This work was submitted to the
Institute for High Voltage Equipment and Grids, Digitalization and Energy Economics

Integrating flexibility and characteristics of active distribution grids into a large-scale European multi-energy system model

Integration der Flexibilität und Charakteristika aktiver Verteilnetze in ein europäisches Multi-Energie-Systemmodell

Master's thesis

by

Mr. Steffen Kortmann

1st Examiner:	Univ.-Prof. Dr. sc. ETH Andreas Ulbig
2nd Examiner:	Univ.-Prof. Dr.-Ing. Albert Moser
Supervisor:	Luis Böttcher, M. Sc.
	Julian Saat, M. Sc.
	Henrik Schwaeppe, M. Sc.

Aachen, 30. September 2022

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Kortmann Steffen**	Personal ID number:	**495481**
Faculty / Institute:	**Faculty of Electrical Engineering**		
Department / Institute:	**Department of Economics, Management and Humanities**		
Study program:	**Electrical Engineering, Power Engineering and Management**		
Specialisation:	**Management of Power Engineering and Electrotechnics**		

II. Master's thesis details

Master's thesis title in English:

Active distribution grids in European large-scale Multi Energy System Model

Master's thesis title in Czech:

Active distribution grids in European large-scale Multi Energy System Model

Guidelines:

- Integration of distribution grids (DG) into Multi energy system (MES) modelling framework
- Modelling on aggregated level of DG network constraints under different DG operation schemes
- Techno-economic analysis (DG impacts on flexibility and transport needs as well as distribution and transmission grid expansion needs for different scenarios)

Bibliography / sources:

[1] Multi-Horizon Planning of Multi-Energy Systems - T. Felling; O. Levers; P. Fortenbacher (Amprion GmbH) - Power Systems Computation Conference (PSCC), 2022, Porto, Portugal
[2] Reduced and Aggregated Distribution Grid Representations Approximated by Polyhedral Sets - P. Fortenbacher; T. Demiray (Research Center for Energy Networks, ETH Zürich) - not published yet
[3] Determination of the Time-Dependent Flexibility of Active Distribution Networks to Control Their TSO-DSO Interconnection Power Flow - D. Mayorga Gonzalez; J. Hachenberger; J. Hinker; F. Rewald; U. Häger; C. Rehtanz; J. Myrzik (TU Dortmund) - Power Systems Computation Conference (PSCC), 2022, Dublin, Ireland

Name and workplace of master's thesis supervisor:

M.Sc. Luis Böttcher   RWTH Aachen

Name and workplace of second master's thesis supervisor or consultant:

Tim Felling, Ph.D.   Amprion GmbH

Date of master's thesis assignment: **24.03.2022**   Deadline for master's thesis submission: ___________

Assignment valid until: **19.02.2024**

M.Sc. Luis Böttcher Supervisor's signature	Head of department's signature	prof. Mgr. Petr Páta, Ph.D. Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

.	
Date of assignment receipt	Student's signature

Statutory Declaration in Lieu of an Oath

Kortmann, Steffen — 357919

Name, First Name — Matriculation Number

I hereby declare in lieu of an oath that I have completed the present Master's thesis entitled

Integrating flexibility and characteristics of active distribution grids into a large-scale European multi-energy system model

independently and without illegitimate assistance from third parties (such as academic ghostwriters). I have used no other than the specified sources and aids. In case that the thesis is additionally submitted in an electronic format, I declare that the written and electronic versions are fully identical. The thesis has not been submitted to any examination body in this, or similar, form.

Aachen, 30. September 2022

City, Date — Signature

Official Notification:

Para. 156 StGB (German Criminal Code): False Statutory Declarations
Whoever before a public authority competent to administer statutory declarations falsely makes such a declaration or falsely testifies while referring to such a declaration shall be liable to imprisonment not exceeding three years or a fine.

Para. 161 StGB (German Criminal Code): False Statutory Declarations Due to Negligence
(1) If a person commits one of the offences listed in sections 154 through156 negligently the penalty shall be imprisonment not exceeding one year or a fine. (2) The offender shall be exempt from liability if he or she corrects their false testimony in time. The provisions of section 158 (2) and (3) shall apply accordingly.

I have read and understood the above official notification:

Aachen, 30. September 2022

City, Date — Signature

Abstract

Planning of infrastructure is rather a matter of decades than years. Thus, even though the target years 2045+ seem far away, it is of significant importance to start planning the energy transition to a carbon emission free system today. In addition, new required technologies still need time for technical development until they are ready for the market. The key to zero emissions across all energy sectors in 2045+ lays in the reduction of the final energy consumption while increasing the share of electricity of the primary energy sources, as most of the renewable energy sources (RES), mainly photovoltaic (PV) and wind, provide electricity. As their infeed is highly fluctuating, an interlinked energy system will enable to better cope with flexibility and even store surplus energy over a longer period of time, e.g. by linking the power system to hydrogen, heat or gas system. In response, this helps to decarbonize these sectors. Hence, the individual sectors should no longer be considered on their own but rather together in an integrated manner. In consequence, expansions of energy infrastructures such as gas pipelines or power transmission lines need to be planned on an integrated level to outweigh their overall value across the interlinked sectors. In sum, this imposes the need for multi-energy system (MES) models that capture the interactions between several energy carriers and are able to plan the composition of the future energy system. Planning over the entire transition pathway requires special attention on the model choice as the value of infrastructures can only be assessed by models that run on high temporal and spatial resolutions. In addition, a yearly dispatch horizon is required to quantify the impacts on seasonal variations. Altogether, this requires to solve large-scale optimization problems. Therefore, it is crucial to bring their computational complexity to a manageable level by finding tractable formulations.

Contents

List of Figures

List of Tables

List of Abbreviations

CLC CORINE land cover

GDP Gross domestic product

DSO Distribution system operator

FOR Feasible operation region

openmod open energy modelling initiative

MES Multi-energy system

OP Optimisation problem

FOR Feasible operation region

DER Distributed energy resources

PV Photovoltaic

HP Heat pump

IPF Interconnection power flow

DAC Direct air capture

RES Renewable energy sources

1 Introduction

1.1 Background and motivation

The future energy system must be renewable, and long-term planning toward this helps determine a cost-optimal path. In this context, the sectors, which have often been considered separately from each other up to now, must be thought of more coherently, as they offer the possibility of flexibility. The paradigm shift requires this flexibility from mechanically and deterministically operated power plants to digital and stochastically driven decentralised generation plants. These plants, powered mainly by renewable energies, are subject to the fluctuations of wind and sun and are thus dependent on the supply. If the primary energy fails to materialise, the secondary energy also fails to materialise, primarily electricity. However, other sectors also drive electrification, such as heat and transport. In the case of heat, this is possible through heat pumps, which can provide thermal energy with the help of electrical energy. In transport, mechanical energy can be converted from electrical energy. At the same time, these two sectors offer an excellent advantage for the future energy system because they can store energy on a large scale. This means that at a time when there is a surplus of energy, it can be used for a later time and stored again later. This form of temporal transfer of energy enables the system to be flexible. Flexibility can also mean that energy is not used at one point, and its use is postponed later.

In addition to all these aspects, one thing that usually comes to light is that most of these processes occur at the distribution level and not at the transmission level. In large-scale multi-energy system analyses, however, only the transmission grid is usually considered, while the distribution grid usually receives little attention. This must change in order to understand all processes. A large-scale aggregation could reduce inaccuracies.

Figure 1.1 presents a graphical abstract of the work and should indicate the methodology used within this work. The basic idea is to incorporate distribution grids into large-scale multi-energy systems by exploiting flexibility.

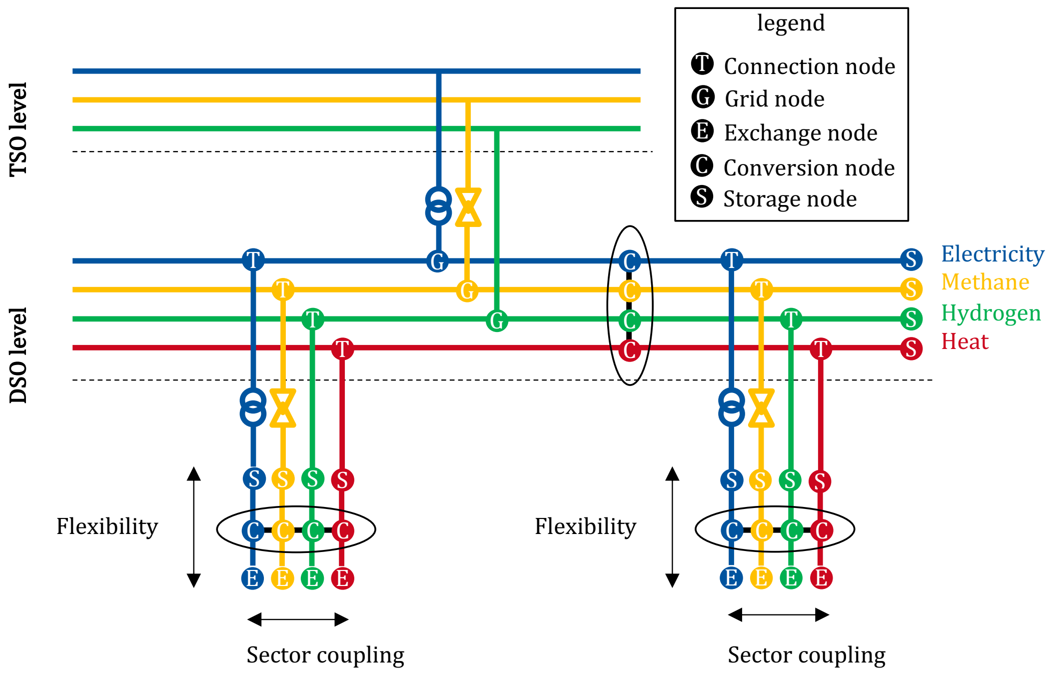


Figure 1.1: Integrating flexibility from distribution grids into a large-scale European multi-energy system model

1.2 Current point in literature

The current point in literature stands manifold in active development for more accurate multi-energy systems. Current challenges were identified by [FOD22], among others, spatial-temporal resolution, uncertainty and sector coupling. In [KRI18], further challenges included the modelling structure's data coverage and formulation details. Here, Multi-energy system (MES) were identified as grid-based, meaning that the flow patterns have to be considered. The classification of MES was done in [PRI20].

Building an integrated multi-energy flow calculation method for the three sectors electricity-gas-thermal is considered in [ZHU21], deriving necessary mathematical formulations to be considered in the optimisation problem. However, this paper includes the non-linear formulation for the electric power flow equations, which would supersede current computational power for large-scale systems. In [WU19], this approach was applied to large-scale systems. Further explanations are justified in [CAO21]. The optimal operation of multi-energy systems is further explained in [NAZ21], leading to an advanced formulation of the limitations of other energy sectors. These definitions are also proposed in a general form for a MILP optimisation framework specially designed for multi-energy hubs [GÖT19]. The general formulation of energy hubs was first proposed by Geidl [GEI07]. Handling complexity in multi-energy system analysis and using justified simplifications is considered in [KOT21]. This led to a study conducted at our IAEW research institute at RWTH Aachen University [SCH22].

The integration of distribution grids into a multi-energy system has only a little research been conducted yet. Therefore this is still an undiscovered topic. Here, the work of Müller [MÜL19] provided insights and gave the indication to use only a limited number of representative distribution grids to indicate the total sample. It was also one of the earlier studies that incorporated transmission and distribution system expansion planning, considering the flexibility of the Distribution system operator (DSO). A comparable study was done at TU Munich [REV22], that also included distribution systems in their Optimisation problem (OP). Both studies reconsider the entire topology of the distribution grids and include them in the OP. This approach seemed reasonably hard to solve, considering that during this work, the inclusion of all European distribution grids was considered. A concept to approximate the grid limits of distribution grids as proposed as the FOR.

The FOR is a concept not novel but following the early developments that synchronous generators are described via their constraints, e.g. forming almost a half circle. This conception can be brought to a more significant number of generators, not just synchronous ones. The general form of the FOR is described as non-convex and non-linear but can also be derived from linearised approximations for the power flow equation [FOR19], which was one of the foundations of this work. Furthermore, this model was extended to capture all non-linearities and as a description of not just the feasible set of these equations but as the flexible potential that could be added from the distribution grids [SAV20]. An exhaustive study of all the methods to derive the FOR can be found in [CON21]. The idea was to transform the grid limits into linear constraints that would limit the possible power exchange between the transmission and distribution system.

1.3 Object of research

The objective of this master thesis is two-fold. First, several methods should be developed to integrate DGs in the MES modelling framework PyPSA. Several effects, such as DG network constraints (voltage and thermal line constraints) under different DG operation schemes, including aggregator, DSO, and individual prosumer perspectives, should be modelled on an aggregated level. Second, a techno-economic analysis shall be carried out analysing DG impacts on flexibility and transport needs as well as distribution and transmission grid expansion needs for different scenarios in the presence of a highly integrated European energy system.

Research question

Given the future need for flexibility in multi-energy systems, it seems urgent to capture the interlinking of different sectors in adequate models. Considering that most of these technologies are installed in the distribution grid, it is essential to include them in multi-energy systems' formulation.

Therefore, the central research question is: **How to integrate grid characteristics of active distribution grids into large-scale multi-energy systems?**

The proposed workflow will be as follows:

1. Derive feasible solution space of the non-linear optimal power flow in distribution grids,
2. Propose a set of distribution grids that are representative of Europe from a benchmark dataset,
3. Implement flexibility providing units in the multi-energy system and characterise their usage,
4. Quantify the impact of modelling distribution grids from both the increased system size and higher information quantity.

1.4 Aim and structure of work

First, the analysis discusses the basic principles of multi-energy system analysis and elaborates on the need to conduct such intensive studies to determine cost-optimal expansion paths for a target period. Subsequently, the solution set of distribution grids is determined, which will later be used as a constraint in the optimisation problem. This solution set describes a non-convex and non-linear solution space that describes the power exchange between the distribution and transmission grid. The solution space can be described here as a two-dimensional surface related to the slack node's active and reactive power.

In the method, we will go into more detail about how we proceeded in this work and which steps were necessary to be able to answer the research question. This is not based on the framework used but is formulated independently, which means that other tools could also be used to calculate the system. In particular, it is discussed how it is possible to include distribution networks as simple constraints in the optimisation problem. Furthermore, unique technologies that can provide flexibility are also presented here.

The framework will first be introduced in the results and exemplary investigations, and the results will be presented and analysed. These are to be derived in terms of their significance, whether the integration of distribution networks in optimisation problems leads to an added value in terms of information or whether this merely increases the problem size and the optimal result is otherwise the same.

In the last part, the most critical findings from this work are summarised again and presented. Furthermore, an outlook is given, which is intended to point out possible further points of analysis and also describes further work steps that were not part of this work. Furthermore, it will be explained whether the inclusion of distribution grids in the large-scale planning of European energy systems could play an important role or whether it significantly increases the overall problem.

2 Analysis

The remainder of the analysis is structured as follows (2.1) deals with multi-energy systems, whereas (2.2) is about active distribution grids.

2.1 Multi-energy systems

Forming multi-energy systems aims to further integrate renewable energy sources across multiple energy carriers (e.g. electricity, heating/cooling, gas and transport) to reduce the emission of carbon dioxide (CO_2). Low-carbon technologies (e.g. wind or solar power) are mainly operated to generate electricity. However, there are situations in which generation exceeds demand. In order to prevail curtailment, energy is transferred via conversion technologies from one carrier to another, which can be described as flexibility [CHI20]. Therefore it is necessary to further include individual sectors in a system-wide analysis in an integrated manner. The expansion of the infrastructure of one energy carrier, e.g. electricity, can directly influence the expansion planning from another, e.g. gas. In an integrated, optimised system, the interlinking of sectors can reduce the overall system cost. As all energy vectors, e.g. electricity, heat, gas or transport, are infrastructure dependent and therefore rely on physical networks that connect supply with demand, they can be referred to as grid-based MES [KRI18]. An integrated energy system enables flexibility better to exploit volatile RES with the existing grid infrastructures.

Challenges

The formulation of a multi-energy system is not trivial and demands profound knowledge of the interaction between the different carriers, e.g. the conversion from one to another by sector-coupling technologies. Furthermore, the level of detail is of high interest, e.g. in the dimension time and space [FOD22]. Renewable energy can vary in time and space, as not all regions across Europe are in an advantageous position to employ large-scale solar or wind power. Whereas countries in the south benefit from solar, coastal countries mainly integrate wind power in their systems and hydropower as a steady load. The overall European system could therefore benefit from the exchange. Nevertheless, this is limited by the given grid infrastructure. Gird congestion and network bottlenecks are further limiting this exchange. With rising importance, the questions for a higher level of spatial detail are required to consider the economic potential and generation costs depending on a given location. The intermittent nature of renewable energy can also be leveraged using a more balanced spatial distribution.

System boundaries

In order to describe the entire system, it is, therefore, necessary to balance all system boundaries adequately and to include them in the optimisation problem. It is vital to ensure that all energy sources are comprehensively defined, with their costs and based on further limits, such as the maximum expansion rates. In this work, the secondary energy sources are chosen as the system boundary, so there is no consideration of the extraction or production of the primary energy sources.

Flexibility

In future power systems, there is an increased need for flexibility. First, a definition can be found as

Definition 2.1.1 *Flexibility can generally be seen as a system's ability to provide secure and economic supply-demand balance across spatial and temporal scales by leveraging and seamlessly coordinating various controllable assets [CHI20].*

Flexibility, therefore, also describes the ability of the system to find the optimal cost operation of a system. It is employed by interlinking different energy vectors combined and linked via converter and networks. Defining a flexible system with an increasing share of renewable energy is essential.

Spatial scope

The spatial resolution of an energy system model describes the number and shape of the spatial units, e.g. administrative boundaries, used in the model [SIA20]. The challenge in multi-energy systems' spatial resolution is finding a balance between data availability and computational tractability. Data availability varies from high spatial resolution or rasterised distributed information to aggregated and country-based energy data. Models can typically distinguish between bottom-up, and top-down approaches [PRI20]. Top-down models typically only capture a simplified representation of the complexity of energy systems and are not suitable to capture all interactions in an integrated multi-energy system but are instead used for policymakers. Traditionally, the captured aggregated regions, e.g. countries, and a small time frame, e.g. one day, to keep the computation requirements within limits. These models were suitable in a system where most of the load was supplied by dispatchable power generation, but these simplifications hold no longer true with a rising share of renewable energy. In opposition are bottom-up models, which aim to get a complete image with detailed insight from a techno-economic point of view. Sector-coupling can be better interrogated, and cost-optimal pathways to reach an objective, e.g. minimal system cost or emission reduction. However, increasing size makes these models take longer to execute and are not as resilient. Therefore it is

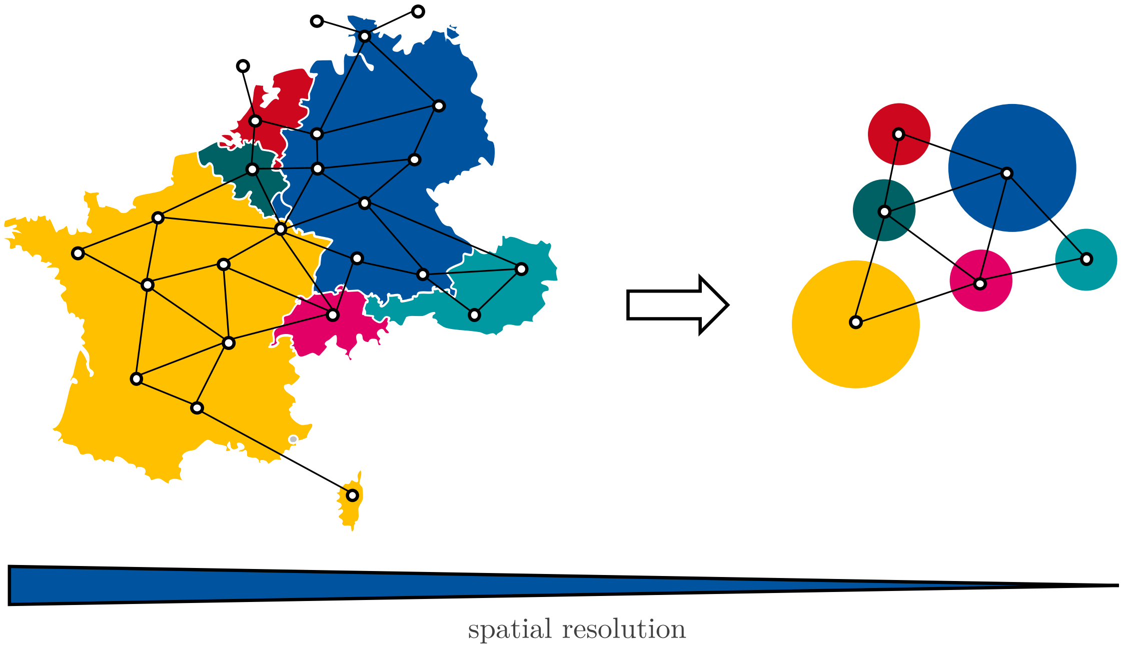


Figure 2.1: Spatial complexity reduction from many nodes to one-node-per-country

a modeller's choice to pick all necessary information while keeping the computational effort tractable.

Multi-energy systems are a particular challenge regarding spatial resolution, as different energy carriers have to be modelled here with a different spatial scale. On the one hand, the demand for transport and heat is centred on one point and can only be met economically on site; here, it comes to considering individual buildings or at the neighbourhood level. However, modelling all energy sources on such a large spatial resolution would pose too significant an optimisation problem, apart from the fact that no data are available, to begin with. Thus, an adequate model can only be set up with a different choice of spatial resolution, and it is incumbent on the modelling to offer flexibility in this respect.

Temporal scope

Integrating temporal resolutions in multi-energy systems defines the same trade-off challenges mentioned earlier. On the one hand, models with a more acceptable temporal resolution will lead to a more in-depth knowledge of technological characteristics. On the other hand, they are much harder to solve and are impracticable for many variations and running several scenarios simultaneously.

Nevertheless, it bears an essential characteristic of the model, as, for example, seasonal storage can only be considered if a time frame of at least one year is chosen, whereas the frequency may remain low with only four time steps (6 hours) per day to compute. The contrary is battery storage, as they would need a higher frequency of one to two hours because otherwise, the changes in the state of charge cannot be considered. In general, the time frame and frequency for simulation can be chosen depending on the inter-temporal constraints within the model that will be considered. Notice that ramp limits or blocking times also possess inter-temporal linking of constraints and not just storage technologies. Hence, this challenge is answered depending on the technologies used in the model.

Network perspective

Sector-coupling occurs through energy networks that carry energy vectors, such as electricity, gas, and heat at different enthalpy levels, e.g. steam or hot water and cooling. Energy networks can thus enable optimal management of multi-energy resource portfolios on the one hand and introduce further complexity in the system operational and planning analysis on the other hand, for instance, relevant to what energy network type is most appropriate in a given MES context.

For a power system, the voltage level of the grid serves as a criterion to select the relevant lines at a given scale: whereas only lines above 220 kV are usually modelled at a European scale to define the power system, the voltage levels below are primarily not included. Hence, the level of detail varies with the scale of the system. For smaller regions, mostly one or two voltage levels are included.

Open source energy systems modelling

One particular driver in the space of energy system modelling was undoubtedly the publication of models as open source. The insight into modelling and setting up environments for analysis was one key that enabled researchers to step into this topic. However, the consideration is not just on the model itself but also other driving forces such as toolboxes or open data. While the first denotes smaller programMES that could run as standalone but are also highly regarded in energy system modelling for such purposes as deriving renewable energy feed-in profiles or for geometric operations. The second is also of urgent importance, as data is needed to input into models.

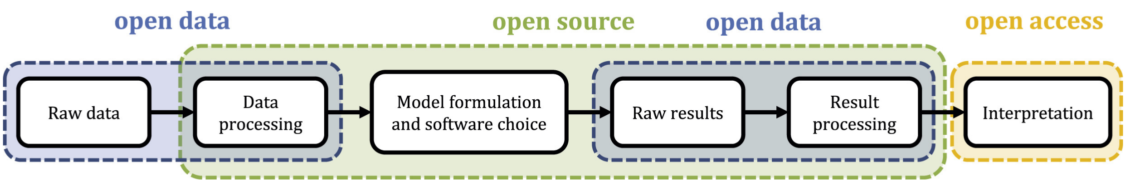


Figure 2.2: openmod [PFE18]

In figure 2.2 the idea of the openmod is displayed, an initiative among researchers to share and publish both code and results from their models.

The basis of the energy hub concept is a general theoretical framework for studying MES, including multi-carrier energy networks and their specific physical characteristics.

2.1.1 Concept of multi-energy hubs

The groundwork for the concept is laid in the work [GEI07], where the first proposal was made to create an integrated multi-energy system. His work states that the future energy system can no longer be thought of without considering the interaction between different carriers. Multi-energy systems exist and describe the optimisation problem of making assumptions of cost-optimal transition paths needed to derive the optimal determined system.

Such a system can be described by figure 2.4.

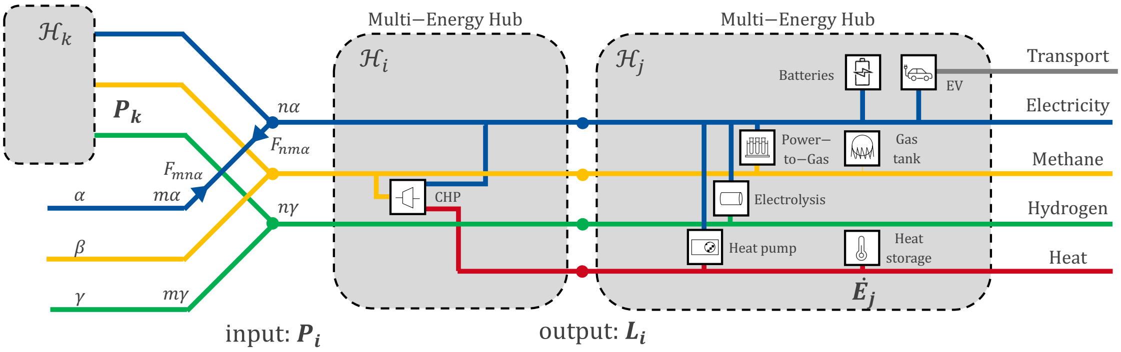


Figure 2.3: Multi-energy hubs [GEI07]

A multi-energy hub connects the input with output via a conversion matrix C_i and a storage matrix S_i. To form the following equation

$$L_i = \begin{bmatrix} C_i & S_i \end{bmatrix} \begin{bmatrix} P_i \\ \dot{E}_i \end{bmatrix} \tag{2.1}$$

where L_i, P_i is output and input respectively. C_i describes the conversion matrix, and S_i is to be seen as the storage matrix.

The example 2.4 will further describe the matrix notation of the problem.

Therefore with the obtained matrix notation, the optimisation problem can be easily defined and scaled even to large-scale problems [SON21]. The formulation of energy hubs is very efficient as the matrix formulation is efficiently solved with today's solvers and allows an easy-to-amend structure of the problem formulation.

Furthermore, the idea was made that the energy hub concept can also be applied to describe distribution systems and large-scale transmission grids. Overall the concept suited to describe multi-energy systems is proposed for usage throughout this work.

As depicted in figure 2.5, a local region can also be displayed as a multi-energy hub. This motivation was used for this work.

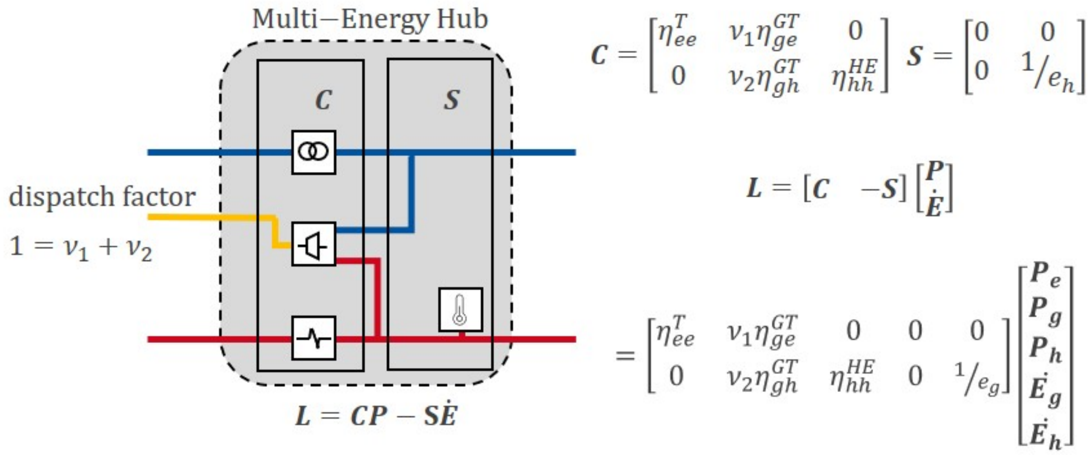


Figure 2.4: Matrix notation [GEI07]

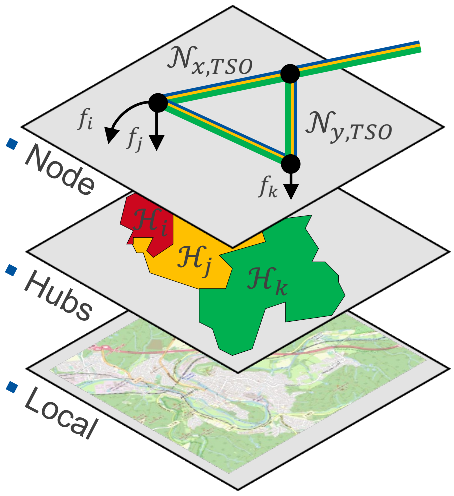


Figure 2.5: Distribution systems as multi-energy hubs [SCH10]

2.2 Active distribution networks

The transmission system has been operated in the past based on generation from conventional power plants, e.g. coal, hydro, lignite, nuclear and gas. Electricity was transmitted over long distances to serve load centres via distribution grids. However, new technologies applying Distributed energy resources (DER) are being installed in the system to bring generation and consumption closer by reducing the power losses of the system. This leads to a paradigm change regarding the depletion of traditional energy resources, as the awareness of environmental issues is on a steady rise. Another driver of DER is that new renewable energy sources are also becoming more affordable [**Zhang2021**].

This also leads to a substantial transformation for distribution grids, which can no longer be seen as passive distribution grids that only consume energy from the upstream system.

Figure 2.7 displays this paradigm shift, in which energy is not just consumed by distri-

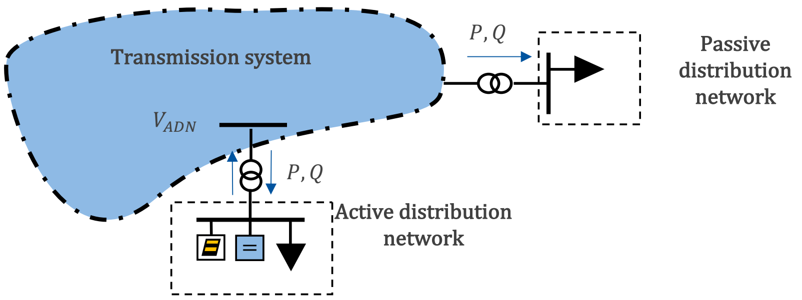


Figure 2.6: Developement of active distribution grids

bution grids but also fed back into the system. This exchange is

2.2.1 From passive to active distribution networks

The following developments mainly influenced the transition from passive to active distribution networks [ZHE21]

- The development of technologies for local energy generation from Renewable energy sources (RES), which reached an appropriate technological maturity.
- The possibility of integrating DER in distribution systems, not just for a generation but also for consumption
- The uprise of technical solutions for electrical storage, including the introduction of electric vehicles (EVs).
- The supply of power to the upstream grid
- A fast evolution of the information and communication technologies (ICT)
- The changing role given to the demand side, with the combined role of producers-consumers (prosumer)

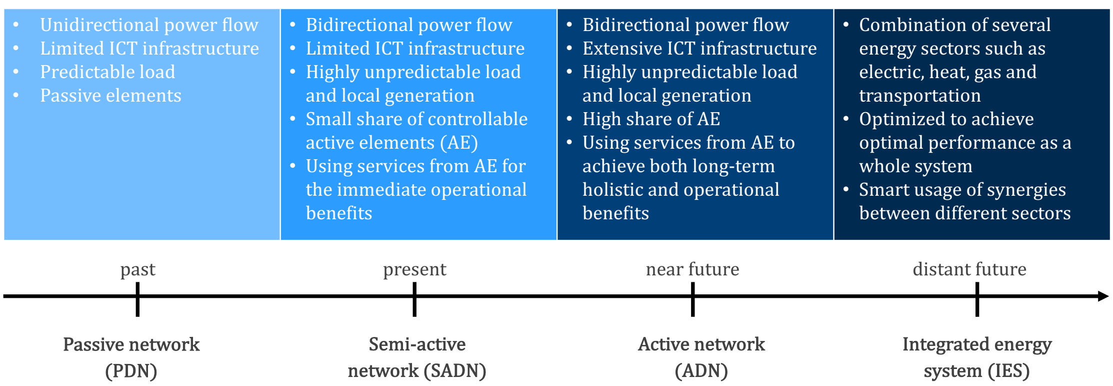


Figure 2.7: Developement of active distribution grids [KLY19]

Figure 2.7 displays this transition and gives further examples of the needed development and the one still due to form integrated energy systems.

2.2.2 Flexibility providing units

The following possible flexibility potentials within the active distribution grid are represented and described.

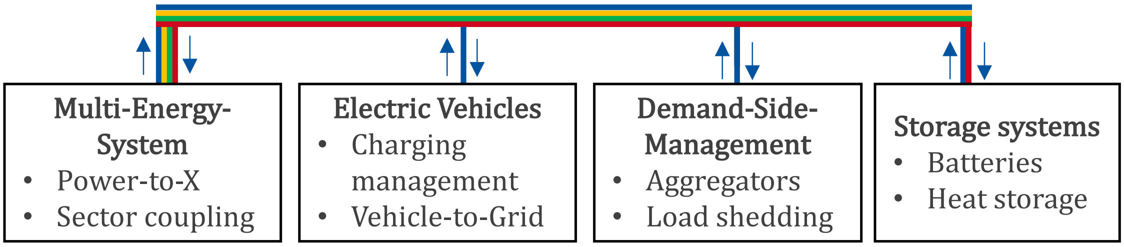


Figure 2.8: Flexibility providing units

In figure 2.14 the recent progress of flexibility in active distribution grids is displayed. A few technologies that fall within are further explained in the following sections.

Distributed energy resources

DER convert primary energy resources, such as wind, photovoltaic or hydropower, into secondary resources, such as electricity or heat. The wide adaptation and increasing usage are motivated by the environmental advantage of reducing greenhouse gas emissions (SO_x, NO_x, CO_2) from fossil-fuelled power plants, including extraction, refining and transportation. DER also contributes to a reduction in transmission losses as it connects further to the point of consumption. A further advantage of DER is the potential curtailment that can be applied to reduce the output power. Therefore they can also be classified as limited dispatchable. Most of the DER units are electronically coupled via converters with the ac distribution systems.

Storage systems

In the future, electrical energy will often be generated from renewable energy sources, as mentioned, and will thus be subject to weather-dependent conditions. This means that there will be an increased need to design the system so that energy can be stored in the future. This should make it possible to transfer energy from one point in time to the next. Unfortunately, this is only possible through energy loss since both storage and withdrawal generate losses. Therefore, it is essential how this energy can be used. Thus, in an optimisation problem, the feed-in and feed-out should take losses into account and thus not be available to the system indefinitely.

2.2.3 Distribution grid representation in multi-energy systems

Significant bottom-up optimisation problems have long been seen as Pandora's box, as it describes a detailed description of the technical components of the energy system.

Due to the detail level, simplifications are needed to remain tractable. In the current, primarily uncontrolled operational behaviour of flexibility options, the distribution grids benefit from aggregation effects, e.g. low simultaneity, which is also taken into account at the stage of grid planning. Nevertheless, in distribution grids with a high number of DER there could occur a high number of load and feed-in peaks. While the second appears evident due to the steady rise of Photovoltaic (PV) units being deployed, the first is down to a further increase in Heat pump (HP) installations. Therefore flexibility not only provides the potential to reduce grid expansion but may also increase the need. As an alternative for grid expansion, the limiting grid restriction could be applied to the optimisation problem to reduce the flexibility potential but to be a more realistic consideration of limited grid capacities.

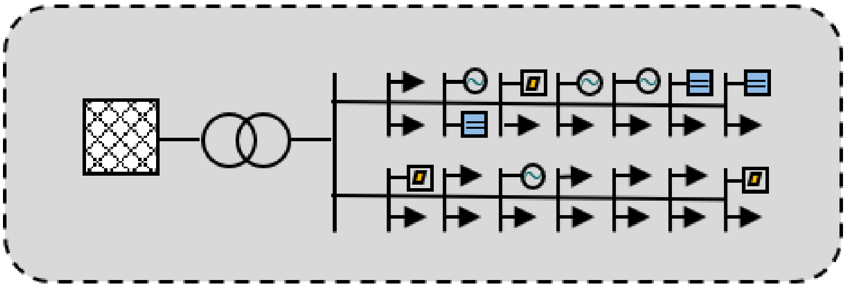


Figure 2.9: Representation of an active distribution grid

Integrating distribution grids into large-scale multi-energy systems is challenging due to the constraints limiting the power provided to the upstream grid. Setting up an optimisation problem, including distribution grids with the full representation of all non-linear and non-convex optimal power flow constraints, is likely to exceed computational power nowadays, especially for large-scale areas, e.g. continental Europe.

Therefore it is indispensable to use a reduced and aggregated representation of distribution grids, where the constraints are limited to a minimal number. As such, a representation in a $2n$-dimensional PQ-plane is considered, describing the active and reactive power exchange at the point of standard coupling between the upstream grid and the distribution level. The advantage of this representation is a linearisation of the original non-linear problem, whereas the disadvantages are possible overestimating the actual operation region.

2.2.4 Feasible operation region

The FOR of a distribution grid defines the set of all valid interconnection power flows between the transmission and distribution system at the point of standard coupling. Therefore it can be seen as the power exchange to the upstream grid, which could either supply or draw power.

It is bounded by several constraints, which are displayed in the following

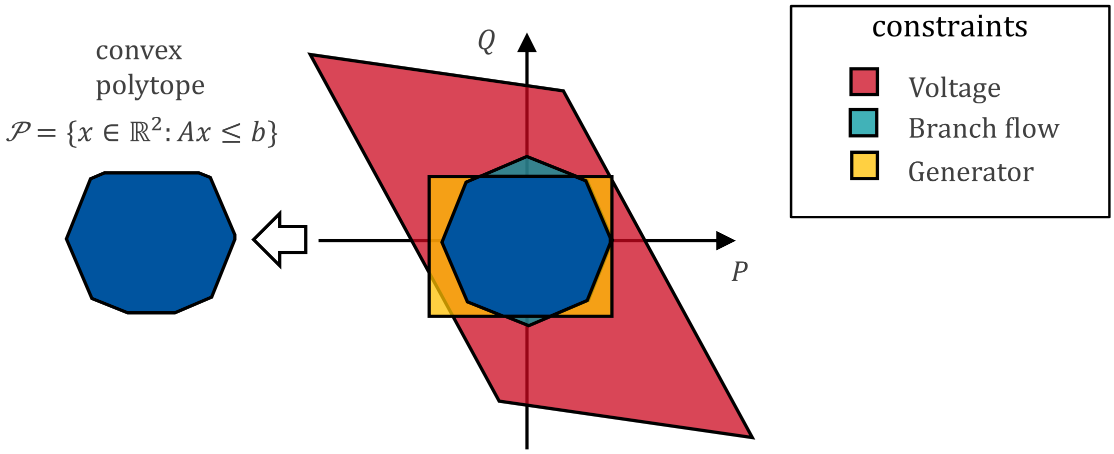


Figure 2.10: Linearised grid limits for distribution grids [FOR19]

Not only are these constraints bounding, as displayed in figure 2.10, but also several others. Here, they have been plotted in their linear form, which is not their actual nature but should indicate some interesting properties.

Having this in mind, it may seem intimidating in the first place to find all points that lay within the feasible set that would describe those power flows that are feasible. For this, the power flow equations must first be defined appropriately.

Power flow equations

The complex power flow equations [BER01] can be described as

$$S_i = V_i I_i^* = V_i (\sum_{k=1}^{N} Y_{ik} V_k)^* = \sum_{k=1}^{N} Y_{ik}^* V_k^* \quad \forall i \in N \tag{2.2}$$

where N is the set of buses, i and k are sending and receiving buses, S_i is the complex power flowing from bus i, V_i is the complex voltage at bus i, I_i the complex current from bus i. Y_{ik} is the line admittance between bus i and k, and V_k is the voltage at bus k.

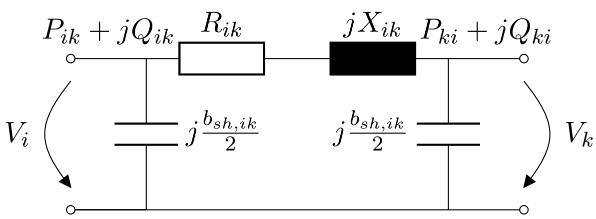


Figure 2.11: π-branch model of a transmission line [FRA16]

The complex line admittance and complex voltage are defined in polar coordinates by

$$Y_{ik} \triangleq |Y_{ik}|\angle\theta_{ik} \quad \forall i \in N$$
$$V_i \triangleq |V_i|\angle\delta_i \quad \forall i \in N \tag{2.3}$$
$$\delta_{ik} = \delta_i - \delta_k \quad \forall i \in N$$

Where δ_i is the phase angle at bus i, δ_{ik} is the phase angle difference between bus i and k and θ_{ik} is the admittance angle.

This led to the complex power flow equation S_i with

$$S_i = P_i + jQ_i = \sum_{k=1}^{N} Y_{ik}^* V_k^* = \sum_{k=1}^{N} |V_i||V_k|e^{j\delta_{ik}}|Y_{ik}|e^{j\theta_{ik}} \quad \forall i \in N \tag{2.4}$$

However, for numerical analysis or usage in optimisation, these non-linear power flow equations are further separated into real and imaginary parts in polar coordinates

$$P_i(V,\delta) = P_i^G - P_i^D = \sum_{k=1}^{N} |V_i||V_k||Y_{ik}|cos(\theta_{ik} - \delta_i + \delta_k) \quad \forall i \in N \tag{2.5}$$

$$Q_i(V,\delta) = Q_i^G - P_i^D = \sum_{k=1}^{N} |V_i||V_k||Y_{ik}|sin(\theta_{ik} - \delta_i + \delta_k) \quad \forall i \in N \tag{2.6}$$

These formulations can vary whether polar coordinates (eq. 2.3) or rectangular coordinates are used for the complex line admittance and complex voltage [FRA16].

With Kirchhoff's laws, the algebraic sum of all power flowing from and to the bus and the generated and consumed power meeting at a bus is zero. The solution to the power flow problem can be obtained by using numerical methods to find the solution to the set of non-linear equations. One such example is the Newton-Raphson method, which is iterative and finds the roots of the equations.

Newton's method

The first application of Newton's method for power flow solution dates back to as early as 1967 [TIN67]. In the work, the method outperformed the widely used Gauss-Seidel algorithm. It repeatedly solves a system of linear equations derived from the non-linear equations given by (eq. 2.4). The Jacobian matrix forms these linear equations

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \approx \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \approx J \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{2.7}$$

that describes the mismatches in the power flow equations from (eq. 2.5 and 2.6). An important characteristic of the Jacobian matrix in power flow solution is its sparsity, meaning that due to missing connections between buses in large-scale power systems, the entry of the admittance matrix is zero. This leads to an efficient solving process. One advantage of calculating the Jacobian is the repeated use throughout Newton's method, given a fixed network state. However, this no longer holds with changing network states, for example, by introducing flexible AC transmission systems (FACTS). As for such, other techniques must be used, like the bus injection model. Further insight into the computation of power flow solutions can be gained from [BER01; FRA16; TIN67].

In the following, an example is considered to describe Newton's method. May $f(x) = x^3 - x - 1$, then the first derivative is calculated with an update of x_n to x_{n+1}. The next update step repeats calculating the derivative as the gradient at point x_{n+1}. After a predefined number of iterations are completed, the final solution can be obtained.

$$f(x) = x^3 - x - 1$$

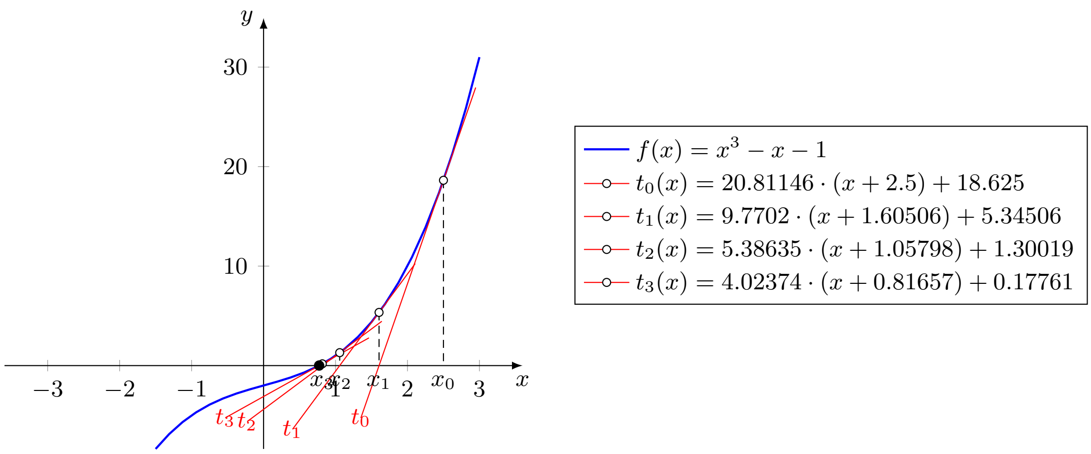
$$f'(x) \approx \frac{f(x + \Delta x) - f(x)}{\Delta x}, \quad \Delta x = 0.01$$

$$t_n(x) = f'(x_n) \cdot (x - x_n) + f(x_n)$$

$$x_0 = 2.5, \quad x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

n	x_n	$f(x_n)$	$f'(x_n)$	x_{n+1}
0	2,50000	18,62500	20,81146	1,60506
1	1,60506	5,34506	9,77020	1,05798
2	1,05798	1,30019	5,38635	0,81657
3	0,81657	0,17761	4,02374	0,77245

$\Rightarrow$ $\boldsymbol{x \approx 0.77245}$



With the formulation of the power flow equations, all feasible power flows can be determined using statistical methods as such random sampling was applied in this work.

Random sampling

The complete set of valid Interconnection power flow (IPF) could be obtained by executing load flow calculations for all operation points of each generator in the network deterministic. Nevertheless, this would be impractical to solve. Therefore other routines have to be set. One such is executing Monte-Carlo simulations, which is a probabilistic routine to limit the number of draws that has to be taken from the set of all operation points. Load flow calculations that are valid are collected and represented in $\mathbb{R}^2$-space by the convex hull of all points.

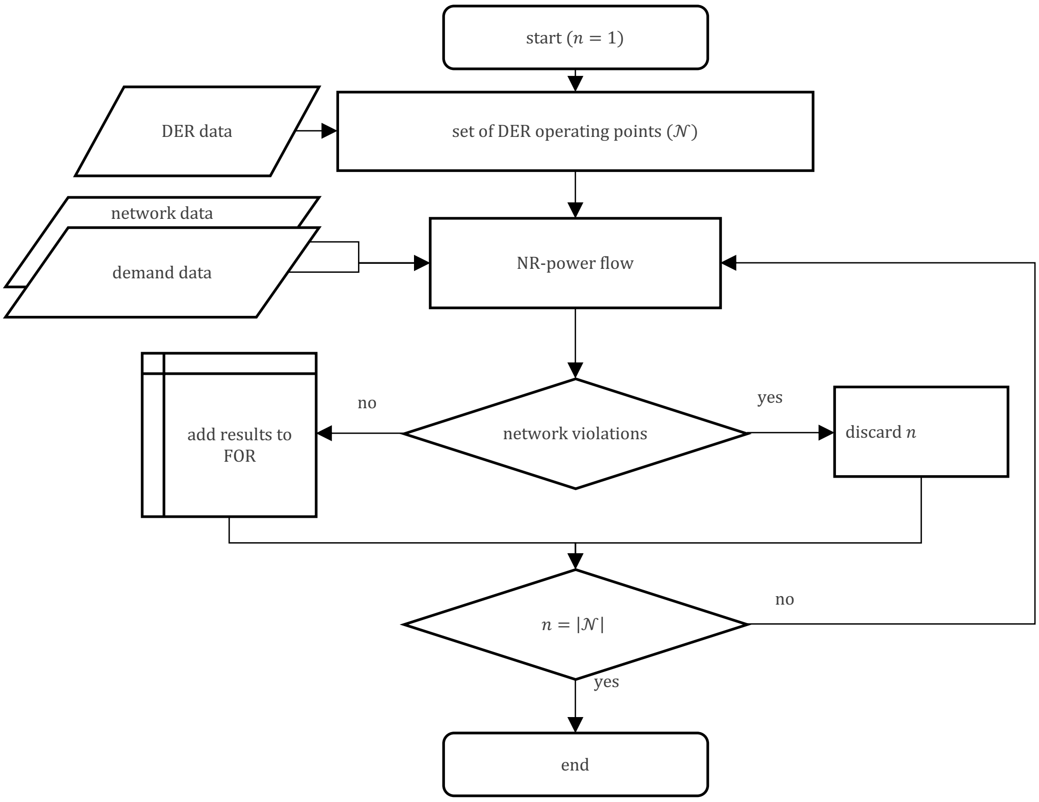


Figure 2.12: Random sampling

The figure 2.12 describes the basic workflow of computing the convex hull that would enclose the complete set of all valid IPF.

Definition 2.2.1 *The convex hull of a finite point set $\mathcal{P} \in \mathbb{R}^d$ forms a convex polytope. Each $p \in P$ for which $p \notin conv(P \not p)$ is called a vertex of conv($\mathcal{P}$). A vertex of conv($\mathcal{P}$) is also called an extremal point of $\mathcal{P}$. A convex polytope in $\mathbb{R}^2$ is called a convex polygon.*

$$Z = \{z \in \mathbb{R}^n : z = \lambda x + (1 - \lambda)y, x \in X, y \in Y, \lambda \in [0,1]\} \tag{2.8}$$

Figure 2.13 displays the FOR as defined by the random sampling for a given network with a small number of buses from [BAB19]. The area mismatch between the convex and a concave hull is at 27.3% for 1000 iterations. With a higher number of iterations, this mismatch will be decreased to detect the true region of the FOR. Nonetheless, the power flow solution is still time-consuming and inappropriate, especially for large grids. Thereby more efficient solution methods must be applied. As for this, a combination with optimal power flows was a promising approach as defined by [LOP21]. For this, the optimal power flow equations must be first defined. The power flow solution can be

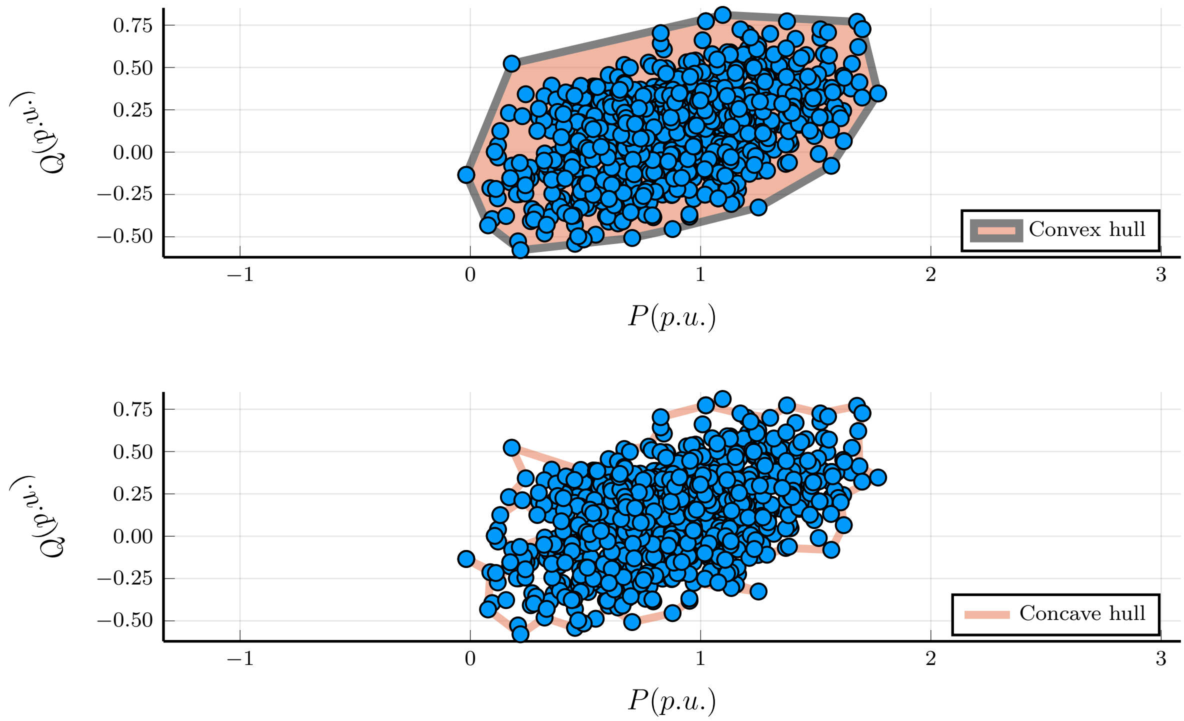


Figure 2.13: Random sampling of the FOR

combined with an objective function to form an optimisation problem. This is referred to as the optimal power flow.

Optimal power flow

Optimal power flow is a widely used term encompassing the range of optimisation problems in power system analysis. The objective is to use variables to optimise an objective function that contains both the equations for nodal balance and the power flows over lines, as well as all inequalities that describe the upper and lower bounds of the variables. Depending on the consideration of different variables or objective functions, different variations can thus be determined, e.g. economic dispatch (ED), unit commitment (UC), security constrained optimal power flow (SCOPF) and combinations (UC-ED, SC-ED, SC-UC).

The equations can be defined by [COF18]

sets:

N - buses

R - slack bus

B - branches

G, G_i - generators and generators at bus i

L, L_i - loads and loads at bus i

Sh, Sh_i - shunts and shunts at bus i

data:

$P^g_k, Q^g_k \;\; \forall k \in G$ - generator complex power bounds

$c_k \;\; \forall k \in G$ - generator cost components

$v^l_i, v^u_i \;\; \forall i \in N$ - voltage bounds

$S^d_k \;\; \forall k \in L$ - load complex power consumption

$Y^{sh}_k \;\; \forall k \in Sh$ - bus shunt admittance

$Y_{ij} \;\; \forall (i,j) \in B$ - branch π-section parameters

$s^u_{ij} \;\; \forall (i,j) \in B$ - branch apparent power limit

$i^u_{ij} \;\; \forall (i,j) \in B$ - branch current limit

$\delta_{ij} \;\; \forall (i,j) \in B$ - branch voltage angle difference bounds

(2.9)

variables:

$$P_k^g \ \ \forall k \in G \tag{2.10}$$

$$Q_k^g \ \ \forall k \in G \tag{2.11}$$

$$V_i \ \ \forall i \in N \tag{2.12}$$

$$S_{ij} \ \ \forall (i,j) \in B \tag{2.13}$$

minimise:

$$\sum_{k \in G} c_k(P_k^g) \tag{2.14}$$

subject to:

$$\angle V_r = 0 \ \ \forall r \in R \tag{2.15}$$

$$P_k^{g,min} \leq P_k^g \leq P_k^{g,max} \ \ \forall k \in G \tag{2.16}$$

$$Q_k^{g,min} \leq Q_k^g \leq Q_k^{g,max} \ \ \forall k \in G \tag{2.17}$$

$$V_{min} \leq |V_i| \leq V_{max} \ \ \forall i \in N \tag{2.18}$$

$$P_i(V,\delta) = P_i^G - P_i^D \ \ \forall i \in N \tag{2.19}$$

$$Q_i(V,\delta) = Q_i^G - Q_i^D \ \ \forall i \in N \tag{2.20}$$

$$|S_{ij}| \leq s_{ij}^u \ \ \forall (i,j) \in B \tag{2.21}$$

$$|I_{ij}| \leq i_{ij}^u \ \ \forall (i,j) \in B \tag{2.22}$$

$$\delta_{i,min} \leq \delta_i \leq \delta_{i,max} \ \ \forall i \in N \tag{2.23}$$

The equation 2.16 and 2.17 describe the generator constraints as box constraints. However, this must not always be true, and a further improvement would be implementing the true generator limits.

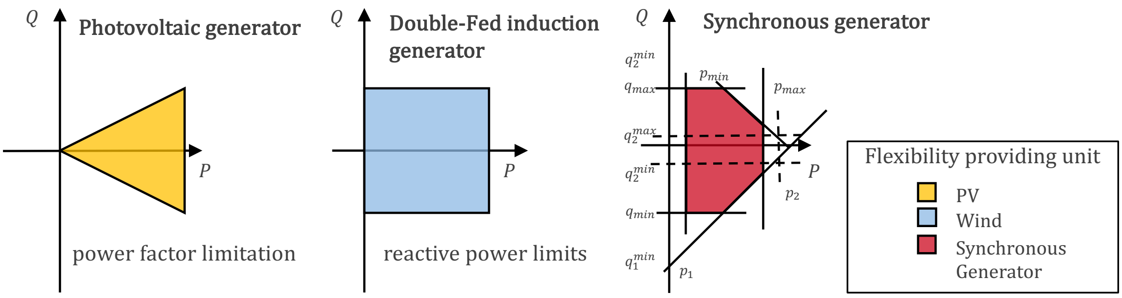


Figure 2.14: Generator limits per flexible providing unit

However, as seen in picture 2.14, this also increases constraints and the solving time. In this work, the problem formulation only requires the optimal active power exchange with the transmission system. Therefore the box constraint approximation is sufficient.

The optimal power flow equations are usually defined to minimise generation costs for all generators (eq.2.14, however, this must not always hold, and another optimisation is

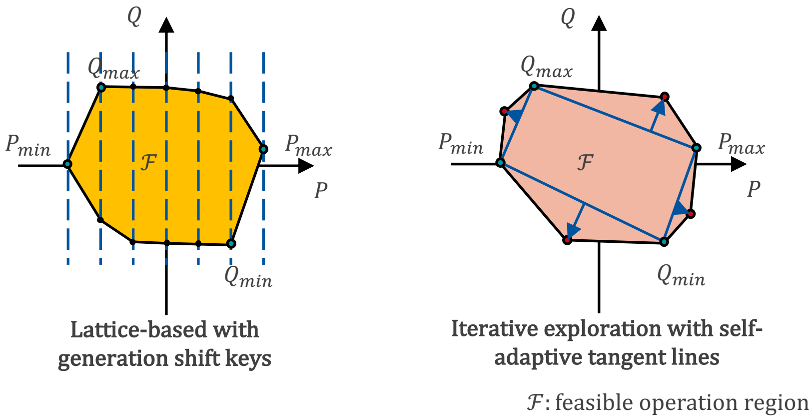


Figure 2.15: Comparison of lattice-based approach and inner polyhedral approximation

possible.

Lattice-based approach

For instance, the optimal power flow could also be defined to maximise or minimise the grid's reactive power supply or demand, given a set active power in-feed.

$$\textbf{min,max:} \quad \sum_{k \in G} Q_k^g \tag{2.24}$$

Given a set resolution, the true region of the optimisation problem can be found. However, as also described in figure 2.15, an advanced approach was implemented in this work.

Inner polyhedral approximation

The basic idea follows the same description from the optimal power flow [LOP21]. This time the initial solution space is provided

min,max:

$$P_s^g \quad \forall S \in S \tag{2.25}$$

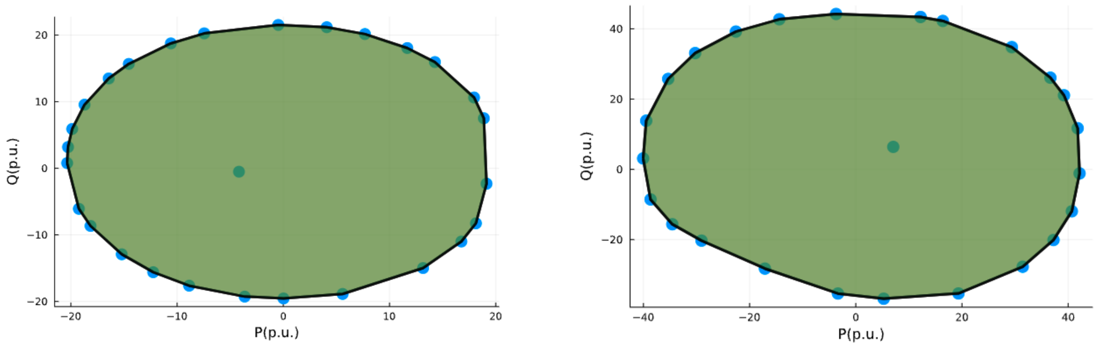
$$Q_s^g \quad \forall s \in S \tag{2.26}$$

$$\tag{2.27}$$

where S denotes the set of slack buses. This way, a box approximation is first derived. From this approximation, the vertices are fully described. Iteratively, the algorithm continues. It picks two vertices and tries to maximise the distances from the line between those two points. Therefore a new vertex is created that increases the solution space. This continues until a tolerance value is fulfilled. Namely, the increase in solution space is less than the tolerance value. The algorithm stops and displays the FOR. This can also be referred to as a polyhedral inner approximation.

Definition 2.2.2 *A set $\mathcal{P}$ is a polyhedral inner approximation of a convex set X if $\mathcal{P}$ is a polyhedron (an intersection of a finite number of closed half-spaces, i.e., linear inequalities of the form $a_i^T x \leq b_i$) and $\mathcal{P}$ contains X, i.e., $X \subseteq \mathcal{P}$.*

Comparing the results for two distribution grids



(a) FOR representation of a German MV distribution grid [MEI20]

(b) European representative distribution network [MAT18]

Figure 2.16: Inner polyhedral approximation of FOR

This leads to figure 2.16, representing a German MV distribution network and a European representative network. Both show similarities but differ in the amount of power that can be interchanged with the transmission grid. Notice that the inner point marks all generators' initial optimal power flow defined for minimum power generation.

2.2.5 Integration in optimal power flow problems

The integration of these grid limits will then be continued by introducing limits for the active power exchange between a distribution grid class and the upstream grid. Every link connected is limited by the lower and upper limit from the FOR.

$$P_{lb,FOR} \leq P_{IPF} \leq P_{ub,FOR} \tag{2.28}$$

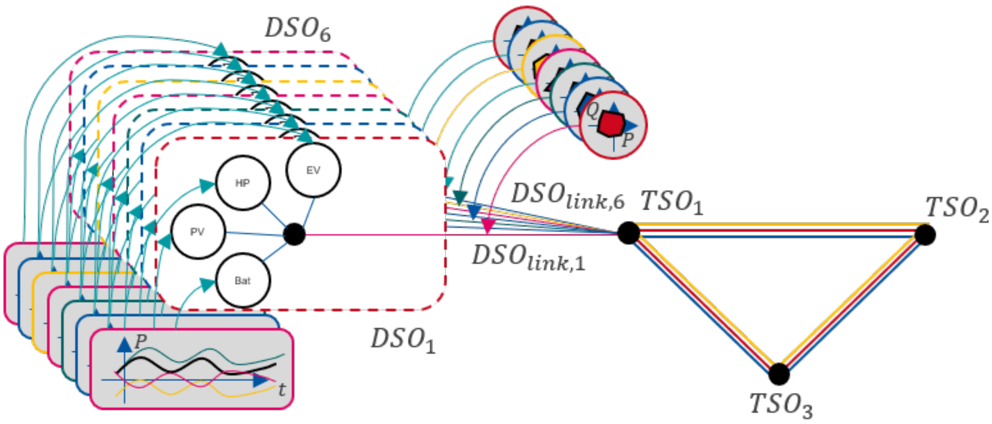


Figure 2.17: NTC limits for power exchange

3 Methodology

In this section, the basic workflow of the model is described as well as all necessary steps that have been undertaken to formulate the problem.

3.1 Workflow

In the following, an overview of the method will first be given an initial derivation as to why which steps were necessary will be explained. These will then be analysed more closely and described in detail. The focus here is on the derivation of the respective question and the integration into the programme process.

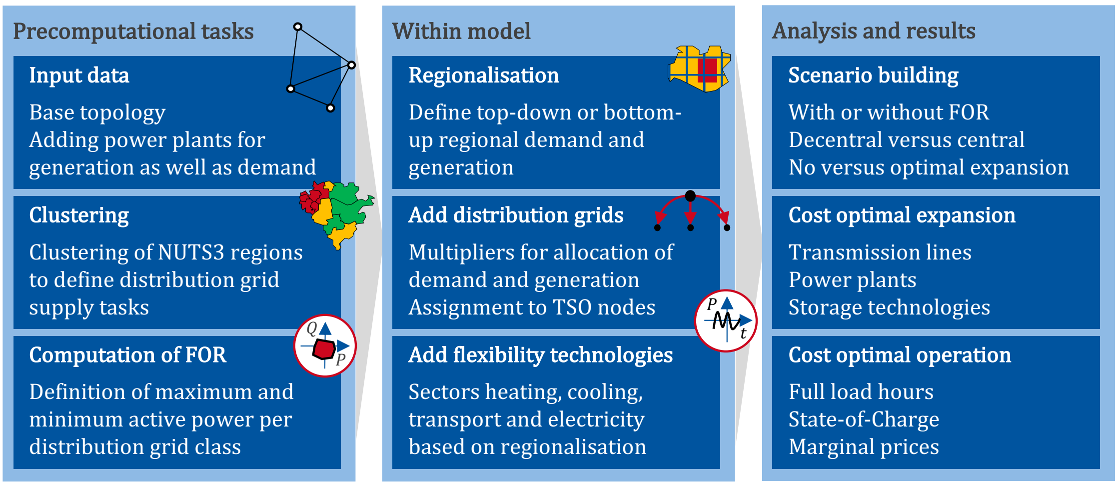


Figure 3.1: Workflow diagram

3.1.1 Input data

The methodology for analysing multi-energy systems first requires input data. The data must be linked to a given topology, representing a graph's nodes and edges. This topology can be different from the physically existing one in that a given network can be reduced in complexity and thus reduced to a simplified network. Furthermore, the system can be equipped with already existing power plants.

When modelling large-scale multi-energy systems, one core challenge is data granularity. Most data is available on an aggregated level, whether at the country or federal state level. Within this work, the focus was to analyse the potential of the distribution grids for flexibility provision. Therefore it was urgent to find data on a more acceptable grade, e.g. for smaller regions. The European Union defined for this the NUTS classification (fr. *Nomenclature des unités territoriales statistiques*). Its definition ranges from NUTS0 to NUTS3, with NUTS0 describing the national level and NUTS3 being smaller regions. This minor administrative boundary was sufficient to describe homogeneous distribution on a regional scale. In [RAV22] it was shown that at least data from the NUTS 3 level is required to depict the effects of regionalisation on the transmission grid. Otherwise, the differences are smoothed out.

(a) NUTS1 **(b)** NUTS2 **(c)** NUTS3

Figure 3.2: NUTS classification in Europe

3.1.2 Clustering

In order to describe the distribution networks in Europe, it initially seems impossible to rebuild them precisely. There is a lack of data and comprehensive information on the local conditions. Therefore, it seems unavoidable to represent them via groups, where a small number can reflect the total quantity. This procedure can also be called clustering.

Clustering is a procedure that enables the discovery of similar structures of data. The structures that emerge from the data are then combined into groups, so-called clusters. The similarity groups found can be graph-theoretical, hierarchical, partitioning or optimising. A multitude of cluster algorithms are only referred to here but will not be looked at in more detail. However, one method, the k-means method, has gained popularity in recent years and is increasingly being used. Here, a previously known number of k groups is formed from a set of similar objects. The algorithm is one of the most commonly used techniques for grouping objects, as it quickly finds the centres of clusters. In doing so, the algorithm prefers groups with low variance and similar size.

The k-means algorithm aims to minimise the within sum-of-squares criterion over all clusters:

$$\sum_{i=0}^{n} \min_{\mu_j \in C}(||x_i - \mu_j||^2) \tag{3.1}$$

where n is the predefined number of clusters that have to be obtained, x_i are the data points, and μ_j are the cluster centres derived iteratively from this procedure. Notice that x_i is in $\mathbb{R}^n$-dimensional space, and therefore many features can be used as clustering input.

For example, the following data is plotted in $\mathbb{R}^3$-dimensional space with $n = 6$ as the designated cluster size.

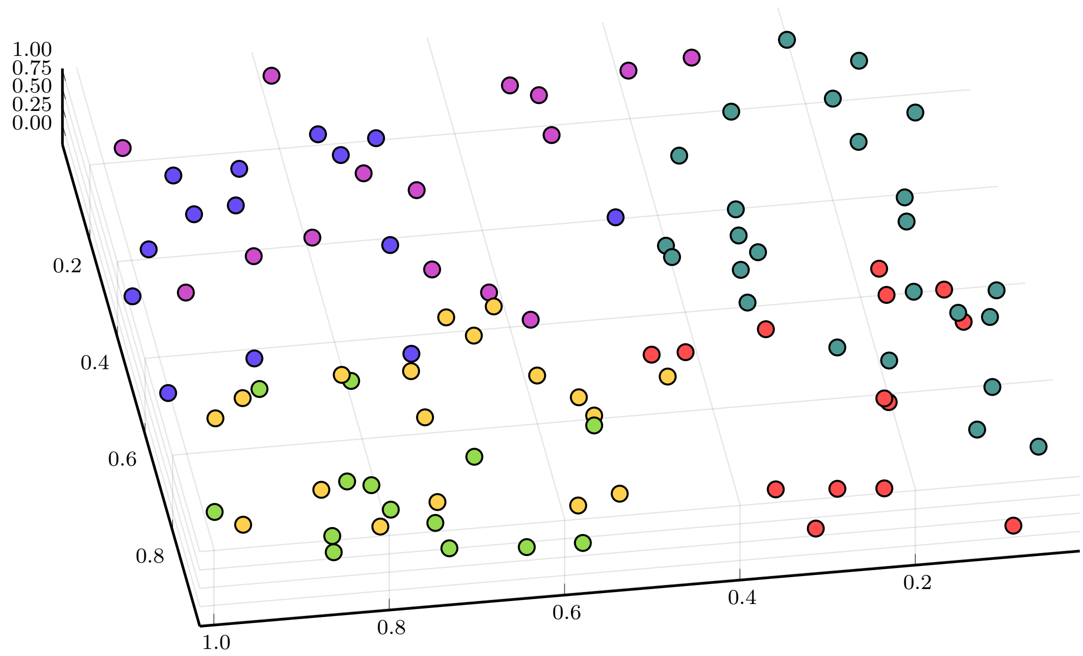


Figure 3.3: Scatter plot for scaled data with $x_i \in (0,1)$ in $\mathbb{R}^3$

In figure 3.3, the data is spread across the space and assigned by colour to its cluster. However, from this perspective, it does not seem very easy to understand why points have been assigned to a designated cluster. Therefore different perspectives are further needed for an investigation.

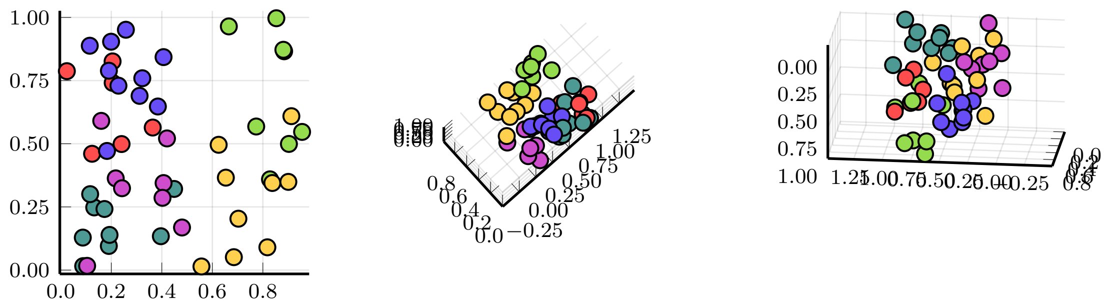


Figure 3.4: Depicting from different view angles in 3 dimensions

With figure 3.4, the clustering is more prominent, and patterns can be detected. Clusters have been assigned to each other with the same weight because, in this small example, the quantities are within the same range $x_i \in (0,1)$. However, this will no longer be the case

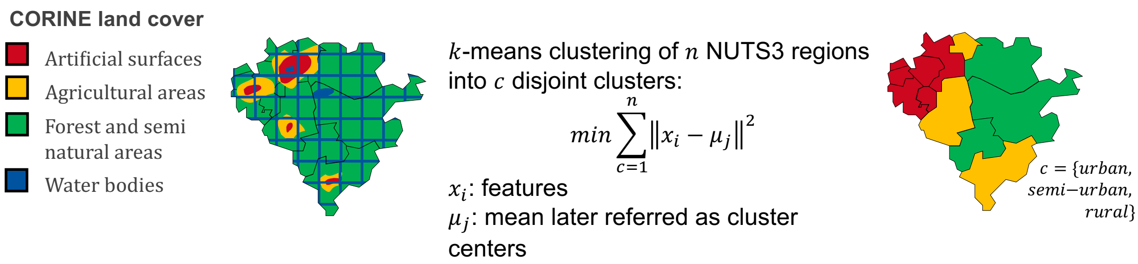


Figure 3.5: Clustering

as soon as clustering is applied to real data. At this point, data must be preprocessed and scaled to avoid computational sensitivities to larger quantities.

In this work, standardisation is used for preprocessing by removing the mean and scaling to unit variance [PED11]

$$z = \frac{x_i - \overline{x}}{s} \tag{3.2}$$

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{3.3}$$

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3.4}$$

where $\overline{x}$ denotes, the mean and s is the standard deviation.

With these steps, the proceeding is to apply clustering to the NUTS3 regions in Europe, representing the most minor administrative boundary, for which a sufficient database can be found. The data can be described in table 3.1, where each NUTS3 region is attached with data for population and GDP obtained from *EUROSTAT*. Furthermore, the CLC [1] cover has been added. Here the share of each land classification per NUTS3 region was calculated.

As for the features used in the clustering, population, settlement ratio (artificial surfaces), and population density have been used in a previous study to identify the grid supply tasks for regions [KIT18].

These results are then used to assign a distribution grid class to a designated cluster. For example, the NUTS3 region AT111 was distributed with grids from cluster class 0, which corresponds to rural grids. All grids in this area will be of type 0.

[1] CLC is a project for the uniform classification of the most important forms of land cover, which the EU Commission initiated.

index	nuts3	pop	gdp	country	area_grid	Agricultural areas	Artificial surfaces	Forest areas	Water bodies	Wetlands	cluster
0	AT111	38	21800	AT	6,77E+08	0,44	0,06	0,47	0,00	0,00	0
1	AT112	152	29000	AT	2,11E+09	0,52	0,08	0,16	0,08	0,07	1
2	AT113	97	23200	AT	1,65E+09	0,50	0,06	0,44	0,00	0,00	0
3	AT121	241	29200	AT	3,57E+09	0,50	0,05	0,45	0,01	0,00	2
4	AT122	254	27700	AT	3,54E+09	0,24	0,06	0,70	0,00	0,00	2
5	AT123	149	39800	AT	1,43E+09	0,55	0,09	0,35	0,00	0,00	0
		in [thds.]	in [€/hab.]		in [m^2]	in [%]	in [%]	in [%]	in [%]	in [%]	

Table 3.1: Data on NUTS3 regions by population, GDP, country, area and their designated share from the CLC and their predicted cluster

3.1.3 Regionalisation

Within models, data is mainly assigned to large regions such as countries or federal states, which makes it hard to estimate the exact value of containing smaller regions. As for such, regionalisation approaches must be incorporated into the model. As explained earlier, there are two ways of deriving data for smaller regions, top-down and bottom-up approaches. In this work, both have been considered and will be explained.

Top-down

Within top-down approaches, data from larger regions, e.g. countries, is distributed to smaller regions, e.g. local administrative, using different strategies. For example, if there is a profile for the national demand for transport, a top-down approach would be to use estimations from the distribution of the GDP or population to allocate the figures to smaller regions further. These estimations could be distribution keys that can be obtained from regression analysis. The regression analysis is a technique that allows to study and measure of the relationship between a dependent y and several independent variables x_i.

$$y = \beta_0 + \beta_1 x_{i1} + \beta_2 (x_{i2})^2 + \epsilon_i \qquad i = 1, \ldots, n \tag{3.5}$$

Notice that despite the quadratic term in eq. 3.5, the coefficients β_j are linear. Therefore it is still defined as linear regression analysis.

In the following, the analysis will be made on what influencing factors on the regionalisation of electric vehicles.

The first assumption is that cars are aligned with the population.

From figure 3.6, this assumption can be proven right, as cars are showing a high R^2-value. Furthermore, we could think that cars would be aligned not just with the population but also with the GDP. Therefore a multiple regression is performed on this parameter.

In figure 3.5, this observation cannot be agreed on. The additional information from GDP is neglectable, and most of the model can be explained via the population. This also is in line with most studies, which see that the population is a transport driver.

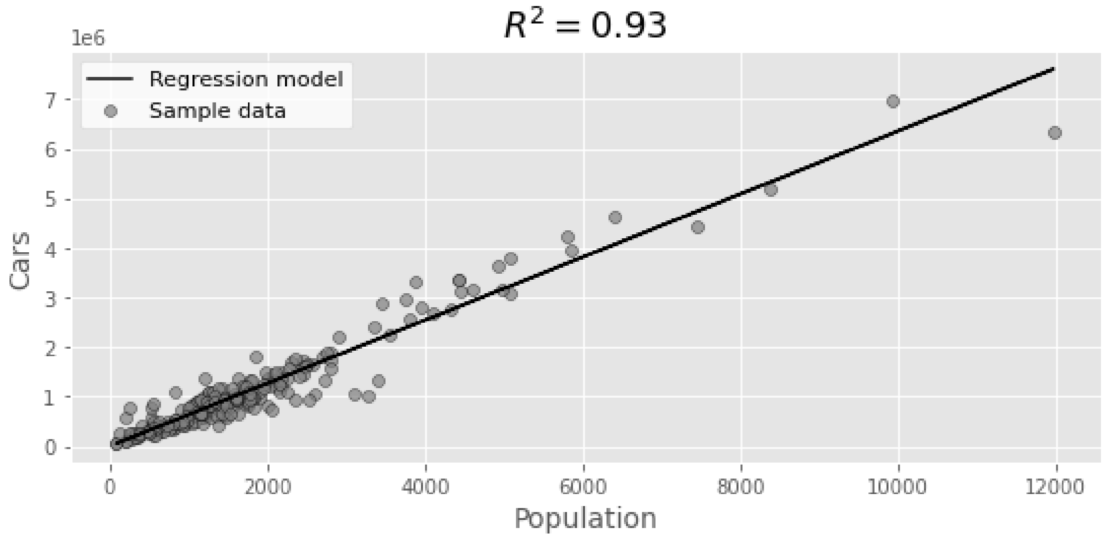


Figure 3.6: Linear regression

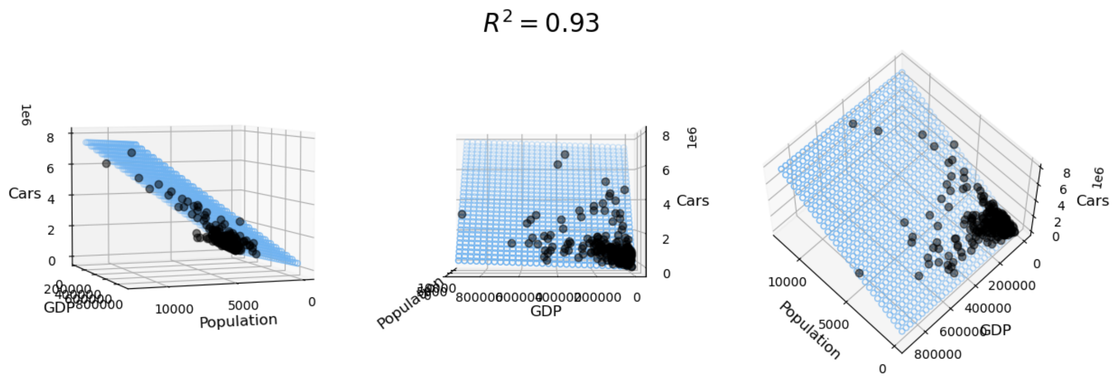


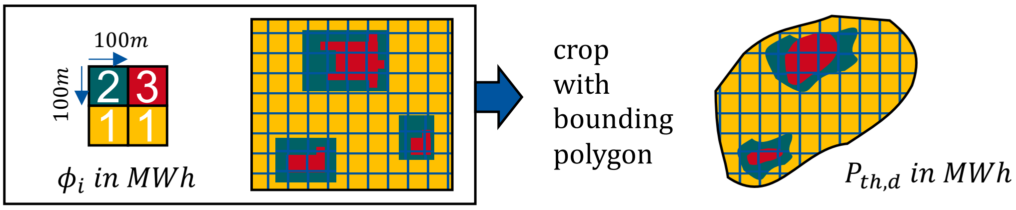
Figure 3.7: Multiple regression

Bottom-up

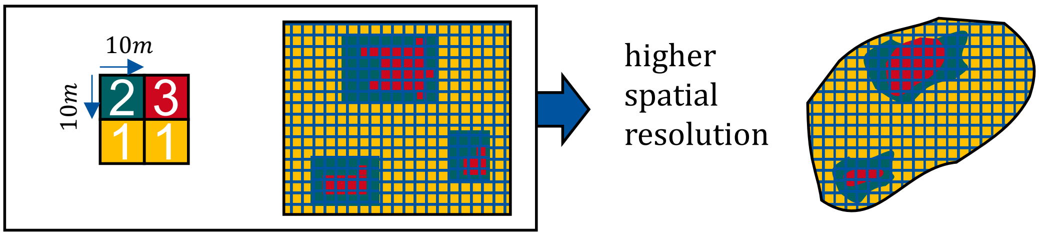
A bottom-up approach is intended to analyse interactions between different energy sectors in more detail. It allows our more profound understanding from a techno-economic point of view. The weakness lies in its strength as well, as it is harder to capture all necessary details and can lead to misinterpretation. In opposition to the already proposed top-down approach, it intends to follow the opposite path from smaller regions to larger ones. While it might seem at first glance more accurate, notice that this amount of extra information is not always necessary. When data gets aggregated in a later stage, then the effect is also smoothing out. For more information consider the textbox 3.1.3.

Raster data

For the bottom-up approach, data with a high spatial resolution from accurate data sources are available via raster data. A raster consists of a matrix of cells (or pixels) spread over a grid with columns and rows, with each cell containing a value representing spatial information, e.g. temperature, population or potential for renewable energy. The rendered dataset can display either floating point values, e.g. height or spectral values, and integers to distinguish categorised data, such as land use classes, as needed for the CLC. Storing data as raster files, e.g. `GeoTIFF`, bears many advantages, such as a simple data structure for an advanced spatial and statistical analysis with the ability to execute fast geometric operations such as performing overlays with other vectorial geospatial data, e.g. `Shapefile`.



The dimensioning of the cells is arbitrary and can take any value, e.g. hectares or even square kilometres, and determines how coarse the data is aggregated to a cell. Typically, finer cell size leads to a smoother transition between cells and a greater level of information. Nevertheless, the processing takes both more time and memory. Therefore the correct cell size is dependent on the use case.



Raster files are suitable for modelling in a bottom-up approach, as they allow the connection of spatial data with regions of arbitrary size.

In this work, raster data was used to identify the demand for energy on the spatial resolution of NUTS3 regions. The dataset used was obtained from the Hotmaps project.

3.2 Integrating flexibility from active distribution grids

The exchange with the superimposed transport network is represented by an edge that is provided with an exchange capacity. The distribution grid can only be supplied with a maximum via this edge. The edge of the so-called NTC is the FOR, which was determined in advance. This describes the possible network boundaries at the transfer point between the distribution network and the transmission network. These maximum theoretical exchanges can be fed from the distribution grid into the transmission grid and vice

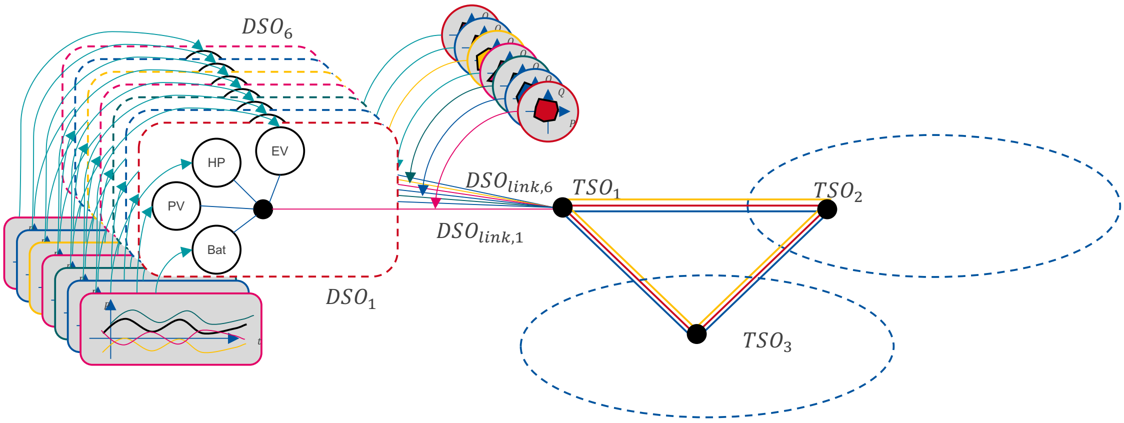


Figure 3.8: Overview of process

versa.

3.2.1 Distribution grid representation

There is a conflict between an increased need for grid expansion in the distribution grids and the use of flexibility options on the market or system side. The solution space of this conflict extends between the consideration of unrestricted market access of flexibility options in the grid planning and a limitation of the usable plant flexibility according to the requirements of the distribution grid. While the first case leads to increased grid expansion costs, the technical restriction of plant flexibility means a restriction of competition and can thus lead to an inefficient market result in the energy markets. This section will, therefore, only analyse the extent to which the usable plant flexibility is impaired by the limited grid capacity in low and medium voltage and under the condition of avoiding additional grid expansion costs. Distribution grids are generally characterised by a high degree of heterogeneity. Statements about the overall situation of the distribution network can, therefore, usually only be made by analysing a large number of individual distribution networks. In the study context, the analysed distribution grids represent a sample from the `SimBench` benchmark dataset [MEI20].

This data set was generated to create representative network classes and use them for network calculations. In this approach, the network classes are considered representative of the group. This makes it possible to assign a type of network class to a previously clustered region. Homogeneity is assumed within a region, so the network class no longer changes. This makes it sufficient to determine the electrical load occurring in the region and divide it by the load assigned to the grids. This results in the number of grids created for a region and then calculated. These multipliers play an important role and are essential for the subsequent calculation. They also define how the exchange to the transmission grid is possible.

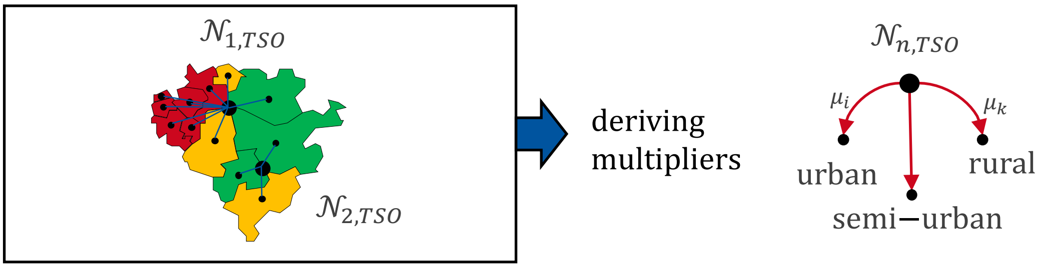


Figure 3.9: Multipliers for distribution grids

3.3 Deriving flexibility from sector-coupling

The individual sectors are modelled in such a way that they can exchange data with each other via converters. This means that with the help of the multi-energy hubs, exchanges can take place between individual energy vectors. This makes it possible in times when there is a surplus of electrical energy first to use it in other sectors or to bring about an expansion of storage. In the worst case, decentralised generation plants are shut down, which entails high penalty costs.

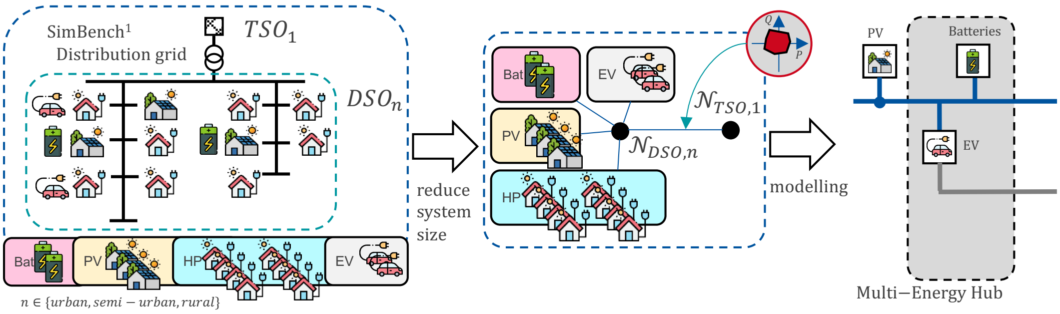


Figure 3.10: Flexibility provision

This modelling should make it possible to create a cost-optimal generation system for a given year using the optimisation problem. The advantage of this type of formulation is that individual sectors can be operated with different carriers. At the same time, the influence of individual sectors can be examined in the modelling. For example, sectors can be added or taken away.

Overall, this creates an optimisation problem that minimises the annuity system costs. Both the investment and the operating costs are considered. Furthermore, some regions have restrictions on emissions or the expansion of renewable energies.

Figure 3.11 should supply an overview of the problem.

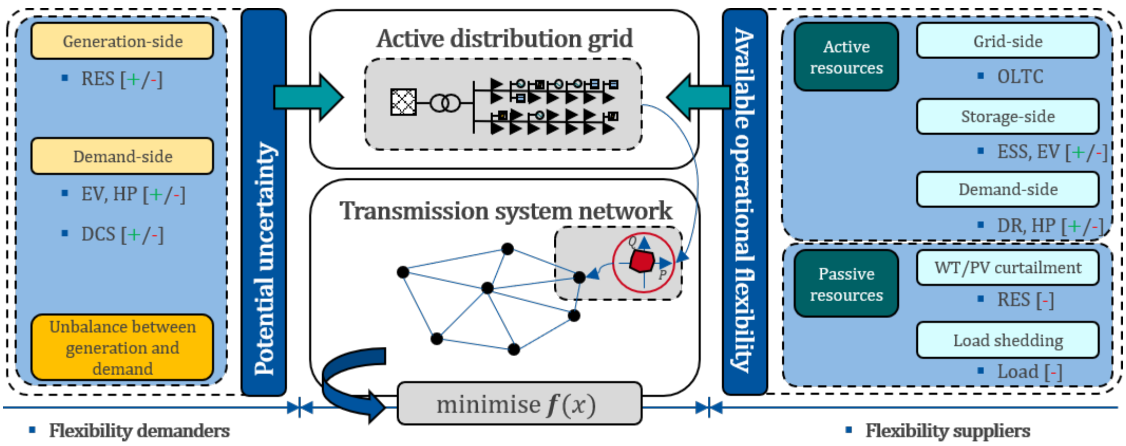


Figure 3.11: Flexibility needs in distribution grids [YAN21]

4 Verification of method and exemplary results

4.1 European sector-coupled model

The framework used was the open-source tool PyPSA, an abbreviation for Python for Power system analysis [BRO18a]. From the literature research as displayed in the following, it was chosen as one of the most suitable tools for conducting a multi-energy system analysis. Recently, one extension to PyPSA, called PyPSA-Eur-Sec [BRO18b], describes a sector-coupled model for Europe. This work was further extended within this work.

4.1.1 Spatial scope

The analysis of the geographical spread is based on the European EU-28 countries, as well as the countries Great Britain, Switzerland, Norway, Albania, Serbia, Bosnia-Herzegovina, Bulgaria, Macedonia and Romania. A comprehensive data basis is available for these countries.

Where available, the energy sources are linked to their physical infrastructure, but this is not possible everywhere. For example, while the electric and hydrogen networks are mapped with node precision, a copper plate is assumed for the gas network.

Furthermore, not all demands are distributed this way, so the electrical demand is added to the respective nodes. Starting from a Voronoi partition, the network area is divided, and the respective load centres are added to the nearest node.

In figure 4.1, the database for the power plants is depicted. This should give just a small insight into the mighty model set up in PyPSA.

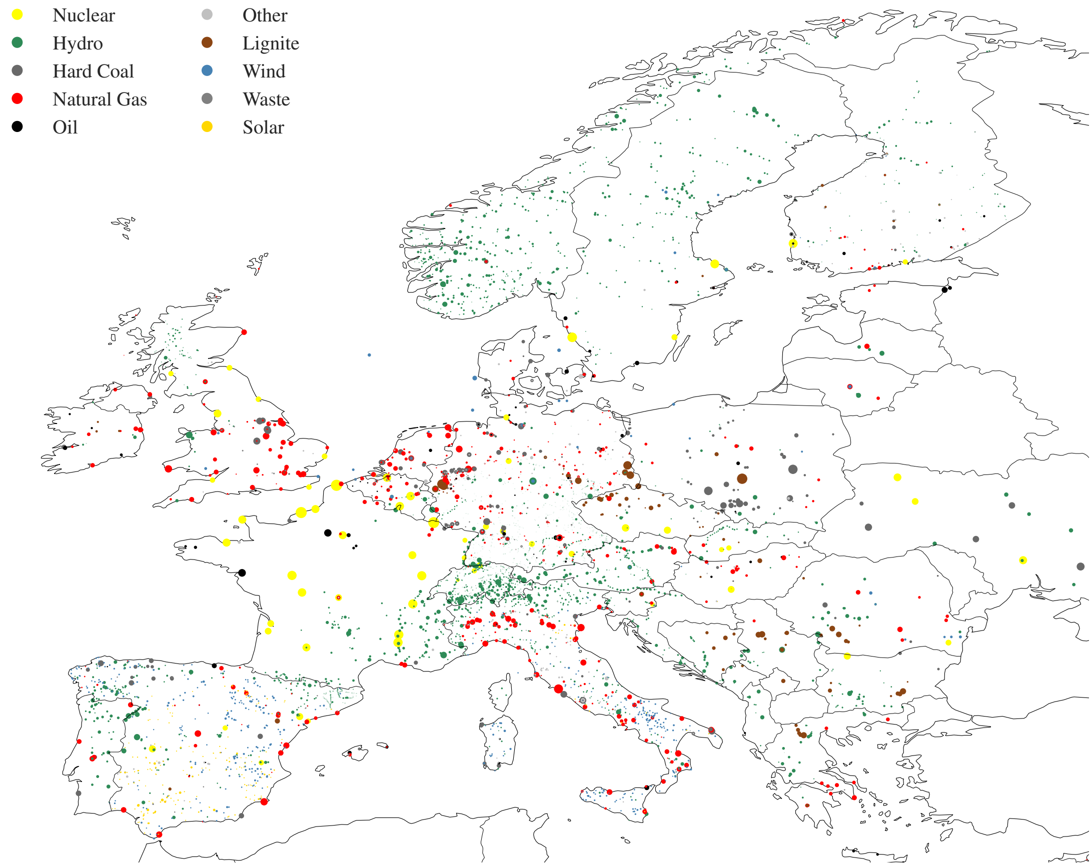


Figure 4.1: Powerplants database for Europe [GOT19]

	Software				**Grid Analysis**		**Economic Analysis**					**Other Sectors**		**General Information**
	Name	*Version*	*Plattform*	*Open Source*	*PF*	*CPF*	*Transport Model*	*LOPF*	*NLOPF*	*Multi-Period*	*Investment*	*Gas*	*Heat*	*Institution*
Power system tools	MATPOWER	7.1	MATLAB	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	
	OpenDSS	9.4.1	Delphi	No	Yes	Yes	No	No	No	No	No	No	No	EPRI
	NEPLAN	10.9.1		No	Yes	No	Yes	Yes	Yes	No	No			
	pandapower	2.9.0	Python	Yes	Yes	No	Yes	Yes	Yes	No	No			
	PowerFactory	2022		No	Yes	No	No	Yes	Yes	No	No			
	PSAT	2.1.11		Yes	Yes	Yes	No	Yes	Yes	Yes	No			
	PSS/E	35.3		No	Yes	No	No	Yes	Yes	No	No	Yes	No	
	PSS/SINCAL	18.0		No	Yes	No	No	Yes	Yes	No	No			
	PowerModels	0.19.5	Julia	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	No	
	PYPOWER	5.1.15	Python	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	
	PyPSA	0.20.0	Python	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	KIT, TU Berlin, Frankfurt
Energy system tools	LISA	bundle_2022	MATLAB	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Amprion
	calliope	0.6.7	Python	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	
	Euro-calliope	1.2.0	Python	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	ETH Zürich, University Cambridge
	minpower	5.0.1	Python	Yes	No	No	Yes	Yes	No	Yes	No	No	No	
	MOST	6.0	MATLAB	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Cornell University
	oemof	0.1.4	Python	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Reiner Lemoine Institute
	OSeMOSYS	2021	Python	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	KTH Stockholm
	PLEXOS		C#, VB.NET	No	Yes	No	Yes	Yes	No	No	No	Yes	Yes	Energy Exemplar
	PowerGAMA	1.1.3	Python	Yes	No	No	Yes	Yes	No	Yes	Yes	No	No	SINTEF Energy Research
	PRIMES	2018		No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	NTU Athens
	TIMES	4.6.1	GAMS	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	IEA-ETSAP
	urbs	1.0.1	Python	Yes	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Technical University of Munich

Table 4.1: Tools for energy system modelling

4.1.2 Linearisation of power flow equations

The nonconvex and non-linear power flow equations from chapter 2 have been modified, and linearised [HÖR18]. This approach is called the DC-OPF. However, one does not mislead this with the use of direct current. It is instead a simplification which neglects the reactive power losses. These simplifications are helpful for the transmission grid, which can be seen later.

In order to demonstrate the simplifications introduced, the power flow equations and the active and reactive powers flowing from bus i to j can be written as:

$$\begin{aligned} p_{ij} &= \frac{1}{r_{ij}^2 + x_{ij}^2}\left[r_{ij}\left(v_i^2 - v_i v_j \cos(\delta_{ij})\right) + x_{ij}\left(v_i v_j \sin(\delta_{ij})\right)\right], \\ q_{ij} &= \frac{1}{r_{ij}^2 + x_{ij}^2}\left[x_{ij}\left(v_i^2 - v_i v_j \cos(\delta_{ij})\right) + r_{ij}\left(v_i v_j \sin(\delta_{ij})\right)\right]. \end{aligned} \tag{4.1}$$

Three assumptions lead to a simpler expression for the active and reactive power flows (p_{ij} and q_{ij}):

1. Resistance r_{ij} of each branch is negligible, i.e. $r_{ij} \approx 0$ or rather $r_{ij} \ll x_{ij}$

$$\begin{aligned} p_{ij} &\approx \frac{1}{x_{ij}}\left(v_i v_j \sin(\delta_{ij})\right) \\ q_{ij} &\approx \frac{1}{x_{ij}}\left(v_i^2 - v_i v_j \cos(\delta_{ij})\right) \end{aligned} \tag{4.2}$$

2. Bus voltage magnitudes are approximated by one per unit, i.e. $v_i \approx 1$

$$\begin{aligned} p_{ij} &\approx \frac{\sin(\delta_{ij})}{x_{ij}} \\ q_{ij} &\approx \frac{1 - \cos(\delta_{ij})}{x_{ij}} \end{aligned} \tag{4.3}$$

3. Voltage angle difference of each branch is small, i.e. $\cos(\delta_{ij}) \approx 1$ and $\sin(\delta_{ij}) \approx \delta_{ij}$.

$$\begin{aligned} p_{ij} &\approx \frac{\delta_{ij}}{x_{ij}}, \\ q_{ij} &\approx 0. \end{aligned} \tag{4.4}$$

The formulation as DC-OPF reduces the complexity of the original power flow problem significantly, as the non-linear nature is linearised. With efficient solvers, this problem formulation reduces the runtime significantly. For this problem formulation, the interior-point methods or simplex methods are applicable.

The full description of the DC-OPF is as follows

$$
\begin{aligned}
&\textbf{Variables:} && \\
&\quad \delta_i && \forall i \in \mathcal{N} \\
&\quad p_g^G && \forall g \in \mathcal{G} \\
&\quad p_{ij} && \forall (i,j) \in \mathcal{E} \\
&\textbf{Objective function:} && \\
&\quad \min \sum_{g \in \mathcal{G}} C_g(p_g^G) && \\
&\textbf{Constraints:} && \\
&\quad \sum_{g \in \mathcal{G}_i} p_g^G - \sum_{l \in \mathcal{L}_i} p_l^L = \sum_{(i,j) \in \mathcal{E}} p_{ij} && \forall i \in \mathcal{N} \\
&\quad \delta_r = 0 && \forall r \in \mathcal{R} \\
&\quad p_{ij} = \frac{\delta_{ij}}{x_{ij}} && \forall (i,j) \in \mathcal{E} \\
&\quad \underline{v}_i \leq v_i \leq \overline{v}_i && \forall i \in \mathcal{N} \\
&\quad \underline{p}_g^G \leq p_g^G \leq \overline{p}_g^G && \forall g \in \mathcal{G} \\
&\quad \underline{\delta}_{ij} \leq \delta_{ij} \leq \overline{\delta}_{ij} && \forall (i,j) \in \mathcal{E} \\
&\quad |p_{ij}| \leq \overline{p}_{ij} && \forall (i,j) \in \mathcal{E}
\end{aligned}
\tag{4.5}
$$

4.2 Scenarios

Within the modelling framework, the proposed methodology from chapter 3 has been introduced, and all distribution grids were defined by their limits combined with the multipliers. From this viewpoint, general observations can be made considering the integration of distribution grid constraints.

First, we consider the system costs when no distribution grids are considered.

As shown in figure 4.2, the system costs are mainly due to the large share of solar and onshore wind capacities. They are in the range of 950 € billion per year. The energy is aggregated at the country node level for a European system with 37 nodes. The sectors transport, heat, building and agriculture are considered.

The following scenarios describe the consideration of distribution grids.

The figure 4.3 already expresses that the system costs are higher with 975 € billion per year. An increase in solar rooftops can be seen, arguably in installation costs. Also, the share of Direct air capture (DAC) is increased. The remaining parts are primarily steady compared to the base reference scenario. The higher system costs can also be linked to the level of aggregation at the TSO node because, by now, the different sectors cannot just exchange power at all but just within their distribution grid class. This also expresses

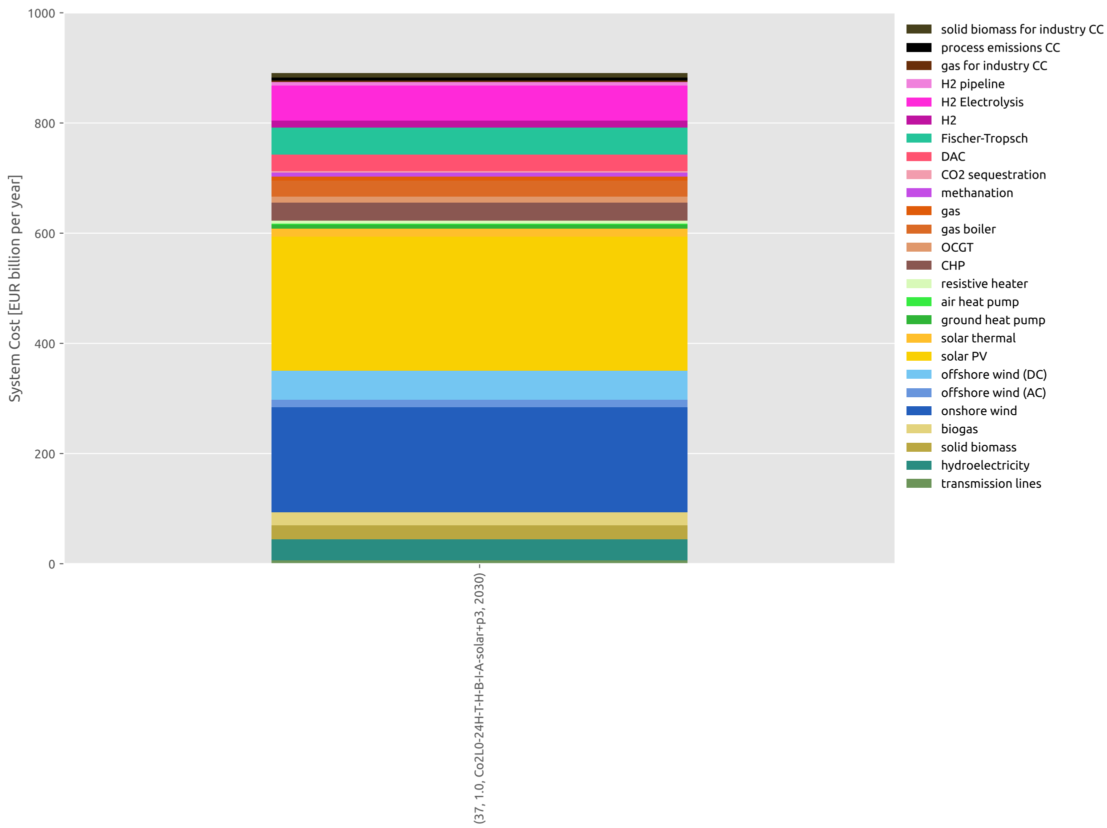


Figure 4.2: Costs with no distribution grid consideration

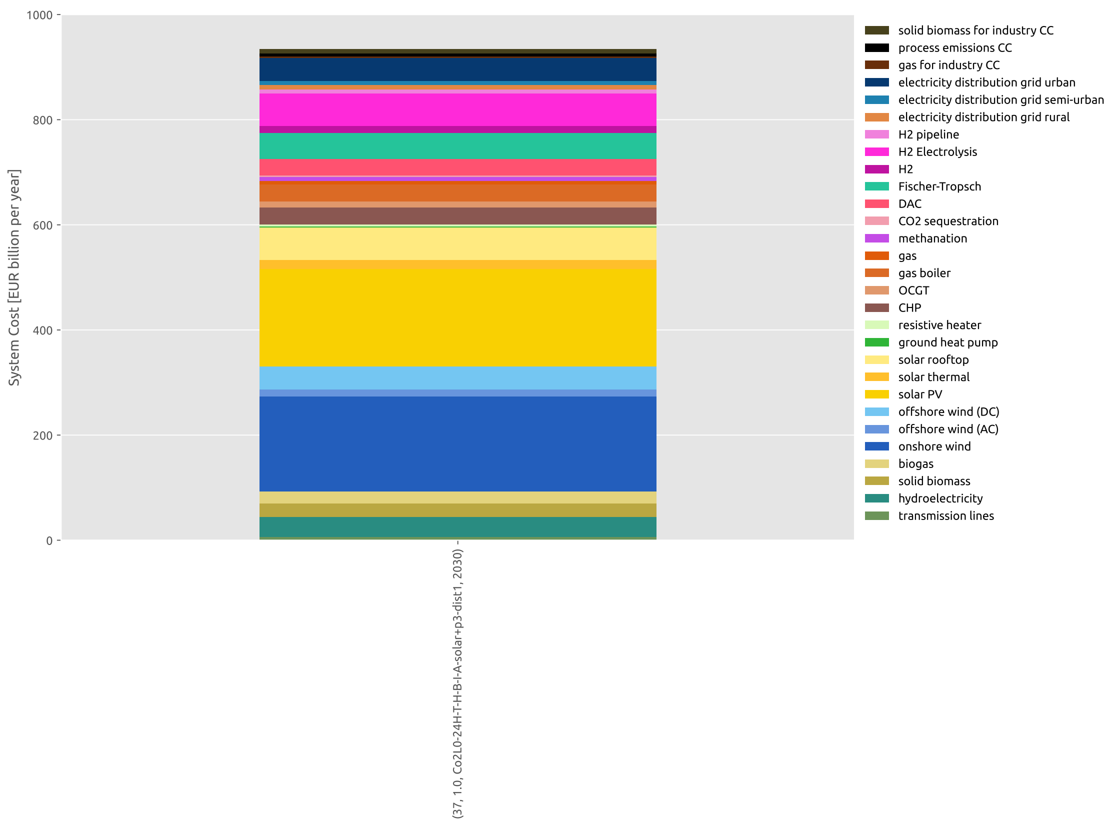


Figure 4.3: Costs with distribution grid consideration

one weakness of the proposed model, as exchanging power within one distribution grid class is possible without restriction. This may potentially not reflect reality.

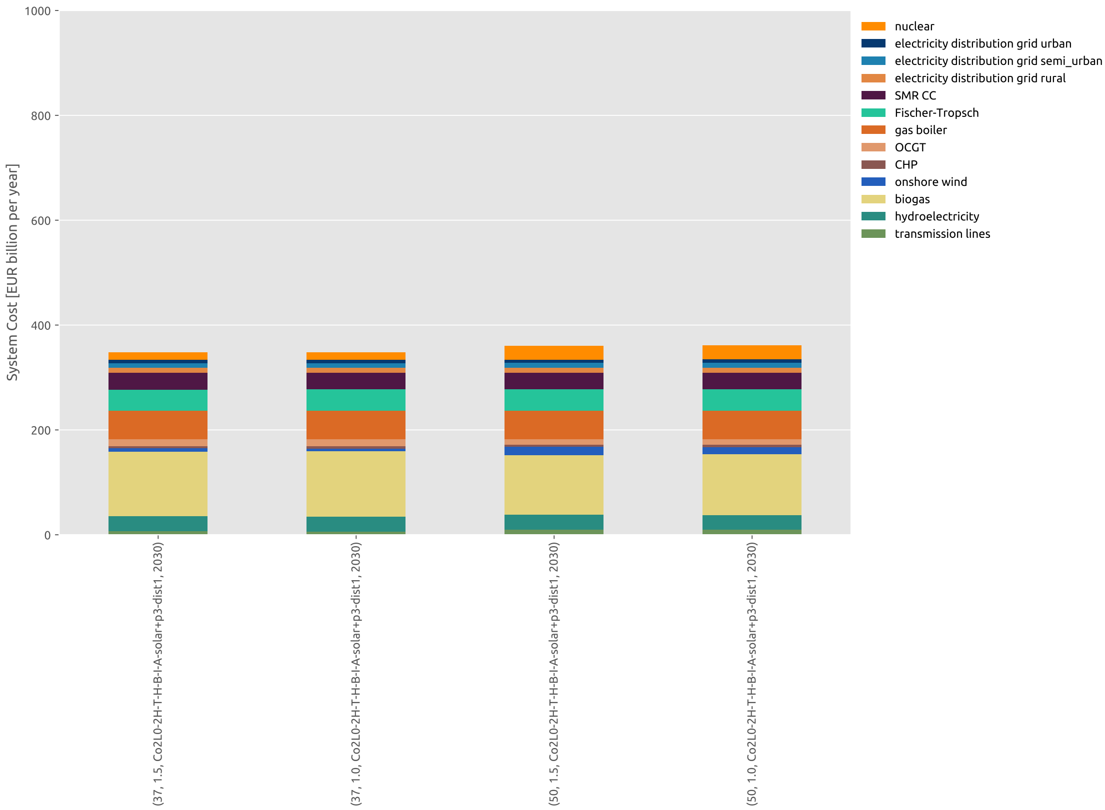


Figure 4.4: Costs with distribution grid consideration and comparison of cluster and optimal transmission grid expansion

The last scenario in figure 4.5 has two differences. First, the number of clusters is increased, so there can now be more than just one bus per country. Second, the transmission line expansion was possible to increase. LV1.5 means that the line volume could be increased by a factor of 1.5. The transmission line expansion can be mainly seen in Germany, as seen in the following figure. However, what is to observe is the increase in system costs. This is interesting as this means that a further increase in spatial resolution leads to different costs. This would indicate that models with a considerably higher spatial resolution are more likely to reflect the true costs.

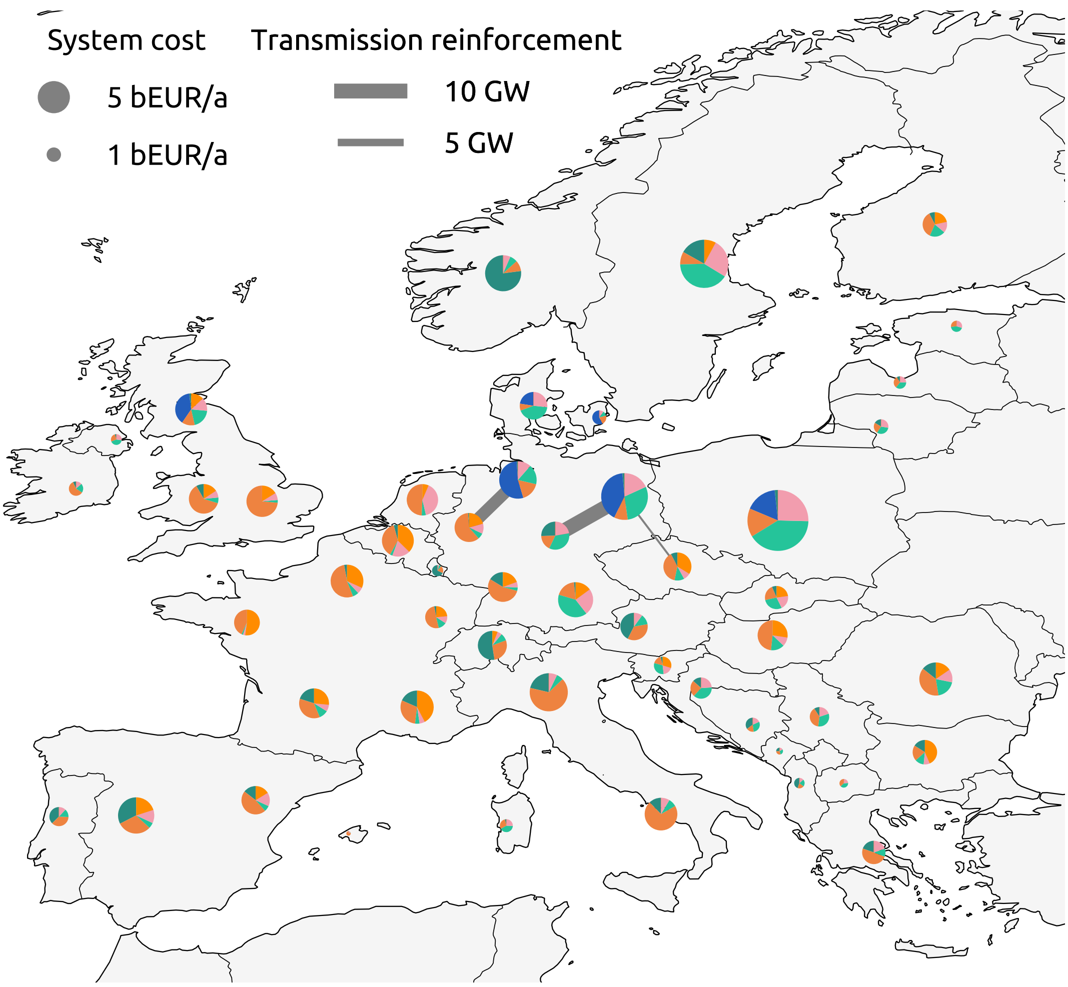


Figure 4.5: Line expansion for the scenario with 50 clusters and an allowed line volume expansion of factor 1.5

4.3 Operational difference

In the next chapter, the operational behaviour is compared in which the generation and load consumption has been executed for over one year. First, the load is described

Figure 4.6 displays the load that is consumed for over a year. Large parts are consumed by the heating sector, especially in the early time of the year, when it is especially very cold. There is no difference in the amount of energy consumption between the scenario of considering distribution grids and not.

In figure 4.7, the generation for over one year is plotted and as can be seen large parts are generated by gas and onshore wind. All in all the generation appears to be more steady compared to the following scenario with distribution grid consideration.

Figure 4.8 depicts are more fluctuating generation, as solar rooftop in the distribution grids is further enhanced used. The standard deviation is higher, an indicator that a less

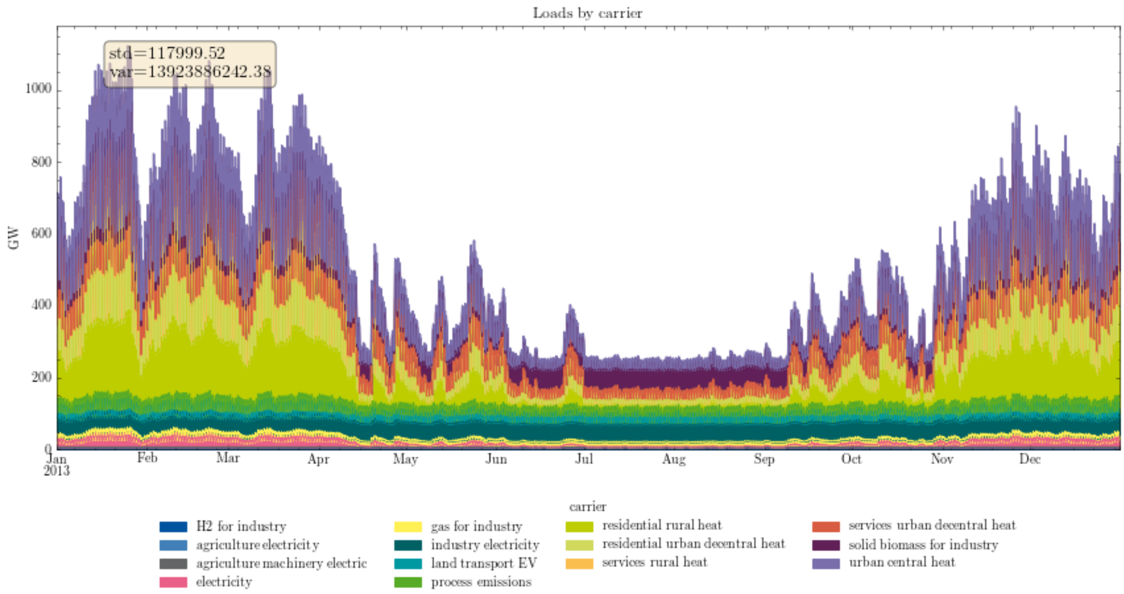


Figure 4.6: Dispatch of loads for one exemplary year

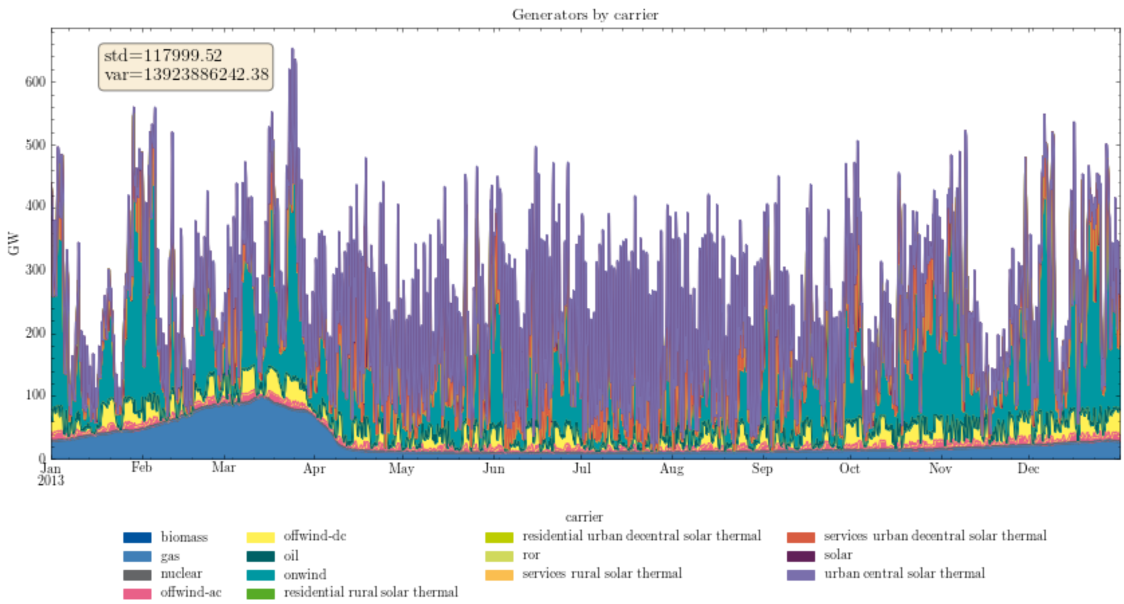


Figure 4.7: Dispatch of generation without distribution grid consideration for one exemplary year

steady generation is observed.

In general the difference can be further examined

The difference in figure 4.9 clearly is largest in the winter months. However there are times when the generation is higher between considering and vice versa. This can be also plotted time-dependent against each other.

Figure 4.10 also exemplifies the phenomena that there is a clear difference between the two scenarios. In here, for each hour both consequent generation amounts are shown for

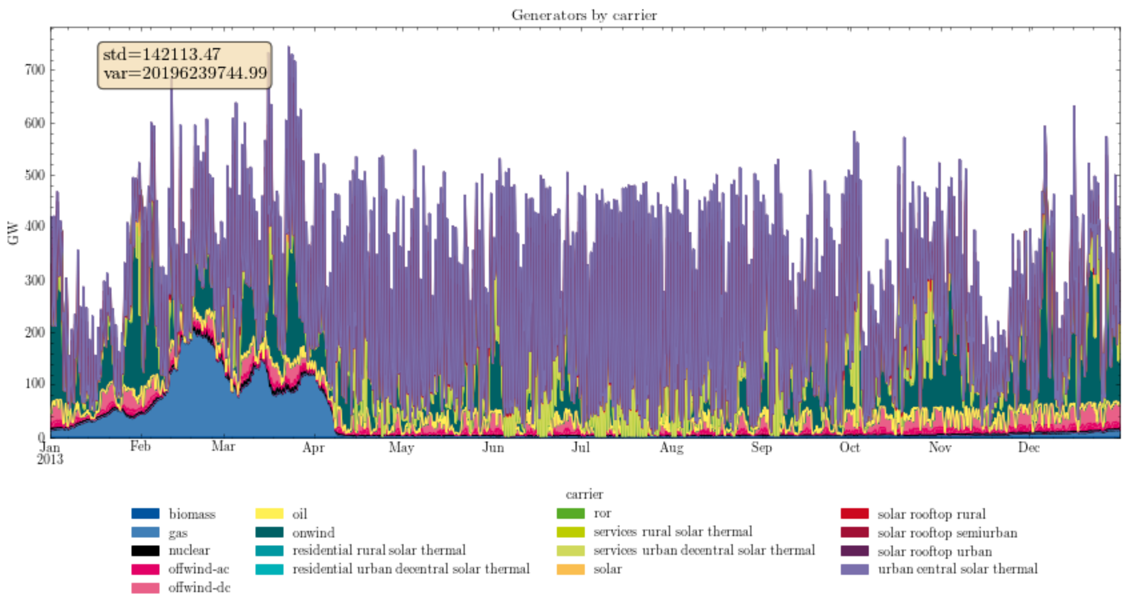


Figure 4.8: Dispatch of generation without distribution grid consideration for one exemplary year

the same point in time. Interestingly, the amount of generation with distribution grid consideration is arguably larger for each point in time.

In general, the consumption of energy is the same in both scenarios and a larger generation could be seen as a shift in time of consumption or that larger parts are consumed by storage technologies. To understand this in further, the generation can also be plotted in an ascending order to find any inequalities, this process is also referred to as Lorenz curve.

In figure 4.11, the Lorenz curve is plotted for both scenarios against each other. As can be seen, the plot shows that there are inequalities that considering distribution grids leads to a larger generation share.

In general, the consideration of distribution grids leads to considerable difference between the two scenarios. Having the research question in mind, the assumption can be made, that considering distribution grid classes makes indeed a difference in the modelling results. However, this does come at cost, for example the computational burden, as now described.

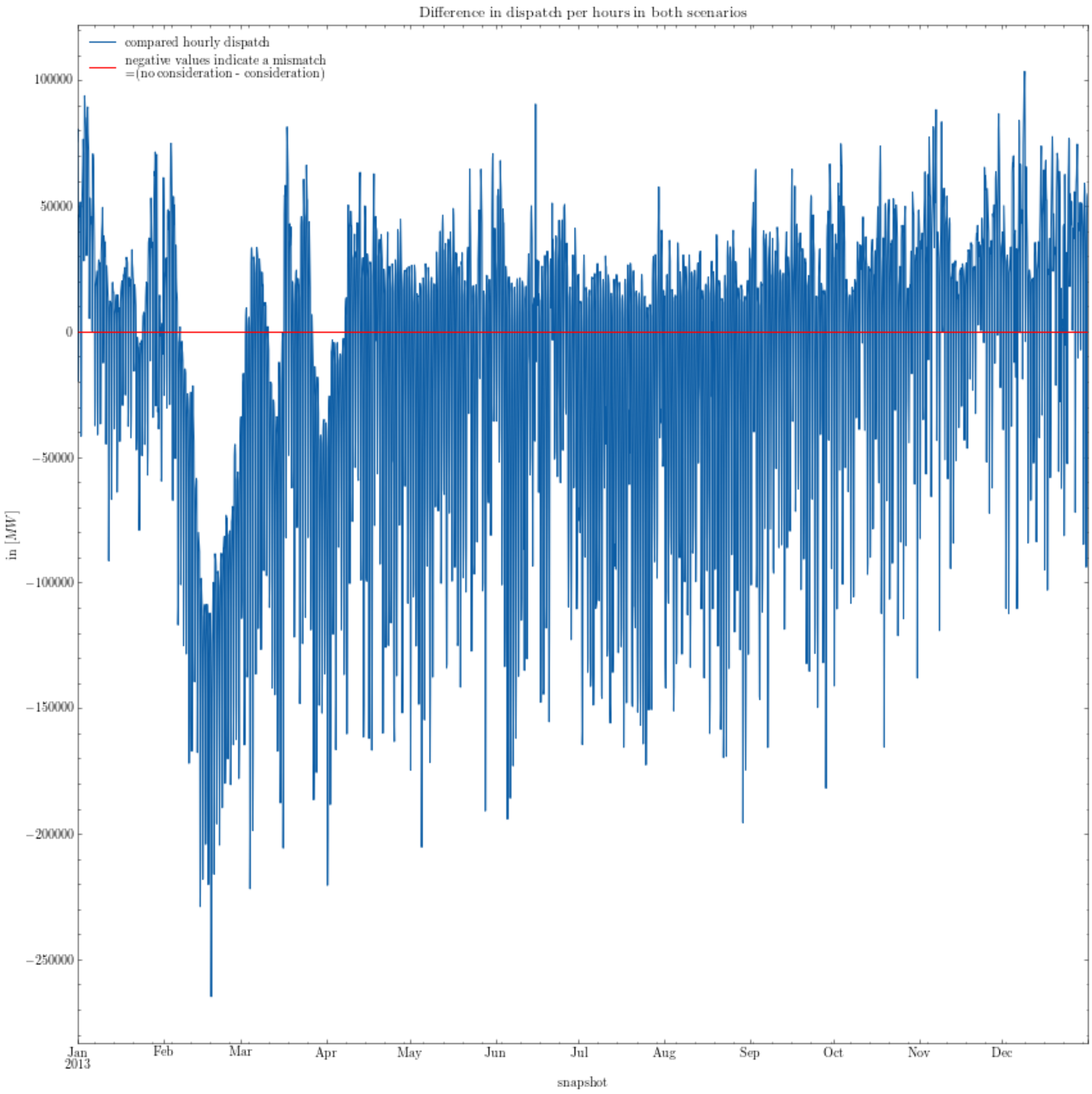


Figure 4.9: Dispatch of loads for one exemplary year

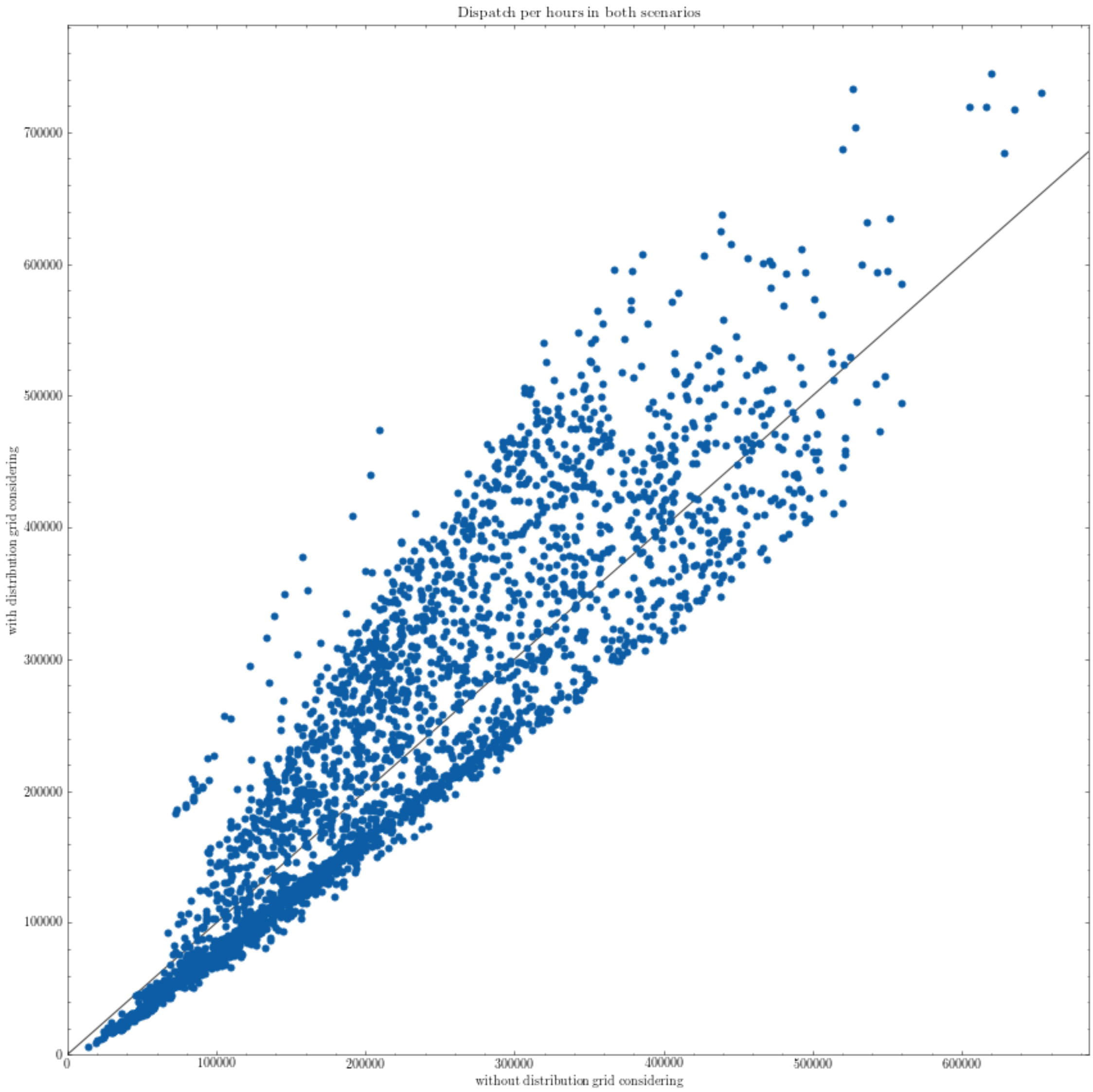


Figure 4.10: Generation compared between considering distribution grids for each hour

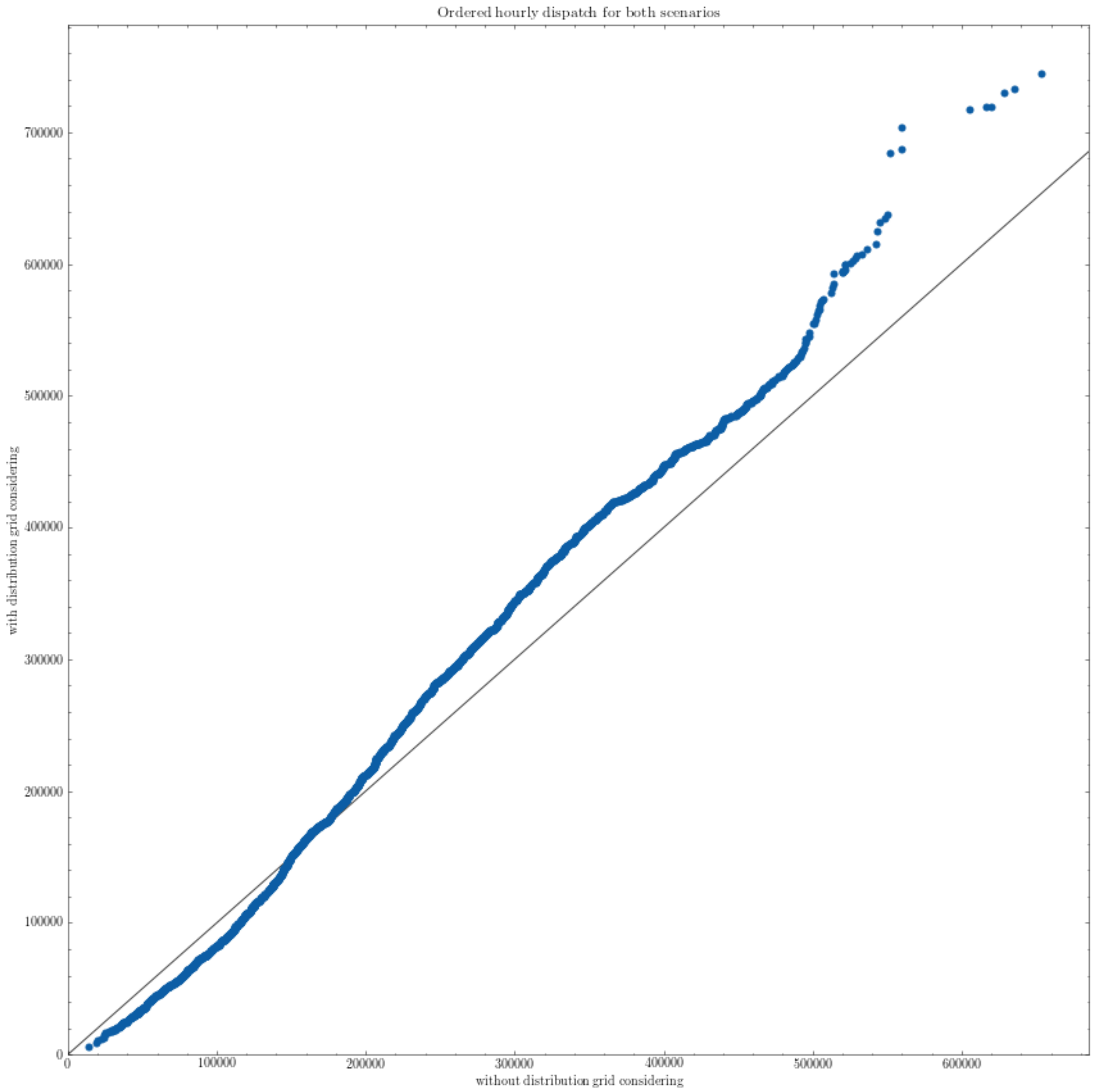


Figure 4.11: Lorenz curve

4.4 Computational burden

As for the computational burden, the sparse A matrix from the optimisation problem is compared. The A matrix describes by rows the number of constraints and by columns the number of variables.

First, the A matrix is displayed after the model formulation.

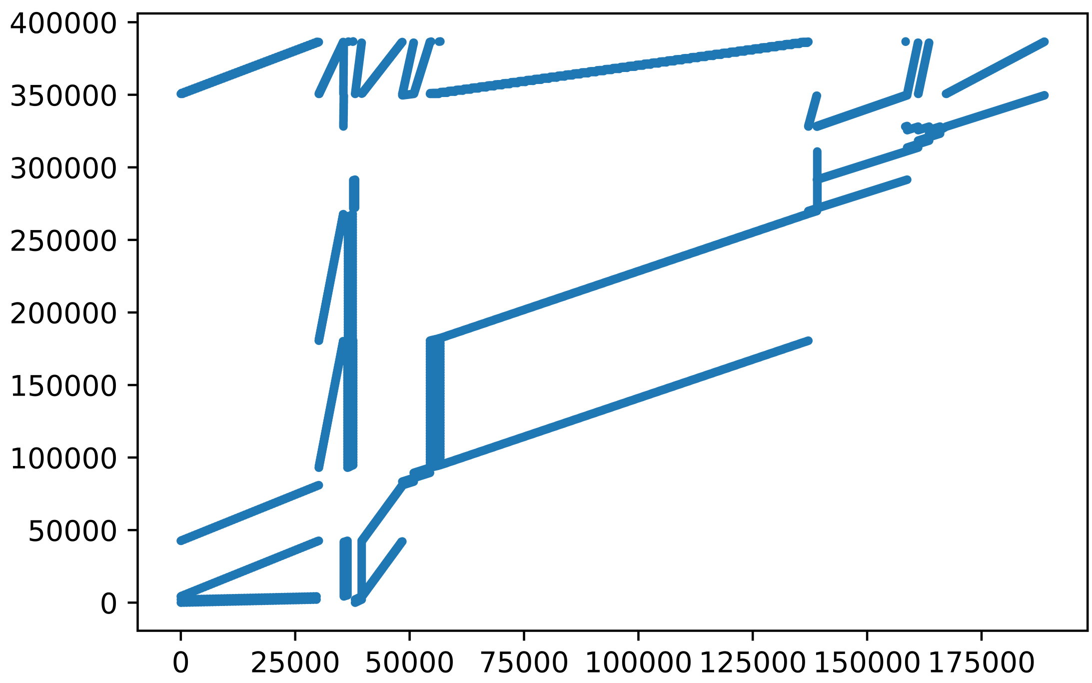


Figure 4.12: No presolve

In figure 4.12 the sparsity of the matrix is very high. The model is highly complex and most likely not very well defined. This can be observed when using the solvers' property of presolving some constraints that are not necessarily used for optimisation. A new figure can be created if the solver presolves some of these constraints beforehand.

The figure 4.13 shows a different image. Most of the constraints have been reduced from almost 400.000 down to a reduced number of less than 160.00, so by even a half. This allows the formulation of the hypothesis that the model is not well defined by the newly introduced constraints. Further investigation would be needed to analyse the difference between the model formulation with and without distribution grid constraints.

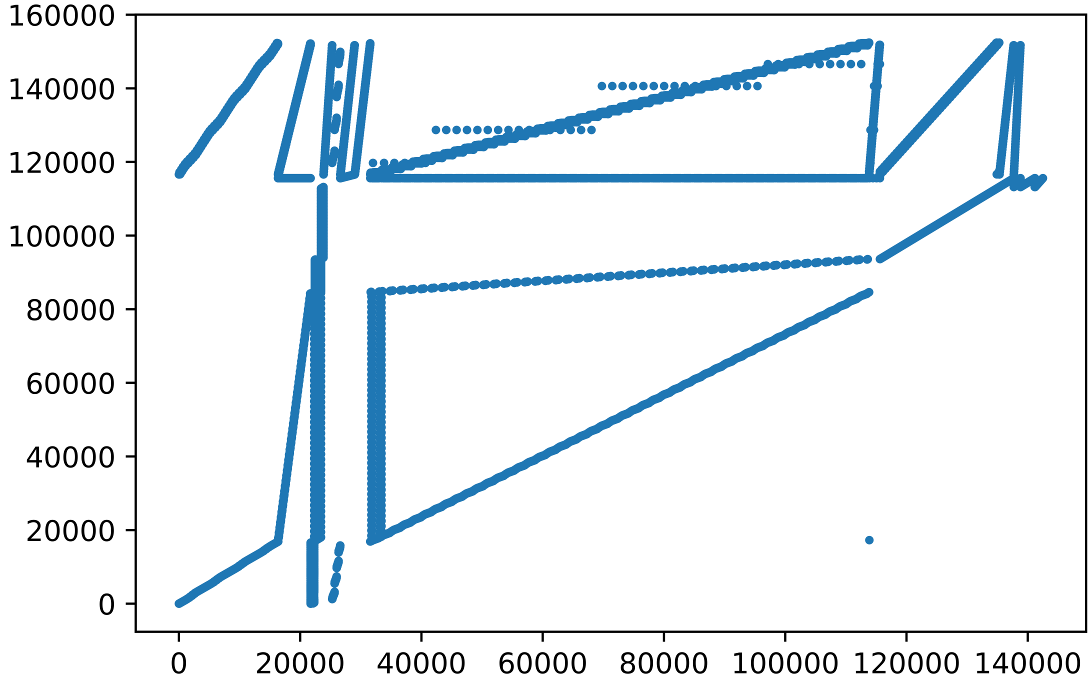


Figure 4.13: presolve

5 Summary and outlook

In the last chapter, all results will be summed up, and an outlook on future potential work is given. The overall workflow is described and further work is described that is necessary to capture further details of multi-energy systems.

5.1 Summary

In summary, the representation of distribution grids in the multi-energy system was analysed. Distribution grids play a vital role in the future of the power system as, on the one hand, a side they are the centre of the load. On the other hand, they will also become the centre of the generation. Therefore it is urgent to represent them in multi-energy systems adequately. As described, all equations resulting from the power flow would exceed the computational power nowadays. Following this, it is necessary to define suitable linear limitations to the distribution grid that would limit the power flow with its nonlinear nature. For this operation, the FOR was proposed. It defines the limits of the power exchange that can feed in or draw from the upstream power system. With this limiting an NTC link to the upstream transmission system, it is possible to include the distribution grid limits without a high computational burden. Generally, this framework can be applied to any modelling tool. However, after an exhaustive literature review, the open-source package PyPSA has been used to analyse the influence of distribution grids. The model was changed and analysed for the influence on the optimal system costs. It was observed that introducing more distribution grid classes is increasing the costs. This was linked to the level of aggregation, which would smooth out the effect of power exchange between the sectors. Therefore it seems necessary to include distribution grids in multi-energy system analysis. However, this does not come without costs. The computational burden was increased and, therefore, the runtime needed for execution. To answer the proposed research question, the inclusion of grid limits in multi-energy systems via the technique of the FOR is a suitable way of representing distribution grids.

5.2 Outlook

As for future work, there are various applications of this technique. The FOR can also be applied to the inclusion of distribution grids in large-scale solely transmission grid expansion planning. Furthermore, it can also be thought to calculate not just the feasible but also the flexible operation region by including the initial start point and using the flexible providing units to derive this region, as in [SAV20].

More research is needed in exploring distribution grid representation in multi-energy systems, as up to now only two studies have been found, which have their limitations.

Therefore the research field of multi-energy systems will be fascinating to examine in the future. It is crucial to define models that are easy to adapt, especially in the changing field of the current energy landscape. Polices can change in a very quick manner and these changing situations have to analysed carefully as the system must be resilient at all times. The future foresees the further integration of larger parts of renewable energy and this also means that the generation of energy is more variable. Still it must be met at all time, however recent progress allows the system to be operated in a more flexible way, as new technologies arise. Such can be storage technologies for instance, but also the further integration of load shifting technologies. All in all, flexibility will be the cornerstone to enable an energy system that is operated in an optimised way, sustainable, economically and environmentally.

Bibliography

[BAB19] Babaeinejadsarookolaee, S.; Birchfield, A.; Christie, R. D., et al.: The Power Grid Library for Benchmarking AC Optimal Power Flow Algorithms. 2019. DOI: 10.48550/ARXIV.1908.02788. URL: https://arxiv.org/abs/1908.02788.

[BER01] Bergen, A. R.; Vittal, V.: Power Systems Analysis. Vol. 2nd Edition. Prentice Hall. Pearson, 2001.

[BRO18a] Brown, T.; Hörsch, J.; Schlachtberger, D.: "PyPSA: Python for Power System Analysis". In: *Journal of Open Research Software* 6.4 (1 2018). DOI: 10.5334/jors.188. eprint: 1707.09913. URL: https://doi.org/10.5334/jors.188.

[BRO18b] Brown, T.; Schlachtberger, D.; Kies, A., et al.: "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system". In: *Energy* 160 (2018-10), pp. 720–739. DOI: 10.1016/j.energy.2018.06.222. URL: https://doi.org/10.1016%2Fj.energy.2018.06.222.

[CAO21] Cao, K. K.; Haas, J.; Sperber, E., et al.: "Bridging granularity gaps to decarbonize large-scale energy systems—The case of power system planning". In: *Energy Science and Engineering* 9 (8 2021-08), pp. 1052–1060. ISSN: 20500505. DOI: 10.1002/ese3.891.

[CHI20] Chicco, G.; Riaz, S.; Mazza, A., et al.: "Flexibility From Distributed Multi-energy Systems". In: *Proceedings of the IEEE* 108.9 (2020), pp. 1496–1517. DOI: 10.1109/JPROC.2020.2986378.

[COF18] Coffrin, C.; Bent, R.; Sundar, K., et al.: "PowerModels.jl: An Open-Source Framework for Exploring Power Flow Formulations". In: *2018 Power Systems Computation Conference (PSCC)*. 2018-06, pp. 1–8. DOI: 10.23919/PSCC.2018.8442948.

[CON21] Contreras, D. A.; Rudion, K.: "Computing the feasible operating region of active distribution networks: Comparison and validation of random sampling and optimal power flow based methods". In: *IET Generation, Transmission and Distribution* 15 (10 2021-05), pp. 1600–1612. ISSN: 17518695. DOI: 10.1049/gtd2.12120.

[FOD22] Fodstad, M.; Crespo del Granado, P.; Hellemo, L., et al.: "Next frontiers in energy system modelling: A review on challenges and the state of the art". In: *Renewable and Sustainable Energy Reviews* 160 (2022), p. 112246. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2022.112246. URL: https://www.sciencedirect.com/science/article/pii/S136403212200168X.

[FOR19] Fortenbacher, P.; Demiray, T.: "Reduced and Aggregated Distribution Grid Representations Approximated by Polyhedral Sets". In: (2019-03). URL: http://arxiv.org/abs/1903.07549.

[FRA16] Frank, S.; Rebennack, S.: “An introduction to optimal power flow: Theory, formulation, and examples”. In: *IIE Transactions* 48.12 (2016), pp. 1172–1197. DOI: 10.1080/0740817X.2016.1189626. eprint: https://doi.org/10.1080/0740817X.2016.1189626. URL: https://doi.org/10.1080/0740817X.2016.1189626.

[GEI07] Geidl, M.: “Integrated Modeling and Optimization of Multi-Carrier Energy Systems”. en. PhD thesis. Zürich: ETH Zurich, 2007. DOI: 10.3929/ethz-a-005377890.

[GOT19] Gotzens, F.; Heinrichs, H.; Hörsch, J., et al.: “Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases”. en. In: *Energy Strategy Reviews* 23 (2019-01), pp. 1–12. ISSN: 2211467X. DOI: 10.1016/j.esr.2018.11.004. URL: https://linkinghub.elsevier.com/retrieve/pii/S2211467X18301056 (visited on 2018-12-03).

[GÖT19] Götze, J.; Dancker, J.; Wolter, M.: “A general MILP based optimization framework to design Energy Hubs”. In: *At-Automatisierungstechnik* 67 (11 2019-11), pp. 958–971. ISSN: 2196677X. DOI: 10.1515/auto-2019-0059.

[HÖR18] Hörsch, J.; Ronellenfitsch, H.; Witthaut, D., et al.: “Linear optimal power flow using cycle flows”. In: *Electric Power Systems Research* 158 (2018-05), pp. 126–135. DOI: 10.1016/j.epsr.2017.12.034. URL: https://doi.org/10.1016%2Fj.epsr.2017.12.034.

[KIT18] Kittl, C.; Sarajlić, D.; Rehtanz, C.: “k-means based identification of common supply tasks for low voltage grids”. In: *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. 2018, pp. 1–5. DOI: 10.1109/ISGTEurope.2018.8571658.

[KLY19] Klyapovskiy, S.; You, S.; Cai, H., et al.: “Incorporate flexibility in distribution grid planning through a framework solution”. In: *International Journal of Electrical Power Energy Systems* 111 (2019), pp. 66–78. ISSN: 0142-0615. DOI: https://doi.org/10.1016/j.ijepes.2019.03.069. URL: https://www.sciencedirect.com/science/article/pii/S0142061518325079.

[KOT21] Kotzur, L.; Nolting, L.; Hoffmann, M., et al.: “A modeler’s guide to handle complexity in energy systems optimization”. In: *Advances in Applied Energy* 4 (2021-11). ISSN: 26667924. DOI: 10.1016/j.adapen.2021.100063.

[KRI18] Kriechbaum, L.; Scheiber, G.; Kienberger, T.: “Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges”. In: *Energy, Sustainability and Society* 8.1 (2018), p. 35. DOI: 10.1186/s13705-018-0176-x. URL: https://doi.org/10.1186/s13705-018-0176-x.

[LOP21] Lopez, L.; Gonzalez-Castellanos, A.; Pozo, D., et al.: QuickFlex: a Fast Algorithm for Flexible Region Construction for the TSO-DSO Coordination. 2021. DOI: 10.48550/ARXIV.2107.00114. URL: https://arxiv.org/abs/2107.00114.

[MAT18] Mateo, C.; Prettico, G.; Gómez, T., et al.: “European representative electricity distribution networks”. In: *International Journal of Electrical Power Energy Systems* 99 (2018), pp. 273–280. ISSN: 0142-0615. DOI: https://doi.org/10.1016/j.ijepes.2018.01.027. URL: https://www.sciencedirect.com/science/article/pii/S014206151731801X.

[MEI20] Meinecke, S.; Sarajlić, D.; Drauz, S. R., et al.: “SimBench—A Benchmark Dataset of Electric Power Systems to Compare Innovative Solutions Based on Power Flow Analysis”. In: *Energies* 13.12 (2020). ISSN: 1996-1073. DOI: 10.3390/en13123290. URL: https://www.mdpi.com/1996-1073/13/12/3290.

[MÜL19] Müller, U. P.; Schachler, B.; Scharf, M., et al.: “Integrated Techno-Economic Power System Planning of Transmission and Distribution Grids”. In: *Energies* 12.11 (2019). ISSN: 1996-1073. DOI: 10.3390/en12112091. URL: https://www.mdpi.com/1996-1073/12/11/2091.

[NAZ21] Nazari-Heris, M.; Asadi, S.; Mohammadi-Ivatloo, B.: Planning and Operation of Multi-Carrier Energy Networks. Ed. by M. Nazari-Heris; S. Asadi; B. Mohammadi-Ivatloo. Springer International Publishing, 2021. ISBN: 978-3-030-60085-3. DOI: 10.1007/978-3-030-60086-0. URL: https://link.springer.com/10.1007/978-3-030-60086-0.

[PED11] Pedregosa, F.; Varoquaux, G.; Gramfort, A., et al.: “Scikit-learn: Machine Learning in Python”. In: *Journal of Machine Learning Research* 12 (2011), pp. 2825–2830.

[PFE18] Pfenninger, S.; Hirth, L.; Schlecht, I., et al.: “Opening the black box of energy modelling: Strategies and lessons learned”. In: *Energy Strategy Reviews* 19 (2018), pp. 63–71. ISSN: 2211-467X. DOI: https://doi.org/10.1016/j.esr.2017.12.002. URL: https://www.sciencedirect.com/science/article/pii/S2211467X17300809.

[PRI20] Prina, M. G.; Manzolini, G.; Moser, D., et al.: “Classification and challenges of bottom-up energy system models - A review”. In: *Renewable and Sustainable Energy Reviews* 129 (2020), p. 109917. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2020.109917. URL: https://www.sciencedirect.com/science/article/pii/S1364032120302082.

[RAV22] Raventós, O.; Dengiz, T.; Medjroubi, W., et al.: “Comparison of different methods of spatial disaggregation of electricity generation and consumption time series”. In: *Renewable and Sustainable Energy Reviews* 163 (2022), p. 112186. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2022.112186. URL: https://www.sciencedirect.com/science/article/pii/S1364032122001101.

[REV22] Reveron Baecker, B.; Candas, S.: “Co-optimizing transmission and active distribution grids to assess demand-side flexibilities of a carbon-neutral German energy system”. In: *Renewable and Sustainable Energy Reviews* 163 (2022), p. 112422. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.

2022.112422. URL: https://www.sciencedirect.com/science/article/pii/S136403212200329X.

[SAV20] Savvopoulos, N.; Hatziargyriou, N.: "Estimating Operational Flexibility from Active Distribution Grids". In: IEEE, 2020-09, pp. 1–6. ISBN: 978-1-7281-6919-4. DOI: 10.1109/EEM49802.2020.9221991. URL: https://ieeexplore.ieee.org/document/9221991/.

[SCH10] Schulze, M.; Gašparović, G.; Lee, J.: "Pricing of multi-energy network flow". In: *2010 IEEE International Energy Conference*. 2010, pp. 542–547. DOI: 10.1109/ENERGYCON.2010.5771741.

[SCH22] Schwaeppe, H.; Böttcher, L.; Schumann, K., et al.: "Analyzing Intersectoral Benefits of District Heating in an Integrated Generation and Transmission Expansion Planning Model". In: *Energies* 15 (7 2022-03), p. 2314. ISSN: 1996-1073. DOI: 10.3390/en15072314. URL: https://www.mdpi.com/1996-1073/15/7/2314.

[SIA20] Siala, K.: "Spatial Complexity in Energy System Modeling". PhD-Thesis. Technical University Munich, 2020.

[SON21] Son, Y.-G.; Oh, B.-C.; Acquah, M. A., et al.: "Multi Energy System With an Associated Energy Hub: A Review". In: *IEEE Access* 9 (2021), pp. 127753–127766. DOI: 10.1109/ACCESS.2021.3108142.

[TIN67] Tinney, W. F.; Hart, C. E.: "Power Flow Solution by Newton's Method". In: *IEEE Transactions on Power Apparatus and Systems* PAS-86.11 (1967), pp. 1449–1460. DOI: 10.1109/TPAS.1967.291823.

[WU19] Wu, Q.-H.; Zheng, J.; Jing, Z., et al.: Large-Scale Integrated Energy Systems. Springer Singapore, 2019. ISBN: 978-981-13-6942-1. DOI: 10.1007/978-981-13-6943-8. URL: http://link.springer.com/10.1007/978-981-13-6943-8.

[YAN21] Yang, X.; Xu, C.; He, H., et al.: "Flexibility Provisions in Active Distribution Networks With Uncertainties". In: *IEEE Transactions on Sustainable Energy* 12.1 (2021), pp. 553–567. DOI: 10.1109/TSTE.2020.3012416.

[ZHE21] Zheng, D.; Zhang, W.; Netsanet Alemu, S., et al.: "Chapter 1 - The concept of microgrid and related terminologies". In: *Microgrid Protection and Control*. Ed. by D. Zheng; W. Zhang; S. Netsanet Alemu, et al. Academic Press, 2021, pp. 1–12. ISBN: 978-0-12-821189-2. DOI: https://doi.org/10.1016/B978-0-12-821189-2.00008-5. URL: https://www.sciencedirect.com/science/article/pii/B9780128211892000085.

[ZHU21] Zhu, M.; Xu, C.; Dong, S., et al.: "An integrated multi-energy flow calculation method for electricity-gas-thermal integrated energy systems". In: *Protection and Control of Modern Power Systems* 6 (1 2021-12). ISSN: 23670983. DOI: 10.1186/s41601-021-00182-2.