Sub-autonomous micro-grids in the national power system

Research in the context of the carpeDIEM project

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Executive summary

In the carpeDIEM research project, funded by INTERREG5A, questions of an optimization of a local power system was dealt with. While the inclusion of local storage options is one option to increase the use of local resources to cover local demands, it is necessary to raise the question whether a local optimization is useful or not from a system perspective.

Researchers at Europa-Universität Flensburg (EUF) dealt with this issue. By substantially revising their energy system simulation model it has become possible to use local system elements and sequences and simulate their impact on the entire power system of Germany and its neighbours.

With the adjusted model, different sets of scenarios were simulated. For comparison reasons, the status quo as of 2015 was modelled. A first set of scenarios was considered as an isolated approach in which a local optimization would lead to a scenario-specific residual load curve that would need to be managed in the overlaying power system. A second set of scenarios was considered as an integrated approach in which the previously locally available storage options was available in the entire power system.

The simulations clearly showed that a local optimization under the assumptions made would increase the CO_2 emissions in the entire power system. Even though the interaction between system elements is complex, the result can be explained with the use of local surplus power: previously that would be transferred to the national power system and dispatchable generation could be reduced. Using a local battery would increase the total system emissions during the day while the emissions saving at night due to the usage of the battery would not be as high. The comparison with the integrated approach shows furthermore that any storage would reduce the CO_2 emissions if it was available to the entire system. Even though the integrated approach represents an option that is more beneficial to the entire power system and reduces CO_2 emissions, calculations have shown that the utilization of the battery storage taken into account is a comparably expensive option to reduce CO_2 emissions with CO_2 abatement costs of more than 2300 Euros per ton.

It can be recommended that battery storage options should be made available to the entire system if possible in order to use them best from an emissions reduction point of view.

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Acronyms

aCAES	Adiabatic compressed air energy storage
AT	Austria
BE	Belgium
CBC	COIN Branch and Cut solver
CAES	Compresses air energy storage
CAPEX	Capital expenditures
carpeDIEM	CarpeDIEM
CCGT	Combined cycle gas turbines
CH	Switzerland
CHP	Combined heat and power
CLI	Command-line interface
csv	Comma-separated values
CZ	Czech Republic
dCAES	Diabatic compressed air energy storage
DIEM	Distributed Intelligent Energy Management
DK	Denmark
DoD	Depth of discharge
EEG	Gesetz für den Ausbau erneuerbarer Energien ("Erneuerbare-Energien-Gesetz") (Renewable Energy Sources Act)
EEX	European Energy Exchange
EUF	Europa-Universität Flensburg
FHHL	University of Applied Sciences Lübeck
FR	France

GmbH	Limited liability company (Gesellschaft mit beschränkter Haftung)
json	JavaScript Object Notation
LU	Luxembourg
NL	Netherlands
OEMoF	Open Energy Modeling Framework
OPEX	Operational expenditures
ORM	Operation, repair and maintenance
OVGU	Otto von Guericke University Magdeburg
php	Hypertext preprocessor
PL	Poland
PHS	Pumped-hydro storage
PV	Photovoltaics
renpass	Renewable ENergies PAthways Simulation System
RES	Renewable energy sources
RLI	Reiner Lemoine Institut
ROI	Return on investment
RoR	Run-of-the-river hydro power
SDU	University of Southern Denmark (Syddansk Universitet)
SE	Sweden
TH Luebeck	Technische Hochschule Luebeck
VRF	Vanadium redox flow
WP	Working package

1 Introduction and problem statement

In recent years questions about the self-sufficiency of electrical systems have become more and more important in the scientific and popular discussion. In particular the idea of using local resources and storages only to supply to the local load, for instance in a village or a large company, independently from the overlaying national power grid, has been increasingly discussed.

That is for various reasons. First, an independence from the national power grid, thus an independence from external power suppliers, might seem to be economically attractive: If a local system can rely only on its own resources and infrastructure it might become independent from a price development of an external power supplier, in particular when it comes to covering demand peaks that usually are quite cost-intense. Second, many renewable energy plants such as wind turbines and PV plants will run out of their guaranteed feedin tariff period within the next years, meaning that the power generated by these plants might get paid for far less in the future than today. Owners of such plants are seeking ways to operate them more cost-efficient even after the feedin tariff payments have ended.

The idea of operating a local power system – in the following also referred to as "micro-grids" – independently from the overlaying electrical grid raises technical, legal, economic and ecologic questions, to name some. Technically a great challenge is to find ways to match power supply and demand at any time, that is with storage options included and a smart way of control as found in a Distributed Intelligent Energy Management (DIEM) system. A legal question is, for instance, whether or not such an envisaged independence is permitted or not. A background to such questions is that not every conceivable sub-system can be operated independently from the national power system, for instance due to a locally lacking renewable resource, while others can. So it might not be acceptable if local power systems that indeed could technically be operated self-sufficiently would escape from the national system. Moreover, creating an independence from the national power system would only make sense if it leads to economic results. Moreover, any change in the power system would have an effect on resulting CO_2 emissions, which needs to be contrasted to the national emissions reduction targets.

Within the frames of the INTERREG 5A project "carpeDIEM", the research focus was put on questions related towards such local power grids and their potential independence from or role in the national power system. In this context such local systems are not considered to be autonomous from the overlaying power system but rather "sub-autonomous", i.e. reaching a high level of energetic self-sufficiency but not being full independent from the overlaying power system. In the project, sub-autonomous local power systems were simulated and analyzed, i.e. local systems that would still be linked to the national power system to a limited extent, while a specific level of independence from that system and therefore a specific level of self-sufficiency would be reached.

In this section the following topics will be introduced and explained:

- the carpeDIEM research project,
- Europa-Universität Flensburg (EUF)'s role in the carpeDIEM research project, and
- problem statement, aimes of the research work and research questions.

1.1 The research project carpeDIEM

In the carpeDIEM research project, the partners focused on different aspects related to sub-autonomous power systems. The consortium of the carpeDIEM project consisted of

- University of Southern Denmark (Syddansk Universitet) (SDU) (lead), Sønderborg,
- Technische Hochschule Luebeck (TH Luebeck) (also referred to as University of Applied Sciences Lübeck (FHHL) due to a change of name in 2018),
- cbb Software GmbH, Lübeck, and
- Europa-Universität Flensburg (EUF).

The project work started in April 2016 and ended in March 2019. The total budget was approx. 2.7 Million Euros. On the project website at

`https//www.project-carpediem.eu`

further information about the research project can be obtained.

1.2 Europa-Universität Flensburg in the carpeDIEM project

While the researchers of SDU and FHHL, accompanied by coders and developers from cbb Software GmbH, thoroughly analyzed potential optimization strategies of local power systems and the impacts of, for instance, local storage options in DIEM systems, the EUF's focus in the carpeDIEM project was somewhat different. The team of EUF researchers worked with the same showcase and its data, however in the context with the overlaying national and international power systems and applying a different model (Working package (WP) 3 of the project description).

To be more precise, the following tasks were processed or carried out by EUF:

- Task 3.6: Modelling of individual objects
- Task 3.8: Model simulation for clusters
- Task 3.9: Simulation of the CO_2 reduction with and without DIEM implementation for structural regions
- Task 3.11: Economic potential analysis

For the research work, new software applications were developed at EUF and available software tools were substantially further developed and utilized. The fundamental principle of the applied model was the utilization of a cost-optimization of all units in a power system, i.e. a cost-optimization of the units' mode of operation, driven by the power demand in the system and considering the electricity production from non-regulated renewable energies as well as dispatchable technologies, storages and transmission infrastructure, within pre-defined economic and technical secondary constraints. The model was fed with input data characterizing several scenario settings and their variants, describing possible future settings of the regional power system on the one hand and of the total power system on the other.

1.3 Problem statement and research questions

While the project partners focused on locally optimized and partly autonomous subsystems, i.e. on micro-grids, EUF's focus was put on questions related to the effects such a local optimization would have in the entire national power system. The former can be understood as the micro-percpective, the latter can be understood as the macro-perspective on the same subject. Both perspectives have their relevance, advantages and disadvantages. In Figure 1.1 the different perspectives are exemplarily illustrated in a simplified manner. The black box represents the entire national power system, the blue ellipses represent sub-systems within that national power system. In the left image the optimization at the micro-level is illustrated which does not take into account what is happening in the overlaying energy system. On the right hand side the macro-perspective is depicted, highlighting that the sub-system is part of a more complex and interdependent structure of elements of an overlaying power system that can be optimized.

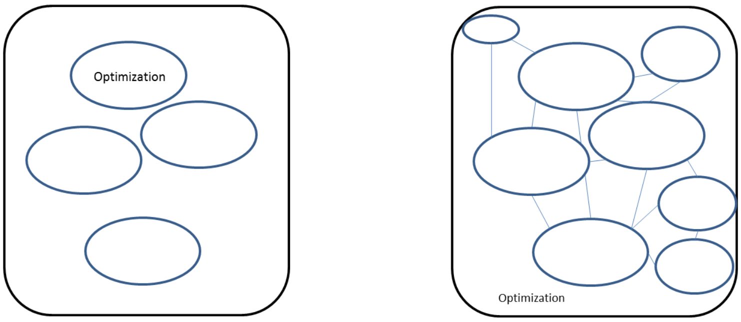

Figure 1.1: Different perspectives on the research subject
Black box: power system. Ellipses: parts of the power system, e.g. loads, power plants, sub-systems; lines: interconnections between system elements.
Left: micro-perspective, right: macro-perspective.
Own illustration.

As described, the perspective that local parties have on an allegedly optimized sub-autonomous power system can substantially differ from the national and international perspective. However, only the consideration of that latter perspective can help detect potentially beneficial or maleficial local system settings within the national power system, thus an evaluation of such sub-systems in the context of the overlaying level.

Key research questions therefore were:

- How beneficial or maleficial is a specific high level of energetic self-sufficiency of a locally optimized sub-autonomous power system in the context of the national and international power systems?
- What are the impacts on resulting CO_2 emissions of the national power system if a local system is intended to reach a specific high level of energetic self-sufficiency?
- How do resulting CO_2 emissions relate to additional cost implied by the envisaged high level of energetic self-sufficiency of the sub-system?

In this paper such questions are covered and answers to them are presented.

2 Methodology: the research approach

To find answers to the research questions and to fulfill the formal project tasks, a simulation model was developed and edited, adjusted and applied. In this paper the model's application and its outputs are presented, however before that, the modelling approach, key input parameters and relevant procedures are introduced. In this section the following topics will be covered:

- basic principle of the applied model and access to the model,
- temporal and spatial resolution of the model and its input and output data,
- the model's alignment and application in the context of the carpeDIEM project,
- model inputs to the simulations:
  1. inputs on the German and European power systems and
  2. inputs on the regional showcase's powersystem,
- outputs from the model, and
- post-processing of model outputs.

2.1 The applied simulation model

The basis to the model utilized within the carpeDIEM context have originally been developed by researchers from EUF, Reiner Lemoine Institut (RLI) and Otto von Guericke University Magdeburg (OVGU), initially in the context of earlier research activity. They are characterized first of all by an open-source and open-data approach, which means, in basic terms, that they strive to use freely and openly available programming code and input data. Moreover, output data are provided in an open data fashion. The open-source and open-data approach allows full transparency and reproducability of modelling results, below other advantages over closed-shop models. In the research project, the utilized simulation model built up on a so-called model framework. The applied model framework is called Open Energy Modeling Framework (OEMoF) and a full documentation can be found online at:

`oemof.readthedocs.io`.

OEMoF can freely be cloned from:

`github.com/oemof`.

The applied model is oriented at the energy system simulation model Renewable ENergies PAthways Simulation System (renpass). The full renpass model code in various variants and an extensive documentation can be found online at

`github.com/znes/renpass`.

renpass (v0.3.1) basically provides a command line interface script. The user calling the interface script passes as a mandatory argument the path to an energy system datapackage. Optional arguments include e.g. the solver-library to use, the directory to write results to or the structure of the results. The command-line interface (CLI) script expects a single and predefined input datapackage. In the context of the carpeDIEM project each scenario has a separate input datapackage, but is based on a single representation of the German electricity system, with minor, methodologically similar changes in each datapackage. Thus, it is convenient, that carpeDIEM software builds these datapackages automatically, which cannot be done in renpass. renpass is an application of the Open Energy Modeling Framework OEMoF and relies on the framework's functions and classes. Recreating renpass can be done by using the same functions and classes. In order to gain more control over the process of handling optimization results, particularly CO_2 emissions, in carpeDIEM renpass is replaced by a separate script.

`https://github.com/znes/carpeDIEM`.

In the model, an optimization algorithm approaches the least-cost state of a defined energy system, namely in terms of operational cost. For doing so, the model requires the installation of a solver such as CBC (cf. **?**) or Gurobi (cf. **?**). To achieve this, the behaviour of a defined energy system is simulated in a high temporal resolution under consideration of technical and economic parameters that describe all system components. The optimization thus corresponds to a market simulation with perfect market conditions. The approach can be understood as a fundamental model which does not predict a system's behaviour for hours or days ahead but which allows to simulate a longer period in order to draw conclusions about structural interrelations for a pre-defined system setting. That optimization in particular takes variable cost of dispatchable units into account, thus it considers the merit order of all technologies that can provide to a positive residual load.

2.1.1 Modelling individual objects

Technically, the utilized model is based on a model framework, i.e. a toolbox of model functionalities, that can describe virtually any component of an energy system. The actual model makes use of such functionalities. With the model framework, all elements of an energy system can be described in the model with their technical and economic characteristics. In principle, system elements are linked with each other through so-called flows between so-called nodes (**?**) or edges. A flow always connects a component of the energy system with – a so-called "bus" – or vice versa, thus it is bipartite, and it can be illustrated by a bipartite graph (cf. Figure 2.1). By instantiating nodes and flows, a full energy system can be described.

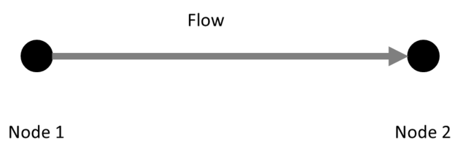

Figure 2.1: Basic scheme of a directed graph

Own illustration.

All input data to the model describing the elements and components of an energy system such as the installed capacities, the regions or the description of connections between two regions need to be defined in files of csv format (csv = comma-separated values) that are stored in a user-friendly and structured manner. In order to let the model use these data, an additional library file of json format (json = JavaScript Object Notation) is necessary in which the structure and the formats found in the csv files – i.e. all relevant metadata – are described, adhering to the tabular datapackage standard for model input datasets. It is possible to create the csv and json files from scratch. Alternatively, existing files can be used as blueprints or helping tools can be applied to create them.

The model therefore enables a user to specify every single individual object, i.e. component, in the system with its technical and economic characteristics. Such an input is technology-specific and in many cases it includes a maximum capacity and marginal costs. For instance, the capacity and production pattern of PV plants and wind turbines can be specified. Storages can be described with their energetic volume and charging and discharging capacity. The demand side requires both a demand level and a load curve. Depending on the technology, further specifications are required, for instance a normalized production sequence for volatile generators or a maximum limit of annual operational hours for fuel-based power plants. When the simulation of a specific system setting is started, an objective function is created that includes all the inputs of all individual objects specified, either as part of the objective function or as a boundary constraint to that objective function. A full documentation of the mathematical background and formulation of individual objects can be found online in the OEMoF documentation at:

`https://oemof.readthedosc.io/` (cf. **?**)

Basically the number of individual objects that can be considered in a scenario simulation is unlimited in simulation models based on and relying on the OEMoF framework. Therefore it is possible to simulate comparably small clusters of individual objects, to scale such objects to larger clusters or to simulate even further clusters with further objects. Moreover, in the simulations some technologies with same characteristics can be aggregated. For instance, all PV plants in one region can be represented as one virtual PV plant with the summed peak capacity. That procedure does not change simulation results, however it reduces the complexity of the optimization problem, thus computation times. By doing so, however, the complexity of the results files would be reduced down to main categories, too. Instead of enormous resulting csv files with production patterns of every single power plant, smaller resulting csv files are generated with aggregated production patterns. In the aforementioned example, there would be only one resulting production pattern for all PV installations instead of one pattern for every single Photovoltaics (PV) plant.

2.1.2 Model simulations for clusters

The interlinkage of individual objects with the same electrical system in the model, represented by an oemof bus, allows to simulate not only the individual object's behaviour in the system but aggregated it corresponds to the simulation of a cluster, which can be understood as a settlement, a region, or a country, for instance. By doing so, results can be generated and analyzed not only for individual objects but also for regions.

In frames of the carpeDIEM research project, the individual demand and production objects and time series of the local and national power systems were integrated into the substantially adjusted simulation model. In order to generate reasonable results, components with the same technical and economic characteristics were aggregated in clusters. Scenarios have been simulated with the model and the model framework. In this context the term "scenario" is understood as a set of input parameters and input data to the model, the applied model functions, and the output parameters and output data from the model. As these items depend on each other, only a set of these three categories describe a full scenario. Leaving out just one would cause a lack of necessary knowledge about the scenario, i.e. the scenario description would be incomplete. In the following, however, it is assumed that the substantially adjusted simulation model has been applied unless specified otherwise.

Besides the presented scenarios it is possible to create own scenarios with different components or for other regions, to be simulated with the adjusted simulation model. In order to do so, the respective model inputs need to be prepared accordingly.

2.1.3 Model files

The framework and the model have been implemented in Python (cf. **?**). Python is a freely available object-oriented programming language that recently has been increasingly used (cf. **?**), in particular for scientific purposes. Once Python and specific additional Python packages have been installed on a local computer, the adjusted simulation model will operate successfully.

The chosen data structure follows the approach of so-called frictionless data, i.e. it uses the frictionless data format (**?**), which is intended to make data easily producible and consumable. To be more precise, the modelling approach uses the so-called tabular datapackage which is a standard format from the Open Knowledge Foundation (**?**). With the model, input data do not need to be available at the local computer on which the model is run but the json file that is called by the model script and the corresponding csv files can be stored virtually anywhere as long as the link between the local model and these files can be established when the model is executed. In figure 2.2 the relation of the involved files is illustrated.

The model framework and the model scripts have been stored online on the Github platform (cf. **?**, **?**) in so-called repositories to make them available to anyone interested and to easily and commonly work on the model code. The repositories can be cloned from that platform to be utilized on a local computer. Input data as described in section 2.2 have also been stored in data repositories at the Github platform. For other or further calculations, however, either such existing files can be utilized and adjusted or other data files can be created that fulfill the structure requirements of the model and of the model framework.

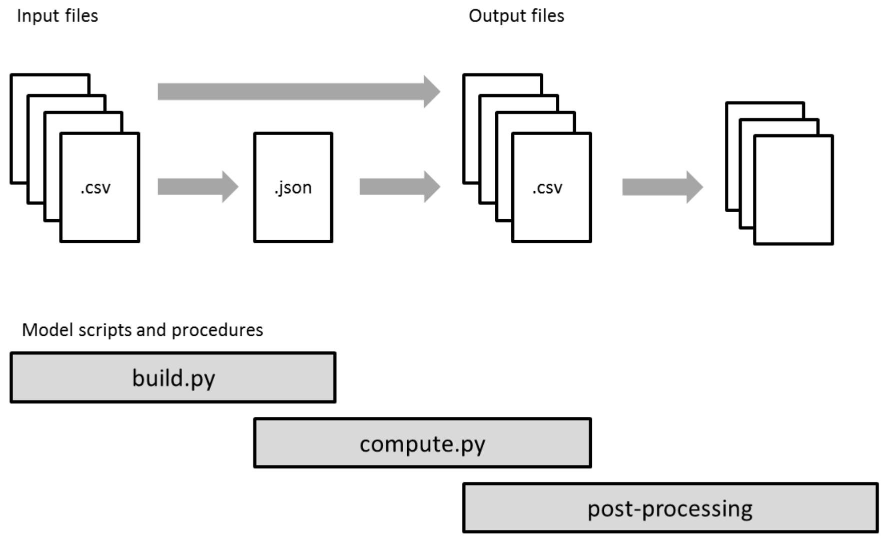

Figure 2.2: Relation of model files

Own illustration.

In the model, the nominal load curves were calculated by utilization of the respective normalized load profiles and the corresponding annual sums that would scale them to the correct load level. The nominal production curves of PV and wind power were calculated by utilization of the respective normalized PV and wind power production profiles and the corresponding PV and wind power installation, i.e. installed capacity, that would scale them to the correct production level.

2.1.4 Temporal and spatial resolution

The model's temporal resolution is hourly, while a full year can be modelled, i.e. 8760 successive timesteps. For the carpeDIEM research project the national and international power systems as of 2015 were utilized for the simulations. Therefore, besides the scenario data, recorded data from 2015 were utilized as inputs to the simulations. Using data from that particular year is in line with the approach followed by the project partners (cf. **?**).

From a technical perspective the model's spatial resolution is virtually unlimited, however for the research question it was defined to consider Germany and its electrical neighbours as individual regions in the model. The sub-region of the showcase was modeled on its own, however it was integrated into the national and international power systems as presented in the following sections. In Figure 2.3 the regions of consideration are depicted, including the selected showcase of the village of Dörpum. The utilization of the newly created model structure was not restricted to only utilize the real-life showcase only but is is flexible to include multiple sub-regions.

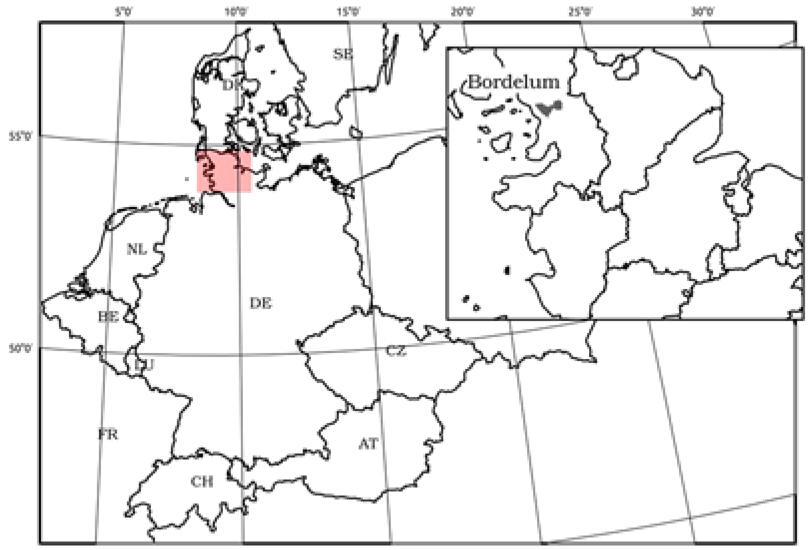

Figure 2.3: Regions considered in the simluations
Sources: National borders created ? and ?. Boundary of Bordelum taken from ?. District borders copyright ?.

2.1.5 Model set-up in the context of the carpeDIEM project

The simulation model can be run on any local computer. The basic approach is to separate code and data, because it increases transparency, reproducability and from a user's perspective helps to navigate a repository. Having cloned the repository and all additionally necessary software and packages will allow a user to exactly simulate the scenarios presented in the following sections. Its execution however requires the installation of additional software such as the Python language, additional Python packages, including the OEMoF framework and the newly developed oemof.tabular module, a solver, and the Git software for version control.

The following steps will clone and install the simulation tool locally. The procedure guide refers to Linux computers and is tested in a Linux environment, but the strategy in setting up the environment would be the same on Windows machines.

1. Clone the model's repository from `github.com/znes/carpeDIEM` to the local computer.

2. Create a virtual environment in which the model is to be executed.
   Using a virtual environment allows to run the model with Python packages and modules, that are different from system-side global Python packages, thus preventing potential dependency conflicts. Each Python package needed to run the simulation is defined in a so called requirements.txt file.

3. Navigate to the newly created `carpeDIEM` folder and install the requirements with the Python package installer pip. Within the virtual environment the necessary packages are now available and carpeDIEM scripts can be executed.

A more detailed installation guide on how to install carpeDIEM from scratch including each terminal command on a Ubuntu 18.04 LTS machine can be found online at:

`https://github.com/znes/carpeDIEM`.

With the model, all kinds of scenarios and scenario settings can be simulated. For the context of the carpeDIEM project, a set of scenarios has been prepared that are built and simulated in parallel when the code is executed. The number of cores that should be used to optimize each mathematical model representation of an energy system can be adjusted within the code to fully allow to use the computational capacity of the system used. In order to execute the model once the required software has been successfully installed, first the respective json and csv files, the tabular datapackages, need to be generated. In order to do so, a user needs to use the command terminal again and navigate to the folder in which the python scripts have been stored and simply confirm

```
python build.py
```

The command comprises the execution of the Python language and creates for each scenario a different tabular datpackage in the subfolder datapackages. For this task the reference datapackage is downloaded from `https://github.com/ZNES-datapackages/Status-quo-2015`. Executing the build script will subtract or add system elements and sequences as necessary for the simulation of the scenarios.

The link points to the pre-built datapackage of the code developed in the Status-quo-2015 repository. As a consequence, if the underlying reference scenario, representing the Status-quo of the German and European electricity system is subject to further development or change, carpeDIEM could easily be updated to work with a different version of the Status-quo datapackage. In addition if another datapackage following the same standard is developed in the future, e.g. representing the German and European electricity system of the year 2030, carpeDIEM would also work with that.

All technology-specific costs and emissions factors are stored at and accessed online from:

```
https://github.com/znes-datapackages/technology-cost/data/carrier.
csv
```

All sequences representing the load curve and the residual load curves of the sub-system of consideration were stored in a separate xls file, hence following the basic approach of separating code and data. This file is directly read by the build script. The xls file location is:

```
https://github.com/znes/carpeDIEM/archive/data.xls
```

For the actual model execution, starting the optimization processes, a user simply needs to confirm

```
python compute.py
```

which will use the Python language again to call the respective json meta files that again refers to the related csv files containing all the input data for the simulations, optimize the corresponding systems and save resulting sequences and sums in output csv files. The location of the results is, if it does not exist yet, a newly created folder in the user's home directory named results. The results folder holds for each scenario a copy of the input datapackage and the generated output csv files. In the compute script model results are processed to calculate and to include the CO_2 emissions of each country and the overall emissions in the energy system.

While the model's structure as presented in sections 2.1.1 and 2.1.2 is valid for basically any simulation independent from the carpeDIEM context, additional features were added to the model code in particular for the carpeDIEM project. For the carpeDIEM research project the available model was substantially adjusted and further refined in order to be able to work on the research questions presented. In more detail the following advancements have been developed and implemented:

- Utilization of a structured data format: In earlier and less advanced applications of the model framework, input data on the system components (nodes) of a scenario

needed to be defined in one excessive and complex csv file in which all components of the power system would be specified with their technical and economic parameters and their relation to each other. In the refined model application, all input data can and need to be specified in a substantially more structured way. In general adhering to the tabular datapackage standard, a standard on how to structure tabular data and how to write a meta file describing the data contributes to the standard becoming more established and thus to a more accessible data format in the scientific community.
As presented in section 2.1, the inputs to a scenario need to be specified in several csv files and one json file. In the json file, all the fields of the corresponding csv files and prospectively also a documentation of the respective data sources are described. In the csv files, all system elements are described quantitatively, i.e. all the loads, the volatile generators, the dispatchable generators, the production sequences, the demand sequences, storages, the grid etc. . Such data include information about capacities, marginal cost, normalized sequences, and performance parameters, to name some. The approach of using several csv files for all the inputs to the calculations of a scenario allows a substantially clearer and more transparent definition of input parameters than in earlier model versions. Furthermore the new approach creates the possibility of an easier and more straightforward adjustment of input parameters for different scenarios, if necessary.
The newly developed data structure did not only require fundamental changes in the structure of the input data files themselves in which the resources (nodes) are described but also substantial changes in the actual model scripts.

- Modelling and utilization of the showcase sub-system
  Relevant data for all scenarios representing the showcase were collected, adjusted to the model's requirements and revised if necessary. This refers to the load profile, the load level and the installed production capacities, storages and production patterns. Such data were structured according the requirements of the csv input files to the model and further processed in the specific scenarios.

- Besides the development of new features and structures, the model, the individual model scripts and model procedures as well as the input data were repeatedly tested, adjusted and calibrated. If necessary, input and output data were aligned in order to have the model calibrated.

2.2 Model inputs

In order to approximate the model and reality as close and reasonable as possible, various input parameters were collected, pre-processed and eventually fed into the input files to the simulation model. The input data can be categorized as

- data that describe the national power system,
- data that describe the power systems of Germany's electrical neighbouring countries and
- data that describe the showcase to be used for the simulation of scenarios.

All simulation inputs can be found online at:

`https://github.com/znes/carpeDIEM`

`https://github.com/ZNES-datapackages/Status-quo-2015`

As the German power system is part of the European power system, the simulations included both levels. In some parts of the coding it was necessary to combine the showcase and the national power system whereas in the largest part of the analysis it was crucial to take the entire international power system into account. A focus on the German power system alone would have been misleading. As the optimization of the model included all demands and production in Germany and its electrical neighbours, a change of the German power system – as found due to the consideration of the showcase subsystem – would affect the entire system and not only the German system. For instance, a specific scenario setting could basically reduce the CO_2 emissions in Germany while they could simultaneously rise in neighbouring countries. Only the overall picture allows to analyze the impact of a sub-systems's scenario setting within the overlaying power system.

2.2.1 Germany's power system

The following data of the German power system were used as inputs to the simulations:

- Load curve
  Data sources: **?**
- Demand (annual sum)
  Data sources: **?**

- Installed capacity (by technology)
  Data sources: **?**, **?**, **?**
- Production data (RES)
  Data sources: **?**, **?**, **?**, **?**, **?**, **?**
- Economic parameters, service life of technologies, emissions coefficients etc.
  Data sources: **?**

Additionally, the following sources have been used to model the German and European power system: **?**, **?**, **?**, **?**, **?**, **?**, **?**, and **?**.

These sources are the main sources used. Single literature values of costs, emission factors or variable operation and maintenance cost are included in the aforementioned technology-cost datapackage, which is also used in building the Status-quo datapackage.

In order to keep the model's complexity at a reasonable level and also in order to limit the number of variables in the simulation, Germany was considered to be one electrical region, i.e. the internal grid infrastructure and information about the locations of system elements could be disregarded. The German power system was represented as a cluster in the model, i.e. it was represented by all its loads and production units that were aggregated if possible and the power system was regarded to be one node in the model. Based on the existing plant stock, dispatchable technologies were sub-categorized, e.g. into capacities with gas turbines, steam turbines, combined cycle gas turbines (CCGT) and other.

2.2.2 The power system of Germany's electrical neighbours

Similar to the case of the German power system, the simulations required input data for Germany's electrical neighbours. While geographical neighbouring countries might not have a transmission link to the German power system, electrical neighbours might not be direct geographical neighbours even though they are linked to the German power system. In the model therefore those countries were taken into account that are directly linked through a power line to the German power system, i.e.

1. Austria (AT),
2. Belgium (BE),
3. Switzerland (CH),
4. Czech Republic (CZ),

5. Denmark (DK),
6. France (FR),
7. Luxembourg (LU),
8. the Netherlands (NL),
9. Poland (PL), and
10. Sweden (SE).

All these countries were represented in the model with their power demand and supply structure, i.e.:

- Load curve
  Data sources: **?**
- Demand (annual sum)
  Data sources: **?**
- Installed capacity (by technology)
  Data sources: **?**, **?**, **?**
- Production data (RES)
  Data sources: **?**, **?**, **?**, **?**, **?**, **?**, **?**
- Economic parameters, service life of technologies, emissions coefficients etc.
  Data sources: **?**, **?**
- Transfer capacity between the countries in the model
  Data sources: **?**

As previously presented, additional sources have been taken into account.

As in the case of Germany, input data were aggregated if possible and necessary in order to keep computation times at a reasonable level. Each country was represented as one cluster in the model. In the following, the entire system consisting of Germany and its electrical neighbours is also referred to as "Europe" even though it does not cover the whole of the continent.

2.2.3 The power system of the showcase

While the original intention of the research project was to detect up to ten showcases, the focus was put on one specific showcase in more detail and it was modeled in several system settings. For the calculations of a sub-autonomous sub-system within the German power system, the showcase of Dörpum was selected. Dörpum is a part of the village of Bordelum, a small village located in the North-West of the German federal state of Schleswig-Holstein, in the district of North Frisia (cf. Figure 2.3). It is located at 54°38'N, 8°56'E. The project partner FHHL used the same showcase for their own simulations (cf. **?**).

For the simulation of the showcase, data were derived from various sources. In order to be in line with the underlying input parameters of the project partner's simulations, all system elements such as renewable power plants, the hourly resolved renewable production and the load curve were synchronized with FHHL data. As the source of meteorological data and hourly-resolved production series, **?** and **?** was selected. Moreover, information from **?** were used for a further alignment of input data on the sub-system's demand side. All data of the sub-system were pre-processed and stored in the respective xls input file in the model, representing both the sub-system's elements as well as the demand and production patterns found in the sub-system. Specifically, the following input data describing the setting of the sub-autonomous sub-system were obtained, pre-processed and utilized in the simulations:

- Load profile
  In the model, a load profile of the showcase system was stored. That profile comprised the consumption patterns of various individual consumers. The load profiles of individual demand categories were adjusted according to the information gained from **?** and **?** and they were aggregated in order to utilize one village-specific normalized load curve in the scenario simulations. The aggregated load curve of the village consisted of individual load curves representing the demand of the residential houses, business buildings, cow and pig stables, street lighting, and self-consumption of the CHP plant. In Figure 2.4 the resulting load curve that incorporates all individual load profiles is illustrated.
  Data sources: Profiles H0–L2 from **?**, street lighting profile from **?**, consumption data from **?** and **?**.

- Annual demand
  As in the case of the load curve, the annual demand – to be unserstood as the load level – of the sub-system was stored in the model and it comprised the annual de-

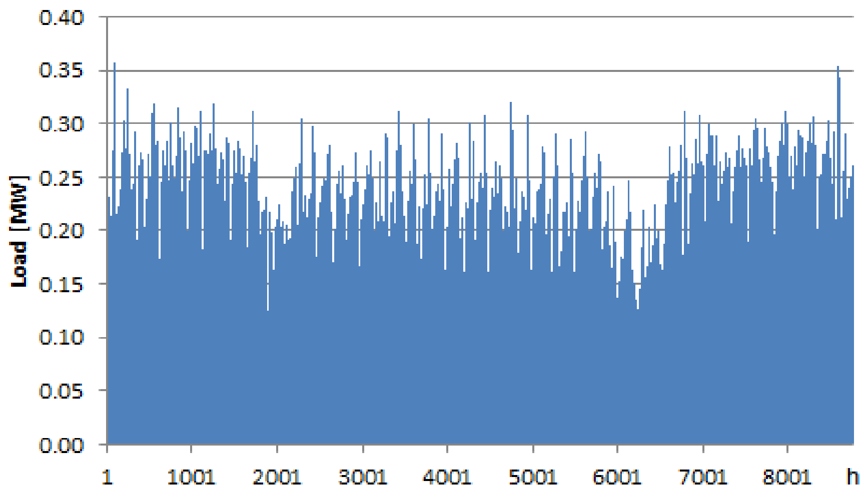

Figure 2.4: Load curve of the showcase of Bordelum

Based on **?**, **?**, **?** and **?**.

Table 2.1: Demand structure in Bordelum

Category	Annual demand
Residential	658 385 kWh/a
Cow stable	125 000 kWh/a
Pig stable	120 000 kWh/a
Other businesses, street lighting	82 296 kWh/a
Self-consumption biogas plant	750 000 kWh/a
Total w/o CHP plant	985 681 kWh/a

Sources: **?** and **?**.

mand of individual consumers. For specific consumers, information was available about the level of their individual annual power demand and additionally about a representative load profile to be applied (cf. **?**).

In Table 2.1 an overview over the annual demand and load profiles utilized is given. Even though the total annual demand of all loads sums up to 986 MWh, a slightly lower value (974 MWh) was utilized in the simulations to be covered, assuming minor losses in the distribution grid.

Data sources: **?**, **?**

- PV installations
  By definition a specific set of PV installations was part of the scenarios to be modeled for the showcase. The capacity of the PV installations in the village of Dörpum were stored in the respective xls input file prepared for volatile generators. They were synchronized with the data used in **?**. A total PV capacity of $2940\,\mathrm{kW_p}$ was utilized for the base case and deviating for one of the modelled scenarios, respectively (cf. table 3.1).
  Besides the installed capacity, in the model a normalized hourly-resolved production curve as illustrated in Figure 2.5 was stored, based on **?** and **?**.
  Data sources: **?**, EEG plant register, **?**, **?**

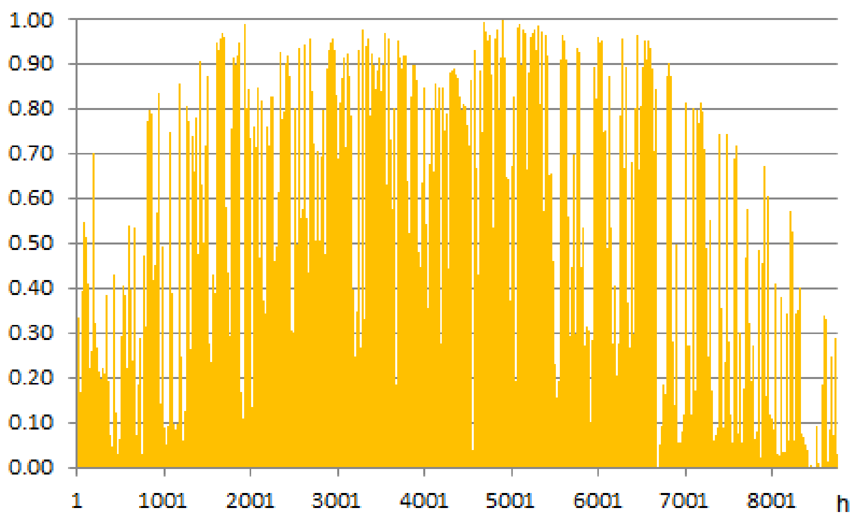

Figure 2.5: Normalized power production from solar PV in Bordelum (2015)
Based on **?**.

- Wind turbine
  In some of the simulated scenarios of the showcase a 1 MW wind turbine was included. For the calculations it was characterized with its specific wind turbine power curve in order to generate an hourly-resolved production curve for a full year.
  As in the case of PV, a production time series was required for that wind power installation. Based on **?** and representative wind turbine power curves, a production profile as illustrated in Figure 2.6 was generated and stored as inputs to the model.
  Data sources: **?**, **?**

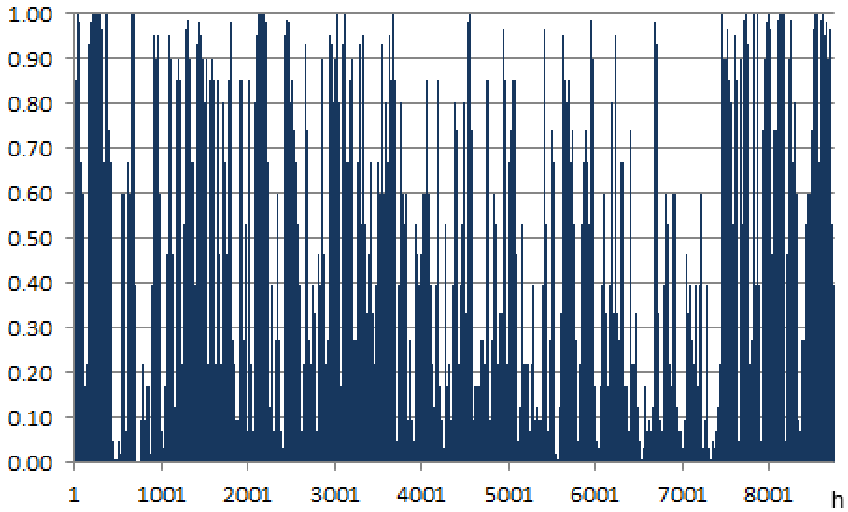

Figure 2.6: Normalized power production from wind power in Bordelum (2015)
Based on **?**, **?** and **?**.

- CHP plant
  The two biogas-based combined heat and power (CHP) plants in the village of Dörpum have an electrical capacity of 875 kW_{el} combined. In the simulations it was assumed that the capacity would be constantly available during the year. In practice, however, the larger of both however operates at 500 kW_{el} during summer time. In winter it operates at its full 625 kW_{el}.
  Data sources: **?**, **?**, **?**

- Storage
  In some of the scenarios, storage options were included. If necessary and available, storages can absorb excess electricity until their maximum filling level has been reached. Storages can deliver power during moments of additional demand in the system until it reaches its minimum filling level. Battery storage is characterized by its storage capacity, i.e. the amount of energy that can be stored at maximum, its charging and discharging capacity – to be understood as the inverter capacity –, and specific efficiencies of charging and discharging. In the simulations it is also important to know the storage's filling level at the start of a simulation. In the current version of the simulation model battery storage reaches the same filling level at the end of a simulation period that it had at the beginning.
  The exact technical parameters used in the simulations are scenario-dependent and

can be found in table 3.1. Data souce: **?**

Due to the multitude of objects in the sub-system and in the national and international power systems with different technical and economic characteristics and data, the following aspects were taken into account for the simulations:

- All calculations were based on capacity and energetic figures specified in MW and MWh, respectively.
- All demand profiles were stored as normalized hourly-resolved series that built an integral equal to 1. They would be scaled with the respective annual power demand in the simulations.
- All production sequences of non-regulated, i.e. volatile, renewable energies were stored as normalized hourly-resolved series that would be scaled with the installed capacity in the simulations.
- For calculatory reasons, additional variables for potentially occurring energetic surpluses or shortages needed to be specified in the model. In case the simulations resulted neither in any surplus or shortage in the system, the corresponding columns in the results files were set zero.
- Transshipment capacity between one region and another was by definition chosen to be bidirectional with the same maximum transmission capacity value. A flow to the inverse direction was automatically described by the model with an inverse sign.

2.3 Model outputs and post-processed simulation results

The model generated hourly resolved operation data for every element defined in the input files. The outputs were written in newly generated csv files, specified with a unique timetag for identification purposes. For the results analysis, the following output parameters were key. Some of them were automatically generated, others needed to be derived by the utilization of additional post-processing procedures attached to the actual model outputs:

- operation of volatile production units in the power system, i.e. hourly resolved operational capacity of PV plants and wind turbines,

- operation of conventional dispatchable units in the power system, i.e. hourly resolved operational capacity of conventional power plants,
- operation of the transmission grid connections, i.e. hourly resolved operational capacity of both directions,
- hourly resolved variable production mix of the national and international power systems,
- annual sums of the production of all power generating elements in the system,
- annual sums of the utilization of transmission grid links,
- annual sums of the utilization of storages.

Besides the actual model framework, model scripts and input data, it was necessary to further process the output data provided by the model at the end of a simulation. Some of such further procedures were directly included into the model scripts customized for the carpeDIEM research project. That includes, for instance, the following procedures:

- regression analysis and comparison of results from different simulations,
- calculation of induced or avoided direct CO_2 emissions,
- further minor and major post-processing procedures aiming at generating the desired outputs, e.g. automatic creation of diagrams,
- further calculations of the system's economic efficiency.

2.4 Residual load curves

The residual load represents the remaining load to be covered, i.e. after a specific sort of power production has been subtracted from the load. Depending on the subtrahends considered, i.e. the systematic categories taken into account in the subtraction, the residual load can exist in different degrees. The residual load can be positive or negative. In a working power system, it needs to be covered by power production from further sources or it needs to be used, i.e. consumed, stored or exported, unless power shortages or surpluses are to appear in the power system.

The residual load can be described as a specific figure found during a particular moment. As the residual load can vary by the hour it is possible to generate and analyze residual load sequences, i.e. residual load curves. The following sequences were generated with the enhanced simulation model and in the further post-processing procedures:

- Load curve
- 1^{st} degree residual load: Load curve minus power production from PV plants and wind turbines
- 2^{nd} degree residual load curve: 1^{st} degree residual load curve minus power production from dispatchable loads
- 3^{rd} degree residual load curve: 2^{nd} degree residual load curve minus storage inflow and outflow
- 4^{th} degree residual load curve: 3^{rd} degree residual load curve minus imports plus exports

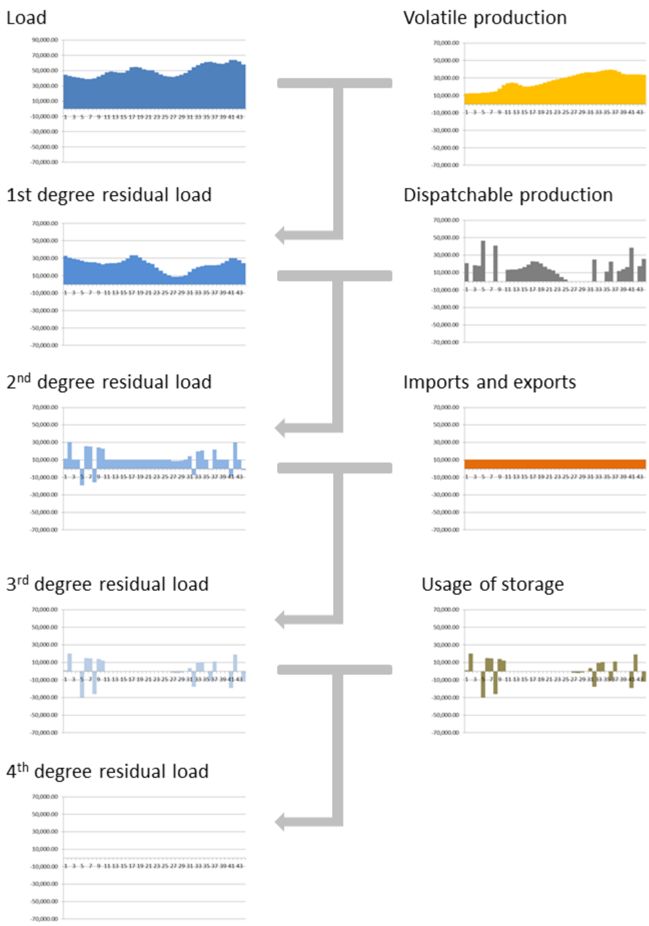

Figure 2.7: Depiction of degrees of the residual load
Own illustration with exemplary figures, based on own simulations.

As in the simulations not only Germany but also its electrical neighbours were taken into account (cf. section 2.2.2), the residual load of different degrees would not only be found for the German power system but for all regions represented in the model. Moreover, the different degrees of the residual load were also generated for the entire power system modeled in the simulations.

2.5 Validation of model results and model calibration

Before the simulations were run with a project-oriented focus their results quality and suitability to the project was repeatedly tested. For doing so, intermediate and final model outputs were compared with historically recorded data in order to detect potential deviations between the model ouputs and historical values. That comparison was conducted with several parameters.

First of all, the first-degree residual load curve in Germany, i.e. the residual load curve resulting from the subtraction of the unregulated renewable production from the load curve in Germany, was simulated and related to the recorded spot market price of electricity in Germany in 2015 (cf. **?**). The comparison substantiated that the residual load curve derived with the model approaches closely the historical price curve. The simulation with the model reflects real-life market mechanisms: in practice, a high production of unregulated renewables decreases the spot market price of electricity ("merit-order effect", cf. **?**) whereas a low production of unregulated renewables requires partly substantial amounts of additional production from dispatchable technologies, i.e. prices increase during such hours. In Figure 2.8, the first-degree residual load in Germany and the spot market price as of 2015 according to **?** are depicted the first four days of the year of analysis in an hourly resolution. For display reasons both curves have been normalized. It becomes obvious that the two curves follow a similar course with minor differences.

Another way of displaying and analyzing two sets of observed data are scatter plots, using Cartesian coordinates. In the scatter diagram in Figure 2.9 the absolute residual load in the national power system (x-axis) as simulated with the model is related to the spot market prices (y-axis) as described in **?** on an hourly basis for the year 2015. The image substantiates the correlation between the two parameters that can be approximated with a linear function.

Additionally to this comparison, intermediate model results – e.g. annual sums – of conventional generation, power imports and exports and the usage of storage compared with recorded data from 2015 (**?**).

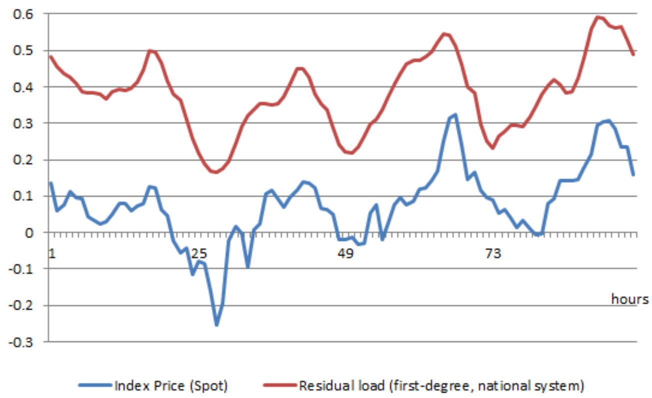

Figure 2.8: First-degree residual load and spot market electricity price in Germany in 2015 (hourly, normalized)

Based on **?** and own simulations.

The comparison of the hourly sequences as well as the comparison of the annual sums showed minor deviations between a technology's results and recorded figures. In order to approximate the model close to recorded data, the minimum utilization duration of gas-fired power plants was defined to be 2000 hours per year.

As every model is approximation to reality, minor deviations between the simulated values and recorded values exist due to to the following reasons. This list is not definitive but covers central reasons for differences between the model and reality:

1. A perfect correlation between the first-degree residual load and the spot market price would theoretically be found only if the market reacted fully and solely to the residual load in the national power system, i.e. if there was an absolute cause-effect relationship. In reality, however, the electricity market underlies further influences, e.g.

   a) The situation in neighbouring countries and markets, i.e. the residual load and market prices abroad, can affect the domestic national power production and market prices.

   b) The Operation of dispatchable power plants can differ from what an operational cost-optimization would suggest, e.g. due to company policy or technical reasons, directly affects market prices.

   c) Besides the spot market, there are other markets on which quantities of electricity are traded. The spot market therefore is indeed an excellent representative of the market activity, however it does not cover the entire market.

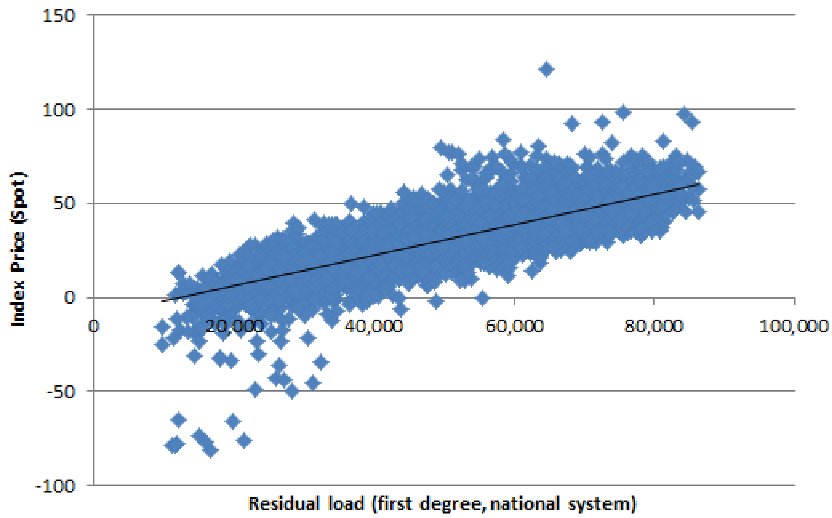

Figure 2.9: First-degree residual load and spot market electricity price in Germany in 2015 (XY-Diagram)

Based on **?** and own simulations.

2. In the model, the power production from unregulated renewable energy sources is an approximation to reality. For instance, the model uses a wind turbine model whereas in practice power production from wind turbines might be exposed to location-specific influences or they might operate slightly different than under perfect conditions, for technical reasons (e.g. unscheduled downtimes due to failure or ORM).

3. The domestic and international transmission grid might limit the maximum capacity of PV plants and wind turbines in specific regions in reality, for technical reasons. This aspect has not been included in the model.

2.6 Calculation of CO_2 emissions

In every hour of the year in which non-renewable power production units in the national and international power systems are in operation, CO_2 emissions are induced. The amount of such induced emissions depends on the particular technologies that are in operation in that specific hour of the year. In the case of the simulated scenarios, this is again a result of the operational optimization. In every hour of the year a different operative technology mix can be found which can be translated into hourly varying $C0_2$

Table 2.2: Emissions factors

Technology	Factor g CO_2/TJ_{el}
Hard coal	93.50
Lignite	111.00
Oil	73.30
Natural gas	55.90
Nuclear power	0
Waste	91.50

Direct emissions only.
Sources: **?** and **?**.

factors, i.e. tons of CO_2 per TJ of the fuel or – under consideration of the technologies' efficiencies – per kWh of produced electricity.

For the analysis of the simulated scenarios, the CO_2 factors of the different power generating technologies according to **?** and **?** were analyzed and fed into the model (cf. table 2.2). In the calculations only direct CO_2 emissions were taken into account, and potential additional emissions induced in the supply chain were neglected. Other literature sources such as **?** and **?** use slightly different values for the various technologies, based on minor differences in the assessed carbon content of the fossil fuels of the respective power plants.

In the post-processing of the model, the technology-specific emissions factors were multiplied with the respective production of the individual technologies, for every hour of the year of analysis, as presented in equation 1. The sum of all technologies' emissions and of all hours of the year would result in the annual induced CO_2 emissions. The comparison of the emissions of different scenario settings would allow to calculate differences in the induced emissions, i.e. a delta between two scenarios would translate into additional or avoided CO_2 emissions due to changes in the scenario settings.

As presented, in this approach data from and simulations for the year 2015 were used. The production mix, especially related with international and national climate protection targets and political goals, might change in the future and so might the technology-specific plant efficiencies, which would result in differences in the calculated amounts of CO_2 emissions.

$$E = \sum_{T} \sum_{t=1}^{8760} e_T \eta_T E_{T,t} \tag{1}$$

with

- E: Total CO_2 emissions (in tons per year)
- T: Technologies
- t: Time index (hour of the year)
- e: Emissions factor (technology-specific, in tons of CO_2 per GJ)
- η: Efficiency (technology-specific, dimensionless)
- E: Electricity production (technology-specific, time-dependent, in MWh/h)

2.7 Calculation of CO_2 abatement cost

The simulation and calculation of induced and avoided CO_2 emissions already gives an idea of what system setting appears to be more beneficial over others. In order to get a fair comparison of the scenarios, however, it was necessary to relate the CO_2 emissions induced or avoided by optimization measures towards the cost the respective system settings would be faced with. In doing so, the scenarios can be compared with each and moreover they can also be compared with other measures to reduce CO_2 emissions. Equation 2 is based on **?** and shows the relation between the system settings of the reference case and under consideration of the optimization measures is presented.

$$c_{abat} = \frac{c_m - c_{ref}}{e_{ref} - e_m} = \frac{\Delta c}{\Delta e_m} \tag{2}$$

with

- c_{abat}: CO_2 abatement costs (in Euros per ton of CO_2)
- c_m: specific cost of a measure (in Euros per annum)
- c_{ref}: specific cost of the reference case (in Euros per annum)
- e_{ref}: specific emissions of the reference case (in tons per annum)
- e_m: specific emissions of the measure (in tons per annum)

In order to do so, all CO_2 emissions calculated for the individual scenarios were related to their respective annuitized cost, i.e. the average annuitized investment cost (capital expenditures (CAPEX)) and the annual operational expenditures (OPEX), i.e. costs for operation, repair and maintenance (ORM). Such calculations were conducted for an assumed service life of specific system components of 20 years and 30 years, respectively.

All calculations were conducted on an annual basis, taking annual depreciation, due interest as well as annual ORM cost into account. Not all of such figures tend to be constants in any year of consideration. For instance, the due interest decreases from year to year as the debt is reduced by the annual redemption. In order to get comparable numbers, annual figures of all the scenarios were summed for a period of twenty years and for a period of thirty years. The total costs within these periods were then related again to the amount of induced or avoided CO_2 emissions during the same period.

As presented, all calculations were conducted for the national German and international European cases in which the emissions factors varied on an hourly basis due to different power plants in operation (cf. section 2.6). In the following, however, the focus is set on the European system and its CO_2 emissions. All the other calculations results can be found in the appendix (section 4.3).

All economic calculations required various inputs that were based on inputs gained from relevant literature sources, own estimates and definitions. The economic parameters are scenario-specific and they are presented in section 3.6.2.

The calculation strongly depends on the depreciation of the system components, meaning the depreciation duration and interest rates assumed, and the period of consideration. The analysis resulted in CO_2 abatement cost that provide information about how much an avoided ton of direct CO_2 emissions due to the optimization of the local sub-system would cost.

2.8 Assessment of system benefit

The overarching idea of the carpeDIEM project's working packages (cf. section 1.2) was to detect how a sub-system's behaviour would fit to the overlaying power system. Broadly speaking, a power surplus in the sub-system in a moment with a concurrent power surplus in the overlaying power system is opposing the latter because it does not require any additional production. Or vice versa, for instance, a power surplus in the sub-system in a moment with a concurrent power shortage in the overlaying power system is supporting the latter because it does require additional production.

As exemplarily depicted in Figure 2.10, the residual load curve of the sub-system and the 1^{st}-degree residual load curve of the national power system can have different relations to each other. They oppose each other in case both have the same sign or they support each other in case both have different signs. Between these conditions, a neutral state can be detected in which the residual load of at least one of the systems is zero, i.e. one of the systems acts as if it was not there.

In the analysis the residual load of the sub-system and of the overlaying national and international power systems were contrasted to each other on an hourly basis. By applying a simultaneity criterion, the comparison did not only comprise a simple relation between the datasets but also an evaluation. From this hourly resolved comparison and assessment the full picture of the whole year of analysis could be drawn, including e.g. the accumulation of annual values, relevant diagrams were created and summarizing figures of the different scenarios were compared with each other.

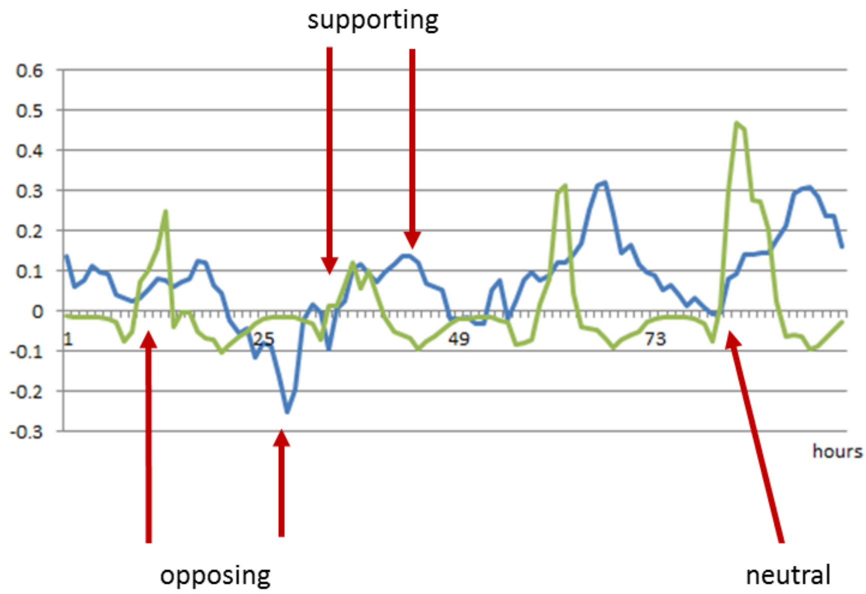

Figure 2.10: Exemplary residual load curves of a sub-system and the overlaying power system

Own illustration based on own simulations.

In order to conduct a more simplified assessment a matrix was compiled (cf. Table 2.3) that would describe all potential combinations of the sub-systems's residual load and the residual load of the overlaying systems, to be applied for the assessment in every hour of the year. A set of 21 possible combinations of the residual loads of the sub-system and an overlaying system were mapped in the matrix, categorically depending on the sign of the residual loads in the sub-system and in the overlaying system. For each combination, an assessment value was utilized which is presented in more detail further below. In practice the cases of the combinations are indirectly represented in the price curve for electricity as documented in **?** (cf. Figures 2.8 and 2.9), too.

The matrix of possible combinations consisted of nine base cases that were further subdivided:

1. The residual load of the overlaying system is positive and
    a) the residual load of the sub-system is positive, or
    b) the residual load of the sub-system is zero, or
    c) the residual load of the sub-system is negative.
2. The residual load of the overlaying system returns zero and
    a) the residual load of the sub-system is positive, or
    b) the residual load of the sub-system is zero, or
    c) the residual load of the sub-system is negative.
3. The residual load of the overlaying system is negative and
    a) the residual load of the sub-system is positive, or
    b) the residual load of the sub-system is zero, or
    c) the residual load of the sub-system is negative.

Additionally, the analysis was complemented with the following further cases:

1. The value of the sub-system's residual load is larger than the value of the overlaying system's residual load (either in the positive range or in the negative range).
2. The value of the sub-system's residual load is smaller than a pre-defined tolerance range (either in the positive range or in the negative range).
3. All other cases.

This additional subdivision means that the description of the condition of the sub-system's residual load were increased from 3 (base cases: 1 positive, 1 zero, 1 negative) to 7 (3 positive, 1 zero, 3 negative), based on the following aspects:

1. A sub-system's residual load greater than the overlaying system's residual load is an extraordinary situation that corresponds to a sub-system's excess power that is larger than the residual load to be covered in the overlaying system. Or vice versa: the shortage in the sub-system might be larger than potentially available surpluses in the overlaying system.
   Example: In a specific hour in the year of analysis, excess power from the sub-system is greater than the positive residual load of the overlaying system. This might be the case, for instance, if large amounts of wind power at heavy wind

speeds as found in a sub-system meet a low residual load in the overlaying system. In that case the sub-system would support the overlaying system to a certain extent in that moment but not all of its excess power could be used by the overlaying system.

2. A sub-system's residual load might be too small to be fairly evaluated whether or not it is supportive to the overlaying system. Without any tolerance range, even the smallest residual load of the sub-system would be counted as being supportive to or opposing the overlaying system, i.e. a comparably small value of excess or shortage power of the sub-system would be evaluated the same way as a theoretical large value of excess or shortage power of the sub-system, which would not be reasonable.
   Furthermore, the natural background noise of the model (cf. section 2.5) might be greater than a presumably precise result close to zero, meaning that potential uncertainties of the model – that naturally occur in any model – might affect modelling results stronger than the value of a comparably small result figure.
   The tolerance range was therefore defined to be a percentage of the maximum and minimum residual load, respectively, of the sub-system. The absolute tolerance value therefore could be different in the positive range and in the negative range. Within the tolerance range, by definition the comparison of the residual load figures would be regarded to be neutral.
   Example: A positive residual load of 1 kW in a sub-system during a specific hour of the year of analysis is comparably small if the maximum residual load during the full year is 200 kW. The comparatively small residual load value would therefore regarded to equal zero, to be assessed as being neutral towards the overlaying system.

For the results analysis a tolerance range of 0.05 = 5 % of the maximum residual load during the year of analysis was chosen, meaning that in case the residual load of the sub-system would fall into that range it would not be considered to be negative or positive but exactly zero instead.

In total, any of the three residual load conditions of the overlaying system was related to seven residual load conditions of the sub-system, hence 21 combinations. For every hour of the year of analysis the systems' states were assigned to one of these possible combinations which again were related to an individual assessment factor. The assessment factor could either be –1, 0 or 1. By doing so, an assessment of the relation between the residual loads could be conducted for every hour of the year of analysis.

Table 2.3: Combinations of system states and assessment factors

Residual load in the sub-system	Residual load in the overlaying system: negative	zero	positive
positive, exceeding the residual load in overlaying system*	1/−1	−1	−1
positive	1	−1	−1
positive, close to zero**	0	0	0
zero	0	0	0
negative, close to zero**	0	0	0
negative	−1	−1	1
negative, exceeding the residual load in overlaying system*	−1	−1	1/−1

*) according to amount **) i.e. within the defined tolerance range
Own compilation.

In the definition of the assessment factors it was crucial to take a theoretical case into account in which the sub-system would be attached to the overlaying power system and the assessment would take into account whether the sub-system's state in a specific hour would support or counteract the overlaying system or whether it would do neither of both. It is possible to conclude different assessment factors from different angles. As in the assessment the sub-system is regarded as a black box that only delivers its residual load curve and that does not react to signals from the overlaying system, the assessment does not take into account how well or bad a sub-system's component, i.e. storage, supports or counteracts the overlaying system in a specific moment. In Table 2.3 the respective assessment factors are indicated. Three categories were available:

1. The sub-system basically fits well to the overlaying system, i.e. the sub-system acts supportive the overlaying system or the overlaying system benefits from the sub-system (German: "systemdienlich") This case was assessed with a factor of 1.

2. The sub-system acts neutral towards the overlaying system, i.e. the overlaying system is not or is hardly affected by the sub-system.
   All cases in which the sub-system's residual load is insignificantly above or below zero or even exactly zero were assessed with 0 towards the overlaying system.

3. The sub-system basically does not fit to the overlaying system (German: "nicht systemdienlich"), i.e. the sub-system acts opposed to the overlaying system or the overlaying system malefits from the sub-system.
   This case was assessed with a factor of –1.

An assessment factor of 1 could only be achieved if the signs of the residual loads of the two compared systems that were opposite. A value of –1 indicates that the two compared residual loads have the same sign. All the other cases were assigned to an assessment factor of 0, representing a neutral relation between the compared systems. Such a three-class evaluation describes all system cases robustly and it would deliver sound results. The resulting hourly-resolved sequence of such a sequence assessment using the –1/0/1 evaluation scheme can be understood as an abstract price curve and the sub-system's effective potential towards the overlaying system.

For the assessment of system benefit an additional tool was developed, consisting of hypertext preprocessor (php) scripts and tables in a MySQL database. With hourly resolved sequences of the sub-system, the national and the European power system as simulated with the energy system simulation model it can conduct the assessment by one click and automatically generate heat maps, too. The tool can be downloaded from `https://github.com/znes/carpeDIEM/phpviewer`.

2.9 Economic assessment of local surpluses and shortages

With the results of the simulation model it is possible to evaluate the systems' situation for every hour of the year in conjunction with the respective spot market price of electricity in that very hour (cf. **?**). While the assessment presented in section 2.8 was of reduced complexity (binary evaluation), a further assessment with local power surpluses and shortages and the simultaneously arising electricity prices was conducted.

For every hour of the year of consideration and for every scenario, the sub-system's residual load was therefore linked to the respective spot market price, i.e. a positive or negative value in terms of power provided from or to be delivered to the sub-system is related to a positive or negative value in terms of electricity cost. Every hour's energy amount induced by the sub-system therefore could be economically evaluated. This can be understood from the sub-system's operator's perspective: power surpluses from the local system can be sold to the overlaying system at the time-dependent spot market price whereas power shortages in the sub-system need to be covered by power purchases from the overlaying power system. In practice, however, this would require a sub-system's operator to trade at the European Energy Exchange (EEX). The balance of all sales and purchases during the year can be calculated. Results of scenarios with additional storage in the sub-system compared with the results of the respective reference case without such additional storage shows whether the battery storage can help saving money for power purchases from the overlaying power system or whether it is economically maleficial. Equation 3 summarizes the calculation of the revenues:

$$Y = \sum_{t=1}^{8760} p_t E_t \quad (3)$$

with

- Y: financial yield (in Euros)
- t: time index (hours of the year)
- p_t: specific spot market price of electricity (time-dependent, in Euros per MWh)
- E_t: energy amount (time-dependent, in MWh).
  The energy amount can be positive or negative, depending on whether energy is sold or purchased.

The higher the spot market price for electricity is, the more additional power production would be required in the overlaying power system. If the sub-system delivers power during such a period, that amount of energy has a high value. Such an assessment thus would not only deliver information about the support of or opposition of the sub-system towards the overlaying power system but this support or opposition would also be weighted differently.

3 Application of the model and modelling results

In this section the following aspects are covered and presented:

- presentation of the modelled scenarios for the showcase,
- modelling and analysis of the national and international power systems related to the sub-system, both in an isolated and in an integrated approach, for different scenario settings, and
- further modelling and analyses.

As presented, the guiding question was how the locally optimized sub-system would operate in relation to the overlaying power system and what impact that would have. In order to find answers to such questions, the revised model was used for the simulation of various scenarios and scenario groups. In principle, the following categories of simulations were conducted. Their details and results are presented in the following sections:

I) Simulation of a reference case of the German and international power system the subsequent simulations could be related to and for the purpose of calibration of the sub-system's input data and the simulation model, which again was relevant for all simulations

II) Simulation of the German and international power system as of 2015 in which the sub-system would behave according to the optimization as calculated by the project partners from FHHL (cf. **?**) ("isolated approach")

III) simulation of the national German and international power systems in which additional storage options would be included in accordance with the DIEM scenarios ("integrated approach").

The modelling of the status quo of national and international power system (case I), the modelling of the isolated approach (case II) and the modelling of the integrated approach (case III) helped comparing resulting system benefit, induced or avoided CO_2 emissions and the evaluation of the optimization at the local level, for different scenario settings. This taxonomy allowed to simulate scenarios with and without signals from the overlaying power systems. In case II such signals would be neglected whereas in case III the overlaying power systems' signals would directly affect the utilization of the storage options. The approach to specify the exact scenario settings in the model is presented in the following sections. Figure 3.1 illustrates the three cases schematically.

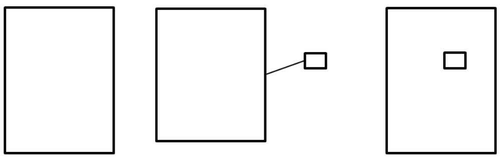

Figure 3.1: Scheme of the investigated scenario groups

Own illustration.

3.1 The scenario settings of the showcase

In frames of the carpeDIEM research project, various settings of the sub-system were utilized as inputs to the simulations. Each scenario setting included scenario-specific information for the sub-system about the total consumption, the consumption pattern, the installed renewable capacity, accompanied by renewable production patterns.

From a micro-perspective, the sub-system in these scenario settings appeared to be optimized with DIEM in that way that the available local storage was adjusted according to the sub-system's requirements and a comparably high level of self-sufficiency was reached by making use of existing and potentially available local renewable energy plants and such potentially available local storage options. For the research approach presented in this paper, the system boundary was laid around a specific set of local loads and renewable energy plants in order to generate results that related to the results derived by the project partner FHHL. Compared to the existing PV installation, the calculations comprised the largest share of the rooftop PV plants installed in the showcase village. Moreover, the existing 1 MW wind turbine located close to the showcase village as well as the CHP plant were included in some of the scenarios. If desired, the model allows to include further system components such as other PV or wind power installations in further calculations.

The scenario settings of the sub-system listed below were simulated for the isolated case and partly for the integrated case. Unless otherwise stated, additional system elements described in the following list refer to additions to the base system setting (case "A"). In total, seven settings of the sub-system were subject of the modelling and analysis:

1. System setting A:
   Name: "Base case"
   Description: system components as of 2015. Supply side: PV only.

2. System setting B:
   Name: "Prosumer batteries"
   Description: additional decentralized batteries in households that already have had rooftop PV installations in 2015.

3. System setting C:
   Name: "Prosumer expansion"
   Description: additional PV installations on rooftops that have not had such by 2015, additional decentralized batteries in all households with PV installations.

4. System setting D:
   Name: "Centralized battery"
   Description: additional centralized battery storage.

5. System setting E:
   Name: "Wind turbine"
   Description: additional wind turbine.

6. System setting F:
   Name: "Wind turbine and centralized battery"
   Description: additional wind turbine, additional centralized battery storage.

7. System setting G:
   Name: "Combined heat and power (CHP) plant"
   Description: additional biogas-based CHP plant.

An overview over the annual demand and the installed capacities in the scenarios based on **?** are presented in Table 3.1. All values in the table refer to the whole year of analysis. While all scenario setting describe a system of existing components except for additional storages, scenario setting "C" describes a special case: here it is assumed that also additional PV capacity will be installed.

The local optimization of the sub-system resulted in scenario-specific hourly resolved demand and production patterns that could be used for further analyses. For the carpeDIEM research project, residual load curves of the sub-system were derived for every scenario. They can be understood as the power that would be delivered to or obtained from the overlaying power system, i.e. the German and international power system, once the optimization of the sub-system has been conducted. In other words, the residual load curves represented the power that would be either missing in the sub-system – i.e. a local power shortage – or that would be exeeding the capability of the

Table 3.1: System settings of the showcase in the scenarios

System setting	Demand	PV	Wind power	CHP	Batteries	Batteries	Batteries	Batteries
					Capacity	Capacity	Capacity	Efficiency*
	MWh/a	kW_p	kW	kW_{el}	kWh	kW (in)	kW (out)	%
A	986	2940						
B	986	2940			349	180	166	95
C	986	4269			1678	865	796	95
D	986	2940			2263	1000	1000	95
E	986	2940	1000					
F	986	2940	1000		560	560	1000	92
G	1736	2940		875				

*) one-way.
Own calculation and compilation based on **?**, **?** and own assumptions.

sub-system – i.e. local excess power –, both measured at the connection point between the sub-system and the overlaying power system. The residual load curves of the sub-system modeled for the presented scenarios all differed in their pattern, resulting in differences in energy amounts required from or delivered to the overlaying power systems and also resulting in differences in the number of hours of local power surpluses or shortages.

Scenario G represented a special case: It included the local CHP plant with an electric capacity of 875 kW and therefore the local power production would always be above the local demand, i.e. the local system reached a self-sufficiency rate of 100 % and it would excess power in every hour of the year.

3.2 Simulation of the showcase

While the residual load curves of the showcase as provided from the project partners were taken into account in the successive simulations, the showcase's system setting were also rebuilt with the simulation model, for two reasons. First, the capacities and sequences – both on the demand side and on the production side – were required in the further simulations with the simulation model. Second, the reproduction of system setting would show how the the different models applied in the carpeDIEM project would simulate the same scenario settings.

For doing so, the scenario setting described were translated into inputs to the simulation model. The model was then run under the theoretical assumption that the

Table 3.2: Simulation results of the showcase

Scenario	Demand	PV	Wind power	Biogas plant	shortage	excess	charging	discharging
0	974	0	0	0	0	0	0	0
A	974	2775	0	0	519	2320	0	0
B	974	2775	0	0	409	2198	123	111
C	974	4029	0	0	138	3155	403	363
D	974	2775	0	0	171	1838	483	349
E	974	2775	2185	0	201	4187	0	0
F	974	2775	2185	0	86	4051	137	116
G	974	2775	0	1088	0	2124	0	0

All values: MWh
Based on **?** and own simulations.

Table 3.3: Simulation results of the showcase (annual sums)

Scenario	demand MWh	excess MWh	shortage MWh
A	974	2320	519
B	974	2198	409
C	974	3155	138
D	974	1838	171
E	974	4187	201
F	974	4051	86
G	974	2124	0

Source: own simulations.

sub-system would be completely isolated from the overlaying power systems, i.e. a transmission link was not taken into account. That would lead to power surpluses and shortages, respectively, comparable to power excess and shortages calculated by the project partners.

In order to integrate the showcase setting into the simulation model, the recreated scenario settings of the sub-system as presented in **?** were saved in the corresponding csv input files to the simulation model (cf. section 2.1.3). If necessary, they were adjusted to the model's requirements. For every scenario, specific json files comprising metadata were generated that would be called when the model was executed in order to access the respective csv files.

In Table 3.2 and in Table 3.3 the simulations' results are presented. In comparison with the same scenarios presented in **?**, the simulation model produced results that were highly similar. Deviations, however, were found due to various reasons:

- As both models were fed with a high number of input data, variables and functionalities, a complex interaction during the optimization resulted. Naturally, any even minor difference would have an impact on the results.
- There were minor deviations in the input data due to inconsistencies in the underlying sources, round-off errors and for other reasons. Even though such differences were comparably small, their impact on results cannot be underestimated.
- In the simulation conducted by **?**, battery storage was defined inter alia with its input and output capacity, to be understood as the capacity of the inverter. Both parameters tend to be rather similar, however in the simulation model only one value was used for the storage capacity of a specific scenario which resulted in differences in the utilization pattern of the batteries.
- While **?** distinguishes between the battery efficiency of charging, discharging and the charging process itself, in the simulation model only one efficiency value was used that would incorporate all such individual efficiencies.
  Notwithstanding, for scenario D an efficiency of 0.95 was utilized.
- Additionally, in the adjusted model the filling level of the batteries in the scenarios was assumed to be 1, i.e. full, at the beginning of the simulation period. In **?** the batteries had a specific filling already in the first hour of the simulation period, too, however fully documented.
- Due to the optimization algorithm and boundary constraints in the model the batteries reached the same filling level at the end of the simulation as they had at the beginning. It is unknown whether this was the case in the calculations conducted by **?**.
- The optimization algorithms of both models were not identical. Using a specific solver in the simulation model meant that a specific way of finding the least-cost solution of the system was applied, which was different in the calculations conducted by **?**.
- While **?** used a quarter-hourly resolution for the simulations of FHHL, the simulation model used an hourly resolution. Even though the hourly values approximate

an excerpt from the quarter-hourly values, differences might appear, for instance if the battery's filling level reaches the maximum between two full hours.

The showcase scenario settings independent from the overlaying power systems can be found online at

`https://github.com/ZNES-datapackages/Bordelum`

In a nutshell, the simulation model's input data approached both a realistic setting of the national and international power systems as well as of the sub-autonomous sub-system in several scenario variants.

During the course of the research project it was decided to put emphasis on one specific showcase only, however with various scenario settings. The scenarios differ in their complexity, in their production and demand patterns and in their structure. Researchers from EUF visited the showcase village on-site and used location-specific date in their simulations.

3.3 Simulations I: Reference case

With the substantially adjusted simulation model, simulations were conducted that would take the inputs presented in section 2.2 into account. As a reference case, the national and international power system was modelled independently from the described showcase scenarios in a first step. This status quo scenario represented a reference case that was necessary for the subsequent simulations for comparison and calibration purposes. The national figures of the demand, the load curve, the power plants and volatile production sequences comprised all the elements and sequences of the sub-system.

In that base variant the model simulated the utilization for every technology and every region, i.e. country, for every hour of the year as defined in the inputs to the simulations. This included the hourly demand, the hourly production of every technology considered, the hourly utilization of storages and the hourly utilization of transmission links between the regions in the model. The simulation comprised the full year of 2015 and all the technologies in the German and European power systems of that year.

As 8760 values for each output parameter resulted, only an excerpt of the simulation results can be presented here. The full results can be found online at

`https://github.com/znes/carpeDIEM`

. In Table 3.4 the annual sums of demand and production in Germany and in the European system consisting of Germany and its electrical neighbours are listed. An exemplary pattern of the load and production for scenario B is illustrated in Figure 3.2. Key outputs and results can be summarized as follows:

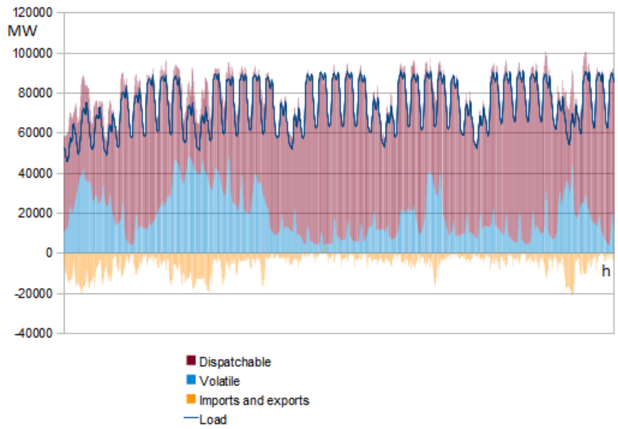

Figure 3.2: Demand and production pattern of the reference scenario
Exempary first 100 hours of the year.
Own illustration based on own simulations.

- As specified in the inputs to the simulations, the demand is 596 TWh/a in Germany and 1916 TWh/a in Germany and its electrical neighbours, respectively.
- Due to their marginal costs close to zero the volatile RES PV, wind power (onshore and offshore) and run-of-the-river hydro power (RoR) produce before any dispatchable production is in operation. Their production depends on the available resource. In total they produce 146 TWh/a in Germany and 352 TWh/a in Europe, respectively.
- As these volatile RES cannot cover the whole demand, further production is necessary. Depending on technical and economic parameters of the dispatchable units available in the German and in the European power system, respectively, fuel-based power plants operate.
- In sum, this dispatchable production in Germany covers the national residual load and even produces a surplus of 6 TWh/a that is utilized to cover the remaining load in the neighbours's power systems.

For the reference case, the resulting CO_2 emissions were calculated as presented in section 2.6 (cf. Table 3.5). A full list of all country-specific CO_2 emissions can be found

Table 3.4: Simulation results: Power production in the status-quo scenario

	Germany	Europe*
Demand	596	1916
PV	44	73
Wind power (onshore)	74	150
Wind power (offshore)	11	19
Run-of-the-river hydro power	17	111
Sum volatile	146	352
Residual demand (1st degree)	450	1564
Nuclear	89	722
Hard coal	93	129
Lignite	157	261
Natural gas	58	170
Biomass	53	61
Reservoir Hydro Power	2	225
Sum dispatchable	453	1568

*) corresponds to Germany and its electrical neighbours
All values: TWh/a.
Source: own simulations.

in Table A11 in the appendix. It was found that 428.1Mt of CO_2 were produced in the European power system, as defined in and based on the model simulation. In Germany, 264.1 Mt would be produced.

The calculated values resembles the figures found in literature sources. For Germany, however, sources indicate the CO_2 emissions of the national power sector as of 2015 to be 331 Mt (**?**) and 305 Mt from electricity production (**?**), respectively. The calculated values therefore can be regarded as underestimating the actual CO_2 emissions. The deviation can be explained with differences in the underlying data (emissions factors, efficiencies) and additional losses that have not been included in the simulations.

3.4 Simulations II: Isolated approach

The base case as presented in section 3.3 was utilized for further simulations in which the relation of the sub-system and the overlaying power systems was simulated and analyzed. First, a set of simulations was conducted that was considered an "isolated approach". In this approach the optimization of the local sub-system (DIEM optimization) would be independent from the overlaying power system, which would be the case if a sub-system

Table 3.5: Simulations I: resulting CO_2 emissions

Country	Mt/a
Austria	7
Belgium	4
Switzerland	0
Czech Republic	32
Germany	264
Denmark	0
France	2
Luxembourg	1
Netherlands	27
Norway	0
Poland	91
Sweden	0
Total	428

Source: own simulations.

is locally optimized and does not react to signals from the overlaying power system. For a fair relation of the sub-system and the overlaying power system and in order to avoid double-counting, it was however necessary to take additional input data into account and therefore to adjust the model code. Figure 3.3 depicts the general procedure that is described below.

As mentioned before, a data file data.xls was stored in the carpeDIEM repository's archive folder that contained all the necessary information regarding the sub-system's configuration in the carpeDIEM models. For each scenario of the isolated approach a separate sheet was created that held timeseries data of the residual load of the sub-system on the one hand. This data represented the results of the previously optimized sub-system, excess and shortage in each timestep over one year of the micro-system, that had to be met by the overlaying macro-system.

On the other hand, if the sub-system was acting autonomously, the demand and renewable or any other generation associated with the sub-system would no longer contribute to the demand and generation of the overlaying system. Timeseries data representing this demand and generation, correctly parameterized with the capacity of generation or the total amount of the sub-system's demand in each particular scenario, was thus included in each corresponding timeseries sheet. In a last step the timeseries data was summed up for each timestep, resulting in a balance timeseries, which represents the

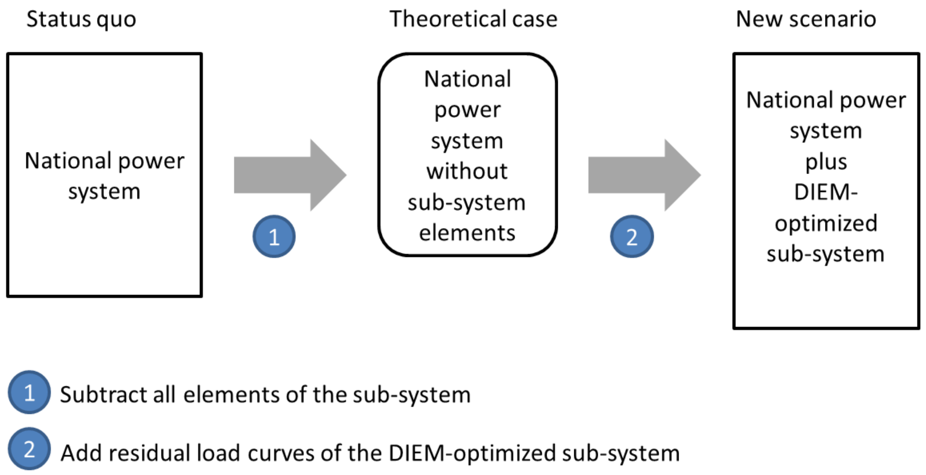

Figure 3.3: Model procedure in the isolated approach

Own illustration.

process of subtracting demand and generation of the sub-system from the macro-system and connecting the pre-optimized sub-system with the macro-system, in one timeseries. This timeseries data was split into generation and demand and it was attached to the German electricity bus.

– PV production curve of the sub-system

– wind production curve of the sub-system

+ load curve of the sub-system

- residual load curve of the sub-system

= balanced timeseries

In addition the xls file, the carpeDIEM `build` script respectively, allowed to be further adapted for the reference case . In a sheet named "adaptations" the user is enabled to define changes to be applied to specific fields within the reference datapackage, e.g. subtracting or adding capacities. This requires some basic knowledge about the underlying datapackage structure, e.g. the resource name, the label of the affected element and the parameter name. However, this functionality is needed only once in the context of the carpeDIEM scenarios. In scenario G the biomass powerplant was accounted for in the sub-system setting and as a consequence in the residual load of the sub-system.

Table 3.6: Annual sums of the optimized sub-system

Category	Scenario A	B	C	D	E	F	G
Load	975	975	975	975	975	975	1736
Feed-in	−2320	−2265	−3278	−1867	−4317	−4187	−7989
Purchase	519	481	263	139	200	80	0
Balance	−1800	1784	−3015	−1728	−4117	−4107	−7989

All values: annual figures in MWh.
Negative values: flow from the sub-system to the overlaying system.
Source: Own calculations based on **?**.

Without the timeseries profile of the plant, it could not be accounted for in the net-balance timeseries, thus the loss of generation was met by decreasing the capacity in the overlaying system itself.

In Table 3.6 the annual sums of the demand, of the volatile production and of the residual load of the sub-system are listed for all scenarios modelled. The differences between the scenario settings become obvious. As in scenarios A–D solar PV is the only source in the sub-system, the feed-in is rather small and the purchase is rather large in relation to scenarios E–G in which a wind turbine and a biogas plant are additionally taken into account. The net balance of feed-in and purchase depends on the included resource, however also on the considered storage option. It ranges from 1728 TWh (scenario D) to 7989 TWh (scenario G).

3.4.1 Resulting direct CO_2 emissions

For the scenario settings described in section 3.4, the direct induced or avoided CO_2 emissions were calculated according to the approach presented in section 2.6 and for all scenarios presented. The CO_2 emissions were calculated for the entire overlaying power system, i.e. for Germany and its electrical neighbours. The summarizing results of the analysis can be found in Table 3.7. For illustrative purposes the table includes the net emissions only that would be induced and avoided, respectively, in the European and national power system, in relation to the base case described in section 3.3. The country-specific absolute CO_2 emissions can be found in Table A11 in the appendix.

The simulations reveal the following:

- As expected, in scenarios A and E the amount of CO_2 emissions was found to be the same as in the showcase. That is a result of the approach and the model: in both scenarios the status quo of the national power system was essentially reduced

Table 3.7: Isolated approach: Induced and avoided direct CO_2 emissions

Scenario	CO_2 (t/a)
A	0
B	9
C	−578
D	45
E	0
F	7
G	0*

All figures: annual balances, related to the reference case I. Net values only, i.e. without emissions induced during the production of the fuels. All emissions avoided or induced emissions in the power consisting of Germany and its electrical neighbours.
Positive values: net induced emissions. Negative values: net avoided emissions.
*) not simulated with the revised model.
Based on own simulations.

by the local load, load profile, RES installation and corresponding RES profiles. After that reduction the model added the respective residual load curves to the system again. As those residual load curves corresponded to the local demand and production, the overall system result was expected to be the same.

- As presented, scenario C represents a special case. Due to additional PV installations the induced CO_2 emissions are reduced by 645 t/a. That value is comparable to the other scenarios only to a limited degree due to the substantial difference in the underlying data.

- In scenario G, as expected, the avoided CO_2 emissions were even higher due to the high amount of CO_2-neutral surplus power from the sub-system.

- The scenarios in which battery storage was included show an increase in CO_2 emissions (scenarios B, D and F). The largest increase (36 t) is found in scenario D.

3.4.2 Analysis of usefulness of the system

As presented, a central question in the carpeDIEM research project was how the residual load curves of the sub-system related to conditions of the overlaying national and international power systems. Besides the impact on induced or avoided CO_2 emissions in the overlaying system, the resulting residual load curves from the showcase as described in section 3.1 were therefore transformed to hourly series and compared to different sequences in the national and international power system as modelled with the simulation model. That comparison was conducted for different degrees of the residual load curves of the national and international power system as exemplarily illustrated in Figure 2.7. The usefulness of the DIEM-optimized sub-system was assessed according to the method presented in section 2.8.

In this procedure, the residual load curves of the different scenarios of the sub-system and of the overlaying national and international systems were compared with each other in order to analyse how the sub-system's behaviour related to the state of the overlaying power systems. As the showcase represented a comparably small part of the entire system it was decided to leave the national and international power system as described in the status quo (cf. section 3.2) in order to keep the complexity of numbers and results at a reasonable level.

The sequences gained from the local optimization directly translated to the power that the sub-system either additionally required from the overlaying power system or that exceeded the local demand and could therefore be fed into the overlaying power system. The, sequences therefore exactly corresponded to what would be demanded from or delivered to the overlaying power system. For every scenario, such a sequence was compared to the system state of the overlaying power systems. In sum, the following data sets were related to each other and their relation was analyzed:

1. Residual load curves of the Bordelum showcase:
   7 variants (= scenarios A–G)

2. Residual load curves of the overlaying German power system:
   5 variants (= 4 degrees of residual load curves plus the load curve)

3. Residual load curves of the overlaying European power system:
   5 variants (= 4 degrees of residual load curves plus the load curve)

The number of conducted comparisons between the systems equaled the product of variants on each side, i.e. the comparison of the Bordelum showcase (7 scenarios) and the European power system (5 degrees of the residual load) was conducted 35 times and so was the comparison of the Bordelum showcase with the European power system.

As presented in section 2.8, the generated residual load curves of the sub-system and of the overlaying systems were related to each other and that relation was assessed on an hourly basis with a defined assessment factor. Exemplary results of that assessment are presented in Table A2. For reasons of display only the results for the 1st degree residual load of the overlaying national system is displayed. Further results for other degrees of the overlaying systems' residual load can be found in the appendix (section 4.3).

Table 3.8: Residual load assessment (sub-system vs. 1st degree residual load of the European power system)

System setting (sub-system)	negative	neutral	positive
A	5429	126	3205
B	5577	120	3063
C	5079	210	3471
D	1446	4554	2760
E	2353	227	6180
F	1110	1725	5925
G	0	0	8760

All values: hours per year.
Based on **?** and own simulations.

The relationship between the sub-system and the overlaying power systems according to the assessment scheme as specified in section 2.8 can also be illustrated by heatmaps. In the example, the relationship of the sub-system with the European system is depicted. As exemplarily shown for the case of scenario B in Figure A2, every day of the year (abscissa) and every hour of every day (ordinate) is marked as a coloured rectangle. The colouring, again, represents the system's relationship: blue represents hours in which both systems fit well together (assessment factor: 1), white represents a neutral condition (assessment factor: 0) and red represents hours in which both systems do not fit together (assessment factor: –1). Further heatmaps for all the other scenarios can be found in the appendix (section 4.3).

From the results of the assessment it can be concluded:

1. Related to the 1st level residual load of the overlaying power systems, there was found no difference in the assessment between the German and the European power system. That can be explained by the simultaneity of the demand and volatile RES production patterns in the German and the European power system. On the other levels of the residual load, minor differences between the German and the European power system can be detected, however the 1st level residual load is most important as it does not include any dispatchable sources that would operate differently anyhow if the load pattern changes. That is why in the following

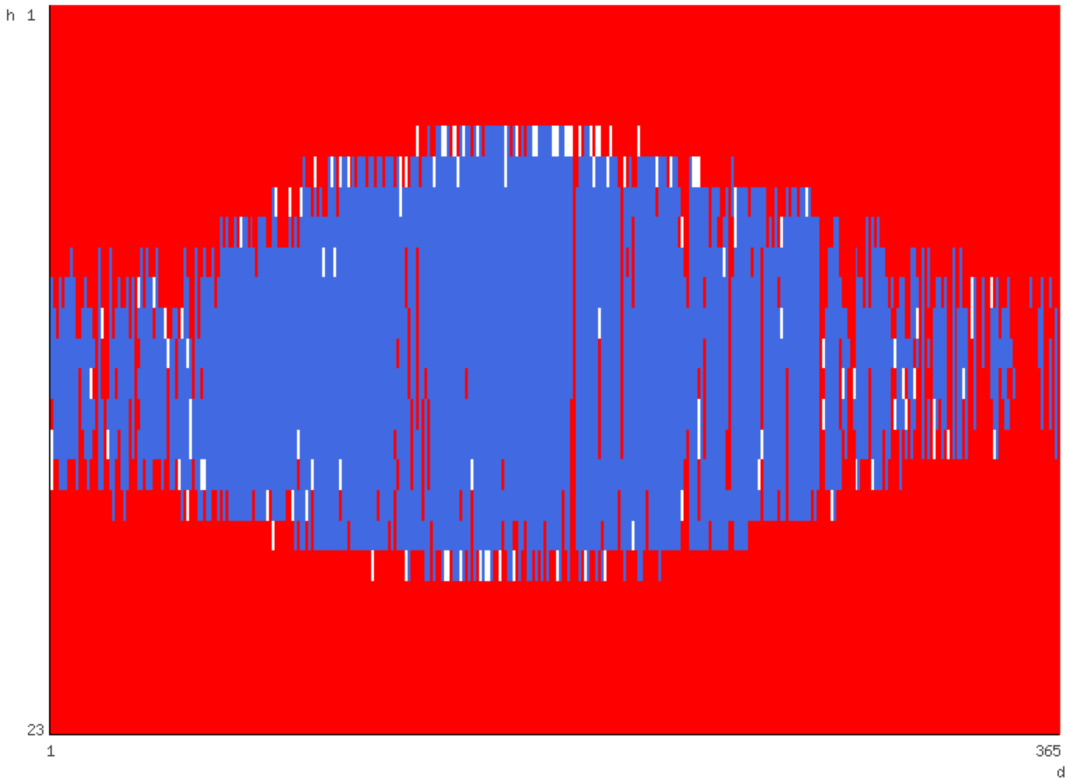

Figure 3.4: Exemplary heatmap: Scenario B, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

bulletpoints the focus is put on the 1st level residual load of the overlaying power systems.

2. The settings A and B show the largest negative value, i.e. the highest number of hours in which the sub-system is opposing the overlaying system, related to all the other cases. Setting B even appears to be more maleficial due to the inclusion of battery storage.

3. Setting C in which additional battery storage and additional PV installation is included in the sub-system acts more supportive to the overlaying power system than settings A and B, however not substantially.

4. A substantial difference can be detected in setting D in which the number of opposing moments during the year is substantially reduced compared to scenarios A, B and C. However also the number of supportive hours during the year is reduced and the number of neutral hours is substantially increased.

5. Scenarios E and F act more supportive to the overlaying power system, reaching about 6000 hours with a positive assessment. In scenario F, the number of negative hours is approximately half of what is found in scenario E while the number of a neutral state is substantially increased.

6. As expected, in scenario G a supportive system state is found during all hours of the year.

The impact the additional storage options have on the sub-system's residual load and its assessment towards the overlaying power system can clearly be detected in these figures. Even though the precise capacity differs between the scenarios, the batteries in principle get charged during the day and get discharged at night, which also means that at night less power is required from the overlaying system than in the reference case, which affects the utilization of dispatchable units in the power system, thus their CO_2 emissions. Power surpluses that cannot be stored in the batteries or cannot be used directly are fed into the overlaying system in which the residual load is positive during most of the hours

A sub-system's setting can be regarded as to be more supportive, i.e. useful, to the overlaying power system the higher the number of positive values according to the assessment and the lower the number of negative values according to the assessment. For that perspective, scenario F acts most supportive to the overlaying power system.

3.5 Simulations III: Integrated approach

While in the previous sections the optimized system of the showcase was regarded to be locally optimized independent from the overlaying power system, in a further step the same scenarios in which battery storage was added to the system (scenarios B, C, D and F) were modelled as to be embedded in the overlaying national and international power systems. Generally that would lead to a utilization of the storage according to the signals and requirements from the national and international power system. In the model scripts, the status quo of the national and international system would be supplemented by the additional storage option, i.e. an additional element in the system that would represent an additional option to charge or discharge with specific technical characteristics.

Table 3.9: Integrated approach: Induced and avoided direct CO_2 emissions

Scenario	CO_2 (t/a)
B	−7
D	−48
F	−5

All figures: annual balances, related to the reference case I. Net values only, i.e. without emissions induced during the production of the fuels. All emissions avoided or induced emissions in the power system consisting of Germany and its electrical neighbours.
Positive values: net induced emissions. Negative values: net avoided emissions.
Based on own simulations.

In order to integrate the showcase setting into the adjusted simulation model, the scenario settings as utilized by FHHL in the carpeDIEM project were recreated and saved in the `data.xls` input file of the carpeDIEM tool (cf. section 2.1.1). If necessary, the original data were adjusted to the model's requirements.

3.5.1 Resulting direct CO_2 emissions

For the scenario cases in which batteries were included, the induced CO_2 emissions were calculated according to the approach presented. A summary of the induced emissions is presented in Table 3.9. The country-specific CO_2 emissions can be found in Table A11 in the appendix.

As the case of scenario C cannot be directly compared with the status quo due to the addition of PV installations, the analysis has been conducted for the scenarios B, D and F. Scenario C, however, was simulated in the integrated approach in order to compare it with scenario C in the isolated approach.

In all cases it was found that the total CO_2 emission would be reduced (scenarios B, D and F) if the respective storage capacity was available in the system. Similar to the results of the isolated approach, the emissions reduction is no direct function of a lower power generation from dispatchable units but it is rather dependent on the exact system state in every single hour of the year, which again translates into a specific mix of operational units in every particular hour.

Table 3.10: Induced and avoided direct CO_2 emissions: Absolute values

Category	Scenario	CO_2 total	CO_2 delta*	CO_2 delta**
I		428 063 526		
II	A	428 063 526		
II	B	428 063 535	9	
II	C	428 062 948		
II	D	428 063 571	45	
II	E	428 063 526		
II	F	428 063 533	7	
II	G^x	428 063 703		
III	B	428 063 519	−7	−16
III	C	428 062 890		−58
III	D	428 063 478	−48	−93
III	F	428 063 522	−5	−12

All figures: annual balances in t. Negative values: net avoided CO_2 emissions.
*) Difference with the reference case of the same main category (integrated approach and isolated approach, respectively). **) Difference between the integrated and the isolated approach. ^{x}) not simulated with the model.
Based on own simulations.

3.6 Summary

The modelled scenarios and simulation sets were related to each other in order to detect the impact an isolated and an integrated approach have on the national and international power system, i.e. on the utilization of dispatchable power plants, the connected CO_2 emissions, the costs of additional storage options and the derived CO_2 abatement costs.

3.6.1 CO_2 emissions

Table 3.10 summarizes the results. The full country-specific CO_2 emissions can be found in Table A11 in the appendix.

The optimization finds the least-cost system setting and dispatchable, fuel-based technologies are in operation in dependence of the overall system setting. Therefore CO_2 emissions are induced in all regions, i.e. countries, in which dispatchable power plants are in operation according to the optimization. Hence CO_2 emissions reductions or increases are found in the overall sum of the entire system whereas in a specific country the trend might differ from that. It might even be inverse and that is why it is key not to consider the national German power system and its CO_2 emissions alone but the entire system.

The comparison of the isolated and the integrated approach with the same scenario settings shows that in the isolated approach CO_2 emissions are additionally induced while in the integrated approach CO_2 are avoided.

In Figure 3.5 the absolute induced and avoided, respectively, CO_2 emissions are depicted for the scenarios B, E and F in the isolated and in the integrated approach, i.e. those scenarios in which additional storage was added to the local and the national system, respectively.

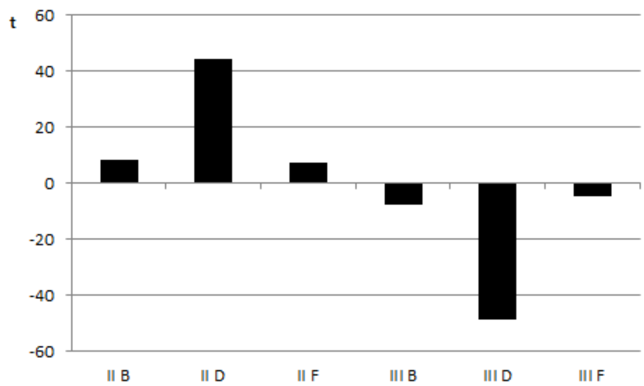

Figure 3.5: Induced and avoided CO_2 emissions

Based on own simulations.

In Figure 3.5 the same values are depicted, however corresponding scenario settings modelled in the isolated and in the integrated approach are related to each other. The absolute span between induced and avoided CO_2 emissions of the same scenario but in the two approaches reveals the net reduction of CO_2 emissions reached by using the battery storage within the entire system in contrast to using it within the local subsystem only.

3.6.2 Cost

As presented it was assumed that the same storage components would be available in the isolated and in the integrated approach. Therefore in both approaches the same costs were utilized. Table 3.11 summarizes the most important parameters. Basically the economic data can be categorized into centralized and decentral batteries with differences in their specific cost, ranging from 930–1040 Euros per kWh to (decental) 660–1050 Euros per kWh (central) (cf. **?**). For decentral batteries it was assumed that the technology of

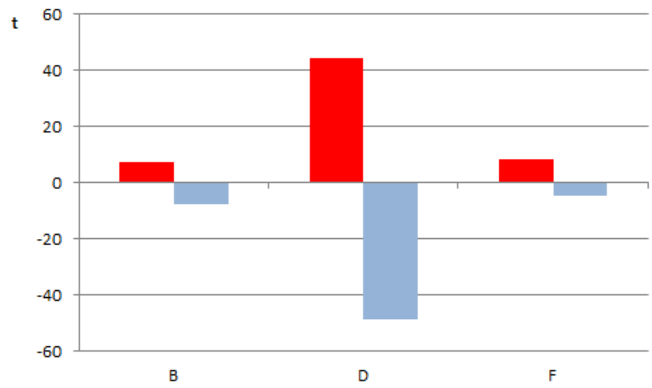

Figure 3.6: Induced and avoided CO_2 emissions: Relation between isolated and integrated approach

Based on own simulations.

Table 3.11: Economic input parameters (storage)

Category	Unit	Decentral*	Decentral**	Central***	Central****
Specific investment	€/kWh	930–1040	930–1040	660–1050	660–1050
Interest rate	%/a	1.26	1.26	1.26	1.26
Redemption duration	a	10	10	10	10
Depreciation duration	a	20	20	20	20

*) in scenarios ″B″, **) in scenario ″C″, ***) in scenario ″D″, ****) in scenario ″F″

Source: own simulations.

Source: **?**.

Vanadium redox flow (VRF) batteries is utilized whereas for the centralized approach Li-ion are used. In the calculations, the mean value of the technology-specific cost range was applied, i.e. 985 and 855 Euros per kWh, respectively. Moreover, financial parameters such as an interest rate and a depreciation duration were inputs to the calculations, however not diversified between the scenarios. The rated capacity was assumed to be available in the simulations and it was therefore divided by the DoD in order to use the gross capacity in the economic calculations.

3.6.3 CO_2 abatement cost: Economic potential analysis

As presented in section 2.7, the absolute figures of induced or avoided CO_2 emissions would not allow meaningful conclusions about the economic usefulness of the presented

Table 3.12: CO_2 abatement costs in the scenarios

Scenario	Costs	Costs
	€/t	€/t
Period	20 a	30 a
B	2729.73	1819.82
D	2370.18	1580.12
F	5416.66	3611.10

All values: annual figures, averaged over the respective period. Period represents the number of years that have been included.
Based on own simulations and **?**.

approaches unless the respective costs were taken into account in a further step of analysis.

For those scenario settings in which additional storage was included in the local or national power system (scenarios B, D and F), the induced or avoided CO_2 emissions were therefore related to the respective costs, i.e. additional storage costs in the subsystem (cf. section 2.7). Scenario C was left out at this point as it included additional storages and additional PV installations and it could not be related to a reference without such storages. The results of the analysis can be found in Table 3.12. The calculation of CO_2 abatement costs obviously can only be conducted for scenarios in which additional components are introduced, i.e. in scenarios B, D and F. Scenario C was taken out of this consideration because in that scenario not only additional storage was included but also additional PV installation, i.e. scenario C could not directly compared with a reference case.

A full list of key input parameters to the economic calculations are presented in Table 3.11. It can be concluded that the isolated and the integrated approach substantially differ in the respective CO_2 abatement costs. In any case, the isolated approach resulted in additional CO_2 emissions net induced in the entire power system. The CO_2 abatement costs are therefore negative, quantifying the cost per additional ton of CO_2, i.e. not only CO_2 emission increase in the isolated approach but so do the according costs.

The comparison of both approaches in terms of CO_2 avoidance cost, however, reveals that the integrated approach is fundamentally cheaper, i.e. a ton of CO_2 can be avoided cheaper in an integrated approach than in an isolated approach. In the simulations of the isolated approach, the abatement costs were even found to be negative.

The scenario setting D appears to be the one in which an integrated approach reduces the CO_2 emissions most in relation to the isolated approach. A centralized battery storage therefore seems to be more beneficial than multiple distributed battery storages.

3.7 Economy of local battery systems

As presented in section 2.9, the residual load curves of the sub-system was further analyzed with reference to potential financial yields from sales and purchases of electricity to the overlaying power system. The main idea behind this analysis was the fact that a battery included in the sub-system would affect the sub-system's residual load cuve, thus the requirements to purchase power from or the ability to sell power to the overlaying power system. The change of economic cost and benefit would quantify in economic terms whether such a local optimization would be useful.

For the scenarios B, D and F it was analyzed how beneficial or maleficial additional storage would be in financial terms. As a reference case for scenarios B and D, the same calculations were conducted for scenario A. As a reference case for scenario F, the same calculations were conducted for scenario E.

The theoretical cost and benefit of a reference case was calculated and so was the theoretical cost and benefit of the cases with battery storages. First of all, the positive or negative residual load of the sub-system was multiplied with the spot market price of electricity in every hour of the year. Depending on the specific hour of the year, i.e. the situation in the overlaying power grid, additional electricity to the national system or additional demand from the sub-system would have a time-specific value. The annual sum of positive and negative cost and benefit would give the annual net yield or cost.

It was found that the battery storage indeed would reduce the amount of electricity, thus money, to be spent for electricity purchases. On the other hand it was detected that in most cases the yield of sold electricity would also be reduced, even further than the increase of cost savings. As shown in Table 3.13, the balance of both cost and benefit resulted in negative values in scenarios B and D whereas in scenario F a positive value was found.

The aforementioned negative balances indicate that financially it will be more expensive with a battery included in the sub-system – or rather be a loss – than in the respective reference case that has not additional battery storage included. The positive balance in scenario F indicates that it is financially beneficial to include a battery storage in the system, however the cost for the battery needs to be set against that figure. The return on investment (ROI) therefore is negative, meaning that despite financial yields such a system would operate with losses.

Table 3.13: Income from power sales and expenses for power purchases

Scenario	Income	Expenses	Balance	Relation to reference case
A	75 500.07	18 183.20	57 316.87	
B	73 551.64	16 821.20	56 730.44	−586.43
D	60 475.21	5079.30	55 395.91	−1920.96
E	127 925	9741.81	118 183.44	
F	123 638.60	4812.22	118 826.38	642.94

All figures in Euros.
Own calculations based on **?**.

The calculations, however, assume that power can be sold to and purchased from the EEX, which might not be possible in a real sub-system. Instead, purchase and sales prices of power might not be as volatile as the spot market price of electricity from EEX, and the financial result might look different.

3.8 Sensitivity assessment

Due to the complexity of the subject and the large number of variables that are part of the optimization, specific inputs to the model and the model itself were further analyzed. It was investigated what impact a variation of modeling inputs can have on modelling results, thus how sound the obtained results are.

The optimization algorithm of the model will find the least-cost operational state of the system, under consideration of the system's elements and connections as well as technical and economic boundary constraints (cf. section 2.1). Basically, different solvers are available and different optimization algorithms can be utilized. Even though such differences exist, the model's output should be merely identical. As long as the merit order, i.e. the order of usage of dispatchable units in the system, does not change, model results will be identical. Minor deviations, however, are expected to occur.

The resulting CO_2 emissions have been calculated on the basis of the production pattern, which again results from the economic operational optimization, the technology-specific CO_2 emissions factors and the plants' efficiencies (cf. equation 1). As long as the technology mix remains unchanged in the national and international power system, the resulting CO_2 emissions will be the same. Indeed the power plant stock undergoes a constant change. Scenarios of a future capacity development of the national and international stock of dispatchable power plants should therefore be taken into account in further simulations and analyses.

In the economic analysis, various parameters have been utilized that strongly affect the results. However, a change in a specific parameter throughout all modelled scenarios would change the model's outputs but the relation between the scenarios modelled would remain the same. For instance in the utilized interest rate would either increase or decrease the corresponding cost, however that would affect all scenarios in the same way. In case CAPEX of battery storage is assumed differently for one of the utilized technologies due to the wide range of CAPEX figures found in literature, the costs of the different scenarios might move closer together or apart.

3.9 Simulations IV: Further simulations

Besides the previously presented simulations further simulations and analyses were conducted with the simulation tool, the analysis tools and additional post-processing in order to further classify the obtained results.

3.9.1 Utilization of a different storage technology

While the presented scenarios included battery storage available to the sub-system, in further simulations it was researched what the impact would be if the same amount capacity was available with a storage technology other than batteries. In these scenarios, the input data of different storage options were assumed to correspond to the input data in the modelled scenarios. Other storage technologies, however, imply different efficiencies, which again affect cost (cf. **?**, **?**). Moreover the economic parameters, were found to differ from the calculations related to battery storage. In particular, the investment costs of other storage options were substantially lower than with batteries. In the analysis, pumped-hydro storage (PHS), diabatic compressed air energy storage (dCAES) and a future adiabatic compressed air energy storage (aCAES) were taken into account.

Technically, the same system behaviour as found in scenarios B, D and F (cf. section 3.5) was simulated. That also translates into the same amounts of induced or avoided CO_2 emissions. As now the total and annual costs were lower than in the cases previously presented, the resulting CO_2 abatement costs were lower, too.

In Table 3.14, investment costs and other parameters of different storage options according to **?** are listed. The CAPEX do not only differ between the technologies but for each technology a wide range of CAPEX was found. In the calculations mean values were utilized. Depending on the economic parameters and the expected service life, the annual cost can be substantially lower than the annual costs of battery storage.

Table 3.14: Cost parameters of other storage options

Technology	Specific CAPEX	Financial lifetime	Efficiency
PHS	260–560 €/kW	80 a	0.76
dCAES	220–340 €/kW	35 a	0.55
aCAES	380–620 €/kW	70 a	0.70

Source: **?**.

Table 3.15: CO_2 abatement cost of other storage options

Scenario Period	Technology	Costs €/t 20 a	Costs €/t 30 a	Costs €/t service life*
B	PHS	1345.54	897.03	336.38
B	dCAES	1269.76	846.51	725.58
B	aCAES	1666.09	1110.73	476.03
D	PHS	1258.72	839.15	314.68
D	dCAES	1270.14	846.76	725.80
D	aCAES	1782.09	1188.06	509.17
F	PHS	3417.71	2278.47	854.43
F	dCAES	3225.23	2150.15	1842.99
F	aCAES	4525.19	3016.79	1292.91

*) PHS: 70 a, dCAES: 35 a, aCAES: 70 a
Based on **?**, **?** and own assessment.

Due to the assumed same operational behaviour, the calculation of CO_2 abatement cost as presented in equation 2 is reduced to the difference in the annual cost (cf. Table 3.14). With the underlying data, CO_2 abatement costs as presented in Table 3.15 were obtained. For those scenarios in which storage was added – except for scenario C in which PV capacity was added, too – various variants were calculated: three further technology options, and for different periods of consideration. The latter is key when it comes to calculating the annual cost, thus annual CO_2 abatement costs. For the three additional technologies, their expected financial lifetime of 35–80 years was also utilized.

Not surprisingly, the longest period of consideration resulted in the lowest CO_2 abatement costs. They were found to be substantially lower than the CO_2 abatement costs calculated for battery storage. The cheapest option was found for scenario B with PHS expansion by the aforementioned capacity. With 542 Euros per ton CO_2 avoided, that option is just a share of the according scenarios with battery storage, however still costly in comparison with other power generation technologies.

Table 3.16: Sub-autonomous showcase scaled: CO_2 emissions

Scenario	CO_2 total	CO_2 delta*
B	428 063 612.01	85.67
C	428 057 745.94	−5780.40

All figures: annual balances in t. Negative values: net avoided CO_2 emissions.
*) Difference with the reference case I.
Based on own simulations.

3.9.2 Sub-autonomous showcase scaled

The Bordelum showcase was utilized as a blueprint for the modelling of further sub-automomous micro-grids within the national and international power system. As a first approximation it was assumed that the optimization, thus residual load curve of such other sub-systems would be identical with the one of the Bordelum showcase. It was assumed that the showcase is representative for the demand and production structure in Northern Germany. In practice indeed differences between villages can be found, this however also depends on the system boundary of the optimization. Therefore two of the previously presented scenario settings were assumed to exist tenfold in the German power system. The resulting CO_2 emissions of such scenarios were simulated then.

In the model the residual load curves as presented above could be scaled by a defined factor, i.e. factor 10. In order to automatically simulate such scenarios with the model, the `build.py` script was accordingly adjusted. When that script is executed, the scenarios as presented in section 3.4 are multiplied with a defined factor in order to generate the respective json files that are again required during the actual modelling using the `compute.py` script. To be more precise, the individual scenario's pre-processed timeseries data was multiplied with that factor. A summary of the respective results is presented in Table 3.16.

As expected, the multiplication of the showcase data resulted nearly in a multiplication of the totally induced or avoided CO_2 emissions. This can be explained with the input data involved: With a multiplication, the residual load patterns are scaled accordingly, inducing more (or less) power generation from dispatchable units in the overlaying power system. Their operation however is scaled just to a limited extent, i.e. within the available capacity and according to their marginal costs, and that is why the total CO_2 emissions in the different scenarios mainly depend on the (multiplied) residual load curves but also on the production mix from the dispatchable technologies.

3.9.3 Sub-autonomous systems across Germany

The simulations previously presented take a specific showcase into account (REF). A central question also is, however, what would happen if there were many of such 'optimized' systems across Germany, i.e. with different load and residual load patterns in contrast to section 3.9.2 in which the same conditions were assumed.

Sub-systems can differ a lot, i.e. in the number of loads and production elements they include, the demand patterns due to different consumers involved and production patterns due to location-specific conditions, and local battery storages. Due to the complexity of the task and the focus on the showcase scenarios and analyses, that issue is dealt with in a qualitative manner.

Generally speaking, the big picture would not change from the findings of the showcase previously presented. In all cases, a local battery storage will behave sub-optimal in comparison with their utilization in the entire power system. Their role, however, might differ from sub-system to sub-system, depending on all the input parameters and, moreover, on the grid connections. A distribution of such sub-systems across Germany is expected to smoothen the effects a multiplied showcase system would have, due to various reasons. Most important is the fact that meteorological conditions differ between locations and that is why the production patterns from RES differ. The residual load curves of the sub-systems therefore can be expected to differ, too, leading to regional balancing. This, again, strongly depends on the exact system specifications.

4 Conclusions and further research direction

In this section, conclusions are drawn and the simulations results are further analyzed. Even though the modelling results have shown a clear impact of an isolated or an integrated approach of storage options in local or national power systems, further research should substantiate findings and tackle further questions that arise.

4.1 Conclusions

As previously shown, there are several dimensions to be taken into account when it comes to evaluating whether a sub-system is supportive to or opposing its overlaying power system. The method applied has shown itself as reasonable and working. Moreover, all input data to the model and the individual scenarios can be regarded as sound.

While from a local perspective it might make sense to reduce positive or negative peaks in order to reduce the electricity bill, the system perspective can come to completely different conclusions.

From a technical point of view it might make sense to increase the level of self-sufficiency, for various reasons. In the sub-system this results in a lower amount of power required to be purchased from the overlaying system. In the overlaying system it might be technically helpful to, for instance, reduce the power consumption at night (due to the use of batteries), thus increase the sub-systems support towards the overlaying power system.

The simulations result have clearly shown that a local optimization of a sub-system does not reduce CO_2 emissions as much as if the same storage options were available to the entire power system. In the scenarios presented, a local optimization even led to an increase of the total system's CO_2 emissions, resulting from a lower demand mainly at night provided from the battery storage and simultaneously a lower RES production during the day, when the battery would be charged. If the reduced RES production meets a different production mix than the reduced local demand, a delta of positive and negative CO_2 emissions results. A local optimization will always be sub-optimal within the entire power system.

The results however also show that the impact of a sub-system on a country's CO_2 emissions can be larger than on the entire system's CO_2 emissions. That can for instance be detected in scenario B in the integrated approach: while in the scenario a total amount of 7 t of CO_2 are avoided in relation to the reference case, in specific countries the national CO_2 emissions reductions are higher (e.g. France: 8 kt) and in others CO_2 emissions can even increase (e.g. Belgium: 0.2 kt). This is a result of the optimization and highlights that a system's subset might act differently from the total system.

In any case, additional storage will be used best if integrated in the entire system. If necessary, such storage will be charged or discharged, based on its technical characteristics and on the general condition in the system, i.e. storages need to be centrally dispatched. The net balance of additional CO_2 emissions – for instance, during the day when the battery is charged instead – and avoided CO_2 emissions – for instance at night when the battery is discharged – will always be negative, i.e. CO_2 emissions will be avoided because the optimization algorithm seeks to find the cost-optimum, which will include by tendency more cheap RES production than other possible solutions.

As presented, not only the absolute amount of CO_2 emissions is crucial for a comparison but its relation to the induced cost e.g. for battery storages are helpful to relate different options to each other and to other CO_2 emissions reduction measures.

From the simulations and their results it can be concluded:

- Even though an integrated approach reaches the least CO_2 emissions, differences between scenarios can be detected. The exact CO_2 emissions reduction will depend on the size and the characteristics of the battery integrated.

- The scenario setting with a centralized battery storage reaches the largest CO_2 emissions reduction if the integrated approach is related to the isolated approach.

- For any case, the entire power system is key for the results gained with the simulations. Changes in the stock of power plants, their efficiencies, the annual demand, the demand profile and in further parameters such as operational or fuel cost can lead to different results. However, the big picture will not change: the least-cost solution will always be found if the additional storage option is available to the entire system.

- If a centrally dispatchable storage technology is to be included in the national power system, other options such as PHS and CAES tend to be cheaper than battery storage.

From those techno-economic results it can be concluded that, in order to make best use of storage options in the power system, incentives should be developed and introduced and business models are required that would allow a battery owner to operate his or her battery storage not only beneficial to the entire system but also economically attractively. For instance, flexibility premiums for available battery capacity should be further investigated. A utilization behaviour of batteries that supports the overlaying power system will basically economically reasonable.

For specific cases a local utilization of local storage options might make sense in case the connection with the overlaying power system is not sufficient for an integrated use of all resources. A local optimization might even help a local system to fully cover its load at all times and to make best use of its power generation from volatile RES. However, this local optimization actually competes with the option of a bigger or a new link to the overlaying power system. Only such a comparison would indeed be fair. In case such a reinforcement of the systems' connection is unrealistic – e.g. for environmental or economic reasons –, the local optimization might act as a solution. If such a reinforcement of the systems' connection is feasible, the options need to be compared e.g. from an economic point of view. This, however, is dependent on the individual case and cannot be generalized.

In the current state of the simulation model, potential energetic losses in the transmission grid have not been taken into account. Their consideration, however, would also affect model results. On the one hand, such losses would need to be replaced by additional dispatchable production, on the other hand a local sub-system might act more beneficial in the region it is located in if such transmission losses could be avoided.

The simulation of the different scenarios and the assessment of the sub-system's residual load curve in relation to the overlaying power system's load curve reveals that there is a discrepancy between the isolated and the integrated approach. While the isolated approach might make sense from a micro-view's perspective, the integrated approach appears to be more meaningful from a system perspective.

It must be emphasized, however, that a setting of a system that might appear similar to the described showcase can have different results. A change in the demand pattern or in the renewable resource, for instance, can lead to a different pattern of the residual load curve of the sub-system, which again will affect the system benefit towards the overlaying system. On the other hand, a setting of the sub-system that reduces the positive residual load of the sub-system at night and only delivers power surpluses around midday – which presumably is the case in a sub-system consisting of mainly household demand and solar PV plants – will lead to rather similar results as presented here.

4.2 Transferability of results

In the carpeDIEM research project, a specific showcase was selected for the different kinds of scenario simulations. The inputs to the particular scenarios, thus their outpus therefore only represent a minor share of the entire national and international power system.

The modelling results, however, can basically be transferred to other locations. This refers to other locations not only in Germany but also in Denmark and elsewhere. As in the showcase selected, it is necessary to specify another or an additional sub-system of the entire power system, with all its loads, the load profile, the producing side and the producing sequences, accompanied by additional storage options.

In any case, the showcases results are transferable to other locations simply by a more general perspective. An additional storage will always be most beneficial to the entire system in terms of avoided CO_2 emissions if it is available to the entire system. That means that an integrated utilization of additional storages will always lead to a higher system benefit than an isolated approach.

This can be explained with the following thought experiment: the optimization of the local sub-system results in a local residual load curve that reduces the total system's CO_2 emissions even further than the same additional storage available to the entire system would:
Such a scenario is indeed impossible. The integrated approach basically can result in a number of possible settings out of which one is the best. The isolated approach actually is a subset of the integrated approach.

There is one presumably rare occasion in which the optimized sub-system can reach the same amount of avoided CO_2 emissions as the integrated approach. In that case the local residual load curve affects the entire system in a similar way as an additional storage in the entire system would do. Even if that is possible the question would remain why the optimization should take place at the local level and not in the entire system.

4.3 Further research direction

Even though the methodology has proved itself as successful and the modelling results have shown themselves as meaningful, further research is required in order to deal with further related questions. In the following list, some of the issues additionally to be investigated are drafted.

- Further scenarios of other showcases with different demand levels, demand patterns, different producing elements and at different locations will allow to deduce what local system setting can be optimized best at the local level, if that is required.

- Limitations in the existing transmission grid might raise the question how to still best use the available local resource if e.g. local power surpluses cannot be transferred into the overlaying power system. Instead of curtailing RES power plants it might make sense to store the produced electricity locally and use it later. That of course is also a matter of the framing legislative and economic conditions.
- Besides additional scenarios it can be helpful to assess sensitivities of specific inputs to the model. For instance, variations in cost assumptions will affect the utilization pattern of dispatchable units and therefore modelling results.
- Both additional scenarios and sensitivities of input parameters will be of interest when it comes to model a future system setting, e.g. for the year 2050 or other, when the power plant stock in the overlaying system has substantially changed from a fuel-based system to an RES-based system in which storages will play a different role from what they do today.
- As any model, the energy system simulation model is an approximation to reality that can always be improved. A Further development of the model and its input data to the scenarios can improve modelling results. Such potential improvements, however, will not substantially change the model's outputs and results from the analysis presented in this report.
- The power sector alone is facing a lot of challenges and questions already. It is and it will increasingly be of need to regard the power sector not in an isolated fashion but integrated with other sectors such as the heat sector and the transportation sector. Different storage options might play a key role in the future, e.g. power-to-x. A local optimization taking such other dimensions into account can help find solutions for making use of potential excess power at the local level, to build bridges between the sectors, and to create new business models.

Appendix

Tables

Table A1: Residual load assessment (sub-system vs. the load of the German power system)

System setting (sub-system)	negative	neutral	positive
A	5429	126	3205
B	5577	120	3063
C	5079	210	3471
D	1446	4554	2760
E	2353	227	6180
F	1110	1725	5925
G	0	0	8760

All values: hours per year.

Source: Based on **?** and own simulations.

Table A2: Residual load assessment (sub-system vs. 1st degree residual load of the German power system)

System setting (sub-system)	negative	neutral	positive
A	5429	126	3205
B	5577	120	3063
C	5079	210	3471
D	1446	4554	2760
E	2353	227	6180
F	1110	1725	5925
G	0	0	8760

All values: hours per year.

Source: Based on **?** and own simulations.

Table A3: Residual load assessment (sub-system vs. 2nd degree residual load of the German power system)

System setting (sub-system)	negative	neutral	positive
A	3756	126	4878
B	3773	120	4867
C	3686	210	4864
D	1581	4554	2625
E	4945	227	3588
F	3998	1725	3037
G	4701	0	4059

All values: hours per year.
Source: Based on **?** and own simulations.

Table A4: Residual load assessment (sub-system vs. 3rd degree residual load of the German power system)

System setting (sub-system)	negative	neutral	positive
A	4076	126	4558
B	4030	120	4610
C	4153	210	4397
D	2413	4554	1793
E	5216	227	3317
F	4618	1725	2417
G	6120	0	2640

All values: hours per year.
Source: Based on **?** and own simulations.

Table A5: Residual load assessment (sub-system vs. 4^{th} degree residual load of the German power system)

System setting (sub-system)	negative	neutral	positive
A	4114	0	4646
B	4068	0	4692
C	4222	0	4538
D	2421	4542	1797
E	5241	0	3519
F	4601	1664	2495
G	6130	0	2630

All values: hours per year.
Source: Based on **?** and own simulations.

Table A6: Residual load assessment (sub-system vs. the load of the European power system)

System setting (sub-system)	negative	neutral	positive
A	5429	126	3205
B	5577	120	3063
C	5079	210	3471
D	1446	4554	2760
E	2353	227	6180
F	1110	1725	5925
G	0	0	8760

All values: hours per year.
Based on **?** and own simulations.

Table A7: Residual load assessment (sub-system vs. 1^{st} degree residual load of the European power system)

System setting (sub-system)	negative	neutral	positive
A	5429	126	3205
B	5577	120	3063
C	5079	210	3471
D	1446	4554	2760
E	2353	227	6180
F	1110	1725	5925
G	0	0	8760

All values: hours per year.
Based on **?** and own simulations.

Table A8: Residual load assessment (sub-system vs. 2nd degree residual load of the European power system)

System setting (sub-system)	negative	neutral	positive
A	3264	0	5496
B	3172	0	5588
C	3444	0	5316
D	2356	4542	1862
E	5687	0	3073
F	5164	1664	1932
G	7439	0	1321

All values: hours per year.
Based on **?** and own simulations.

Table A9: Residual load assessment (sub-system vs. 3rd degree residual load of the European power system)

System setting (sub-system)	negative	neutral	positive
A	4170	126	4464
B	4171	120	4469
C	4127	210	4423
D	2145	4554	2061
E	4515	227	4018
F	3753	1725	3282
G	4666	0	4094

All values: hours per year.
Based on **?** and own simulations.

Table A10: Residual load assessment (sub-system vs. 4^{th} degree residual load of the European power system)

System setting (sub-system)	negative	neutral	positive
A	4301	0	4459
B	4299	0	4461
C	4309	0	4451
D	2212	4542	2006
E	4619	0	4141
F	3796	1664	3300
G	4691	0	4069

All values: hours per year.
Based on **?** and own simulations.

Table A11: Induced and avoided direct CO_2 emissions: Absolute values

	I	II							III			
Country		A	B	C	D	E	F	G	A	B	C	F
AT	7 077 518	7 078 701	7 325 038	7 311 546	7 075 416	7 318 672	7 068 422	7 317 454	7 065 500	7 348 392	7 089 554	7 352 448
BE	3 741 541	3 741 890	3 741 890	3 742 030	3 741 729	3 741 890	3 741 729	3 742 030	3 741 729	3 741 540	3 741 729	3 741 541
CH	0	0	0	0	0	0	0	0	0	0	0	
CZ	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136	31 726 136
DE	264 139 877	264 139 877	264 139 881	264 139 534	264 139 916	264 139 877	264 139 887	264 140 006	264 139 873	264 139 502	264 139 851	264 139 875
DK	452 280	448 876	449 066	448 624	452 532	449 290	452 403	448 625	452 394	449 410	452 172	449 008
FR	1 739 074	1 729 671	1 730 375	1 732 680	1 736 714	1 730 566	1 734 628	1 733 348	1 737 629	1 731 112	1 725 980	1 733 327
LU	528 913	517 951	497 428	501 250	534 976	501 547	534 305	492 102	534 912	470 154	539 808	474 892
NL	27 312 981	27 348 934	27 120 926	27 126 081	27 310 495	27 123 253	27 320 070	27 131 089	27 319 422	27 123 302	27 303 372	27 113 100
NO	0	0	0	0	0	0	0	0	0	0	0	
PL	91 345 169	91 331 453	91 332 757	91 335 029	91 345 619	91 332 258	91 345 915	91 332 875	91 345 886	91 333 305	91 344 838	91 333 158
SE	38	38	38	38	38	38	38	38	38	38	38	38
Total	428 063 526	428 063 526	428 063 535	428 062 948	428 063 571	428 063 526	428 063 533	428 063 703	428 063 519	428 062 890	428 063 478	428 063 522
Delta*			9		45		7		−7		−48	−5
Delta**									−16	−58	−93	−12

All figures: annual balances in t. Negative values: net avoided CO_2 emissions.

*) Difference with the reference case of the same main category (integrated approach and isolated approach, respectively). **) Difference between the integrated and the isolated approach.

Source: Own simulations.

Figures

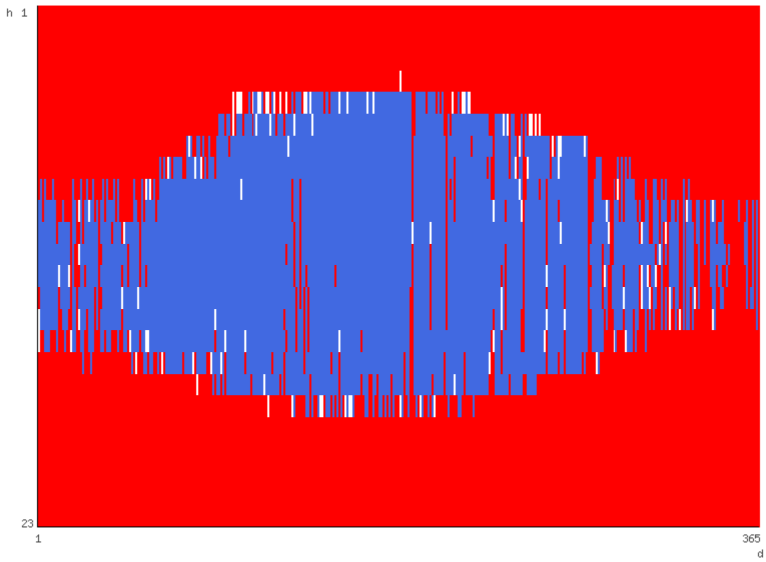

Figure A1: Exemplary heatmap: Scenario A, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

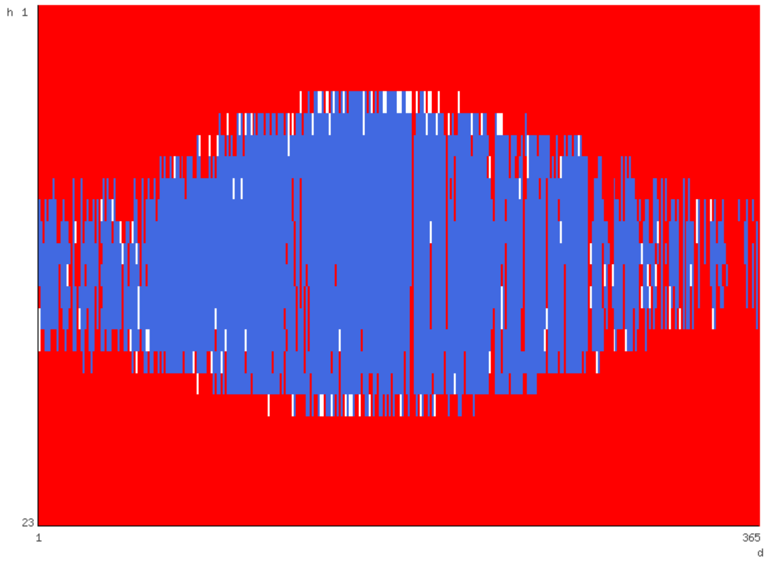

Figure A2: Exemplary heatmap: Scenario B, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

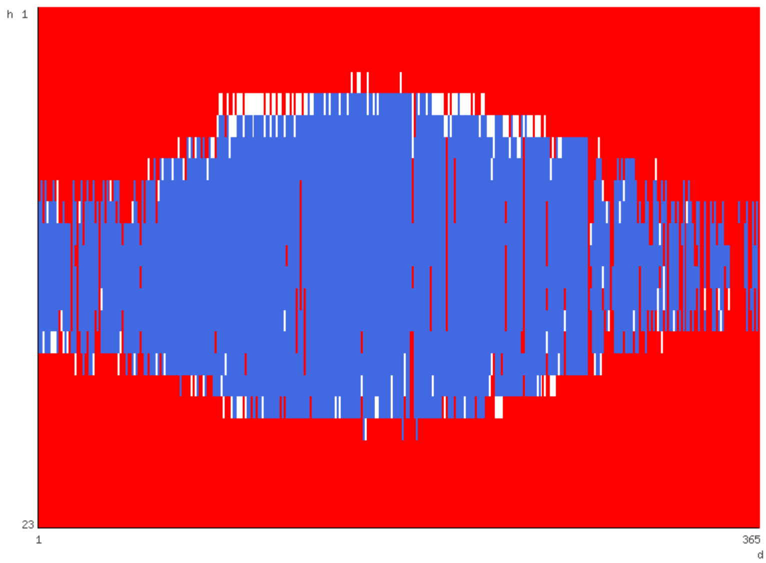

Figure A3: Exemplary heatmap: Scenario C, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

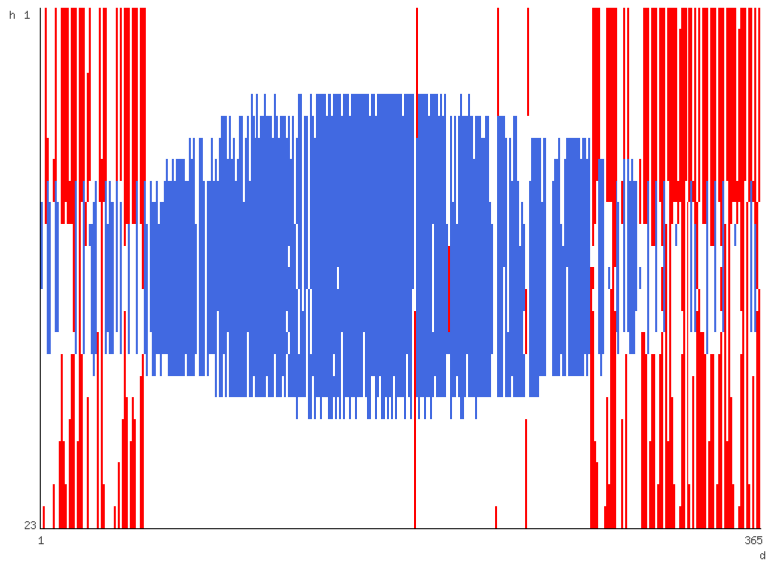

Figure A4: Exemplary heatmap: Scenario D, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

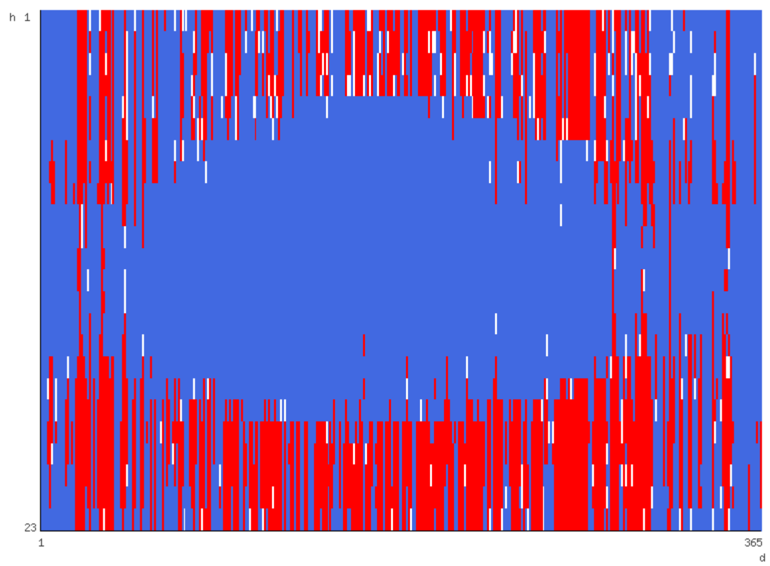

Figure A5: Exemplary heatmap: Scenario E, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

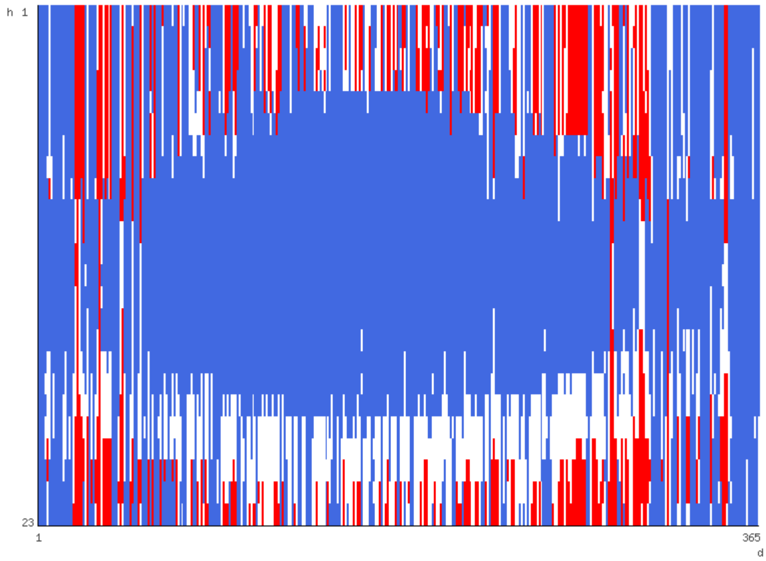

Figure A6: Exemplary heatmap: Scenario F, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.

Figure A7: Exemplary heatmap: Scenario G, 1st degree residual load of the European* system
*) understood as Germany plus its electrical neighbours
Illustration based on own simulations.