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Economic Assessment of Distributed and Centralized Storage in Distribution Networks

Semester Thesis
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Abstract

With an increasing share of renewable generation and falling prices for batteries the integration of battery storage into the distribution grid is frequently discussed. Using an optimization framework based on an optimal power flow formulation, this thesis undertakes an economic assessment of centralized and distributed configurations of energy storage. Influence factors such as storage prices, PV share and grid topology are analyzed. Economic properties such as break-even points and storage revenue are quantified for an example grid topology. Key findings are that the distributed configuration is superior to the centralized configuration in terms of revenue by 160 % for the given scenario. Furthermore it was obtained that the distributed configuration results in an on average two times bigger overall storage, while the increased revenue outweighs the increased storage costs.
Contents

1 Introduction 1
  1.1 Recent Work ................................................. 1
  1.2 Research Objective ........................................ 2
  1.3 Thesis Outline ............................................. 2

2 Costs for Different Storage Technologies 3
  2.1 Key Factors of Energy Storage ............................... 3
  2.2 Costs for Energy Storage .................................... 3
  2.3 Typical Storage Costs ...................................... 4
  2.4 Expected Price Development ................................. 4

3 Business Cases for Energy Storage 5

4 Economic Assessment 8
  4.1 Overall Cost ................................................ 8
  4.2 Storage Investment Cost .................................... 8
  4.3 Storage Revenue ........................................... 9
  4.4 Curtailment Costs .......................................... 9
  4.5 Internal Rate of Return ................................... 9
  4.6 Break Even .................................................. 10

5 Component Modelling 11
  5.1 Grid Topology .............................................. 11
  5.2 PV Generation .............................................. 11
    5.2.1 Power Rating .......................................... 11
    5.2.2 Production Profile ................................... 11
    5.2.3 PV Share .............................................. 12
  5.3 Grid Feeder ................................................ 12
    5.3.1 Power rating ........................................... 12
    5.3.2 Price Profile .......................................... 12
  5.4 Loads ....................................................... 12
  5.5 Storage ..................................................... 12
    5.5.1 State of Charge ........................................ 13
### CONTENTS

**6 Optimization Problem**  
6.1 Time Variant Values .......................... 17  
6.2 Time Coupling ................................ 17  
  6.2.1 Multi-period Optimization Problem .......... 18  
6.3 Storage Energy Constraints ...................... 19  
  6.3.1 Power Constraints .......................... 20  
  6.3.2 Storage Costs .............................. 20  
  6.3.3 Optimization Problem with Storage Constraints 21  
6.4 Optimal Sizing ................................ 21  
  6.4.1 Capacity Sizing Constraints .................. 22  
  6.4.2 Optimization Problem with Optimal Sizing .... 23  

**7 Application**  
7.1 Simulation Framework .......................... 24  
7.2 Extending MATPOWER ............................ 25  
  7.2.1 Topology .................................. 25  
  7.2.2 Feeder Costs .............................. 25  
  7.2.3 PV Costs ................................... 25  
  7.2.4 Storage Costs ................................ 25  
  7.2.5 Energy Constraints .......................... 26  
  7.2.6 Power Constraints .......................... 27  
7.3 Options ......................................... 27  

**8 Results**  
8.1 Computational Challenges ....................... 29  
  8.1.1 Influence of the Problem Size ................. 29  
  8.1.2 Different Solving Algorithms .................. 31  
8.2 Comparison of Centralized and Distributed Storage 32  
  8.2.1 Influence of Storage Costs .................... 33  
  8.2.2 PV Share ................................... 36  
  8.2.3 Marginal Costs of PV Generation .............. 40  
  8.2.4 Influence of PV Subsidies ..................... 40  
8.3 Storage Placement ................................ 41  

**9 Conclusions and Outlook**  
9.1 Key findings ................................... 44  
9.2 Limitations ..................................... 45  
9.3 Outlook ......................................... 45
## List of Figures

3.1 Grid topology with centralized storage .......................... 6  
3.2 Grid topology with distributed storage ........................... 7  

5.1 Power grid of the city of Rheinfelden .......................... 14  
5.2 EEX price profile for the 5.8.2011 ............................... 15  

7.1 General structure of the optimization framework ............... 24  

8.1 Computation time for a centralized scenario for different solvers 32  
8.2 Storage size comparing centralized and distributed configurations ........................................ 34  
8.3 Storage revenue comparing centralized and distributed configurations ........................................ 35  
8.4 Dispatch for a distributed configuration and 1 week of simulation time ........................................ 37  
8.5 Influence of different PV shares for centralized configuration 39  
8.6 Influence of different PV shares for distributed configuration 39  
8.7 Storage placement for different storage prices .................. 41
List of Tables

2.1 Storage Costs for Different Storage Technologies [19] . . . . . 4

8.1 Computation time for a system with 27 busses and 24 - 480
timesteps . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 30
8.2 Linear/Quadratic Fit . . . . . . . . . . . . . . . . . . . . . . . 31
8.3 Estimated simulation time . . . . . . . . . . . . . . . . . . . . . 31
8.4 Simulation parameters for storage cost analysis . . . . . . . . . 33
8.5 Simulation results for a centralized storage . . . . . . . . . . . 36
8.6 Simulation results for a distributed storage . . . . . . . . . . . 38
8.7 Simulation parameters for PV share analysis . . . . . . . . . . 38
8.8 Simulation parameters for PV subsidies analysis . . . . . . . . 40
8.9 Simulation results for PV subsidies analysis . . . . . . . . . . . 41
8.10 Parameters for the optimization of storage placement . . . . . 42
8.11 Mapping of the storages to the busses . . . . . . . . . . . . . 42
Acronyms

**EEG** Erneuerbare Energien Gesetz. 40

**EEX** European Energy Exchange. iii, 12, 15, 24, 25, 44

**EV** Electric Vehicles. 4

**EV** Photovoltaic. 2, 40

**IRR** Internal Rate of Return. 9, 10, 40, 44

**KEV** Kostendeckende Einspeisevergütung. 40

**MEX** MATLAB Executable. 31

**NPV** Net Present Value. 9

**OPF** Optimal Power Flow. 2, 25

**SOC** State of Charge. 12, 13

**STC** Standard Test Conditions. 11
List of Symbols

\( \eta_{\text{gen}} \) Discharging efficiency
\( \eta_{\text{load}} \) Charging efficiency
\( \eta_{\text{rt}} \) Round-trip efficiency
\( S_u \) Evolution matrix of the initial state of charge
\( S_x \) Evolution matrix of the state vector
\( \theta \) Vector of voltage angles
\( e \) Vector of states of charge
\( p_g \) Active power vector of the generators
\( p_g \) Generation power
\( p_g \) Reactive power vector of the generators
\( p_l \) Load power
\( v_m \) Vector of voltage magnitudes
\( x \) State vector of the original system
\( x_{\text{os}} \) State vector for the problem with optimal sizing
\( x_{\text{tc}} \) State vector of the time coupled system
\( z \) Vector of storage sizes
\( C_a \) Overall cost
\( C_{\text{bat}} \) Price of the battery
\( C_{\text{conversion}} \) Costs for energy conversion system
\( C_l \) Costs for energy consumption of loads
\( C_{\text{PV},\text{me}} \) Marginal costs of PV production
Acronyms

\( C_{PV,\text{tot}} \) Costs for PV production
\( C_{si} \) Costs for energy storage
\( C_{stor} \) Costs for storage
\( C_{tl} \) Costs for transmission losses
\( C_{\text{total}} \) Total storage system costs
\( C_{fi} \) Costs for imported energy
\( CF_{si} \) Cashflow to storage investment
\( CF_{stor} \) Cashflow from storage usage
\( e(k) \) Energy content at timestep \( k \)
\( f_P \) Cost function for active power
\( f_Q \) Cost function for reactive power
\( f_{os} \) Cost function for the system with optimal sizing
\( f_{Ps} \) Cost for active power of storage
\( f_{Qs} \) Cost for reactive power of storage
\( f_{is} \) Cost for installation of storage
\( f_{ws} \) Cost function for the system with storage
\( g_P \) Active power balance function
\( g_Q \) Reactive power balance function
\( h \) Horizon (number of timesteps)
\( n_b \) Number of busses
\( N_{cpp} \) Estimated cycles per simulation period
\( N_c \) Specified cycles for the battery
\( n_g \) Number of generators
\( n_s \) Number of storages
\( p \) Power constraint for the storage
\( p \) Total storage capacity constraint
\( P_{\text{gen}} \) Power injection of the storage as a generator
Acronyms

\( P_{\text{load}} \)  Power injection of the storage as a load
\( P_s \)  Active power injection of storage
\( Q_s \)  Reactive power injection of storage
\( R_{bc} \)  Revenue in the base case
\( R_{fe} \)  Revenue from exported energy
\( R_{PV,subs} \)  Subsidies per hour of PV production
\( R_{pvs} \)  Revenue from PV subsidies
\( R_{stor} \)  Storage revenue
\( R_{ws} \)  Revenue of system with storage
\( r_{irr} \)  Internal rate of return
\( T \)  Duration of a timestep
Chapter 1

Introduction

With climate change and air pollution being a more and more urgent problem to the society, a shift away from fossil power generation is a necessary action that needs to be undertaken. Due to the catastrophic consequences in case of failure, also nuclear energy is not popular in many countries. Power generation from renewable sources such as wind and solar however has the drawback of being intermittent and therefore hard to schedule.

Equipping the grid with energy storage could help to balance the load and the renewable generation. With falling prices for storage technologies, an integration of energy storage into the power grid is frequently discussed. Just recently with the Power Wall [20], Tesla announced a concept for distributed storage.

The two main questions underlying this thesis are at which storage price the installation of energy storage becomes economically competitive and how its configuration would look like.

1.1 Recent Work

The question of the economic competitiveness of residential energy storage is frequently addressed in literature. In [7] the economic feasibility of residential storage is assessed for the Australian energy market. The profitability of energy arbitrage through buying in off-peak and selling in peak hours is shown using a probabilistic demand simulation. In [4], this analysis is done for the european market, evaluating the impact of the battery parameters, the price curve and the consumer profile. A detailed analysis of the economic potential depending on the market design is described in [15] for the north american market. While this publications mainly assess the market potential for storage in general, they do not take into account the influence of the grid topology.
CHAPTER 1. INTRODUCTION

A more technical approach taking into account the topology by using the optimal power flow (OPF) method with storages was described in [12]. Also using an OPF approach the optimal placement of energy storage was covered in [14].

While the more technical publications value the impact of different grid topologies and use a realistic model of the grid, they do not assess the economic implications of storage. On the other hand the economic point of view usually does not take into account the technical implications.

1.2 Research Objective

Goal of this work is to combine the economic assessment of energy storage with the detailed technical model using the full nonlinear power-flow with real grid data. To do that, this thesis compares distributed and centralized storage configurations. Research question is if from an economical point of view it is preferable to have a centralized configuration with energy storage at the substation or a group of several storages distributed within the low voltage grid. The influence of different parameters is described. Technical parameters such as the storage efficiencies and the EV share as well as economic parameters such as the storage price and PV subsidies are assessed.

1.3 Thesis Outline

This thesis is structured as follows. In the first Chapter different key features of different technologies are outlined, key factors of the price are described and prices for different technologies are compared. Subsequently, the different possible business cases for grid connected energy storage are described and the key characteristics values for the economic assessment are defined. In Chapter 5 the models used for the different components of the power system are described. In Chapter 6 the optimization problem of the optimal storage sizing is formulated. The implementation details of the simulation framework are described in Chapter 7. Next, in Chapter 8 the simulation results are presented and the key findings are shown.
Chapter 2

Costs for Different Storage Technologies

2.1 Key Factors of Energy Storage

An energy storage system can usually be described mainly by three features: The power rating (kW), the energy storage rating (kWh) and the round-trip efficiency $\eta_{rt}$. The power rating describes the maximum output power that can be delivered by the energy system in one instant. The energy rating describes the maximum amount of energy that can be stored. The round-trip efficiency relates the energy that is put into the storage while charging to the energy that can be drawn from the battery while discharging.

Depending on the amount of energy that needs to be stored and the duration of the charge/discharge different ratings and therefore different storage technologies are needed.

2.2 Costs for Energy Storage

The total costs for a energy storage system can be split up according to [19] into the costs for energy conversion and the costs for the actual storage.

$$C_{\text{total}} = C_{\text{conversion}} + C_{\text{stor}} \quad (2.1)$$

Usually the costs for energy conversion are proportional to the power rating since the limit for the power that can be delivered is usually determined by the power converter that connects the battery to the grid. The energy rating is corresponding to the storage costs since they depend on the amount of actual energy that needs to be stored.

This thesis will focus on the assessment of the business model for price arbitrage as explained further in Chapter 3. For price arbitrage the energy storage capability is more relevant compared to the power output of the
CHAPTER 2. COSTS FOR DIFFERENT STORAGE TECHNOLOGIES

Table 2.1: Storage Costs for Different Storage Technologies [19]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Conversion ($/kW)</th>
<th>Storage ($/kWh)</th>
<th>Round-trip Efficiency</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid Bat.</td>
<td>400</td>
<td>330</td>
<td>80 %</td>
<td>2000</td>
</tr>
<tr>
<td>Lithium-ion Bat.</td>
<td>400</td>
<td>600</td>
<td>85 %</td>
<td>4000</td>
</tr>
<tr>
<td>Vanadium-Redox Bat.</td>
<td>400</td>
<td>400</td>
<td>65 %</td>
<td>5000</td>
</tr>
<tr>
<td>Sodium/Sulfur Bat.</td>
<td>350</td>
<td>350</td>
<td>75 %</td>
<td>3000</td>
</tr>
<tr>
<td>Flywheels</td>
<td>600</td>
<td>1600</td>
<td>95 %</td>
<td>25000</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>500</td>
<td>10000</td>
<td>95 %</td>
<td>25000</td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>1200</td>
<td>75</td>
<td>85 %</td>
<td>25000</td>
</tr>
</tbody>
</table>

battery [5]. Hence, this work will mainly take into account the influence of the storage costs $C_{stor}$ and assume the costs for energy conversion to be constant.

2.3 Typical Storage Costs

Typical costs for different storage technologies can be found in literature. An overview of popular storage technologies and their costs can be found in Table 2.1.

The different storage technologies show substantial differences for their suitability for frequent and infrequent operation. While Lead-acid Batteries have with $\approx 330$ $$/kWh relatively low storage costs they will need to be replaced after $\approx 5$ years if daily cycled. In contrast, supercapacitors have a tremendously higher cycling capacity but are also significantly more expensive. Between the two extremes, Lithium-ion batteries have an expected lifetime of $\approx 10$ years for daily cycling at a relatively low price and are therefore well suited for the energy arbitrage business case.

2.4 Expected Price Development

In recent years, battery technologies have significantly improved in terms of storage densities, cycling capacity and reliability [7]. As a consequence the price per kWh went down in recent years. For technologies like Lithium-Ion many fast growing markets such as the markets for EVs, cellphones and other applications exist. Steady improvements due to high investments into research and scaling effects due to high demand will further bring down price [16]. Since the technologies of mobile and stationary storage are very similar on the battery level this will also result in price drops for fixed installations [10].
Chapter 3

Business Cases for Energy Storage

To assess the use of batteries in electricity grids we introduce possible business cases that could become profitable at different price points for storage.

In non-islanded grid operation, there are mainly three different business cases for energy storage.

Ancillary services  Ancillary Services include all services that are necessary to support the electric power transmission. This includes frequency control, voltage control and providing spinning and non-spinning reserves. Due to their fast discharge capabilities, batteries can act as a synthetic spinning reserve and provide primary control to the system. It is also possible to provide secondary control and depending on the inverter also voltage control.

Deffering of grid extensions  Since the peak capability of equipment is usually only used for short times, it is possible to defer grid extensions such as building lines or transformers by installing storage [5].

Price arbitrage  By exploiting the price differences between times with high production and low demand and low production and high demand it is possible to make profit through buying energy during off-peak hours and selling it during peak.

The scope of this thesis will mainly assess the business case of price arbitrage using energy storage in a distribution grid with a high share of PV. However the simulation tool developed during the thesis could be equally used to assess business cases for ancillary services or the deferring of grid extensions.
A symbolic illustration of the distributed and centralized storage configurations assessed in the following chapters is shown in Figures 3.1 and 3.2.

Figure 3.1: Grid topology with centralized storage
Figure 3.2: Grid topology with distributed storage
Chapter 4

Economic Assessment

To assess the economic impact of adding energy storage to the grid, we define some suitable characteristic values in order to quantify the simulation results.

4.1 Overall Cost

The output variable of the optimization is the value of the cost function in the point of optimum. We define this value as the overall cost $C_a$ of the system. The overall costs consist of:

- Costs for energy storage $C_{si}$
- Costs for energy consumption of loads $C_l$
- Costs for transmission losses $C_{tl}$
- Costs for imported energy (energy from the grid feeder) $C_{fi}$
- Revenue from exported energy $R_{fe}$
- Revenue from PV subsidies $R_{pvs}$

$$C_a = C_{si} + C_l + C_{tl} + C_{fi} - R_{fe} - R_{pvs} \quad (4.1)$$

4.2 Storage Investment Cost

We define the storage investment cost as the (theoretical) price we have to pay to operate the storage for the simulation period. Given the price of the battery $C_{bat}$, the number of cycles $N_c$ the battery is specified for and the estimated cycles per simulation period $N_{cpp}$ we can calculate the storage investment as

$$C_{si} = \frac{C_{bat}}{N_c} \cdot N_{cpp} \quad (4.2)$$
CHAPTER 4. ECONOMIC ASSESSMENT

4.3 Storage Revenue

We define the storage revenue $R_{stor}$ as the revenue of the system with storage $R_{ws}$ compared to a base case without storage $R_{bc}$ as

$$R_{stor} = R_{ws} - R_{bc}.$$  \hspace{1cm} (4.3)

Using this approach we do not only consider revenue due to price differences between the time of charge and discharge, but also the increased revenue due to reduced curtailment of the PV generators.

4.4 Curtailment Costs

If curtailment of the PV generators occurs due to a lack of demand and storage capacity we forgo the opportunity to make revenue from selling the generated energy. Since the PV is already installed at that point in time, the purchase costs are sunk and hence the marginal costs to produce are zero. Therefore the curtailment costs are the (implicit) costs due to curtailment and therefore reduced utilization.

4.5 Internal Rate of Return

The internal rate of return (IRR) can be calculated by setting the net present value (NPV) to zero and solving for $r$ as

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1 + r_{irr})^n} = 0.$$ \hspace{1cm} (4.4)

We only consider two designated cashflows: The (negative) cashflow for the initial investment to build the storage and connecting it to the grid and the (positive) cashflow that can be earned through utilizing price arbitrage using the storage.

We consider cashflows due to costs with a negative sign and cashflows due to revenues as positive cashflows. Therefore the (negative) cashflow caused by the investment into the storage can be defined as the costs for the storage investment $C_{si}$ denoted with a negative sign.

$$CF_{si} = -C_{si}$$ \hspace{1cm} (4.5)

Similarly we define the (positive) cashflow due to the revenue generated by the storage as the revenues from the storage denoted with a positive sign.

$$CF_{stor} = R_{stor}$$ \hspace{1cm} (4.6)
Hence we can rewrite (4.4) using (4.5) and (4.6) as

\[ 0 = CF_{si} + \frac{CF_{stor}}{1 + r_{irr}} . \]  

(4.7)

Since we are only considering two cashflows we can solve (4.4) explicitly for the IRR \( r_{irr} \)

\[ r_{irr} = \frac{-CF_{si} - CF_{stor}}{CF_{si}} . \]  

(4.8)

The internal rate of return \( r_{irr} \) can be interpreted as a rate of return on the investment into the energy storage. Using the IRR it is possible to easily compare the investment into energy storage to other investments.

### 4.6 Break Even

The *Break-even* point is defined as the point of balance between making profit or making a loss. In the scope of our problem the break-even point can be understood as the point when the revenue of the storage becomes higher than the cost for installing the storage. Hence it makes economically sense to build a storage unit.
Chapter 5

Component Modelling

To assess the optimal sizing of batteries in the distribution grid we must model several aspects relevant for the optimization such as the topology of the grid, the photovoltaic generation, the connection to the superior grid levels, the loads and the energy storage.

For the development of the optimization framework the power-flow analysis tool MATPOWER [24] was extended for the simulation of power grids containing storage.

5.1 Grid Topology

For our optimizations we use a reduced version of the distribution grid of the city of Rheinfelden shown in Fig. 5.1. The distribution grid level of 400V is connected to the superior grid level of 16kV through a transformer with a power rating of 630kVA.

5.2 PV Generation

5.2.1 Power Rating

The power rating of a PV generator is usually determined by the surrounding equipment such as the inverter. The inverter is normally dimensioned in a way that it is rated for the maximum energy output of the PV generator under standard test conditions (STC). For example for a generator with $P_{STC} = 6\, kW$ we would set $P_{max} = 6\, kW$.

5.2.2 Production Profile

To model the production profile of the PV generators we use the data series generated by the METEONORM software [13].
5.2.3 PV Share
We define the PV share as the percentage of buses to which a PV generator is attached. For a PV share of 100% we have therefore a system with a PV generator at every single bus. For lower PV Shares we place the PV generators randomly at different buses.

5.3 Grid Feeder

5.3.1 Power rating
As we can see from the grid topology shown in Fig. 5.1 the grid feeder is connected to the distribution grid through a power transformer. The power rating of the transformer is crucial for the simulation results since it determines how much energy we can get from and feed back into the grid.

5.3.2 Price Profile
To model the costs of buying or selling energy from the grid, we have to model the price profile at the grid feeder. In this thesis we use the EEX cost profile for the feeder.

EEX Prices We use price data from the EEX with 15 min accuracy. An example for an EEX price profile is shown in Fig. 5.2.

The data for the profile was obtained from the publicly available EEX data, which can be accessed on the webpage of EEX [1].

5.4 Loads
Given the yearly consumption we generate individual load profiles from a standardized load profile using the load profile generator developed in [6].

5.5 Storage
The state of our storage can be described through several parameters:

- State of charge
- Power rating
- Initial charge

To model the state of charge (SOC) and the power rating of the battery we can define several constraints.
5.5.1 State of Charge

For the constraints of the storage in terms of energy we can write the energy in one storage at time-step \( k + 1 \) as follows:

\[
e(k + 1) = e(k) - T \left( \frac{1}{\eta_{\text{gen}}} \cdot P_{\text{gen}} - \eta_{\text{load}} \cdot P_{\text{load}} \right),
\]

where \( T \) is the duration of the time-step and \( \eta_{\text{load}} \) and \( \eta_{\text{gen}} \) are the efficiencies for charging and discharging discharging the battery. The variables \( P_{\text{gen}} \) and \( P_{\text{load}} \) are the power injections that represent the battery to the network as a load/generator.

We now extend (5.1) for multiple storages and define \( n_s \) as the number of storages in the system.

We construct the vector \( x(k) \) as a vector containing the power injections of the storage as a generator and the (negative) power injections form the storage as a load:

\[
x(k) = \begin{bmatrix} P_{\text{gen},1} \\ \vdots \\ P_{\text{gen},n_s} \\ P_{\text{load},1} \\ \vdots \\ P_{\text{load},n_s} \end{bmatrix}
\]

Using (5.2) we can rewrite (5.1) in matrix form with \( e(k) \) being a vector of length \( n_s \) containing the SOC for all storages at time \( k \)

\[
e(k + 1) = A \cdot e(k) + B \cdot x(k),
\]

with the matrices \( A \) and \( B \) defined as written in (5.4) and (5.5).

\[
A = \text{diag}(1)
\]

\[
B_{ij} = \begin{cases} -T \cdot \frac{1}{\eta_{i,\text{gen}}} & \text{for } i \in \{1 \ldots n_s\}, j \in \{1, \ldots, n_s\} \\ -T \cdot \eta_{i,\text{load}} & \text{for } i \in \{1 \ldots n_s\}, j \in \{1 + n_s, \ldots, 2 \cdot n_s\} \end{cases}
\]

Equally in matrix form this can be written as:

\[
B = -T \begin{bmatrix} \eta_{1,\text{gen}}^{-1} & 0 & \ldots & 0 & \eta_{1,\text{load}} & 0 & \ldots & 0 \\ 0 & \eta_{2,\text{gen}}^{-1} & \ddots & 0 & 0 & \eta_{2,\text{load}} & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ 0 & \ldots & 0 & \eta_{n_s,\text{gen}}^{-1} & 0 & \ldots & 0 & \eta_{n_s,\text{load}} \end{bmatrix}
\]
Figure 5.1: Power grid of the city of Rheinfelden
Figure 5.2: EEX price profile for the 5.8.2011
Chapter 6

Optimization Problem

The general optimization task for the optimal power flow can be formulated according to [24] as

$$\min_{x} \quad f(x)$$
subject to

$$g(x) = 0$$
$$h(x) \leq 0$$
$$x_{\text{min}} \leq x \leq x_{\text{max}}$$

(6.1)

We define the cost function $f(x)$ as

$$f(x) = \sum_{i=1}^{n_g} f_P^i(p_g^i) + f_Q^i(q_g^i),$$

(6.2)

with $f_P$ and $f_Q$ being the polynomial cost functions for active and reactive power.

The state vector $x$ is defined as:

$$x = \begin{bmatrix} \theta \\ v_m \\ p_g \\ q_g \end{bmatrix},$$

(6.3)

Here the vectors $\theta$ and $v_m$ contain the voltage angles and voltage magnitudes for all $n_b$ buses. The vectors $p_g$ and $q_g$ contain the active and reactive power injections for all $n_g$ generators.

The different optimization constraints (6.4), (6.5) and (6.6) are defined as follows:

$$g(x) = 0$$

(6.4)

$$h(x) \leq 0$$

(6.5)
CHAPTER 6. OPTIMIZATION PROBLEM

\[ x_{\min} \leq x \leq x_{\max} \]  \hspace{1cm} (6.6)

Constraint (6.4) expresses the non-linear power balance equations for the active and reactive power and can be split into:

\[ g_P(\theta, v_m, p_g) = 0 \]  \hspace{1cm} (6.7)
\[ g_Q(\theta, v_m, q_g) = 0 \]  \hspace{1cm} (6.8)

The inequality constraint (6.5) contains the branch flow limits as non-linear functions of the voltage angle \( \theta \) and the voltage magnitude \( v_m \).

The constraint (6.6) contains the limits on all bus voltages in magnitude and angle and the generator limits for active and reactive power injection.

This optimization problem is of non-linear and constrained fashion with non-linear costs and constraints [23].

6.1 Time Variant Values

With the generation \( p_g \) and load \( p_l \) being time dependent, we have to run the optimal power flow for all \( h \) time-steps separately. In the case of an accuracy of one hour for generation and demand profiles we have to run 24 optimal power flows to simulate all 24 time-steps.

6.2 Time Coupling

With the introduction of storages the different time-steps described in section 6.1 become coupled. The storage allows us to transfer energy from one time-step to another time-step. In consequence, our optimization problem can not any more be solved independently for every time-step, but most be solved as a whole.

Referring to the original optimization problem (6.2) with the state vector shown in (6.3) we have to modify our problem accordingly. We look at the \( h \) different time-steps. For each time-step \( h \) we get a state vector \( x \) which consists of four parts as shown in (6.3). Hence we get \( h \) vectors for the voltage angles \( \{\theta_1, \ldots, \theta_h\} \), voltage magnitudes \( \{v_{m1}, \ldots, v_{mh}\} \), active power \( \{p_{g1}, \ldots, p_{gh}\} \) and reactive power \( \{q_{g1}, \ldots, q_{gh}\} \).

Stacking these vectors on-top of each other, we can construct a state vector for the coupled system \( x_{tc} \).
\[ \begin{bmatrix} \theta_1 \\ \vdots \\ \theta_h \\ v_{m,1} \\ \vdots \\ v_{m,h} \\ p_{g,1} \\ \vdots \\ p_{g,h} \\ q_{g,1} \\ \vdots \\ q_{g,h} \end{bmatrix} = \begin{bmatrix} \theta_{tc} \\ v_{m,tc} \\ p_{g,tc} \\ q_{g,tc} \end{bmatrix}, \] 

(6.9)

which has \( h \) times the dimension of the original state vector \( x \).

Accordingly we also have to modify the cost function (6.2) which is now a sum over the costs for all time-steps. We define \( p_{g,k}^i \) as the \( i \)-th element of the active power vector \( p_{g,k} \) of the \( k \)-th time-step. Accordingly we define the same relation for the reactive power \( q_{g,k}^i \).

Further we write the cost function for the active power of the \( i \)-th generator in the \( k \)-th time-step as:

\[ f_{P,k}^i \: i \in \{1, \ldots, n_g\} \: k \in \{1, \ldots, h\} \]  

(6.10)

Again the reactive power cost functions \( f_{Q,k}^i \) are defined accordingly.

The cost function for the time-coupled case is defined as

\[ f(x_{tc}) = \sum_{k=1}^{h} \sum_{i=1}^{n_g} f_{P,k}^i(p_{g,k}^i) + f_{Q,k}^i(q_{g,k}^i) \]  

(6.11)

### 6.2.1 Multi-period Optimization Problem

We can now again formulate the optimization problem, this time for the multi-period case without storage.

\[ \begin{align*}
\min_{x_{tc}} & \quad f(x_{tc}) \\
\text{subject to} & \quad g(x_{tc}) = 0 \\
& \quad h(x_{tc}) \leq 0 \\
& \quad x_{tc,\text{min}} \leq x_{tc} \leq x_{tc,\text{max}}
\end{align*} \]  

(6.12)
6.3 Storage Energy Constraints

Referring to section 5.5.1 for the derivation of the state of charge of the storage we can now formulate the energy constraints for charging and discharging the storage.

We write out the first two time-steps explicitly and identify a regularity pattern.

\[
e(1) = A \cdot e(0) + B \cdot x(1) \\
e(2) = A \cdot e(1) + B \cdot x(2)
\]

(6.13)

We define the matrices \( S_x, S_u \) and the vector of the states of charge \( e \):

\[
S_e = \begin{bmatrix} I \ A \ \cdots \ A^k \end{bmatrix} \\
S_x = \begin{bmatrix} B & 0 & \cdots & 0 \\
A B & B & \cdots & \vdots \\
\vdots & \ddots & \ddots & 0 \\
A^k B & A^{k-1} B & \cdots & B \end{bmatrix} \\
e = \begin{bmatrix} e(0) \\
e(1) \\
\vdots \\
e(k) \end{bmatrix}
\]

(6.14)

We can now develop an equation for \( e \) that holds for all time-steps \( k \in \{1, \ldots, h\} \) in the simulation horizon:

\[
e = \begin{bmatrix} e(0) \\
e(1) \\
\vdots \\
e(k) \end{bmatrix} = S_e \cdot e(0) + S_x \cdot x_{tc}
\]

(6.15)

We note that \( S_e \) is a \( n_s \cdot h \times n_s \) matrix and \( S_x \) is a \( n_s \cdot h \times n_{opt} \cdot h \) matrix. The energy constraints can be formulated as

\[
0^{(h)}_{E_{min}} - S_e \cdot e(0) \leq \begin{bmatrix} 0^{(h \times 2 \cdot n_b)} \\
S_x \\
0^{(h \times n_g)} \\
A_s \end{bmatrix} \cdot \begin{bmatrix} \theta_{tc} \\
V_{m,tc}^\top \\
P_{g,tc}^\top \\
x_{tc} \end{bmatrix} \leq \begin{bmatrix} 1^{(h)} \otimes I^{(n_s \times n_s)} \end{bmatrix} \cdot \begin{bmatrix} z_1 \\
\vdots \\
z_{n_s} \end{bmatrix} - S_e \cdot e(0)_{e_0},
\]

(6.16)

with \( h \) denoting the total number of time-steps, \( n_b = n_V = n_\theta \) the number of buses, \( n_g \) the number of generators and \( n_s \) the number of storages. The variables \( z_1 \ldots z_n \) define the capacity of the storages and \( \otimes \) signifies the Kronecker product. We further define \( e_{min}, e_0, A_s \) and \( e_{max} \) as shown in (6.16).

We rewrite (6.16) into two separate inequalities

\[
A_s \cdot x_{tc} \leq e_0 \ ,
\]

(6.17)

\[
A_s \cdot x_{tc} \leq e_{max} - e_0 \ ,
\]

(6.18)
6.3.1 Power Constraints

In addition to the energy constraints, the storage is usually also subject to power constraints in terms of charge and discharge.

\[ P_{\text{gen}} \leq P_{\text{max,dischrg}} \]  \quad (6.19)

\[ P_{\text{load}} \leq P_{\text{max,chrg}} \]  \quad (6.20)

For simplicity, we write this constraint as

\[ p(x_{tc}) \leq 0 \]  \quad (6.21)

6.3.2 Storage Costs

Extending this model to include storages we have to rewrite (6.2) to include storage costs

\[ f_{\text{ws}}(x_{tc}) = \sum_{i=1}^{n_s} (f_{P_s}(p_i^s) + f_{Q_s}(q_i^s)) + \sum_{i=1}^{n_s} (f_{P_{\text{disch}}}(p_i) + f_{Q_{\text{disch}}}(q_i)) + \sum_{i=1}^{n_s} f_{S}(z^i) \]  \quad (6.22)

where \( P_s \) and \( Q_s \) are the active and reactive power injections of the storage, \( f_{P_s} \) and \( f_{Q_s} \) are the cost functions of the storage injections, \( f_{S} \) the cost function of the installation of the storage and \( z^i \) the capacity of the storage.

Since the storage costs do not depend on the power injections of the storage we set

\[ f_{P_{\text{disch}}} = 0 \quad \forall i \]  \quad (6.23)

and

\[ f_{Q_{\text{disch}}} = 0 \quad \forall i \]  \quad (6.24)

The active and reactive power generation costs \( f_{P} \) and \( f_{Q} \) contain the feeder cost profile at the feeder node. In addition to that they contain the costs for PV power which consist of the PV marginal costs and the PV subsidies.

The costs for the storage installation \( f_{S} \) is set as a linear cost function with an equal cost for all storages.
6.3.3 Optimization Problem with Storage Constraints

We can now write the optimization problem for a system with storages

\[
\begin{align*}
\min_{x_{tc}} & \quad f_{\text{ws}}(x_{tc}) \\
\text{subject to} & \quad g(x_{tc}) = 0 \\
& \quad h(x_{tc}) \leq 0 \\
& \quad x_{tc,\text{min}} \leq x_{tc} \leq x_{tc,\text{max}} \\
& \quad p(x_{tc}) \leq 0 \\
& \quad A_s \cdot x_{tc} \leq e_0 \\
& \quad A_s \cdot x_{tc} \leq e_{\text{max}} - e_0
\end{align*}
\]

(6.25)

6.4 Optimal Sizing

To achieve optimal storage sizing we extend the set of optimization variables with the storage size vector \( z \).

We rewrite (6.18) as

\[
A_s \cdot x_{tc} - e_{\text{max}} \leq -e_0 ,
\]

(6.26)

which is equal to

\[
\begin{bmatrix}
0^{(h \times 2 \cdot n_b)} \\
S_x \\
0^{(h \times n_k)}
\end{bmatrix}^\top \cdot \begin{bmatrix}
\theta_{tc} \\
V_{m,tc} \\
P_{g,tc} \\
Q_{g,tc}
\end{bmatrix} - \begin{pmatrix}
1^{(h)} \otimes I^{(n_s \times n_s)}
\end{pmatrix} \cdot \begin{bmatrix}
z_1 \\
\vdots \\
z_{n_s}
\end{bmatrix} \leq S_e \cdot e(0) .
\]

(6.27)

Rewriting (6.27) and (6.17) we can define \( x_{\text{os}} \), \( A_1 \) and \( A_2 \):

\[
\begin{bmatrix}
0^{(h \times 2 \cdot n_b)} \\
S_x \\
0^{(h \times n_k)}
\end{bmatrix} \cdot \begin{bmatrix}
\theta_{tc} \\
V_{m,tc} \\
P_{g,tc} \\
Q_{g,tc}
\end{bmatrix} \leq -S_e \cdot e(0) \quad (6.28)
\]

\[
\begin{bmatrix}
0^{(h \times 2 \cdot n_b)} \\
S_x \\
0^{(h \times n_k)}
\end{bmatrix} \cdot \begin{bmatrix}
\theta_{tc} \\
V_{m,tc} \\
P_{g,tc} \\
Q_{g,tc}
\end{bmatrix} \leq S_e \cdot e(0) \quad (6.29)
\]
CHAPTER 6. OPTIMIZATION PROBLEM

Combining (6.28) and (6.29) into one equation this results as

\[
\begin{pmatrix}
0^{(h\times2\cdot n_h)} & S_x & 0^{(h\times n_h)}\\
0^{(h\times2\cdot n_h)} & S_x & 0^{(h\times n_h)}
\end{pmatrix}
\begin{bmatrix}
\theta_{tc} \\
V_{m,tc} \\
P_{g,tc} \\
Q_{g,tc} \\
z
\end{bmatrix}
\leq
\begin{bmatrix}
-S_e \cdot e(0) \\
S_e \cdot e(0)
\end{bmatrix}
\]

Writing (6.30) more compact we define the matrix \( A \) and the upper bound \( u \) as

\[
A \cdot \begin{bmatrix} x_{\text{ns}} \end{bmatrix} \leq \begin{bmatrix} -e_0 \\ e_0 \\ u \end{bmatrix}
\]

(6.31)

6.4.1 Capacity Sizing Constraints

In some cases it can be interesting to limit the scope of the storage size optimization. This can be done either for each individual storage or for the aggregated storage.

The storage capacities are stored in the optimization variable \( z^{(n_h)} \) assuming a constant storage size over the optimization period.

Individual Storage Capacity

For certain use cases it can be necessary to limit the storage size of a certain storage. This could be the case for space limitations at certain nodes or similar reasons.

We can write the limitations for the storage capacity as

\[
z_{\text{min}} \leq z \leq z_{\text{max}}
\]

(6.32)

Component wise, this results to

\[
z_{i,\text{min}} \leq z_i \leq z_{i,\text{max}}
\]

(6.33)

If we do not have limitations we set \( z_{i,\text{min}} = 0 \) for non-negative capacities and \( z_{i,\text{max}} = \infty \) for an infinite upper limit.

In a case with limitations present, we modify the upper and lower bounds accordingly.

Total Storage Capacity

For the comparison of distributed and centralized storage configurations with equally sized storages we can introduce another constraint limiting the accumulated size of all storages.
CHAPTER 6. OPTIMIZATION PROBLEM

\[ \sum_{i \in n_s} z_i \leq z_{\text{max}} \quad (6.34) \]

Or equally in matrix form:

\[ 1^\top \cdot z \leq z_{\text{max}} \quad (6.35) \]

We further define \( o(\mathbf{x}_{\text{os}}) \) accordingly to express (6.35) as a function of \( \mathbf{x}_{\text{os}} \):

\[ o(\mathbf{x}_{\text{os}}) \leq 0 \quad (6.36) \]

6.4.2 Optimization Problem with Optimal Sizing

We can now write the optimization problem for a system with storages and optimal sizing

\[
\begin{align*}
\min_{\mathbf{x}_{\text{os}}} & \quad f_{\text{os}}(\mathbf{x}_{\text{os}}) \\
\text{subject to} & \quad g(\mathbf{x}_{\text{os}}) = 0 \\
& \quad h(\mathbf{x}_{\text{os}}) \leq 0 \\
& \quad x_{\text{os},\text{min}} \leq \mathbf{x}_{\text{os}} \leq x_{\text{os},\text{max}} \\
& \quad p(\mathbf{x}_{\text{os}}) \leq 0 \\
& \quad A \cdot \mathbf{x}_{\text{os}} \leq \mathbf{u} \\
& \quad o(\mathbf{x}_{\text{os}}) \leq 0
\end{align*}
\]  

(6.37)

with the cost function defined as

\[
\begin{multline*}
f_{\text{os}}(\mathbf{x}_{\text{os}}) = \sum_{i=1}^{n_g} (f_{P_{\text{g}}}^i(p_{\text{g}}^i) + f_{Q_{\text{g}}}^i(q_{\text{g}}^i)) + \sum_{i=1}^{n_s} (f_{P_{\text{s}}}^i(p_{\text{s}}^i) + f_{Q_{\text{s}}}^i(q_{\text{s}}^i)) + \sum_{i=1}^{n_s} f_{S}^i(z^i) .
\end{multline*}
\]  

(6.38)
Chapter 7

Application

7.1 Simulation Framework

For the assessment of the different storage configurations a modular simulation framework which is shown in Fig. 7.1 was developed.

![Diagram](image)

Figure 7.1: General structure of the optimization framework

The network topology can be imported from the grid planning tool Neplan [2] using the Neplan to MATPOWER conversion tool developed in [11]. The load and generation profiles for the consumers and photovoltaic generators are generated from load and metrological data using the tool described in [6]. The feeder cost profile is generated from EEX Data.

After importing all topology and power profiles the data is loaded into the main Szenario class describing the simulation scope.
CHAPTER 7. APPLICATION

To run the optimization, storage and generation constraints are generated as described in chapter 6 and a MATPOWER model of the network is generated. To solve the optimal power flow we use MATPOWER [25] with different solvers. The result data of the optimal power flow is fed back into our model stored in \textit{Szenario} and can be viewed using various visualization options that are encapsulated in the Result Viewer module.

7.2 Extending MATPOWER

To perform an optimization over the optimal storage capacities, we have to extend the OPF of MATPOWER with additional constraints and optimization variables.

7.2.1 Topology

The topology is imported using the \textit{Neplan Importer} module and is converted to a MATPOWER model as described in [11].

7.2.2 Feeder Costs

As described in Chapter 5 we set the costs of the grid feeder to the EEX price profile. This can be done by setting the gencost parameter in the MATPOWER model accordingly for every simulation time-step.

7.2.3 PV Costs

The costs for PV production can be formulated as

\[
C_{PV,\text{tot}} = C_{PV,mc} - R_{PV,subs}.
\] (7.1)

Here, the income from PV subsidies is modeled as a negative cost for the PV generation. The marginal costs of the PV generator are usually set to zero or chosen to include the investment cost for installation of the PV.

Again the PV costs can be set in MATPOWER by using the gencost parameter.

7.2.4 Storage Costs

According to [23] MATPOWER supports extending the cost function with user defined costs. The new cost function can be formulated as

\[
\min_{x, z} f(x) + f_u(x, z),
\] (7.2)

with \( z \) being the vector of user defined optimization variables, in our case the capacity of the different storage units.
The cost function in MATPOWER can be formulated as
\[ f_u(x, z) = \frac{1}{2} w^\top H w + C^\top w, \]
where the \( H \) matrix represents the quadratic part and the \( C \) matrix represents the linear part of the cost function. All of the parameters are \( n_w \times 1 \) vectors except the symmetric \( n_w \times n_w \) matrix \( H \) and the \( n_w \times (n_x + n_s) \) matrix \( N \) [23].

\[ r = N \begin{bmatrix} x \end{bmatrix} \]
\[ u = r - \hat{r} \]

\[ w_i = \begin{cases} m_i f_d(u_i + k_i), & u_i < -k_i \\ 0, & -k_i \leq u_i \leq k_i \\ m_i f_d(u_i - k_i), & u_i > k_i \end{cases} \]

\[ f_d(\alpha) = \begin{cases} \alpha, & \text{if } d_i = 1 \\ \alpha^2, & \text{if } d_i = 2 \end{cases} \]

For \( k_i = 0 \) and \( d_i = 1 \), \( w_i \) simplifies to
\[ w_i = m_i \cdot u_i \]

and as a consequence \( n_w = 1 \).

Aiming for a linear cost function, we set \( H = 0 \), \( \hat{r} = 0 \) and \( m_i = 1 \). To map an equal cost to all storages we set

\[ N = \begin{bmatrix} 0_{n_x}^\top & 1_{n_s}^\top \end{bmatrix}, \]

with \( n_x = n_{opt} - n_s \) being the length of \( x \) and \( n_s \) being the number of storages.

With \( n_w = 1 \) and \( C \) therefore being a scalar we set
\[ C = C_{stor} \]

to the price of storage \( C_{stor} \).

Hence, (7.3) simplifies to:
\[ f_u(z) = C_{stor} \cdot \sum_{i \in n_s} z_i \]

### 7.2.5 Energy Constraints

To define the energy constraints in MATPOWER we refer to (6.30) and take matrix \( A \) and vector \( u \). Passing them to MATPOWER as the variables \( A \) and \( u \), the optimization variables for \( z \) are automatically generated [23].
CHAPTER 7. APPLICATION

7.2.6 Power Constraints

Power constraints can be passed to the MATPOWER model as Pmax and Pmin constraints of the generators using the gen struct.

7.3 Options

The szenario module of simulation framework provides several options to specify the parameters.

**mode**  Specifies the mode of the framework. This can be *opt* for running an optimization, *sim* for running a simulation with a predefined storage value or *pf* to run a normal optimal power flow without storage.

**startDate**  Specifies the starting date of the simulation in american format, e.g. 8-1-2011 for the 1.8.2011.

**endDate**  Specifies the end date of the simulation in american format, e.g. 8-1-2011 for the 1.8.2011.

   Dates are used by the Solar Profile Generator and the Feeder Profile Data module to get the prices and weather data for the corresponding simulation time.

**hoursPerTimestep**  Defines the length of a simulation time-step. A suitable default value is 1h, for large simulations this value can be increased to speed up computation time (with the drawback of lower accuracy).

**horizon**  Number of time-steps for the simulation.

**neplanFile**  Path to the neplan xml file for importing the grid topology.

**batteryPrice**  Investment price for the installing a storage in €/MWh.

**batteryCycles**  Estimated lifetime of the storage system in cycles.

**batteryCyclesPerSimulation**  Estimated battery cycles within the simulation time.

**maxOverallStorage**  Upper bound for the aggregated capacity of all batteries in the system. This can be used to compare equally sized scenarios.

**storType**  This can be set to *centralized* or *distributed*.
storShare  Set the share of storages in percentage of all nodes form 1 – 100%.

storPowerP  Specify the active power of each PV units in MW.

storPowerQ  Specify the reactive power of each PV units in MW.

storEta_load  Efficiency to the storage for discharging.

storEta_gen  Efficiency to the storage for charging.

storX0  Initial state of charge of the storage in MWh

feederCostCurveType  Can be set to ex or peak to specify the type of price curve for the grid feeder.

peakPrice  Only for feederCostCurveType = peak. Price between peak-Start and peakEnd.

offpeakPrice  Only for feederCostCurveType = peak. Price between peak-End and peakStart.

peakStart  Only for feederCostCurveType. Time for the start of the peak period.

peakEnd  Only for feederCostCurveType. Time for the end of the peak period.

feederLimits  Limits for the grid feeder in MVA. This option limits the grid feeder in addition to the grid constraints of the nearby network.

pvShare  Share of nodes that contain a PV generator.

pvP  Active power of the PV generator at each node.

pvQ  Reactive power of the PV generator at each node.

pvEnergyPrice  Marginal cost of PV energy.

pvSubsidies  Subsidies for PV generation such as KEV or EEG.

loadConsumption  Yearly energy consumption for each load in kWh.
Chapter 8

Results

8.1 Computational Challenges

With the introduction of storage we gain the possibility to take energy from a certain point in time and release it in another time-step. This introduces a coupling between the different time-steps.

8.1.1 Influence of the Problem Size

Simulating a network with \( n_b \) busses for a year with the resolution of 1h, we have \( 365 \cdot 24 = 8760 \) time-steps. For the scenario without storage we have to solve 8760 independent optimization problems with \( n_b \) busses each.

For the network with storages however we have to solve the coupled optimization problem with \( 8760 \cdot n_b \) busses where each bus in the original problem corresponds to 8760 busses in the resulting problem. Solving the coupled problem is computational significantly harder since the computational time increases not linearly with the problem size.

The 3 main influence factors on the computation time are:

- profile generation (PV, Feeder and Loads)
- generation of evolution matrices \( S_e \) and \( S_x \)
- power flow calculation

Simulating the timespan of 1 – 20 days of a system with \( n_b = 27 \) busses and 1 storage we measure the computation times on a regular Windows 7 desktop computer. The duration of the different subtasks is shown in Table 8.1.

Approximating the data with a quadratic resp. linear polynomial curve we can extrapolate the computation time.

\[
y(x) = a \cdot x^2 + b \cdot x + c
\]

(8.1)
Table 8.1: Computation time for a system with 27 busses and 24 - 480 timesteps

<table>
<thead>
<tr>
<th>Days</th>
<th>Profile Generation (s)</th>
<th>Evolution matrices (s)</th>
<th>Power Flow (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.98</td>
<td>0.05</td>
<td>1.10</td>
</tr>
<tr>
<td>2</td>
<td>5.21</td>
<td>0.04</td>
<td>2.62</td>
</tr>
<tr>
<td>3</td>
<td>6.63</td>
<td>0.07</td>
<td>4.03</td>
</tr>
<tr>
<td>4</td>
<td>8.49</td>
<td>0.09</td>
<td>6.11</td>
</tr>
<tr>
<td>5</td>
<td>9.67</td>
<td>0.12</td>
<td>8.57</td>
</tr>
<tr>
<td>6</td>
<td>11.27</td>
<td>0.17</td>
<td>10.87</td>
</tr>
<tr>
<td>7</td>
<td>12.49</td>
<td>0.20</td>
<td>14.35</td>
</tr>
<tr>
<td>8</td>
<td>13.80</td>
<td>0.24</td>
<td>19.72</td>
</tr>
<tr>
<td>9</td>
<td>15.17</td>
<td>0.28</td>
<td>20.82</td>
</tr>
<tr>
<td>10</td>
<td>16.49</td>
<td>0.34</td>
<td>25.43</td>
</tr>
<tr>
<td>11</td>
<td>17.86</td>
<td>0.38</td>
<td>30.43</td>
</tr>
<tr>
<td>12</td>
<td>19.20</td>
<td>0.45</td>
<td>35.73</td>
</tr>
<tr>
<td>13</td>
<td>20.73</td>
<td>0.51</td>
<td>41.04</td>
</tr>
<tr>
<td>14</td>
<td>21.77</td>
<td>0.57</td>
<td>54.26</td>
</tr>
<tr>
<td>15</td>
<td>23.22</td>
<td>0.65</td>
<td>64.85</td>
</tr>
<tr>
<td>16</td>
<td>24.57</td>
<td>0.78</td>
<td>71.03</td>
</tr>
<tr>
<td>17</td>
<td>26.04</td>
<td>0.90</td>
<td>95.94</td>
</tr>
<tr>
<td>18</td>
<td>27.30</td>
<td>1.02</td>
<td>100.09</td>
</tr>
<tr>
<td>19</td>
<td>28.55</td>
<td>1.15</td>
<td>145.97</td>
</tr>
<tr>
<td>20</td>
<td>29.91</td>
<td>1.30</td>
<td>116.89</td>
</tr>
</tbody>
</table>
The coefficients for the different fitted curves are shown in Table 8.2. Using the extrapolated curves we can now estimate the computation time for larger scenarios.

The extrapolated computation time for 1 month / 3 months / 12 months is shown in Table 8.3.

Table 8.3: Estimated simulation time

<table>
<thead>
<tr>
<th>Timespan</th>
<th>Profile Generation</th>
<th>Evolution matrices</th>
<th>Power Flow</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 month</td>
<td>0.75 min</td>
<td>0.03 min</td>
<td>5.91 min</td>
<td>6.69 min</td>
</tr>
<tr>
<td>3 months</td>
<td>2.14 min</td>
<td>0.09 min</td>
<td>60.88 min</td>
<td>63.11 min</td>
</tr>
<tr>
<td>6 months</td>
<td>4.23 min</td>
<td>0.19 min</td>
<td>251.87 min</td>
<td>256.29 min</td>
</tr>
</tbody>
</table>

8.1.2 Different Solving Algorithms

MATPOWER [25] offers a variety of different solvers that are either directly integrated or can be integrated using the MEX interface.

To find the best solver for the optimization problem, three powerful solvers of MATPOWER, PDIPM [22], IPOPT [21] and Pardiso [3] [17] [18] have been compared using a centralized scenario and the timespan of 20 days.

The evolution of the computation time for the different solvers is shown in Fig. 8.1.
Due to Pardiso only available for Mac OS X and Linux systems, the computation time for Pardiso was measured on a portable Mac which was less powerful than the Server used for IPOPT and PDIPM measurements (since OptiToolbox [8] including IPOPT is only available for Windows). Hence, the Pardiso is most likely faster than IPOPT for bigger simulations on the same hardware.

8.2 Comparison of Centralized and Distributed Storage

Solving the optimization problem described in chapter 6 for the model described in Chapter 5, we can calculate optimal storage sizes for different network topologies and cost profiles.
CHAPTER 8. RESULTS

Key factors influencing the battery size are

- Storage costs (€/MWh)
- Storage placement (distributed / centralized)
- Network feeder price profile
- Marginal costs of (PV) generation

8.2.1 Influence of Storage Costs

The storage costs for different storage technologies are described in chapter 2.

We compare the two scenarios of a centralized storage that is placed at the feeder bus and a decentralized storage configuration with a storage at every single node.

To evaluate the effect of storage costs on the centralized and the distributed configuration we run simulations with the parameters shown in Table 8.4.

Table 8.4: Simulation parameters for storage cost analysis

<table>
<thead>
<tr>
<th></th>
<th>Centralized</th>
<th>Distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storages</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>PV Share</td>
<td>50 % (≈ 38)</td>
<td>50 %</td>
</tr>
<tr>
<td>PV Power</td>
<td>30 kW</td>
<td>30 kW</td>
</tr>
<tr>
<td>Storage Price</td>
<td>0 - 300 €/kWh</td>
<td>0 - 300 €/kWh</td>
</tr>
<tr>
<td>Storage Charging Efficiency</td>
<td>88 %</td>
<td>88 %</td>
</tr>
<tr>
<td>Storage Discharging Efficiency</td>
<td>88 %</td>
<td>88 %</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>7 d</td>
<td>7 d</td>
</tr>
<tr>
<td>Time-steps</td>
<td>168</td>
<td>168</td>
</tr>
<tr>
<td>Busses</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>PV Energy produced</td>
<td>34.06 MWh</td>
<td>34.06 MWh</td>
</tr>
<tr>
<td>Consumed Energy</td>
<td>1.66 MWh</td>
<td>1.66 MWh</td>
</tr>
<tr>
<td>Households</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>
Figure 8.2: Storage size comparing centralized and distributed configurations

Analyzing the optimization result for the storage size as shown in Fig. 8.2 we can obtain clear differences between the two configurations. For a centralized scenario we can identify the break-even point as $\approx 100 \, \text{€/kWh}$ while for the distributed scenario, the break-even point is at $\approx 190 \, \text{€/kWh}$. We can also see that the storage size for the distributed storage is higher than the centralized configuration.
We further can assess the optimization results for the storage revenue as defined in section 4.3. Inspecting Fig. 8.3 we again can observe the break-even points as described above. Between $\approx 100 \, \text{€/kWh}$ and $\approx 190 \, \text{€/kWh}$ we can observe the distributed configuration being profitable while a centralized configuration would cause a loss. It becomes also evident that the distributed configuration is generally superior in terms of profit to the centralized solution.

The results of this analysis are also shown in Tables 8.5 and 8.6.
Table 8.5: Simulation results for a centralized storage

<table>
<thead>
<tr>
<th>Storage price (€/kWh)</th>
<th>Total capacity (MWh)</th>
<th>Storage costs (€)</th>
<th>Storage revenue (€)</th>
<th>IRR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>100002.32</td>
<td>0.00</td>
<td>288.54</td>
<td>∞</td>
</tr>
<tr>
<td>15.79</td>
<td>2.27</td>
<td>62.80</td>
<td>178.54</td>
<td>284.30</td>
</tr>
<tr>
<td>31.58</td>
<td>1.76</td>
<td>97.26</td>
<td>122.79</td>
<td>126.24</td>
</tr>
<tr>
<td>47.37</td>
<td>1.41</td>
<td>116.72</td>
<td>77.26</td>
<td>66.19</td>
</tr>
<tr>
<td>63.16</td>
<td>1.06</td>
<td>116.72</td>
<td>44.33</td>
<td>37.98</td>
</tr>
<tr>
<td>78.95</td>
<td>0.70</td>
<td>97.26</td>
<td>20.69</td>
<td>21.28</td>
</tr>
<tr>
<td>94.74</td>
<td>0.35</td>
<td>58.36</td>
<td>3.42</td>
<td>5.87</td>
</tr>
<tr>
<td>110.53</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>126.32</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>142.11</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>157.89</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>173.68</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>189.47</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>205.26</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>221.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>236.84</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>252.63</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>268.42</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>284.21</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td>300.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
</tbody>
</table>

An explanation for the superior performance of the distributed configuration can be found by considering the profit we forgo through the curtailment of PV energy. With the transformer being the limited link between the distribution grid and the feeder we can only store a certain amount of energy using a centralized storage at the substation. Using a distributed storage configuration on the low voltage side, we are not limited by the power rating of the transformer and hence can prevent curtailment of energy.

8.2.2 PV Share

To evaluate the effect of different PV shares on the size of storage for centralized and distributed configuration the PV share was varied from 10 % to 100 %.

The parameters used for the simulations are shown in Table 8.7.
Figure 8.4: Dispatch for a distributed configuration and 1 week of simulation time.
### Table 8.6: Simulation results for a distributed storage

<table>
<thead>
<tr>
<th>Storage price ($/kWh)</th>
<th>Total capacity (MWh)</th>
<th>Storage costs (€)</th>
<th>Storage revenue (€)</th>
<th>IRR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>7500005.64</td>
<td>0.00</td>
<td>540.97</td>
<td>∞</td>
</tr>
<tr>
<td>15.79</td>
<td>4.52</td>
<td>125.02</td>
<td>355.81</td>
<td>284.61</td>
</tr>
<tr>
<td>31.58</td>
<td>3.12</td>
<td>172.36</td>
<td>249.84</td>
<td>144.96</td>
</tr>
<tr>
<td>47.37</td>
<td>2.16</td>
<td>179.09</td>
<td>178.48</td>
<td>99.66</td>
</tr>
<tr>
<td>63.16</td>
<td>1.59</td>
<td>176.18</td>
<td>129.04</td>
<td>73.24</td>
</tr>
<tr>
<td>78.95</td>
<td>1.28</td>
<td>176.17</td>
<td>90.30</td>
<td>51.26</td>
</tr>
<tr>
<td>94.74</td>
<td>0.88</td>
<td>145.64</td>
<td>59.32</td>
<td>40.73</td>
</tr>
<tr>
<td>110.53</td>
<td>0.55</td>
<td>107.10</td>
<td>41.28</td>
<td>38.54</td>
</tr>
<tr>
<td>126.32</td>
<td>0.42</td>
<td>92.70</td>
<td>28.18</td>
<td>30.40</td>
</tr>
<tr>
<td>142.11</td>
<td>0.32</td>
<td>80.72</td>
<td>17.33</td>
<td>21.47</td>
</tr>
<tr>
<td>157.89</td>
<td>0.31</td>
<td>85.57</td>
<td>8.74</td>
<td>10.21</td>
</tr>
<tr>
<td>173.68</td>
<td>0.14</td>
<td>42.03</td>
<td>2.14</td>
<td>5.10</td>
</tr>
<tr>
<td>189.47</td>
<td>0.00</td>
<td>1.50</td>
<td>0.69</td>
<td>46.03</td>
</tr>
<tr>
<td>205.26</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>221.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>236.84</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>252.63</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>268.42</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>284.21</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
<tr>
<td>300.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.61</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 8.7: Simulation parameters for PV share analysis

<table>
<thead>
<tr>
<th></th>
<th>Centralized</th>
<th>Distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storages</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>PV Share</td>
<td>10-100 %</td>
<td>10-100 %</td>
</tr>
<tr>
<td>PV Power</td>
<td>30 kW</td>
<td>30 kW</td>
</tr>
<tr>
<td>Storage Price</td>
<td>0 - 300 €/kWh</td>
<td>0 - 300 €/kWh</td>
</tr>
<tr>
<td>Storage Charging Efficiency</td>
<td>88 %</td>
<td>88 %</td>
</tr>
<tr>
<td>Storage Discharging Efficiency</td>
<td>88 %</td>
<td>88 %</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>1 d</td>
<td>1 d</td>
</tr>
<tr>
<td>Time-steps</td>
<td>168</td>
<td>168</td>
</tr>
<tr>
<td>Busses</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Households</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

The simulation results are shown in figures 8.5 and 8.6.
We can obtain from the plots that for the centralized case the storage size is not dependent on the PV share in the grid, but the only influence factor is the price of storage. In the case of distributed storage we can observe that with an increased share of PV the break-even point to install storage moves more to the right. This can again be explained by reduced curtailment in the distributed case.
8.2.3 Marginal Costs of PV Generation

The marginal costs of PV generation are usually defined as zero. Not considering any costs due to the hours of operation of the equipment we do not have any extra costs when producing.

8.2.4 Influence of PV Subsidies

In recent years many countries have been supporting the extension of renewable generation with political instruments like subsidies. These subsidies either provide a fixed price for PV energy or are realized as a direct payment per MWh of generated renewable energy. Popular examples for these political instruments in Europe are the german EEG or the swiss KEV. The market distortions that are introduced through this payments increase the incentive to utilize the PV generators as much as possible and to avoid curtailment at all times.

Based on [9] two scenarios with and without EV subsidies have been compared. The parameters used for the simulations are shown in Table 8.8.

<table>
<thead>
<tr>
<th></th>
<th>Centralized with KEV</th>
<th>Centralized without KEV</th>
<th>Distributed with KEV</th>
<th>Distributed without KEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storages</td>
<td>1</td>
<td>1</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>PV Share</td>
<td>50 % (48.8)</td>
<td>50 %</td>
<td>50 %</td>
<td>50 %</td>
</tr>
<tr>
<td>PV Power</td>
<td>30 kW</td>
<td>30 kW</td>
<td>30 kW</td>
<td>30 kW</td>
</tr>
<tr>
<td>Storage Price</td>
<td>75 €/kWh</td>
<td>75 €/kWh</td>
<td>75 €/kWh</td>
<td>75 €/kWh</td>
</tr>
<tr>
<td>Charging Eff.</td>
<td>88 %</td>
<td>88 %</td>
<td>88 %</td>
<td>88 %</td>
</tr>
<tr>
<td>Discharging Eff.</td>
<td>88 %</td>
<td>88 %</td>
<td>88 %</td>
<td>88 %</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>1 d</td>
<td>1 d</td>
<td>1 d</td>
<td>1 d</td>
</tr>
<tr>
<td>Time-steps</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Busses</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>PV Energy prod.</td>
<td>7.09 MWh</td>
<td>7.09 MWh</td>
<td>7.09 MWh</td>
<td>7.09 MWh</td>
</tr>
<tr>
<td>PV Subsidies</td>
<td>0 €/kWh</td>
<td>0.40 €/kWh</td>
<td>0 €/kWh</td>
<td>0.40 €/kWh</td>
</tr>
<tr>
<td>Consumed Energy</td>
<td>0.224 MWh</td>
<td>0.224 MWh</td>
<td>0.224 MWh</td>
<td>0.224 MWh</td>
</tr>
<tr>
<td>Households</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

Analyzing the simulation results shown in Table 8.9 we can conclude the following. In the distributed case, the subsidies have no influence on the storage sizing. This can be explained due to the fact that we avoid PV curtailment already in the case without subsidies. In the centralized case the influence of the PV subsidies is quite significant. The curtailed energy for the case with subsidies is reduced tremendously and thereby the IRR of the storage is increased by 22%.
Table 8.9: Simulation results for PV subsidies analysis

<table>
<thead>
<tr>
<th>Storage Size (MWh)</th>
<th>Storage Revenue (£)</th>
<th>Curtained Energy (£)</th>
<th>IRR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized without KEV</td>
<td>0.704</td>
<td>7.56</td>
<td>39.08</td>
</tr>
<tr>
<td>Centralized with KEV</td>
<td>0.85</td>
<td>12.69</td>
<td>8.83</td>
</tr>
<tr>
<td>Distributed without KEV</td>
<td>2.04</td>
<td>25.25</td>
<td>0</td>
</tr>
<tr>
<td>Distributed with KEV</td>
<td>2.04</td>
<td>24.76</td>
<td>0</td>
</tr>
</tbody>
</table>

### 8.3 Storage Placement

From the optimization we can also implicitly gain results concerning where to place the different storage units.

![Figure 8.7: Storage placement for different storage prices](image)

Scope of the optimization was a Scenario with the following parameters:
CHAPTER 8. RESULTS

Table 8.10: Parameters for the optimization of storage placement

<table>
<thead>
<tr>
<th>Battery Price</th>
<th>0-300 EUR / kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Share</td>
<td>50 %</td>
</tr>
<tr>
<td>PV Power</td>
<td>30 kW</td>
</tr>
<tr>
<td>Storage Share</td>
<td>100 %</td>
</tr>
</tbody>
</table>

The mapping which storage ID is connected to which bus is shown in Table 8.11.

Table 8.11: Mapping of the storages to the busses

| Storage ID | Bus ID | | Storage ID | Bus ID | | Storage ID | Bus ID |
|------------|--------| |------------|--------| |------------|--------|
| 1          | 2040831| | 26         | 2042732| | 51         | 2040731|
| 2          | 2042902| | 27         | 2042905| | 52         | 2043947|
| 3          | 2044146| | 28         | 2044085| | 53         | 2042830|
| 4          | 2042711| | 29         | 2042732| | 54         | 2043950|
| 5          | 2043944| | 30         | 2040828| | 55         | 2042732|
| 6          | 2042931| | 31         | 2042842| | 56         | 2042833|
| 7          | 2044088| | 32         | 2044003| | 57         | 2042719|
| 8          | 2043997| | 33         | 2044062| | 58         | 2044032|
| 9          | 2042881| | 34         | 2043944| | 59         | 2044021|
| 10         | 2042947| | 35         | 2043005| | 60         | 2044035|
| 11         | 2040731| | 36         | 2044146| | 61         | 2042934|
| 12         | 2044056| | 37         | 2042902| | 62         | 2042677|
| 13         | 2042690| | 38         | 2044032| | 63         | 2044035|
| 14         | 2040831| | 39         | 2042769| | 64         | 2042719|
| 15         | 2043008| | 40         | 2043944| | 65         | 2040822|
| 16         | 2042953| | 41         | 2042950| | 66         | 2042830|
| 17         | 2043005| | 42         | 2042894| | 67         | 2043947|
| 18         | 2042830| | 43         | 2043956| | 68         | 2042735|
| 19         | 2042777| | 44         | 2042785| | 69         | 2042997|
| 20         | 2044021| | 45         | 2042833| | 70         | 2042719|
| 21         | 2040822| | 46         | 2042953| | 71         | 2044021|
| 22         | 2042953| | 47         | 2042788| | 72         | 2040831|
| 23         | 2044032| | 48         | 2042845| | 73         | 2040831|
| 24         | 2043959| | 49         | 2042809| | 74         | 2042918|
| 25         | 2042753| | 50         | 2044003| | 75         | 2042812|

As shown in Fig. 8.7 some storages are comparably large, while others are almost zero. We can observe that even for a storage share of 100 % (that means a storage at every bus of the system), there are nodes where the optimization results to a larger storage size than others. It would go
beyond the scope of this thesis to analyze the different treats that affect the placement of the different storages. We can however conclude that there are busses that are better suited to be equipped with storage than others.
Chapter 9

Conclusions and Outlook

During this thesis a modular simulation framework for the optimal sizing and placing of batteries has been developed. Using the framework it is possible to assess the economic aspects of adding battery storage to the grid. Influence factors of the PV share, the storage price and the grid topology can be analyzed. Furthermore, various cost structures including PV subsidies and different feed in tariffs can be evaluated.

In addition to the development of the framework, several simulations have been undertaken using an example grid of the city of Rheinfelden. The grid used contained 27 households with an average consumption of 3 MWh per year. The PV share in the system was varied from 7 to 75 PVs, each generator with a power rating $P_{\text{rated}}$ of 30 kW. The different households are assumed to have access to EEX.

9.1 Key findings

Analyzing the simulation results, a couple of interesting facts could be obtained. Key findings are different break even points and IRRs for the various input parameters such as storage prices and PV share. Furthermore it was possible to show the economic advantage of distributed storage configurations over centralized storage in terms of storage revenue and IRR. If we exclude the case with a storage cost of 0, for the given scenario the average storage revenue for the distributed configuration is 160 % higher than for the centralized configuration. Within the storage price range where the centralized and the distributed configuration are both profitable, the IRR of the distributed configuration is on average 21.80% higher. In addition to that, the storage sizes are also significantly bigger for the distributed case. The aggregated storage size in the distributed case has on average two times the capacity compared to the centralized case, with still higher revenue. This is due to the fact that in the distributed case it is possible to avoid PV cur-
tailment in most cases. In the centralized configuration, the energy that can be used to charge the storage (and therefore used) is limited by the power rating of the transformer connecting the distribution grid to the substation.

9.2 Limitations

Despite the results found, there are still some limitations that need to be taken into account. As explained in Chapter 8.1 the computation time rises exponentially with the problem size. Hence it was only possible to obtain the results for a simulated time of one week and 168 time-steps. This results in the limitation that seasonal effects cannot be taken into account. To tackle this, either more computation power must be used to solve the problem or alternative ways of solving the optimization problem must be introduced.

9.3 Outlook

The tools developed in the scope of this thesis can now be used for the assessment of a variety of other questions concerning grid connected energy storage. Possible future projects could be a more detailed evaluation of the optimal placement of the storage units in the system. Also longer term simulations studying seasonal effects can be done, however they require high amounts of computation power as shown in Chapter 8.1.

Concluding, one can say that with batteries becoming less expensive, their role in enabling higher shares of renewable generation will become more important and grid connected energy storage and its economic features will remain a topic of interest for various parties.
Bibliography


[9] Der Schweizerische Bundesrat: Energieverordnung (EnV) 730.01. 2015


