	area of the inner walls
A_{roof}	roof area of the cubic house model
A_{wall}	wall area of the cubic house model
A_{window}	window area of the cubic house model
c	heat capacity
c_{air}	heat capacity of air
c_{in}	heat capacity of the inner walls
c_{mat}	heat capacity of the wall material
$c_{\alpha\beta}$	coupling factor of input β to output α
C_{eff}	effective heat capacity of the walls
C	conversion matrix
$\mathrm{COP}^{\mathrm{ac}}_{\mathrm{el,cool}}$	coefficient of performance of the air conditioning

d_{in}	thickness of the inner walls
$d_{\alpha\beta}$	load shift from carrier β to carrier α
D	demand response matrix
E	state of charge of an energy storage
E_{max}	upper boundary of the state of charge
E_{min}	lower boundary of the state of charge
E_{serv}	available storage capacity
$\mathcal{E}$	set of energy carriers
$\dot{E}$	vector of changes in the state of charge
$\dot{E}_{\mathrm{char}}$	energy change in the storage at charging
$\dot{E}_{\mathrm{char,max}}$	upper boundary for charging power
$\dot{E}_{\mathrm{char,min}}$	lower boundary for charging power
$\dot{E}_{\mathrm{dis}}$	energy change in the storage at discharging
$\dot{E}_{\mathrm{dis,max}}$	upper boundary for discharging power
$\dot{E}_{\mathrm{dis,min}}$	lower boundary for discharging power
$\mathcal{F}$	objective function
g	energy transmission value of the windows
G	global irradiation
h	height of the house
h_{i}	number of energy hub
$h_{\#1}$ - $h_{\#6}$	houses in the multiple-level model
H	power shifted by demand response application
H_{+}^{el}	shifted power ≥ 0
H_{max}	upper power boundary for load shift
$H_{\mathrm{max}}^{(\mathrm{el})}$	upper power boundary for electric load shift
H_{min}	lower power boundary for load shift
$H_{\mathrm{min}}^{(\mathrm{el})}$	lower power boundary for electric load shift

$\mathcal{H}$	set of hubs
$\mathcal{H}_{\text{house}}$	subset of hubs modeling a single-family house
$\mathcal{H}_{l_j}$	subset of hubs of level l_j
$\mathcal{H}_{h_i}$	set of subordinate hubs of hub h_i
J	energy boundary for load shift
$J^{(\text{el})}$	energy boundary for electric load shift
l	length of the house
l_{j}	number of level
L	load vector
L_α	load vector of energy carrier α
$\|L_{\text{el}}\|$	sum of electric load
$L^{(\text{act})}$	actual energy consumption
$L^{(\text{nom})}$	nominal energy consumption
$L^{(l_{j+1})}$	load demand of a superimposed level l_{j+1}
$L^{'}$	resulting load after subtraction of renewable generation
m	mass
m_{air}	air mass
m_{in}	mass of the inner walls
m_{wall}	mass of the outer walls
M	charge/discharge power of an energy storage
$M^{(\text{in})}$	power exchange of an input-side energy storage
$M^{(\text{load})}$	power exchange of a load-side energy storage
n_{air}	number of hours to completely replace the inner air volume with ambient air
$n_{\text{opt}}^{(1)}$, $n_{\text{opt}}^{(2)}$	number of optimization sub-runs
N_{int}	optimization horizon

N_{sol}	solution horizon
$N_{\mathcal{H}}$	number of hubs in the multiple-level model
N_{l_j}	number of hubs in the subset of level l_j
$N_{\mathcal{L}}$	number of levels in the multiple-level model
p_{recov}	percentage of heat recovered by the ventilation system
P	vector of input energy carriers
P_α	input vector of energy carrier α
$P_\alpha^{(\beta)}$	input vector of energy carrier α being processed to energy carrier β
$\lvert P_{\text{CHP}}\rvert$	sum of gas consumed by the CHP
$\lvert P_{\text{el}}\rvert$	sum of consumed grid electricity
$P_{\max}$	upper boundary for input carriers
$P_{\max}^{\text{ac}}$	upper boundary for air conditioning input
$P_{\max}^{\text{CHP}}$	upper boundary for CHP input
$P_{\max}^{\text{grid}}$	upper boundary for grid input
$P_{\max}^{\text{fur}}$	upper boundary for furnace input
$P_{\min}$	lower boundary for input carriers
$P_{\min}^{\text{ac}}$	lower boundary for air conditioning input
$P_{\min}^{\text{CHP}}$	lower boundary for CHP input
$P_{\min}^{\text{grid}}$	lower boundary for grid input
$P_{\min}^{\text{fur}}$	lower boundary for furnace input
$P_k^{(l_j)}$	input demand of hub k on level l_j
$\dot{Q}$	thermal power exchange between the interior and the ambient
$\dot{Q}_{\text{air}}$	thermal power loss due to ventilation
$\dot{Q}_{\text{cool}}$	thermal power distracted by the cooling system
$\dot{Q}_{\text{fur}}^{\text{sh}}$	power released by the furnace for space heating

$\dot{Q}_{\mathrm{fur}}^{\mathrm{ww}}$	power released by the furnace for warm water heating
$\dot{Q}_{\mathrm{res}}$	resulting heat flow between house and ambient (with space heating or cooling)
$\dot{Q}^{(\mathrm{sum})}$	resulting heat flow between house and ambient (without space heating or cooling)
$\dot{Q}_{\mathrm{sol}}$	thermal power insertion by global irradiance
$\dot{Q}_{\mathrm{ww}}$	power required to provide warm water
R	renewable energy input vector
$s_{\alpha\beta}$	coupling factor between storage of energy carrier β and power supply of carrier α
S	storage matrix
t	time
Δt	time interval
T_{comp}	computational time
ΔT	time interval for load shift
$\Delta T^{(\mathrm{el})}$	time interval for electric load shift
T_{end}	last time step of an (optimization) interval
T_{DR}	time shift of demand response application
T	vector of grid feed
T_{max}	upper boundary for grid feed
T_{min}	lower boundary for grid feed
$T_k^{(l_j)}$	grid feed of hub k on level l_j
U_{cellar}	heat exchange coefficient of the cellar
U_{roof}	heat exchange coefficient of the roof
U_{wall}	heat exchange coefficient of the walls
U_{windows}	heat exchange coefficient of the windows

U_{stor}	utilization of the energy storage defined by the amount of charged or discharged energy
$U_{\mathrm{sys,stor}}$	utilization of the energy storage defined by the amount of stored energy used by the system
U_{DR}	utilization of demand response defined by the sum of shifted load
V_{DH}	volume of the cubic house model
V_{Stby}	standby losses of an energy storage device
w	width of the house
x_0	initial values for the optimization
x_{end}	final values of the optimization variables

A.2 Greek Symbols

α	conversion factor for global irradiance on a vertical surface
Δ_{p}	price difference
η_{cool}	cooling system efficiency
η_{heat}	space heating efficiency
$\eta_{\alpha,\beta}$	conversion efficiency from energy carrier α to β
η_{char}	charge efficiency of a storage device
η_{dis}	discharge efficiency of a storage device
η_{cycle}	cycle efficiency of a storage device
$\eta^{\mathrm{grid}}_{\mathrm{el,el}}$	grid connection efficiency
$\eta^{\mathrm{fur}}_{\mathrm{gas,th}}$	gas furnace efficiency
$\eta^{\mathrm{CHP}}_{\mathrm{gas,el}}$	electric efficiency of the gas-fueled CHP

$\eta_{\mathrm{gas,th}}^{\mathrm{CHP}}$	thermal efficiency of the gas-fueled CHP
ϑ_{nom}	nominal temperature of the house
$\Delta\vartheta_{\mathrm{nom}}$	temperature bandwidth for the inner temperature of the house
ϑ_{in}	actual temperature within the house
ϑ_{out}	ambient temperature
$\vartheta_{\mathrm{ground}}$	ground temperature
ϑ_{hot}	hot water temperature
$\vartheta_{\mathrm{cold}}$	cold water temperature
$\Delta\vartheta$	temperature change
$\nu_{\alpha,\beta}$	dispatch factor from energy carrier α to β
π_{α}	price for energy carrier α
π_{el}	electricity price
π_{gas}	gas price
π_{CHP}	price for CHP electricity
$\pi^{(\mathrm{sum})}$	overall energy costs
$\pi_{\mathrm{DR}}^{(\mathrm{sum})}$	overall energy costs with demand response
$\pi_{\mathrm{stor,boi}}^{(\mathrm{sum})}$	overall energy costs with hot water tank
$\pi_{\mathrm{DR,stor,el}}^{(\mathrm{sum})}$	overall energy costs with demand response and electric storage
$\pi_{\mathrm{DR,stor,boi}}^{(\mathrm{sum})}$	overall energy costs with demand response and hot water tank
$\pi_{\mathrm{coll}}^{(\mathrm{sum})}$	overall energy costs in cooperation
$\pi_{\mathrm{coex}}^{(\mathrm{sum})}$	overall energy costs in coexistence
$\pi_{\mathrm{DR,coll}}^{(\mathrm{sum})}$	overall energy costs with demand response in cooperation

$\pi^{(\mathrm{sum})}_{\mathrm{DR,coex}}$	overall energy costs with demand response in coexistence
$\pi^{(\mathrm{sum})}_{\mathrm{stor,coll}}$	overall energy costs with electric energy storage in cooperation
$\pi^{(\mathrm{sum})}_{\mathrm{stor,coex}}$	overall energy costs with electric energy storage in coexistence
$\pi^{(\mathrm{el})}$	overall electricity costs
Π_{P}	price matrix
ρ_{air}	air density
ρ_{in}	inner wall density
ρ_{wall}	outer wall density

A.3 Abbreviations

CAES	Compressed-air energy storage
CHP	Combined heat and power (plant)
CPP	Critical peak pricing
DR	Demand response
DSM	Demand-side management
HT	High-tariff (interval)
LT	Low-tariff (interval)
MT	Medium-tariff (interval)
PV	Photovoltaic
UPS	Uninterruptible power supply

Appendix B

Assumptions and Simplifications of the Applied House Model

The house model presented in section 2.1.3 is based on several assumptions and simplifications:

- The temperature within the house is the same for each room. Differences between the rooms, e.g. between bathroom and sleeping room or north and south orientation, are not considered.
- Heat exchange between the house and the ambient is considered to occur only due to the temperature difference $\vartheta_{\text{out}} - \vartheta_{\text{in}}$. Effects such as cooling by wind, rain, etc, as well as solar heating via the walls are not considered.
- The air within the house and the walls are assumed to change their temperatures equally and with the same time constant. Different cooling/heating as occuring e.g. in corners, near windows or due to ventilation are not considered.
- The product of mass and heat capacity, $m \cdot c$, of the house has a significant impact on the inner temperature profile (eq. (2.9)). However, the effective thermal mass C_{eff} is difficult to estimate [13]. The assumptions made in this thesis are based in literature, but are nevertheless only approximations.

- The interior temperature profile $\vartheta_{\text{in}}(t)$ is influenced by a number of different factors, e.g. wind, solar irradiation, ventilation, exterior temperature, thermal inertia of the walls, and especially by the customs of the inhabitants. Cooking, sensible heat of the inhabitants, open doors etc. influence the interior temperature. These effects, however, cannot be considered as they are very specific for each scenario and increase the complexity of the model significantly.

- Space heating shows certain inertia to furnace operation. At the instant the furnace is switched off, there is still some heat stored within the radiators and the pipes. Consequently, some heat will still be introduced into the system after switching off the furnace. This effect, however, is not considered in the presented model. The analogue phenomenon applies for switching on the furnace and for the application of a chiller.

As a consequence of the simplifications, the thermal behavior of the house is only an approximation. Nevertheless, the main influencing factors, namely solar irradiation, heat exchange via the walls, air ventilation and space conditioning are considered [13, 17, 59]. Therefor, the achieved degree of precision is sufficient for the study at hand, as the thermal behavior of the building is indeed necessary to determine the thermal load curve, but small deviations are not likely to cause big changes in the results of the simulations.

Appendix C

Comments on the Matlab Implementation

The house model, the multi-energy hub and the multiple-level model were implemented in Matlab® to run the numerical simulations. In some cases, the implementation necessitates an adaptation or reformulation of the system constraints to comply with Matlab requirements. This chapter comments on these necessary changes.

C.1 Constraints on Heating and Cooling Power

The inner temperature of the house may vary within a temperature band of $\pm\Delta\vartheta$ around the nominal temperature ϑ_{nom} (2.9). In summer, however, it cannot be guaranteed that the temperature stays below the upper boundary if no cooling device is available. Consequently, the upper boundary has to be relaxed for the case that more heat enters the room as would be allowed to stay within the boundaries.

For each time step, the inner temperature has to stay within the given boundaries:

$$\vartheta_{\text{nom}} - \Delta\vartheta \leq \vartheta_{\text{in}}(t) \leq \vartheta_{\text{nom}} + \Delta\vartheta$$

The inner temperature $\vartheta_{\text{in}}(t)$ can be determined from the temperature of the last time step, $\vartheta_{\text{in}}(t-1)$ and the heat flow of the system, resulting in:

$$\vartheta_{\text{nom}} - \Delta\vartheta \leq \vartheta_{\text{in}}(t-1) + \frac{\dot{Q} + \dot{Q}_{\text{sol}} + \dot{Q}_{\text{air}} + \eta_{\text{heat}} \cdot \dot{Q}^{\text{sh}}_{\text{fur}}}{m \cdot c} \Delta t \leq \vartheta_{\text{nom}} + \Delta\vartheta \tag{C.1}$$

Equation (C.1) can be transposed to represent the constraints for the furnace power $\dot{Q}_{\text{fur}}$:

$$\begin{aligned} (\vartheta_{\text{nom}} - \Delta\vartheta - \vartheta_{\text{in}}) \cdot \frac{m \cdot c}{\Delta t \cdot \eta_{\text{heat}}} - \frac{\dot{Q} + \dot{Q}_{\text{sol}} + \dot{Q}_{\text{air}}}{\eta_{\text{heat}}} - \dot{Q}^{\text{sh}}_{\text{fur}} &\leq 0 \qquad \text{(C.2)} \\ \dot{Q}^{\text{sh}}_{\text{fur}} - \left[(\vartheta_{\text{nom}} + \Delta\vartheta - \vartheta_{\text{in}}) \cdot \frac{m \cdot c}{\Delta t \cdot \eta_{\text{heat}}} - \frac{\dot{Q} + \dot{Q}_{\text{sol}} + \dot{Q}_{\text{air}}}{\eta_{\text{heat}}} \right] &\leq 0 \end{aligned}$$

The term including the nominal temperature denotes the amount of heat that could be extracted out of or injected into the system to stay within the temperature boundaries, while the $\dot{Q}$-terms denote the heat flows of the system. If the heat flow, excluding the furnace power $\dot{Q}^{\text{sh}}_{\text{fur}}$, is higher than the maximum possible heat to be inserted (C.2) the upper boundary can only be kept if cooling is available. Consequently, if no cooling is available, the difference

$$(\vartheta_{\text{nom}} + \Delta\vartheta - \vartheta_{\text{in}}) \cdot \frac{m \cdot c}{\Delta\vartheta \cdot \eta_{\text{sh}}} - \frac{1}{\eta_{\text{sh}}} \cdot (\dot{Q} + \dot{Q}_{\text{sol}} + \dot{Q}_{\text{air}})$$

will be negative and (C.2) cannot be compensated by the furnace power, as $\dot{Q}_{\text{fur}}$ has to be greater than zero. To ensure that the optimization will find a solution, and at the time not neglecting the upper boundary for all cases where the furnace is operated, the constraint of (C.2) will be set to

$$\dot{Q}^{\text{sh}}_{\text{fur}} \leq 0 \tag{C.3}$$

This ensures that for all cases where more energy enters the house by solar or ambient heat, the upper bound does not have to be satisfied, but at the same time the furnace must not be operated, as (C.3) together with the constraint that the furnace power has to be larger than zero ensures that $\dot{Q}^{\mathrm{sh}}_{\mathrm{fur}} = 0$.

The analogue case holds true in winter for the lower temperature boundary and a cooling system. Then, the efficiency of the chiller, η_{cool}, has to be considered instead of the heating efficiency, η_{heat}, and the cooling power generally has to be less than zero, $\dot{Q}_{\mathrm{cool}} \leq 0$.

C.2 Interval for Demand Response Balance

Demand response denotes the shift of load in time. Nevertheless, all load demand has to be supplied at some time, as was derived in section 4.1.2. However, the time interval T_{end} for which eq. (4.5) has to be fulfilled can be set in different ways. Obvious choices are

1. the complete time interval under consideration (e.g. one year: $T_{\mathrm{end}} = 8760$),
2. the optimization horizon ($T_{\mathrm{end}} = N_{\mathrm{int}}$),
3. the solution horizon ($T_{\mathrm{end}} = N_{\mathrm{sol}}$).

The first possibility allows the highest flexibility in load shifting. However, this is not reasonable as the inhabitants most probably do not want to wait for more than several hours or even days to get their demand fulfilled. Also, this choice cannot be implemented because of the split optimization (chapter 4.5). The third choice, $T_{\mathrm{end}} = N_{\mathrm{sol}}$, is very strict, as the solution horizon should be selected as small as possible. A selection of $N_{\mathrm{sol}} = 1$ would even prohibit the application of demand response. The optimization horizon N_{int} as time interval for the equality constraint allows the consideration of the largest possible time interval within one optimization run. Thus, the household can fulfill its load demand within a reasonable time interval and can simultaneously make use of all available information (of one optimization run) to determine its demand response strategy.

Certainly, the inhabitants could also define any other time interval T_{end} for eq. (4.5) to be satisfied. But for simplicity and to keep the amount of parameters low, the optimization horizon is selected, resulting in

$$\sum_{t=0}^{N_{\mathrm{int}}} H^{(\mathrm{el})}(t) \cdot \Delta t = 0. \tag{C.4}$$

In each optimization run, only N_{sol} of the N_{int} time steps are included in the final solution. Consequently, there will be an amount of not compensated shifted energy, E_{not}:

$$\begin{aligned} \sum_{t=1}^{N_{\mathrm{int}}} H^{(\mathrm{el})}(t) \cdot \Delta t &= \sum_{t=1}^{N_{\mathrm{sol}}} H^{(\mathrm{el})}(t) \cdot \Delta t + \sum_{t=N_{\mathrm{sol}}+1}^{N_{\mathrm{int}}} H^{(\mathrm{el})}(t) \cdot \Delta t = 0 \\ \rightarrow E_{\mathrm{not}} &= \sum_{t=N_{\mathrm{sol}}+1}^{N_{\mathrm{int}}} H^{(\mathrm{el})}(t) \cdot \Delta t \end{aligned} \tag{C.5}$$

The residual energy E_{not} (C.5) has to be supplied in the next optimization interval to fulfill (4.5) and (C.4), respectively:

$$\sum_{t=1}^{N_{\mathrm{int}}} H_{(n+1)}^{(\mathrm{el})}(t) \cdot \Delta t - E_{\mathrm{not}}^{n} = 0, \tag{C.6}$$

where n is the count of the optimization run.

Curriculum Vitae

April 21, 1983	Born in Dachau, Germany
1989 - 1993	Primary School: Grundschule Schwabhausen, Germany
1993 - 2002	Secondary School: Josef-Effner-Gymnasium, Dachau, Germany
2002 - 2008	Study of Electrical Engineering (Specialization: Control Theory) at Technische Universität München, Germany
09/2005 - 02/2006	ERASMUS Exchange Semester at University of Nottingham, UK
03/2006 - 08/2006	Exchange Semester at the Pontificia Universidad Católica de Chile, Santiago de Chile
2008 - 2011	Assistant at the High Voltage Laboratory, ETH Zurich, Switzerland; PhD thesis under the supervision of Prof. Dr. Klaus Fröhlich