Deliverable 2.2.
Mathematical formulation of the model

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Editors: Henrik Schwaeppe, Luis Böttcher, Marco Franken, Klemens Schumann, Michele Monaci, Antonio Punzo, Paolo Paronuzzi

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Executive summary

This deliverable outlines the mathematical and functional formulation of the PlaMES tools, which will be used for the investigations within the project. The overall target of PlaMES, an integrated planning of multi-modal energy systems, is divided into six sub problems that can be run in required sequences. Common to all presented models is that they base on a single-stage expansion planning approach. Despite a focus on the electrical system, various sector-coupled commodities, such as heat or fuels, can be addressed and thus allow for multi-modal expansion planning.

The tool Central Energy System (CES) allows planning the necessary generation expansion in the centralised energy system. Thereby, necessary grid expansion in the transmission and distribution grid are considered. Furthermore, CO2 emissions can be capped as a constraint. The objective function of CES is minimising the overall costs of investments and operation.

Transmission expansion planning (TEP) allows for a detailed expansion planning of the electrical transmission network, considering the allocation of generation units and their dispatch provided by CES. To reduce investments in poles and wires, innovative technologies are considered.

The generation expansion planned in the CES can be disaggregated onto building level in Decentral Energy System Disaggregation (DESD) to allow a detailed operational planning in Decentral Energy System Operation (DESOP). Since the target of PlaMES is to plan an energy system in 2050, coordination mechanisms can be considered that allow coordinating the energy supply assets in Decentral Energy Systems, based on various approaches such as Local Energy Markets.

A distribution network expansion can be planned within Distributed Network Expansion Planning (DNEP). This expansion is based on nodal time series in the distribution network which have been determined in (DESOP). A model to calculate a factor for determining necessary distribution network expansion costs depending on the integration of technologies is described in Decentral Energy System Aggregation. This cost factor can then be used in CES to consider the distribution network expansion in planning the central energy system.

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Chapter 1

Introduction

The general objective of PlaMES is the development of an integrated planning tool for multi-energy systems on a European scale considering the expansion of generation and storage technologies as well as related infrastructure in an integrated manner. Disruptive structural developments are necessary to deliver to the European Union's COP21 commitments, as defined by the "Clean Energy for All Europeans" package . Specific targets and measures are identified for the energy performance in buildings, renewable energy, energy efficiency, governance and the market designs that envisage an increased cross-border cooperation and mobilisation of public and private investment. Providing European energy system planners with the means to develop efficient strategies to reach these goals is however associated with significant challenges.

In the following, a mathematical and functional formulation of the PlaMES tools is outlined and developed. Not neglecting the intention of an integrated planning, several tools are developed that cater to the individual needs of planning approaches in generation, transmission and distribution infrastructure expansion planning. The core of each tool is a mathematical model which is described with its own nomenclature. As opposed to a monolithic model formulation, decomposing the problem benefits applicability as well as solvability. The decomposition approach follows functionality with different planning aspects in focus. As a result each tool can be run separately, nevertheless, every tool is needed to get a comprehensive understanding.

To achieve the targets of PlaMES and answer the research questions, the tools have to be run in a certain order, giving inputs and requiring the outputs of each other. However, each tool can be run on its own when being given a proper input. By that, each tool can provide its own value for different use cases. Within the use cases that shall be answered in PlaMES, the PlaMES tools will use a shared data collection and to ensure consistent scenarios. Potential input data have already been introduced in Deliverable 2.1 "Definition of common scenario framework, data/modelling requirements and use cases".

The PlaMES tools consists of six tools total. A basic overview is illustrated in Figure 1.1.

1. DESA derives costs for each decentral network area by performing a distribution grid expansion planning for various supply tasks depending on the integration of technologies to the respective area. The result of this model can then be used in central planning.
2. In a fully linearised approach, CES plans the Central Energy System, taking data from DESA and the transmission grid into account.
3. The result of the CES will then be given to the TEP. It will focus on a detailed expansion planning approach analysing different expansion technologies and congestion management interventions.
4. Decentral Energy System Disaggregation (DESD) undertakes the placing of renewable energy sources and other assets, that have centrally been planned in CES for a Decentral Energy System (DES).
5. The operation of a DES can be performed by DESOP and can be enriched by information from CES.
6. DNEP is an optimisation approach to distribution network expansion planning

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Common to all presented models is that they base on a single-stage expansion planning approach, opposed to a multi-stage approach over several years. Focusing on the electrical system, various sector-coupled commodities, such as heat or fuels, can be addressed and thus allow for multi-modal expansion planning.

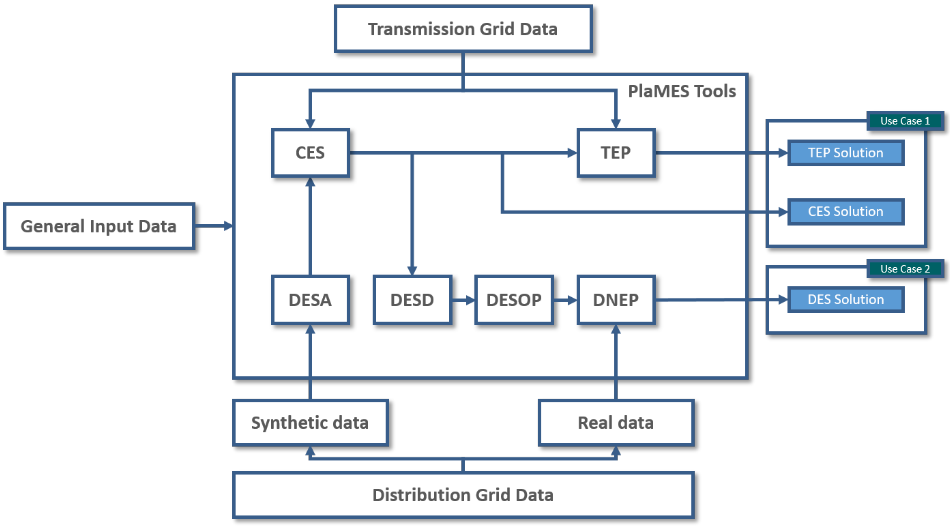

Figure 1.1: Overview of the tools to be developed in PlaMES and how they interact with each other to obtain multi-modal planning results.

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Chapter 2

Central Energy System Planning

Several approaches to multi-modal system planning exist. In PlaMES, central planning aims at a detailed single-stage expansion. It stands in the tradition of conventional Generation Expansion Planning (GEP) problems, with hourly-based linear Unit Commitment (UC). The CES planning tool aims to mirror various forms of energy, often also referred to as commodities. This is especially required, when energy can be transitioned from one commodity to another (electrity can be used to produce hydrogen) or when services can be supplied by several commodities (heat can be supplied by gas, electricity or by the use of waste heat). This is also known as sector-coupling. Generic approaches describe generation, transmission and on aggregated level distribution/consumption in multi-energy systems. As a first outcome of this deliverable, we present a (pure) linear TEP approach as integral part of the central expansion planning.

Whilst CES can be run standalone, it is designed to incorporate and output data in compatible PlaMES tool formats. Detailed expansion costs are obtained by the DESA tool. Although a simple transmission expansion planning takes place, the linear implementation in the CES planning tool does not supersede the detailed planning approach in the classical TEP model. Therefore a detailed expansion planning is required. Furthermore, the results of CES will disaggregated within DESOP to enable further investigation in distributed planning approaches.

2.1 Problem definition

In the following, a generic, single-stage expansion planning model for multi-energy systems is described. It is intended to be described as pure linear program. The problem definition involves several commodities, systems and targets that are interlinked in several aspects. This requires the introduction of a concept to describe several systems, mainly achieved by a set of *nodes* that connect technologies and *areas* that can be used to define constraint or target clusters or correspond to an area represented by a single node. The concept is intended to be versatile and generically extendable.

To illustrate why such nodes are needed we illustrate an imaginary power plant, fired with biofuel, also depicted in Fig. 2.1. It is connected to the electric grid. Residual heat is used for district heating, therefore it is connected to a district heating node[1]. Biofuel supply is restricted to a pre-defined extent in the area the plant is located in. Fuel is supplied by a node that represents the area. This configuration allows for modelling of transport of fuels in later models. Lastly, the power plant contributes to reaching emission or renewable quota targets in pre-defined areas. Technologies can be connected to various nodes for different properties and reasons.

The problem definition intends to be as generic as possible. Besides suggestions and the distinction whether variables relate to power, energy, volume etc., there are no fixed units for variables. Although we currently expect the model to calculate in hourly time-steps, other temporal resolutions are possible[2]. Following a similar logic, the implementation is not limited to

1. District heating networks usually do not exceed a pipe length of 50 kilometres, therefore we treat them as local, independent problems.
2. In chapter 2 most examples should relate to Megawatt (MW) and Megawatt-hour (MWh), if not stated otherwise. Calculating on an hourly basis has the benefit of simple power to energy calculations (P[MW] $\cdot$ t[h] $= E$[MWh]).

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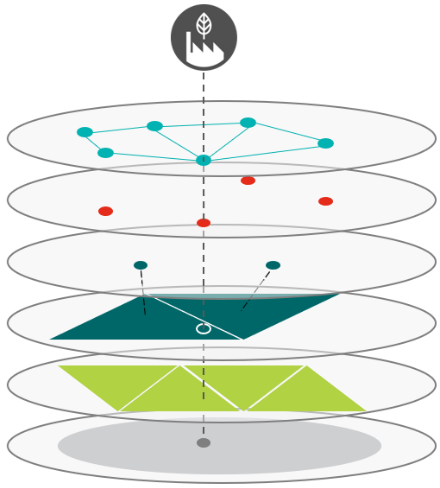

Figure 2.1: Different sets of nodes and layers to depict how decision variables might be linked to various nodes, layers, areas.

fuels introduced in the definition; fuels can be added in a later approach, just as additional emission, pollution or target constraints.

The notation will be based on an *Active sign convention*[3]. A mixed used of *Active* and *Passive sign conventions* will be avoided to prevent signing mistakes and ensure fast checks on the conservation of energy. Hence, a producing component will have positive values ($x_{it} \geq 0$), a passive component will have a negative value ($x_{it}, D_{jt} \leq 0$). Variables will be given as lower case letters (x_{it}), constants as upper case letters (D_{it}). Deviations will be pointed out.

Set	Element of set	Total elements	Description
N	j	n	Set of electric nodes
E	e	m	Set of electric edges (transmission lines)
T	-	θ	Set of time slots
DH	k	d	Set of thermal nodes
F	-	f	Set of fuel node sets
P	c	α	Set of emission nodes

Table 2.1: Sets used within the CES model.

Subset	Element in set	Description
$M(j)$	$j \in N$	technologies available at electric node j
E_{cand}	$E_{cand} \subset E$	Set of transmission *candidate* lines
$B(g)$	$g \in E$	Contains pair of nodes connected by e
$W(k)$	$k \in DH$	Set of technologies available at the district heating node k
$P(c)$	$c \in P$	a set of technologies with emissions at emission node c
$G(q)$	$q \in G$	Set of technologies connected to a fuel entry/exit point q

Table 2.2: Subsets used within the CES model.

3. With an Active sign convention, opposed to a Passive sign convention, producing variables will have a positive sign, consuming variables will have a negative sign. More can be found here: `https://en.wikipedia.org/wiki/Passive_sign_convention`

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Variable	Description
x_{it}	amount of electric power generated / withdrawn by technology i during time slot t
z_{jt}	power injection in the grid through node j during time slot t
y_i	maximum power generated by technology i (installed capacity)
l_{uw}	linear decision variable for transmission corridor expansion between electrical nodes u and w
$v_{uw,t}$	virtual injection variable (needed for transmission corridor expansion)
y^{OP}	Power flow direction (binary variable)
s^-_{jt}	curtailed power at node j during time slot t (due to oversupply / congestion)
s^+_{jt}	power deficit slack at node j during time slot t
$spill_{it}$	spill variable of storages i to counter problems in hydro storage models at time
$g^{\text{FUEL}}_{t,q}$	amount of $FUEL = \{CH4; H2; ...\}$ produced or consumed at fuel node $q \in F$
q_{it}	amount of thermal energy provided by technology i during time slot t
c^T_{et}	transsmission cost variable (absolute value)
$c^{VPI}_{uw,t}$	virtual power injection cost variable (absolute variable)
e_{ui}	total emissions related to technology i

Table 2.3: Variables used within the CES model

2.2 Structure of the optimisation problem

The minimisation function is described as follows. Used sets, subsets, variables and parameters can be taken from (in order) Tables 2.1, 2.2,2.3 and 2.4.

$$\min C_{PROD} + C_{TRAN} + C_{INST} + C_{SLACK} + C_{GAS}$$

$$C_{PROD} = \sum_{t \in T} \sum_{j \in N} \sum_{i \in M(j)} C^p_i x_{it}$$

$$C_{INST} = \sum_{j \in N} \sum_{i \in M(j)} C^C_i y_i$$

$$C_{TRAN} = \sum_{t \in T} \sum_{e \in E} c^T_{et} + \sum_{t \in T} \sum_{l \in L} c^{VPI}_{et}$$

$$C_{SLACK} = \sum_{t \in T} \sum_{j \in N} C^+_j s^+_{jt} + C^-_j s^-_{jt}$$

$$C_{GAS} = \sum_{f} \sum_{q}^{G(f)} \sum_{t} C^{FUEL}_{t,q} \cdot g^{FUEL}_{t,q}$$

Any technology i has a power output x_i, that's limited by its installed capacity y_i.

$$0 \le x_{it} \le y_i \tag{2.1}$$

With installation and operation, y_i and x_{it}, emissions (CO2 equivalent) might be related. Emissions are described as:

$$e_i = E^y_i \cdot y_i + \sum_{t \in T} E^x_i \cdot x_{it} \tag{2.2}$$

The total emissions are capped by a constant

$$\sum_i e_i \le EMISSION_{total} \tag{2.3}$$

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Parameter	Description
Y_i^{max}	maximal installed capacity
D_{jt}	electric demand to be supplied at node j in time slot t
H_{kt}	thermal demand to be supplied at node k in time slot t
η_i	efficiency parameter for technology i
C_i^C	installation cost per unit of capacity of technology i
C_i^p	unit production cost of technology i
C_e^T	unit transmission cost per edge e
C_j^+	cost of positive power slack at node j
C_j^-	costs of negative power slack at node j
C^{VPI}	cost parameter for virtual power injection
E_i^y	emission coefficient related to the installation of a technology
E_i^x	emission coefficient related to the operation of a technology
E_{FUEL}^{Type}	emission (reduction) coefficient related to the import or production of fuel
$C_{t,q}^{FUEL}$	cost of importing a certain $FUEL = \{CH4; H2; ...\}$ at time t, connected to fuel node $q \in F$
F_e	maximum power transmission on line e
$PTDF_{e,j}$	coefficient representing the load on edge e per power unit from node j
$FEEDIN_{it}$	normalized feed-in of technology i at time t
CAP_i	Capacity of storage i in relation to its power output
CAP_{i0}	Initial capacity of storage in relation to its power output
$C_{b,i}$	backpressure coefficient
$C_{v,i}$	loss of electricity generation per unit of heat generated
$INFLOW_{it}$	(natural) energy inflow to storages
$COPi,t$	Coefficient Of Performance, heat conversion efficiency of heat pumps
$SOLARMAX_{i\iota}$	Value to represent maximal area for solar application (photovoltaic, solarthermal)
$LOSSES_{it}$	Thermal losses
W_i^{max}	Maximal storage energy capacity
W_i^{min}	Minimal storage energy capacity
$W_{i,0}$	Storage energy contained at time step 0

Table 2.4: Parameters used within the CES model.

The power slack could theoretically be infinite, but should be constrained by the demand at the given node, as no more slack is necessary.

$$0 \leq s_{jt}^{+} \leq -D_{jt} \tag{2.4}$$

Power feed-in must be curtail-able at any node. Most technologies have distinct decision variables for power feed-in, but especially renewable feed-in only has one expansion variable with normalized feed-in.

$$s_{jt}^{-} \leq 0 \tag{2.5}$$

$$s_{jt}^{-} - \sum_{i} y_i \cdot FEEDIN_{it} \leq 0 \quad \forall t \in T, i \in M(j) \tag{2.6}$$

Nodal injection is described by the former values.

$$z_{jt} = \sum_{i \in M(j)} x_{it} + D_{jt} + s_{jt}^{+} + s_{jt}^{-} \tag{2.7}$$

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2.3 Power Transfer Distribution Factors

To model the electric transmission grid, a Power Transfer Distribution Factor (PTDF) approach is used. It is a linearization of an Alternating Current (AC) power flow, converting it into a Direct Current (DC) power flow, a good and proven approximation of the original problem. The PTDF matrix describes the linear relationship between nodal injections and power flow through transmission lines. Its size is $E \times N$ (Edges × Nodes). Each row represents a power line, each column represents injection at a node. The value units are "per unit" (*p.u.*) and refer to 1 MW of electrical power, but could be chosen otherwise. The process of obtaining a PTDF matrix is neglected at this point and will be given externally.[4] An exemplary PTDF is shown in Figure 2.2.[5]

$$PTDF = \begin{bmatrix} 0.27 & -0.45 & 0 & -0.18 & -0.09 \\ 0.73 & 0.45 & 0 & 0.18 & 0.09 \\ 0.27 & 0.55 & 0 & -0.18 & -0.09 \\ -0.18 & -0.36 & 0 & -0.55 & -0.27 \\ -0.09 & -0.18 & 0 & -0.27 & -0.64 \\ 0.09 & 0.18 & 0 & 0.27 & -0.36 \end{bmatrix}$$

Figure 2.2: Exemplary PTDF matrix

There is a constraint for every power line and time step, constraining nodal injection to a thermal line capacity F_e. Equation 2.8 allows to obtain the absolute flow on a power line f_{et}. The absolute values are used to calculate transport cost. This resembles potential losses through ohmic resistance, secondly it incentivizes to solve problems as close to its occurence as economically reasonable.

$$\sum_{j \in N} z_{j,t} PTDF_{e,j} = \quad f_{et} \quad \forall e, t \tag{2.8}$$

$$f_{et} \leq F_e \quad \forall e, t \tag{2.9}$$

$$-f_{et} \leq F_e \quad \forall e, t \tag{2.10}$$

$$f_{et} \cdot C_e^T \leq c_{et}^T \tag{2.11}$$

$$-f_{et} \cdot C_e^T \leq c_{et}^T \tag{2.12}$$

The sum of nodal injections must fulfill the system balance requirement:

$$\sum_{j \in N} z_{jt} = 0 \quad t \in T \tag{2.13}$$

An exemplary calculation with the values of Figure 2.2 is showcased in Table 2.5. For a conceptual understanding, it's important that voltage angles are part of the equations behind the PTDF. A reference angle is needed and therefore a reference node must be defined to determine the voltage angles of the other nodes. The reference node will be nulled in the PTDF equation. Injecting power at this node will not have an immediate effect on other power lines. In accordance with Equation 2.13, injected power will also be withdrawn at another node, therefore injecting energy at the reference node will have an effect on the system, anyway.

4. The PTDF matrix is based on the assumption that there is no ohmic resistance $R[\Omega]$. More precisely, resistance is neglected, because $R << X$, $X[\Omega]$ being the electric reactance. As a result, power flow depends on electrical reactance only, which determines the corresponding voltage angles at both ends of a power line, respectively δ_N and δ_Q. The calculations can be linearized, as the difference between voltage angles isn't very large and can therefore be simplified to $\sin(\delta_N - \delta_Q) \approx \delta_N - \delta_Q$ and $\cos(\delta_N - \delta_Q) \approx 1$.

5. Kenneth Van den Bergh, Erik Delarue, and William D'haeseleer, *DC power flow in unit commitment models*, University of Leuven - Energy Institute, Leuven, May 2014, accessed May 26, 2020, `https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wpen2014-12.pdf`.

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edge	-capacity	**sum**	+capacity	node 1 +90MW	node 2 (+10MW)	node 3 (0MW)	node 4 (-50MW)	node 5 (-50MW)
(1,2)	-100MW	**33.3MW**	+100MW	24.3	-4.5	0	9	4.5
(1,3)	-200MW	**56.7MW**	+200MW	65.7	4.5	0	-9	-4.5
(2,4)	-300MW	**43.3MW**	+300MW	24.3	5.5	0	9	4.5
(3,4)	-80MW	**-5.8MW**	+80MW	-16.2	-3.6	0	27.5	-13.5
(3,5)	-90MW	**35.6MW**	+90MW	-8.1	-1.8	0	13.5	32
(4,5)	-600MW	**14.4MW**	+600MW	8.1	1.8	0	-13.5	18

Table 2.5: Using the PTDF for an example. Multiplied with the nodal feed-in/withdrawal, values do not represent p.u. anymore, but MW.

2.4 Grid expansion

CES planning incorporates a fully linearised approach for transmission network expansion or, more precisely, line capacity expansion. This is achieved by manipulating the PTDF equations through virtual power injection,[6] but using relaxed binary variables. The PTDF is calculated with *all candidates built*. If two power lines were expandable, the PTDF would be enhanced by two more rows. The number of nodes remains the same as before.

Every candidate line can be supplemented through Virtual Power Injection (VPI). Candidate lines have two power virtual generators, depicted as double lines in Figure 2.3. A candidate line e is connected to two nodes u and w, hence the virtual generators attached to each end of the line are described as $v_{uw,t} = v^{+}_{uw,t} = -v^{-}_{uw,t}$. Virtual generators manipulate the flow on a line. If a line should be built, virtual generators are idle. If a line should not be built, virtual generators inject (and withdraw[7]) power in such a way, that the flow equation of the candidate line equals zero, which is equivalent to the line not being built. Such virtual generators must be added to the existing PTDF equations introduced in Equation 2.8.

$$\sum_{j\in N} z_{jt} PTDF_{e,j} + \sum_{g} (PTDF_{e,u} - PTDF_{e,w}) v_{uw,t} = f_{et} \quad u,w \in B(g), g \in E_{cand}, \forall e,t; \tag{2.14}$$

Whether a candidate line is built between u and w is dependent on decision variable l_{uw}. If lines are fully built ($l_{uw} = 1$), their virtual generators are inoperable. Built, virtual generators only allow for the expanded capacity to be transferred over the particular line.

$$0 \le l_{uw} \le 1 \tag{2.15}$$

$$F_{uw}(l_{uw} - 1) \le v_{uw,t} \le F_{uw}(1 - l_{uw}) \tag{2.16}$$

$$v_{uw,t} - (\sum_{j\in N} z_{jt} PTDF_{e,j} + \sum_{g} (PTDF_{e,o} - PTDF_{e,p}) v_{op,t}) \le \quad l_{uw} \cdot F_{uw} \quad o,p \in B(g), g \in E_{cand} \tag{2.17}$$

$$-v_{uw,t} + (\sum_{j\in N} z_{jt} PTDF_{e,j} + \sum_{g} (PTDF_{e,o} - PTDF_{e,p}) v_{op,t}) \le -l_{uw} \cdot F_{uw} \quad o,p \in B(g), g \in E_{cand} \tag{2.18}$$

Because the described approach is a pure linear implementation of a binary problem, virtual generators have more degrees of freedom, especially when a line is built only half ($l_{uw} = 0.5$). To incentivise the correct behaviour of virtual generators (minimal usage), its operation has a certain cost.

6. Mohsen Rahmani, Gabriela Hug, and Amin Kargarian, "Comprehensive power transfer distribution factor model for large-scale transmission expansion planning," *IET Generation, Transmission & Distribution* 10, no. 12 (2016): 2981–2989, ISSN: 1751-8687, doi:10.1049/iet-gtd.2015.1573.

7. It is important to note that because $v^{+}_{uw,t} = -v^{-}_{uw,t}$, the energy balance remains the same.

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$$v_{uw,t} \cdot C^{VPI} \leq c^{VPI}_{uw,t} \tag{2.19}$$

$$-v_{uw,t} \cdot C^{VPI} \leq c^{VPI}_{uw,t} \tag{2.20}$$

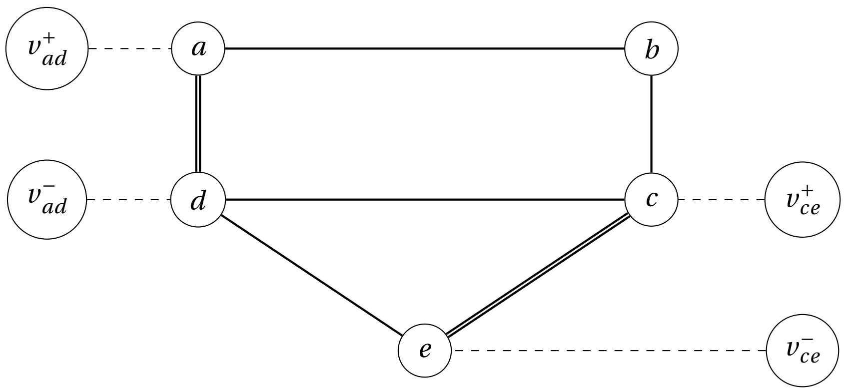

Figure 2.3: Exemplary grid. Double lines indicate expansion candidates. Virtual power injection is described by the suggested virtual power injectors.

2.5 Expansion of electrical technologies

In the following, the construction of the mathematical formulation assumes that system components will be newly built. The straightforward implementation is explained in this section. Existing power plants are a part in the modelling process, too, but only require setting expansion variables to constant.

2.5.1 Renewables: wind turbines and/or photovoltaic systems

Feed-in from wind turbines and photovoltaic systems depends on external conditions, like wind or solar radiation. The feed-in can therefore not be steered, only capped when oversupply occurs. Upfront a normalized feed-in profile is created. For each technology at every node there is a $0 \leq FEEDIN_{it} \leq 1$ that describes the feed-in of the technology per power unit y_i. There is no cost and emissions associated, therefore $C^p_i = 0$ and $E^x_i = 0$. It can be expected that the emissions of a power plant are positive ($E^y_i > 0$).

$$x_{it} = FEEDIN_{it} \cdot y_i \quad t \in T, i \in M(j), j \in N \tag{2.21}$$

$$y_i \leq Y^{max}_i \quad i \in M(j), j \in N \tag{2.22}$$

2.5.2 Energy conversion: Thermal power plants, fuel cells

Electrical feed-in from power plants is described by x_{it}. In most cases, fuel consumption is described by the energy conversion efficiency to electrical energy η_i.

$$g^{\text{FUEL}}_{t,q} = \sum_{i \in G(q)} x_{it} / \eta_i \tag{2.23}$$

The emission and cost related to installation (E^y_i, C^C_i) especially depend on the chosen technology. Emissions and cost related to operation (E^x_i, C^p_i) depend on the related fuel and efficiency parameters. The fuel cost might either be directly attributed to the power plant or to the import of the fuel (described in section 2.6). Additional operational cost may also be added to C^p_i. Emissions directly depend on the fuel, but can be adjusted in case certain technologies are used. For example, if a power plant with Carbon Capture Storage (CCS) could be added, E^x_i and efficiency η_i would be decreased while the effort for installation would increase cost and installation emissions, E^y_i and C^C_i, likewise.

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Future technologies will be flexible in operation, but some power plants might still be constrained by a ramping constraint $0 \leq RAMP_i \leq 1$, describing possible ramps dependent on the total installed capacity. Linear approximations for startup cost are out of scope, but can be added when required.

$$-y_i \cdot RAMP_i \leq x_{it} - x_{i(t-1)} \leq y_i \cdot RAMP_i \tag{2.24}$$

Existing power plants can be modelled just as $y_i = P_i^{max} = const.$ and $C_i^C = 0$. Dismantling of power plants can be approximated by setting it up as $0 \leq y_i \leq P_i^{max}$ and c_i^C reflecting the yearly fixed costs of the power plant, assumably lower than the installation cost of new plants. If the needed operation of the power plant is too costly, the power plant is not built, ergo dismantled.

Power plants can also **supply heat**. Related modelling is described in section 2.7.3.

2.5.3 Electrical Storage

Storage must be described by two variables, x_{it}^c for charging and x_{it}^d for discharging. In a simplified approach it's also possible to describe storage with just one variable, but only at the assumption of 100% efficiency. Efficiencies are defined as $0 \leq \eta_i^d \leq 1$ and $0 \leq \eta_i^c \leq 1$. Storages have a maximal power output, defined as known:

$$0 \leq x_{it}^c \leq y_i \quad t \in T \tag{2.25}$$

$$0 \geq x_{it}^d \geq -y_i \quad t \in T \tag{2.26}$$

Storages have a total energy capacity, related to, and within the modelling predetermined by, its power output that again depends on y_i (Equation 2.27). Storage limit is at zero, but can be capped higher if applicable (Equation 2.28). Storage balance must be fulfilled for every time step (Equation 2.29).

$$W_i^{max} = CAP_i \cdot y_i \tag{2.27}$$

$$W_i^{min} \geq 0 \tag{2.28}$$

$$W_i^{min} \leq W_{i,0} + \sum_{t=1}^{\tau} (-x_{it}^d / \eta_i^d - x_{it}^c \eta_i^c) \leq W_i^{max} \quad \forall \tau \in T \tag{2.29}$$

$W_{i,0}$ equals the amount of energy that is in the battery at the beginning of the optimisation problem with $0 \leq CAP_{i0} \leq 1$. The energy balance must be maintained. If $W_{i,0} > 0$ an additional constraint is required for the last hour of simulation.

$$W_{i,0} = CAP_{i0} \cdot y_i \tag{2.30}$$

$$0 \leq \sum_{t}^{\theta} (-x_{it}^d / \eta_i^d - x_{it}^c \eta_i^c), \quad \theta \in T \tag{2.31}$$

Emissions are not related to the use of storages, but to installation ($E_i^x = 0, E_i^y > 0$). Typically there is no cost related to the operation of batteries, although a small fee might be added to enable the estimation of opportunity costs. Attribution of cost and emissions must be made, but can be adjusted to the modellers need.

In the particular case of **hydro storages**, some properties must be modelled in addition. At first, inflow can be modelled by adding a hydro inflow time-series $INFLOW_{it} \geq 0$. As there is a very strict relation between the size and potential inflow of

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a power plant, we do not recommend to use inflow in expansion problems. To avoid problems due to excess inflow, a spill variable $spill_{it} \geq 0$ is introduced. Maximal storage and power capacity can be chosen as required.

$$W_i^{min} \leq W_{i,0} + \sum_{t=1}^{\tau} (-x_{it}^d/\eta_i^d - x_{it}^c \eta_i^c - spill_{it} + INFLOW_{it}) \leq W_i^{max} \quad \forall \tau \in T \tag{2.32}$$

2.6 Modelling of gas-related aspects

As an essential part of the energy system, gas infrastructure must be part of the optimisation problem. For a first approach, it is assumed that there will be no fatal congestion as well as sufficient gas storage. As a result, gas can be fed into the grid from any location without restrictions. Gases can either be imported or produced locally. There are different types of gases, such as natural gas (methane, CH4) or hydrogen (H2). Lastly, gases can be produced in different ways, conventionally through extraction, chemical processes, or from electrical energy and other forms of conversion. In the following it is assumed that gaseous infrastructure is operated separately. It is unlikely to expect a mixed gaseous infrastructure in the future, except for a special case, when hydrogen plants feed into the natural gas grid. The given example includes constraints for nantural gas (CH4) and hydrogen (H2), but could be extended to various forms of gases. Without further comments, efficiencies are related to the lower heating value.

There is a total import capacity for conventional gases, as well as gases from renewable sources, per year. Import capacities might be constrained generally. Lastly, the import source might vary or different sources are available (varying in cost or general configuration).

- Conventional import restriction: $CH4_{blue,import}^{restriction}$, $H2_{blue,import}^{restriction}$
- Import restriction for renewable gases: $CH4_{green,import}^{restriction}$, $H2_{green,import}^{restriction}$
- Total import restriction: $CH4_{total,import}^{restriction}$, $H2_{total,import}^{restriction}$
- Total import restriction per region: $CH4_{total,import}^{restriction,regionXYZ}$

Gases can be produced in the area studied as well, either in conventional or renewable way:

- $CH4_{blue,domestic}^{restriction}$ and $H2_{blue,domestic}^{restriction}$.
- $CH4_{green,domestic}^{restriction}$ and $H2_{green,domestic}^{restriction}$.

Every power plant that either produces or consumes some sort of gas, will be linked in the model to the certain gas consumption. The gas consumption and production can be further divided in spatial or temporal sections (although spatial affiliation is represented by fuel nodes). In the following this will be outlined for natural gas (not entirely accurately indicated by $CH4$), but can be adapted for any other gas as well.

$$\sum_{t}^{\tau} \sum_{i} x_{it}/\eta_i \leq g_{\tau,q}^{consCH4} \quad \forall \tau \in T, i \in G(q), q \in F, x_{it} \geq 0 \tag{2.33}$$

$$\sum_{t}^{\tau} \sum_{i} -x_{it} \cdot \eta_i \geq g_{\tau,q}^{prodCH4} \quad \forall \tau \in T, i \in G(q), q \in F, x_{it} \leq 0 \tag{2.34}$$

Gas consumption is constrained by the potential import per time and region and local production.

$$g_{\tau,q}^{consCH4} \leq g_{\tau,q}^{prodCH4} + g_{\tau,q}^{BlueCH4} + g_{\tau,q}^{GreenCH4} \quad \forall \tau \in T, q \in F \tag{2.35}$$

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With $g_{\tau,\alpha}^{BlueCH4}$ and $g_{\tau,\alpha}^{GreenCH4}$ being constrained by their import capacities. Various constraints can be implemented, this is only an example.

$$g_{\tau,q}^{BlueCH4} \leq CH4_{blue,import,\tau,q}^{restriction} \quad \forall \tau \in T, q \in F \tag{2.36}$$

$$g_{\tau,q}^{GreenCH4} \leq CH4_{green,import,\tau,q}^{restriction} \quad \forall \tau \in T, q \in F \tag{2.37}$$

Gas can be imported at a certain cost. The base cost for conventional gas are already reflected in the operational cost of operated power plants. The cost for importing gas adds up the cost of transport or the price difference between conventional gas and the gas with different features ("green" gas), such as $C_{t,q}^{BlueH4}$ or $C_{t,q}^{GreenCH4}$. The cost C_{GAS} is part of the minimisation function.

$$C_{GAS} = \sum_{t}\sum_{q} C_{t,q}^{BlueCH4} \cdot g_{t,q}^{BlueCH4} + C_{t,q}^{GreenCH4} \cdot g_{t,q}^{GreenCH4} + \ldots \tag{2.38}$$

Importing "green" gas has the benefit of reducing emissions in the corresponding area.

$$\sum_{i} e_i + \sum_{q}^{F(q)} \sum_{t}^{T} g_{t,q}^{GreenCH4} E_{CH4}^{Green} \leq EMISSION_{total} \tag{2.39}$$

To not allow for excessive emission reduction through gas imports, another constraints is needed:

$$g_{\tau,q}^{GreenCH4} \leq g_{\tau,q}^{consCH4} \tag{2.40}$$

Within the modelling approach it is necessary to keep the formulation as open as possible. Within PlaMES, the current formulation for gas could be enhanced by an additional gas network modelling. First of all, this is out of scope, but could be added at another time and also with respect to the solving time of the current model.

2.6.1 Energy conversion: Power-to-gas

Power-to-gas plants are the counterpart to Gas-to-power plants, converting electrical energy to a desired fuel.

$$x_{it} \leq 0 \tag{2.41}$$
$$-y_i \leq 0 \tag{2.42}$$
$$-x_{it} - y_i \leq 0 \tag{2.43}$$
$$g_{it}^{Power2H2} = -x_{it} \cdot \eta_i^{H2} \tag{2.44}$$

In case of fuel conversion (e.g. hydrogen-to-methane), another gas must also be consumed with conversion efficiency $\eta_i^{A \to B}$. In the particular example, carbon-dioxide is part of the reaction and might therefore equally reduce emissions at a certain conversion rate $E_i^x \geq 0$.

$$g_{it}^{B} = -x_{it} \cdot \eta_i^{B} \tag{2.45}$$
$$g_{it}^{A} = x_{it} / \eta_i^{A \to B} \tag{2.46}$$

If hydrogen is injected into a natural gas grid, additional measures must be applied. First of all, current natural gas infrastructure only allows for hydrogen feed-in to a certain extent, therefore feed-in must be capped at $H2MAX$. The intended

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modelling approach does not allow for a mixed use per se. For this reason, a distinction is made between power-to-gas plants that feed into hydrogen grids and those that feed into natural gas grids. Heating values, efficiencies, etc. must be adjusted to ensure physical correctness, when a mixed infrastructure is used.

$$-x_{it} \cdot \eta_i^{H2\to CH4grid} \leq H2MAX \quad \forall t \in T \tag{2.47}$$

2.7 Modelling of heating and cooling related aspects

An important part in multi-modal modelling is the use of distributed / district heating and cooling. As the name suggests, district heating is restricted to local delivery, typically not exceeding more than 50km of pipe length or typical boundaries of a city. Therefore thermal supply will be handled as local phenomenon. District heating problems will be integrated into the tool by all means. Different temperature levels and heating problems down to house level will be addressed in more aggregated approaches.

Several technologies play a role in thermal delivery. Power plants, heat pumps, heating rods, solar-thermal panels, boilers and thermal storage can take part in heat delivery, using several commodities in electrical or gaseous form.

Heat problems are described by their own delivery problem. Heat demand is described by thermal Megwatthour *MWth* per time step and node k. Heating demand is described by the constant demand $H_{k,t} \leq 0$. Parallel to the electrical problem, the sum of heating injections must be zero:

$$H_{kt} + \sum_k q_{kt} = 0 \quad \forall t \in T, k \in DH \tag{2.48}$$

2.7.1 Heat pumps, heat rods

Heat pumps consume electricity to output heat at a certain ratio depending on the outside temperature, the coefficient of performance ($COP_{i,t} = const.$). A heat pump is connected to the electrical grid at any node n and to the heating grid at any node m. Neither additional cost nor emissions are related to the operation of heat pumps, but emissions. Heat rods can be modelled just as heat pumps, but with a $COP_{i,t}$ typically lower than for heat pumps. As heat pumps/rods only convert energy, costs and emissions are associated to their installation only.

$$0 \leq x_{it} \leq y_i \quad \forall t \in T, i \in W(k), k \in DH \tag{2.49}$$

$$q_{kt} = -x_{it} \cdot COPi, t \quad \forall t \in T, i \in W(k), k \in DH \tag{2.50}$$

2.7.2 Gas boiler

Gas boilers *do not* connect to the electric grid (with significant consumption), but consume gas (efficiency η_h) and must be counted in the emissions balance.

$$q_{it} = x_{it} \cdot \eta_i \tag{2.51}$$

2.7.3 Power plants

A distinction must be made between three different technologies of heat-delivering power plants: backpressure turbines, extraction condensing turbines and the more general use of waste heat in turbines/motors. While the fuel consumption in backpressure and gas turbines can be steered by the electrical output, extraction condensing turbines have two decision variables that influence the electrical output.

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The heat output of **backpressure turbines** is linked directly to the electrical output, given by the backpressure coefficient per power plant i, $C_{b,i}$. Backpressure and gas turbines's fuel consumption is calculated as in 2.33.

$$C_{b,i} \cdot q_{it} - x_{it} = 0 \forall t \in T \tag{2.52}$$

The heat output of **gas turbines** is only *restricted* by the electrical output.

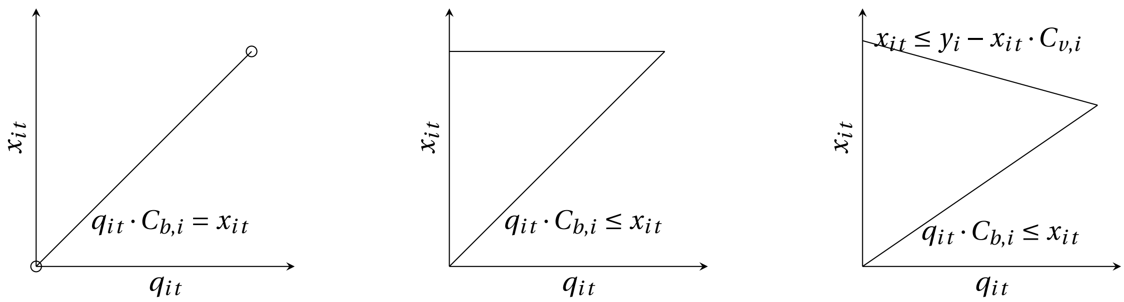
$$C_{b,i} \cdot q_{it} - x_{it} \leq 0 \forall t \in T \tag{2.53}$$

Meanwhile, **condensing extraction turbines** can operate their steam output independently, limited by the loss of electricity generation per unit of heat generated at fixed fuel input, $C_{v,i}$. Therefore fuel consumption is calculated differently. The heat output is furthermore limited by y_i and $C_{b,i}$.

$$x_{it} \leq y_i - C_{v,i} \cdot q_{it} \tag{2.54}$$

$$fuel_{i,t} = (x_{it} + C_{v,i} \cdot q_{it}) / \eta_i \tag{2.55}$$

$$C_{b,i} \cdot q_{it} - x_{it} \leq 0 \tag{2.56}$$



(a) Backpressure turbine (b) Gas turbine (c) Extraction condensing turbine

Figure 2.4: Showcasing three different types of heat extraction in (thermal) power plants. Heat output q_{it} is restricted by $q_{it}, x_{it} \geq 0$ and technology-dependent constraints.

2.7.4 Solarthermal application

Solarthermal panels can also be used to deliver heat to the system. Various technology applications are available. Eventually, such panels compete with photovoltaic panels and may therefore be restricted in an area altogether.

$$q_{\iota t} = y_\iota FEEDIN_{\iota t} t \in T, \iota \in W(k), k \in DH \tag{2.57}$$

$$y_i + y_\iota \leq SOLARMAX_{i\iota} \quad \forall i \in M(j), j \in N, \iota \in W(k), k \in DH \tag{2.58}$$

2.7.5 Thermal storage

Thermal storages are modelled like electrical storage, as described in section 2.5.3. Modelling might divide into daily, weekly and seasonal storage and different available technologies for such applications. Compared to batteries, losses mainly occur over the duration of storage. As for electrical storages, the behaviour of losses is technology-dependent and non-linear, but

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linearising losses comes with a greater error. It is up to modellers whether losses are modelled by adjusting the efficiencies η_i^d, adding constant $LOSSES_{it}$ or using a combined approach.

$$W_i^{min} \leq W_{i,0} + \sum_{t=1}^{\tau} (-q_{it}^d/\eta_i^d - q_{it}^c \eta_i^c - LOSSES_{it}) \leq W_i^{max} \quad \forall \tau \in T, i \in W(k), k \in DH \tag{2.59}$$

2.7.6 Different temperature levels

The above described technologies are common in district heating grids, that operate at certain temperature levels. Thermal energy can also be supplied at different temperature levels. Much higher temperatures are needed in industrial processes; lower temperatures for cooling networks.

Not all formerly mentioned technologies can be applied on higher temperature levels. Efficiencies depend on the operated temperature levels and must be adjusted accordingly. Feeding different temperature levels at the same time is technically possible, but requires extra steps in the modelling approach. Per temperature level an additional district heating node must be declared.

There are two approaches to district cooling:

1. delivering chilled water
2. using the district heating infrastructure with absorption chillers

While the first requires its district heating node $k \in DH$ with separate technologies, absorption chillers can be added to existing district heating infrastructure and therefore just add to thermal energy demand with their respectice coefficient of performance:

$$q_{it} = -COP_{i,t} \cdot x_{it} \quad \forall i \in W(k), k \in DH \tag{2.60}$$

2.8 Transport and Mobility

Several approaches to modelling transport and/or mobility exist. To choose one, the scope of modelling must be clear and necessary data must be available. Focusing on individual mobility and electric vehicles, three options come into play in PlaMES. Technologies besides electric vehicles also add additional demand to either gas, hydrogen or whatever the drive technology is.

1. The simplest approach are **fixed charging profiles**, simply adding electrical demand to any node.
2. As Electric Vehicle (EV)s have their own battery, charging can be shifted in time. A second approach is therefore **smart charging**. This already requires aggregated information about vehicles transport tasks and assumptions about available battery capacities.
3. With **bidirectional batteries**, EVs can not only charge but also discharge to support the grid and charge at a later point in time.

While the first option is very simple, approach 2 and 3 require modelling EVs as aggregated batteries that allow only charging or even discharging. The aggregated battery storage has a time-dependent storage capacity, comprising of the aggregated minimal and maximal capacity of vehicles connected to the grid.

$$E_{it}^{min} = \sum_{m}^{EVatGRID} W_{itm}^{min} \quad \forall i \in M(j), t \in T \tag{2.61}$$

$$E_{it}^{max} = \sum_{m}^{EVatGRID} W_{itm}^{max} \quad \forall i \in M(j), t \in T \tag{2.62}$$

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In addition to an $INFLOW$ (analogous to hydro inflow in section 2.5.3) - cars that plug their *left charge* into a charging station at a time t - cars that leave the charging station create an $OUTFLOW$. Detailed prior simulations are necessary to obtain such data, and can be assumed as constant. In the second approach, x^d_{it} can be constrained to zero.

$$CHARGE_{it} = INFLOW^{incoming}_{it} - OUTFLOW^{outgoing}_{it} \tag{2.63}$$

$$W^{min}_{it} \leq \sum_{t=1}^{\tau} (-x^d_{it}/\eta^d_i - x^c_{it}\eta^c_i + CHARGE_{it}) \leq W^{max}_{it} \quad \forall \tau \in T \tag{2.64}$$

Modelling transport tasks more widely, technologies could be chosen among a set of, e.g., methane, hydrogen, conventional fuels and battery powered vehicles. Being the outcome of personal choices and even hybrid vehicles, this form of consumption optimisation is not considered good practice. It is therefore recommended to estimate the penetration of (battery) electric vehicles to study their systemic impact. More sophisticated approaches will be postponed within PlaMES.

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Chapter 3

Transmission Expansion Planning

The Transmission Expansion Planning (TEP) aims at identifying cost-efficient expansion and congestion management measures to ensure the system security and reliability of future electrical transmission grids. Hence, overall system costs including investment costs (Capital Expenditures (CAPEX)) and operational costs (Operational Expenditures (OPEX)) are minimised. The identification of suitable measures is based on a starting topology including regarded expansion and reinforcement measures as well as on results provided by CES as the allocation of load and generation units as well as corresponding time series and asset-specific parameters (for example installed capacity or marginal cost terms).

Compared to the network expansion planning included into CES, TEP provides a more detailed expansion planning. While a new line can even be fractionally constructed within CES, the investment decision in the TEP formulation is a binary one. Hence, new assets can only be constructed completely. Furthermore, the expansion portfolio is significantly extended by including different options for resolving overloaded lines such as constructing new lines, upgrading as well as reinforcing existing ones and installing power flow controlling devices. Additionally, the grid operation is optimised to reduce investment and operational costs. Therefore, the operation of power flow controlling devices and redispatching of power plants as well as curtailing of renewable energies are investigated.

The TEP model is formulated as a Mixed Integer Linear Programming (MILP) problem and explained by presenting the temporal and technological scope, the objective function as well as corresponding restrictions distinguished into those affecting the construction of new assets (investment problem) and those limiting the grid operation (operation problem). The TEP approach is based on several approaches dealing with the expansion, reinforcement and optimisation of electrical transmission grids.[1]

3.1 Nomenclature

The mathematical formulation is presented using several sets, parameters, variables and indices being defined in the following.

1. Marco Franken et al., "Transmission Expansion Planning via Power Flow Controlling Technologies," *IET Generation, Transmission & Distribution*, 2020, ISSN: 17518687, doi:10.1049/iet-gtd.2019.1897; Marco Franken et al., "Co-Optimization of Multi-Stage Transmission Expansion Planning and Grid Operation," in *21st Power Systems Computation Conference (PSCC), accepted for publication* (2020); Marco Franken, Alexander B. Schrief, and Albert Moser, "Planung elektrischer Übertragungsnetze unter Berücksichtigung netzbetrieblicher Flexibilitäten," in *16. Symposium Energieinnovation* (2020).

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Sets

All sets are defined by the symbol Ω in combination with an corresponding index:

Set	Element of set	Description
Ω_K	k	Set of nodes
Ω_G	g, i	Set of generation units
Ω_{RES}	i	Set of renewable energy units
Ω_{PP}	i	Set of power plants
Ω_D	d	Set of loads
Ω_N	n	Set of places on line towers
Ω_V	v	Set of available voltage levels
Ω_T	t	Set of transmission corridors
Ω_{DC}	dc	Set of High Voltage Direct Current (HVDC) systems
Ω_U	u	Set of grid snapshots
Ω_{CS}	cs	Set of network (outage) situations (N-0 case and N-1 cases)

Table 3.1: Sets used within the formulation of the TEP model.

Parameters

Parameters are described by capital letters or by Greek letters used in the literature for corresponding variables.

Parameter	Description
α	Annual discount factor
γ	Susceptance
C	Cost coefficient
M	Disjunctive parameter
P	Active power
W^{CM}	Coefficient for weighting operational costs

Table 3.2: Parameters used within the formulation of the TEP model.

Variables

Variables are indicated by lower case letters. To distinguish between continuous and binary variables, binary variables are characterised by the letter y.

Variable	Description
f	Power flow
r	Slack (generation curtailment, load-shedding)
Δp	Re-dispatched power in-feed
θ	Voltage angle
y	Expansion status (binary variable)
y^{OP}	Power flow direction (binary variable)

Table 3.3: Variables used within the formulation of the TEP model.

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Indices

Indices are used for specifying the parameters and the variables shown above.

Indice	Description
$kf, kt, kref$	Starting, end, reference node
c	Candidate assets
0	Assets/units of starting topology
AC, ac	Alternating Current (AC) system/circuit
VU, vu	Voltage upgrade
REW, rew	Re-wiring
DC, dc	High Voltage Direct Current (HVDC) system
PST, pst	Phase Shifting Transformer (PST)
$TCSC, tcsc$	Thyristor Controlled Series Compensator (TCSC)
CM	Congestion management
$Slack$	Slack intervention
OP	Grid Operation
max, min	Maximum value, minimum value
$+, -$	Increase, reduction

Table 3.4: Indices used within the formulation of the TEP model.

3.2 Scope of the TEP model

In TEP, a target network structure is identified on the basis of a base/starting topology and given load and generation patterns. The expansion portfolio is also part of the required input data and defines the set of regarded expansion measures and technologies. Within the expansion portfolio, it is distinguished between the following expansion and reinforcement measures:

- Construction of new AC circuits
  - in existing transmission corridors (reinforcement)
  - in new transmission corridors (expansion)
- Re-wiring existing circuits by conductors with an increased transmission capacity
- Upgrade of the voltage level of existing circuits
- Placement of HVDC systems
- Installation of PSTs
- Construction of TCSCs

Expansion and reinforcement measures are modelled by binary decision variables. An activated variable indicates the installation of the corresponding asset. The deconstruction of systems being part of the base topology is not analysed. Each asset is characterised using three main topological attributes to define it clearly: the transmission corridor t, the line tower place n and the voltage level v. The set of line tower places per transmission corridor Ω_{N_t} contains the set of places being already occupied in the base topology $\Omega_{N_{t,0}}$ and the available candidate places $\Omega_{N_{t,c}}$. The set of existing circuits which can be reinforced by re-wiring or upgrading the voltage level are defined by the sets $\Omega_{N_{t,0,rew}}$ and $\Omega_{N_{t,0,vu}}$. Both sets are subsets of the set $\Omega_{N_{t,0}}$. The sets of existing circuits to which PSTs and TCSCs can be placed in series are defined as $\Omega_{N_{t,0,pst}}$ and $\Omega_{N_{t,0,tcsc}}$, respectively. Both sets are again subsets of the set $\Omega_{N_{t,0}}$. It is assumed that equal measures are taken for paral-

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lel circuits of the same voltage level in the same transmission corridor. Hence, corresponding expansion decisions can be modelled by one decision variable. In the following, the different expansion options are explained.

Within a transmission corridor $t \in \Omega_T$, new AC circuits of available voltage levels $v \in \Omega_{V_t}$ can be installed on available line tower places $n \in \Omega_{N_{t,c}}$. The variable y^{AC} indicates both the construction of a new circuit as well as of a new transformer.

$$y^{AC}_{t,n,v} \in \{0;1\}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,c}}, \forall v \in \Omega_{V_t} \tag{3.1}$$

Existing AC circuits $n \in \Omega_{N_{t,0,rew}}$ can be re-wired by conductors characterised by an increased transmission capacity. It is assumed that the reactances will be the same for conductors with standard and increased transmission capacities. For each circuit only one conductor with an increased transmission capacity is analysed.

$$y^{REW}_{t,n,v_0} \in \{0;1\}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,rew}} \tag{3.2}$$

The voltage level v_0 of existing AC circuits $n \in \Omega_{N_{t,0,vu}}$ can be upgraded if a higher voltage level v_{vu} is available. It is assumed that only one higher voltage level per circuit is taken into account for upgrading the voltage level.

$$y^{VU}_{t,n,v_{vu}} \in \{0;1\}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,vu}} \tag{3.3}$$

HVDC systems are modelled as coupled power injection and ejection. The power injected at one of the converters has to be equal to the power ejected at the other one. In general, HVDC systems can be placed within each transmission corridor $t \in \Omega_T$.

$$y^{DC}_{t} \in \{0;1\}, \quad \forall t \in \Omega_T \tag{3.4}$$

PSTs allow a more efficient utilisation of transmission capacities by controlling power flows within meshed AC networks. They are modelled as variable phase shift representing the corresponding operational flexibility and are constructed serially to AC circuits. In the proposed formulation, the reactance of PSTs is neglected and the placement is limited to those in series to existing circuits $n \in \Omega_{N_{t,0,pst}}$.

$$y^{PST}_{t,n,v_0} \in \{0;1\}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,pst}} \tag{3.5}$$

Power flows within meshed AC networks can also be controlled by TCSCs. The operational flexibility of TCSCs is provided by a variable reactance connected in series to AC circuits. To maintain a linear formulation of the grid operation, the variable reactance is modelled similarly to the operational flexibility of PSTs as a variable phase shift. New TCSCs can be placed in series to all existing circuits $n \in \Omega_{N_{t,0,tcsc}}$.

$$y^{TCSC}_{t,n,v_0} \in \{0;1\}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}} \tag{3.6}$$

The grid operation is described by power flows f, voltage angles of nodes θ_k as well as voltage angles θ^{PST} and θ^{TCSC} describing the operational flexibility of PSTs and TCSCs, respectively. The direction of power flows is indicated by the binary variable y^{OP}. Node-specific congestion management and slack interventions are modelled by the variables Δp and r, respectively. All variables will be specified by further indices defined within the nomenclature.

To increase the readability and clearness of the proposed model, in the mathematical formulation it is assumed that the base topology does not contain any power flow controlling devices such as HVDC systems, PSTs or TCSCs. However, such components being already part of the base topology can be modelled as described below assuming an activated expansion variable (the binary variable is not required any more).

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3.3 Objective function

The TEP formulation aims at minimising overall costs resulting from the expansion and operation of the electrical transmission grid. While expansion costs are caused by the installation of assets which are depreciated over several decades, operational costs arise at a single grid snapshot of a single year. Hence, the contribution of each operational measure for alleviating overloads is limited to the corresponding grid snapshot. Consequently, the appropriate analysis of expansion and operational costs requires weighting operational costs within the objective function. This weighting is done by calculating operational costs as perpetual annuity to compare operational costs of one single year with long-term expansion costs. Furthermore, it has to be taken into account that the target year of the planning horizon will be modelled by representative grid snapshots. Therefore, operational costs calculated on the basis of the analysed grid snapshots have to be weighted for capturing the costs of the whole year.

The investment costs IC include the costs for the installation of new assets as well as costs related with the operation of these assets. Operational costs for installed assets are modelled as a percentage of corresponding investment costs. The operational costs OC contain costs for congestion management interventions as well as load shedding and generation curtailment which are modelled as node-specific slack variables to ensure the solvability of the optimisation problem. Congestion management interventions are distinguished in those for redispatch of conventional power plants and curtailment of renewable energies. Costs for positive redispatch and financial returns caused by negative redispatch are calculated via marginal costs of each power plant.

$$\min \quad IC + OC \tag{3.7}$$

$$IC = (1 + C^{OP}(1 + \frac{1}{\alpha})) \sum_{t\in\Omega_T} IC_t \tag{3.8}$$

$$\begin{aligned} IC_t = &\sum_{n\in\Omega_{N_{t,c}}} \sum_{v\in\Omega_{V_t}} C^{AC}_{t,n,v} y^{AC}_{t,n,v} + C^{DC}_t y^{DC}_t + \sum_{n\in\Omega_{N_{t,0,vu}}} C^{VU}_{t,n,v_{vu}} y^{VU}_{t,n,v_{vu}} + \\ &\sum_{n\in\Omega_{N_{t,0,rew}}} C^{REW}_{t,n,v_0} y^{REW}_{t,n,v_0} + \sum_{n\in\Omega_{N_{t,0,pst}}} C^{PST}_{t,n,v_0} y^{PST}_{t,n,v_0} + \sum_{n\in\Omega_{N_{t,0,tcsc}}} C^{TCSC}_{t,n,v_0} y^{TCSC}_{t,n,v_0} \end{aligned} \tag{3.9}$$

$$OC = (1 + \frac{1}{\alpha}) \sum_{u\in\Omega_U} W^{CM,u}(OC^{CM,u} + OC^{Slack,u}) \tag{3.10}$$

$$OC^{CM,u} = \sum_{i\in\Omega_{PP}} C^{PP}_i (\Delta p^{+,u}_{g_i} - \Delta p^{-,u}_{g_i}) + C^{RES} \sum_{i\in\Omega_{RES}} \Delta p^{-,u}_{g_i} \tag{3.11}$$

$$OC^{Slack,u} = C_r \sum_{cs\in\Omega_{CS}} \sum_{k\in\Omega_K} (r^{u,cs}_{g_k} + r^{u,cs}_{d_k}) \tag{3.12}$$

3.4 Restrictions of the investment problem

The investment problem deals with restrictions limiting the construction of new assets due to mutual interdependencies between different measures. On the one hand, the expansion costs can depend on the order in which the assets are placed and, on the other hand, the number of measures which can be realised per circuit is limited.

In context of constructing new AC circuits, it is differentiated between the reinforcement of existing and the development of new transmission corridors. Developing new transmission corridors requires the installation of new line towers whereas reinforcing existing ones requires only an upgrade of existing line towers. Furthermore, costs for upgrading an existing one depend on the number of circuits being already installed within the corridor taking all available voltage levels into account. Therefore, it has to be ensured that per line tower place only one circuit of the available voltage levels can be installed.

$$\sum_{v\in V_t} y^{AC}_{t,n,v} \le 1, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,c}} \tag{3.13}$$

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Furthermore, the order in which parallel circuits can be constructed has to be restricted. A circuit n can only be placed when the circuit $n-1$ is already installed.

$$\sum_{v \in V_t} y^{AC}_{t,n,v} - \sum_{v \in V_t} y^{AC}_{t,n-1,v} \leq 0, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,c}} \tag{3.14}$$

It is assumed that each circuit can only be expanded or reinforced by one technological measure. Hence, either a parallel circuit can be installed, the voltage level can be upgraded, the circuit can be re-wired, a PST can be placed in series or a TCSC can be installed serially. Nevertheless, the restriction allows the parallel placement of more than one parallel measure.

$$y^{AC}_{t,n_c,v_0} + y^{VU}_{t,n,v_{vu}} + y^{REW}_{t,n,v_0} + y^{PST}_{t,n,v_0} + y^{TCSC}_{t,n,v_0} \leq 1, \quad \forall t \in \Omega_T, \forall n_c \in \Omega_{N_{t,c}}, \forall n \in \Omega_{N_{t,0}} \tag{3.15}$$

3.5 Restrictions of the operation problem

The operation problem contains all restrictions required for describing the grid operation and limiting operational variables and flexibilities such as for example power flows, voltages or congestion management interventions. Furthermore, the restrictions coupling the operational variables with the investment variables are also part of the operation problem.

Due to the long-term planning horizon, the grid operation is described via DC power flow equations (Kirchhoff's current and voltage law). Hence, the power flow equations can be formulated linearly and the complexity is reduced significantly. According to Kirchhoff's current law, the power injected into a node has to be equal to the power ejected at the same node. The node balance equation takes into account power flows of connected AC circuits f^{AC} as well as of connected HVDC systems f^{DC}, feed-in P_g as well as load P_d of connected generation units, positive as well as negative redispatch interventions Δp^+_g and Δp^-_g, respectively, and slack variables. Since preventive congestion management interventions are analysed only, redispatch interventions have to be equal for all outage situations. Furthermore, HVDC systems are operated in each outage situation in the same operation point.

$$\begin{gathered}\sum_{t \in \Omega_{T_k}} \sum_{n \in \Omega_{N_t}} \sum_{v \in \Omega_{V_t}} f^{AC,u,cs}_{t,n,v} + \sum_{t \in \Omega_{T_k}} f^{DC,u}_t + P^u_{g_k} - r^{u,cs}_{g_k} + \sum_{i \in \Omega_{PP_k}} \Delta p^{+,u}_{g_i} = P^u_{d_k} - r^{u,cs}_{d_k} + \sum_{i \in \Omega_{G_k}} \Delta p^{-,u}_{g_i}, \\ \forall k \in \Omega_K, \forall u \in \Omega_U, \forall cs \in \Omega_{CS}\end{gathered} \tag{3.16}$$

Kirchhoff's voltage law is formulated separately for existing and candidate circuits as well as for circuits those voltage level can be upgraded. In Kirchhoff's current law for existing circuits, it is taken into account that PSTs and TCSCs can be placed in series to the circuit. The voltage angles of the from and to node of each circuit are indicated by the indices kf and kt, respectively.

$$\begin{gathered}f^{AC,u,cs}_{t,n,v_0} - \gamma^{AC}_{t,n,v_0}(\theta^{u,cs}_{kf_{t,n,v_0}} - \theta^{u,cs}_{kt_{t,n,v_0}} + \theta^{PST,u}_{t,n,v_0} + \theta^{TCSC,u}_{t,n,v_0}) = 0, \\ \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0}} \setminus n \in \Omega_{N_{t,0,vu}}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \setminus cs_{t,n,v_0}\end{gathered} \tag{3.17}$$

Kirchhoff's voltage law for new circuits is formulated using a disjunctive parameter M to ensure a convex formulation of the TEP problem. Hence, power flows are limited only in the case of constructing new circuits.

$$\begin{gathered}|f^{AC,u,cs}_{t,n,v} - \gamma^{AC}_{t,n,v}(\theta^{u,cs}_{kf_{t,n,v}} - \theta^{u,cs}_{kt_{t,n,v}})| \leq M(1 - y^{AC}_{t,n,v}), \\ \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,c}}, \forall v \in \Omega_{V_t}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \setminus cs_{t,n,v}\end{gathered} \tag{3.18}$$

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Upgrading the voltage level of an AC circuit requires the construction of a new circuit with an increased voltage level and different reactances as well as the deconstruction of the existing one. Both measures are indicated by the same decision variable y^{VU}. Due to the option to deconstruct the existing circuit, a disjunctive parameter has to be integrated in Kirchhoff's voltage law of the corresponding circuit as well.

$$|f^{AC,u,cs}_{t,n,v_0} - \gamma^{AC}_{t,n,v_0}(\theta^{u,cs}_{kf_{t,n,v_0}} - \theta^{u,cs}_{kt_{t,n,v_0}} + \theta^{PST,u}_{t,n,v_0} + \theta^{TCSC,u}_{t,n,v_0})| \leq M y^{VU}_{t,n,v_{vu}} \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,vu}}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \setminus cs_{t,n,v_0} \tag{3.19}$$

$$|f^{AC,u,cs}_{t,n,v_{vu}} - \gamma^{AC}_{t,n,v_{vu}}(\theta^{u,cs}_{kf_{t,n,v_{vu}}} - \theta^{u,cs}_{kt_{t,n,v_{vu}}})| \leq M(1 - y^{VU}_{t,n,v_{vu}}) \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,vu}}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \setminus cs_{t,n,v_{vu}} \tag{3.20}$$

The voltage angle at the reference bus is set to zero within each grid snapshot u and each outage situation cs:

$$\theta^{u,cs}_{kref} = 0, \quad \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \tag{3.21}$$

The voltage angle of each node is limited by an maximum voltage angle:

$$|\theta^{u,cs}_{k}| \leq \theta^{max}, \quad \forall k \in \Omega_K, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \tag{3.22}$$

The flow on AC circuits, which can't be re-wired, is limited by the maximum transmission capacity:

$$|f^{AC,u,cs}_{t,n,v_0}| \leq f^{AC,max}_{t,n,v_0}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0}} \setminus n \in \Omega_{N_{t,0,rew}}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \tag{3.23}$$

The maximum flow on AC circuits, which can be re-wired, is formulated under consideration of the binary variable indicating the re-wiring status. In the case of re-wiring the circuit, the maximum capacity is increased, otherwise it is restricted to the original transmission capacity. Within the modelling approach, the reactances of classical conductors and those conductors characterised by an increased transmission capacity are assumed to be equal.

$$|f^{AC,u,cs}_{t,n,v_0}| \leq f^{AC,max}_{t,n,v_0} + (f^{REW,max}_{t,n,v_0} - f^{AC,max}_{t,n,v_0}) y^{REW}_{t,n,v_0}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,rew}}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \tag{3.24}$$

The transmission capacity of new circuits including those circuits being installed in context of a voltage upgrade is limited to the maximum one taking the corresponding construction status into account:

$$|f^{AC,u,cs}_{t,n,v}| \leq f^{AC,max}_{t,n,v} y^{AC}_{t,n,v}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,c}}, \forall v \in \Omega_{V_t}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \tag{3.25}$$

$$|f^{AC,u,cs}_{t,n,v_{vu}}| \leq f^{AC,max}_{t,n,v_{vu}} y^{VU}_{t,n,v_{vu}}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,vu}}, \forall u \in \Omega_U, \forall cs \in \Omega_{CS} \tag{3.26}$$

The outages of a system is modelled by replicating the grid snapshot (N-0 case) and switching off the corresponding system. Consequently, the flow on a circuit those outage is analysed within an outage situation has to be equal to zero in this situation:

$$f^{AC,u,cs_{t,n,v}}_{t,n,v} = 0, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_t}, \forall v \in \Omega_{V_t}, \forall u \in \Omega_U, \tag{3.27}$$

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HVDC systems are modelled as point-to-point connections and the operation of each system is limited by the installed capacity of the converters at the from and to station. Power can only be transmitted by an HVDC system when it is installed:

$$|f_t^{DC,u}| \leq f_t^{DC,max} y_t^{DC}, \quad \forall t \in \Omega_T, \forall u \in \Omega_U, \tag{3.28}$$

The phase shift of each PST is limited depending on the installation status. Only in the case of installing the corresponding PST, power flows can be controlled within the electrical grid. The operating range is assumed to be symmetric.

$$|\theta_{t,n,v_0}^{PST,u}| \leq \theta^{PST,max} y_{t,n,v_0}^{PST}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,pst}}, \forall u \in \Omega_U, \tag{3.29}$$

To maintain a linear formulation of the grid operation the variable reactance of TCSCs representing the operational flexibility is modelled as variable phase shift. The relation between the phase shift and the reactance is defined by the following function:

$$\theta_{t,n,v_0}^{TCSC,u}(\gamma_{t,n,v_0}^{TCSC,u}) = \frac{-\gamma_{t,n,v_0}^{AC}}{\gamma_{t,n,v_0}^{AC} + \gamma_{t,n,v_0}^{TCSC,u}} (\theta_{kf_{t,n,v_0}}^{u,cs} - \theta_{kt_{t,n,v_0}}^{u,cs}) \tag{3.30}$$

Due to the asymmetrical operation range of TCSCs ($|\gamma^{TCSC,min}| \neq |\gamma^{TCSC,max}|$) the corresponding limitation has to be formulated depending on the direction of power flows. The binary variable y^{OP} indicates this direction and is only formulated for the base case situation cs:

$$y_{t,n,v_0}^{OP,u,cs} = \begin{cases} 1, & f_{t,n,v_0}^{AC,u,cs} \geq 0 \\ 0, & f_{t,n,v_0}^{AC,u,cs} < 0 \end{cases}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}}, \forall u \in \Omega_U \tag{3.31}$$

The operating range of TCSCs is limited using the functional relation between the TCSC phase shift and reactance as well as the binary variable indicating the power flow direction and a disjunctive parameter M. Additional restrictions caused by outage situations will not be included into the limitation of the operating range of θ^{TCSC}.

$$-\theta_{t,n,v_0}^{TCSC}(\gamma^{TCSC,min}) + \theta_{t,n,v_0}^{TCSC,u} \leq M(1 - y_{t,n,v_0}^{OP,u}), \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}}, \forall u \in \Omega_U \tag{3.32}$$

$$\theta_{t,n,v_0}^{TCSC}(\gamma^{TCSC,max}) - \theta_{t,n,v_0}^{TCSC,u} \leq M(1 - y_{t,n,v_0}^{OP,u}), \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}}, \forall u \in \Omega_U \tag{3.33}$$

$$\theta_{t,n,v_0}^{TCSC}(\gamma^{TCSC,min}) - \theta_{t,n,v_0}^{TCSC,u} \leq M y_{t,n,v_0}^{OP,u}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}}, \forall u \in \Omega_U \tag{3.34}$$

$$-\theta_{t,n,v_0}^{TCSC}(\gamma^{TCSC,max}) + \theta_{t,n,v_0}^{TCSC,u} \leq M y_{t,n,v_0}^{OP,u}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}}, \forall u \in \Omega_U \tag{3.35}$$

Power flows can only be controlled by a TCSC in the case of installing the asset. The disjunctive parameter used within the corresponding restriction has to be chosen large enough to avoid an additional limitation in the case of placing the TCSC.

$$|\theta_{t,n,v_0}^{TCSC,u}| \leq M y_{t,n,v_0}^{TCSC}, \quad \forall t \in \Omega_T, \forall n \in \Omega_{N_{t,0,tcsc}}, \forall u \in \Omega_U, \tag{3.36}$$

The positive and negative redispatch potential of conventional power plants is calculated on the basis of installed as well as minimum capacity and the grid snapshot-specific feed-in determined by the CES:

$$0 \leq \Delta p_{g_i}^{+,u} \leq P_{g_i}^{max} - P_{g_i}^{u}, \quad \forall i \in \Omega_{PP}, \forall u \in \Omega_U \tag{3.37}$$

$$0 \leq \Delta p_{g_i}^{-,u} \leq max(P_{g_i}^{u} - P_{g_i}^{min}, 0), \quad \forall i \in \Omega_{PP}, \forall u \in \Omega_U \tag{3.38}$$

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Further generation units such as power-to-gas or power-to-heat units which enable the coupling of the electricity sector with the gas or heat sector can be integrated into the optimisation in a similar manner. The potential for curtailing renewable energies results from the available feed-in. The potential of units connected to underlying voltage levels are analysed in an aggregated way.

$$0 \leq \Delta p_{g_i}^{-,u} \leq P_{g_i}^{u}, \quad \forall i \in \Omega_{RES}, \forall u \in \Omega_U \tag{3.39}$$

The slack variables r_{g_k} and r_{d_k} describe load-shedding and virtual generation curtailment. They are defined for each node k and each outage situation cs to ensure the solvability of the optimisation problem and should not be part of the solution. The slack variables will not be limited to enable the solvability within each grid snapshot and each outage situation.

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Chapter 4

Decentral Energy System Disaggregation

After planning the necessary generation expansion and transmission network expansion in the CES and TEP, the decentral energy system should be planned, too. The decentral energy system planning can be split into three parts. First, the location of all assets in a DES should be planned. Then, the operation of the DES has to be determined. Finally, necessary distribution network expansion should be planned. The locational planning of assets in a DES is topic of this chapter.

The CES determines aggregated shell numbers for generation and load technologies for each node in the optimisation problem. Thereby, every node represents one DES. To perform further analysis' in a DES, these shell numbers have to be disaggregated onto a higher granularity. The operational planning (chapter 5) allows planning the operation of a DES on a building level. Therefore, the assets in the DES have to be disaggregated on building level.

In this submodel, the node-sharp installed power will be disaggregated onto a higher granularity, depending on the location of the technologies in the energy system. It has to be distinguished between technologies that are located in buildings and technologies with high installed power, which are usually located in higher grid levels.

4.1 Building-Focused Technologies

Technologies, that are located on building level, are the following:

- Heating technologies
  - Heat pumps
  - CHP-plants
  - Electrical heating rods
  - Gas boilers
- Small scale generation technologies and flexibilities
  - Rooftop-PV-systems
  - Home battery storages
- Electric vehicles

To properly plan the operation of these technologies, they have to be disaggregated on building level. This means, that each technology has to be allocated to one certain building in the DES.

Therefore, first a building register is required. This building register needs to store information about every building in the regarded DES. Necessary information for each building are:

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- Location in the DES Medium Voltage (MV)-grid sharp
- Georeferencing for available solar radiation
- Solar radiation
- Annual electrical load
- Electrical load profile
- Annual room heating load
- Room heating profile
- Annual process heating demand (per heat range)
- Annual process heating profiles (per heat range)
- Rooftop area

The buildings can be divided into the sectors Household (HH), Commerce, Trade and Service (CTS) as well as industry. Information about process heating is only required for industry buildings. The technologies can then be distributed to buildings in a rule-based probabilistic approach.

Heating technologies are allocated to buildings randomly, but also based on the common assumptions in PlaMES and on the results of the chapter 2. The dimensioning of the installed power of heating technologies can be oriented on the maximal heat load of the building, since the heating technology has to provide enough heat in each timestep. The capacity of heat storages can be set in a similar way. Rooftop-PV-systems are dimensioned on basis the available rooftop area of each house. Thereby, it is assumed, that a certain amount of the available rooftop area is used if a PV-system is installed on a building. Home battery storages are just installed in buildings with a PV-system. The installed power and energy of a battery storage can be determined based on the installed PV-power. The installed power of PV-systems and battery storages and the installed capacity of battery storages of all buildings in the DES has to be equal to the shell numbers planned in the CES (comp. chapter 2).

EVs can be allocated to buildings randomly. The installed power and capacity of each EV should orient on actual sizes of EVs.

4.2 Large-Scale Technologies

Large-scale technologies, that are planned centrally and need to be installed in the DES, are the following:

- Open space PV-systems
- Wind Power Plants
- Large-scale CHP-plants
- Electrolyzers
- Fuel Cells

These technologies usually have high installed power and are therefore not installed in the Low Voltage (LV)-system. Depending on the power of a system, it has to be located in the MV- or High Voltage (HV)-grid. The locating of the technologies can be performed either in a rule-based approach or probabilistic. Thereby, the distribution network could be considered.

Open space PV-systems and Wind Power Plants (WPPs) can be placed rule-based on potential areas. Thereby, the area of the DES is analysed. Areas, where no generation plants can be located, are identified. This can be forests, built-up areas or areas with high gradients. In these areas, no power plant can be placed. Furthermore, for WPPs, minimal distances to streets, municipal areas and other WPPs have to be respected. The PV-systems and WPPs can then be located in the remaining areas and allocated to the nearest node of the electrical distribution grid.

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Large-scale CHP-plants, electrolysers and fuel cells can be placed in the MV- or HV-grid probabilistic under consideration of the load centres and municipal areas.

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Chapter 5

Decentral Energy System Operational Planning

After disaggregating the location of centrally planned assets, a further disaggregation is necessary to allow analysing the DES. Every asset in the DES has its own certain time series. The CES considers time series in an aggregated manner, resulting in one time series per DES. For the analysis of a DES, time series for every node in the DES are required. Therefore, the operation of all assets has to be planned. Thereby, the central and aggregated time series doesn't have to be met exactly. There can be a difference between centrally planned and actually driven operation in the DES, since the CES plans the operation of all asset in a highly aggregated manner.

In many DES', utilities install Renewable Energy Sources (RES) and flexibilities. Furthermore, utilities own and operate heating grids for the heating of end customers. In these heating grids, heating technologies are installed and can be operated by the utility freely within constraints. Utilities are interested in having an optimal operation of their portfolio, which means an operational planning of their generating assets, flexibilities and loads. This planning should also consider the possibility to trade energy on central markets and directly to end customers.

Since PlaMES plans energy systems in the future, multiple possibilities for end customers in the DES to sell their produced energy should be considered. These possibilities can be summarised as Coordination Mechanisms (CMs). CMs are mechanisms to operate and coordinate RES, distributed flexibilities and loads in order to achieve economic or grid supportive target. A very basic CM are feed-in tariffs as they are currently used. Different, more sophisticated CMs are Local Energy Markets (LEMs). Since multiple CMs can be used in the scenario year, they shall be investigated an the operational planning and the deviation of the time series from the centrally planned time series shall be assessed.

5.1 Sets and parameters

The problem structure consists of the following sets:

Set	Description
T	Set of time slots $1, \dots, \theta$
I_{tech}	Set of technical sub problems of one entity
I_{econ}	Set of economical sub problems of one entity
I	Set of all sub problems of one entity $I = I_{tech} \cup I_{econ}$
J	Set of all entities in the DES
$K_{p,i}$	Set of all sub problems that a sub problem i can shift electrical energy to
$K_{w,i}$	Set of all sub problems that a sub problem i can shift thermal energy to
$K_{q,i}$	Set of all sub problems that a sub problem i can shift chemical energy to

Table 5.1: Sets used within the DESOP model.

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Parameter of the optimisation problem are:

Parameter	Description
$P_{i,t}$	fixed electrical demand of an entity $i \in I_{tech}, t \in T$
$\dot{Q}_{i,t}$	fixed thermal demand of an entity $i \in I_{tech}, t \in T$
$L_{i,t}$	availability of an EV of one entity $i \in I_{tech}, t \in T$
$P_{i,inst}$	installed electrical power of the asset of an entity $i \in I_{tech}$
$\dot{Q}_{i,inst}$	installed thermal power of the asset of an entity $i \in I_{tech}$
$E_{i,inst}$	installed electrical capacity of a storage of an entity $i \in I_{tech}$
$Q_{i,inst}$	installed thermal capacity of a storage of an entity $i \in I_{tech}$
$SoC_{i,initial}$	initial State of Charge (SoC) of a storage of an entity $i \in I_{tech}$
$Q_{i,initial}$	initially stored thermal energy of a storage of one entity $i \in I_{tech}$
η_i	efficiency of an asset $i \in I_{tech}$
ε_i	Coefficient of Performance of the asset of one entity $i \in I_{tech}$
$M_{i,b}$	Back-pressure coefficient of the asset of one entity $i \in I_{tech}$
$M_{i,v}$	Loss of electricity generation per unis of heat generated at fixed fuel $i \in I_{tech}$
R_{CHP}	Ramping Constant

Table 5.2: Parameters used within the DESOP model.

Variables of the optimisation problem are:

Variable	Description
$p^+_{i,t}$	electrical power that is added to the system of one entity $i \in I_{tech} \bigcup I_{econ}, t \in T$
$p^-_{i,t}$	electrical power that is taken from the system of one entity $i \in I_{tech} \bigcup I_{econ}, t \in T$
$\dot{q}^+_{i,t}$	thermal power that is added to the system of one entity $i \in I_{tech} \bigcup I_{econ}, t \in T$
$\dot{q}^-_{i,t}$	thermal power that is taken from the system of one entity $i \in I_{tech} \bigcup I_{econ}, t \in T$
$\dot{w}^+_{h,i,t}$	chemical power that is added to the system of one entity $i \in I_{tech} \bigcup I_{econ}, t \in T, h \in \{H2, CH2\}$
$\dot{w}^-_{h,i,t}$	chemical power that is taken from the system of one entity $i \in I_{tech} \bigcup I_{econ}, t \in T, h \in \{H2, CH2\}$
$e_{i,t}$	stored electrical energy of a storage of one entity $i \in I_{tech}, t \in T$
$q_{i,t}$	stored thermal energy of a storage of one entity $i \in I_{tech}, t \in T$
$\pi_{i,t}$	dual variable, market clearing price of a LEM $i \in I_{econ}, t \in T$
$p_{i \to k}$	electrical power that is shifted from sub problem i to k $i \in I, k \in K_{p,i}$
$\dot{w}_{i \to k}$	thermal power that is shifted from sub problem i to k $i \in I, k \in K_{w,i}$
$\dot{q}_{i \to k}$	chemical power that is shifted from sub problem i to k $i \in I, k \in K_{q,i}$
$p_{max,i,j}$	maximal energy traded in the deployment contract or LEM of one entity $i \in I_{econ}, j \in J$
$p_{max,LEM,t}$	maximal energy traded in one entity on the LEM $t \in T$

Table 5.3: Variables used within the DESOP model

5.2 Framework

The operational planning will be in form of a dispatch calculated as Linear Problem (LP) that will consider the requirements of each entity in the optimised DES. Possible entities originate from the sectors HH, CTS and industry. However, the utility itself is an entity, too. Every entity maximises its own profit margin while participating on a shared CM. For final customers, these CMs provide a way to purchase and sell electrical energy without using a usual contract of a utility. Possible CMs are LEMs or Virtual Power Plants (VPPs) and described in section 5.5. While optimising its profit, every entity has to consider technical constraints of its assets. These technical submodels are described in section 5.4. The model of each entity is then

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coupled by the CM. The framework of the operational planning on the example of three entities and one utility (which is an entity, too) can be seen in Figure 5.1.

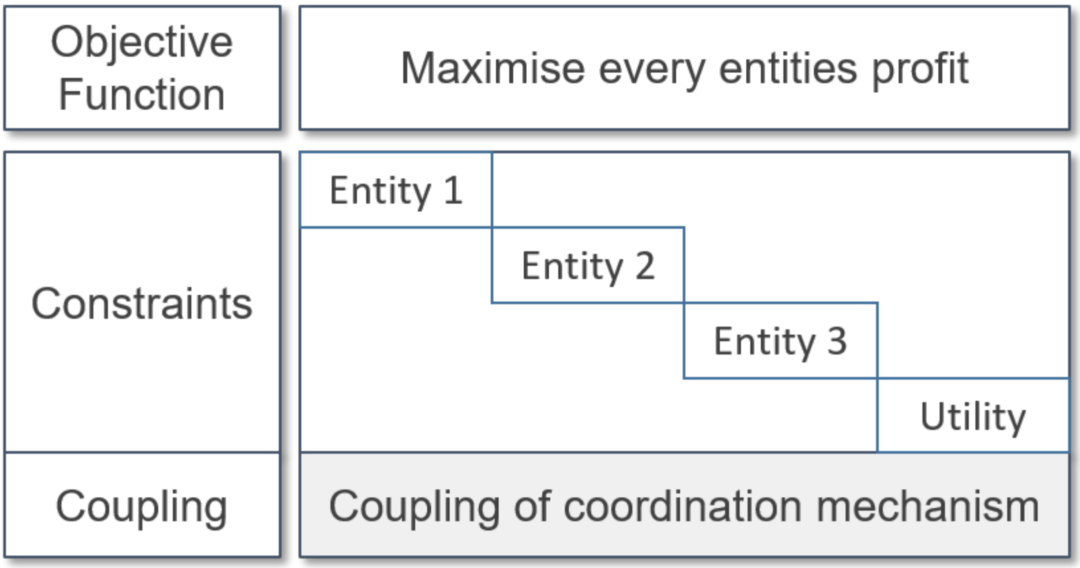

Figure 5.1: Model framework for the operational planning of three entities and one utility

5.3 Entity Models

An entity can be either a building in the sectors HH, CTS or industry or an aggregating company, such as a utility. An entity will always optimise its own profit within the constraints of its technologies and its demand and feed-in time series. The operation of an entity can be planned with a LP. An optimisation problem of an entity can be seen in Figure 5.2. The sub problems can be split into technical and economical problems.

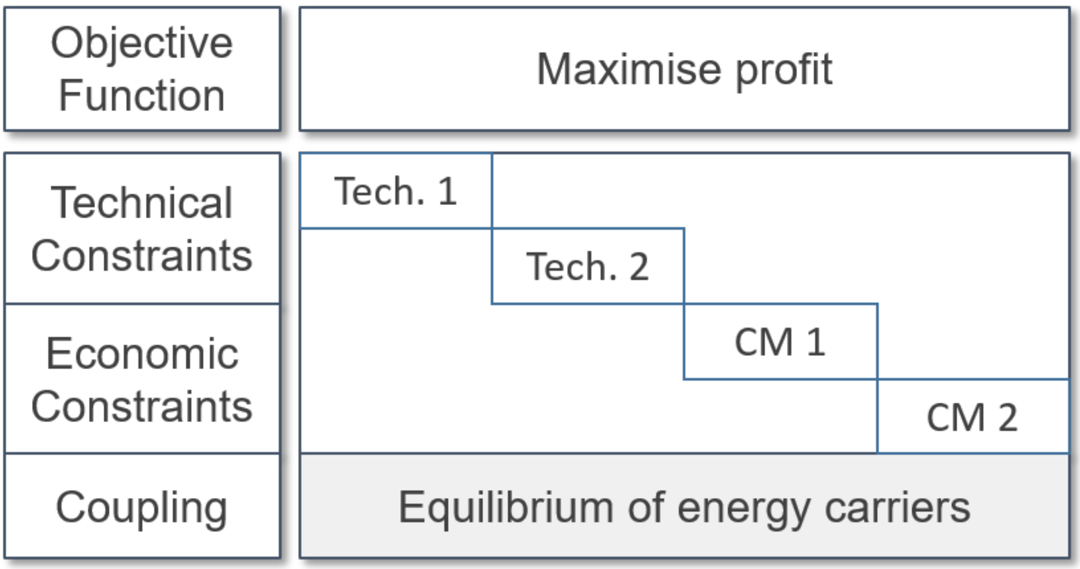

Figure 5.2: Model framework for the operational planning one entity

The technical sub problems belong to all technical assets belonging to the entity. Assets belonging to technical problems originate in all commodities. Possible assets are EVs, the heat demand, RES', battery storages and gas-powered heaters. Technical sub problems are described in section 5.4.

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Economical sub problems depend on the coordination mechanisms used in the investigation. The target of economic sub problems is to allow entities to purchase and sell energy. For every commodity that needs to be purchased or sold, at least one sub problem is required. Possible economic sub problems are described in section 5.5.

All sub problems are coupled by coupling constraints. To consider different feed-in tariffs for different assets (comp. section 5.5), one energy equilibrium based coupling constraint will not be sufficient. Therefore, flow based coupling constraints need to be considered. The coupling constraints are explained in section 5.6.

In this chapter, we will consider three energy carriers and their powers: Electrical power p, thermal power $\dot{q}$, and chemical power from gas $\dot{w}_{H2}$ and $\dot{w}_{CH2}$ for hydrogen and methane. Variables with a subscript $+$ add energy into the system (i.e. purchased or generated). Variables with a subscript $-$ take energy out of the system (i.e. sold or used). The following active sign convention applies for all sub problems:

$$p^{+} \geq 0 \tag{5.1}$$
$$p^{-} \leq 0 \tag{5.2}$$
$$\dot{q}^{+} \geq 0 \tag{5.3}$$
$$\dot{q}^{-} \leq 0 \tag{5.4}$$
$$\dot{w}_{H2}^{+} \geq 0 \tag{5.5}$$
$$\dot{w}_{H2}^{-} \leq 0 \tag{5.6}$$
$$\dot{w}_{CH2}^{+} \geq 0 \tag{5.7}$$
$$\dot{w}_{CH2}^{-} \leq 0 \tag{5.8}$$

5.4 Technical Models

Technical Models can be split into load models, that just represent a load which has to be fulfilled, generator models, that allow generating energy, storage models, that allow storing the energy of a certain commodity, and energy conversion technologies, that allow converting energy of different commodities, such as electricity to heat, gas to heat and gas to electricity. The following listing includes all technologies, that will be considered within DESOP:

- Loads
  - Electrical Load
  - Thermal Load
- Generators
  - PV-systems
  - Wind Power Plants
  - Solar Thermal Plants
- Storages
  - Battery Storage
  - Heat Storage
  - Electric Vehicles
- Energy conversion technologies
  - Electrical Heating Rods

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- Heat Pumps
- Gas heat boilers
- Combined Heat and Power-Plants
- Electrolysers
- Fuel Cells

Technical sub problems have no impact on the objective function, since the deployment and sale of energy is located in economical sub problems. Therefore, the objective function will not be considered in the following sections.

5.4.1 Electrical Load

The sub problem of the electrical load defines a static load $P_{el.load,t}$, that has to be fulfilled with electrical power $p^{-}_{el.load,t}$ in each time step $t \in T$:

$$-p^{-}_{el.load,t} = P_{el.load,t} \quad \forall t \in T \tag{5.9}$$

5.4.2 Thermal Load

The sub problem of the thermal load defines a static load $\dot{Q}_{th.load,t}$, that has to be fulfilled with thermal power $\dot{q}^{-}_{th.load,t}$ in each time step $t \in T$:

$$-\dot{q}^{-}_{th.load,t} = \dot{Q}_{th.load,t} \quad \forall t \in T \tag{5.10}$$

5.4.3 PV-System

PV-Systems generate electrical energy from solar radiation. The generated power $p^{+}_{PV,t}$ is capped by the installed power of the PV-system:

$$0 \leq p^{+}_{PV,t} \leq P_{PV,inst} \quad \forall t \in T \tag{5.11}$$

The constraints of a PV-system depends on the available solar power $P_{PV,t}$ and whether the power can be adjusted by the user. If the power can not be adjusted, the generated power will always equal the possible generated power:

$$p^{+}_{PV,t} = P_{PV,t} \quad \forall t \in T \tag{5.12}$$

If the power can be adjusted, the generated power will just be capped by the possible generated power on the right hand side:

$$p^{+}_{PV,t} \leq P_{PV,t} \quad \forall t \in T \tag{5.13}$$

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5.4.4 Wind Power Plant

WPPs generate electrical energy from wind energy. The generated power $p^{+}_{WPP,t}$ is capped by the installed power of the WPP:

$$0 \leq p^{+}_{WPP,t} \leq P_{WPP,inst} \quad \forall t \in T \tag{5.14}$$

The constraints of a WPP depends on the available wind power $P_{WPP,t}$ and whether the power can be adjusted by the user. If the power can not be adjusted, the generated power will always be equal to the possible generated power:

$$p^{+}_{WPP,t} = P_{WPP,t} \quad \forall t \in T \tag{5.15}$$

If the power can be adjusted, the generated power will just be capped by the possible generated power on the right hand side:

$$p^{+}_{WPP,t} \leq P_{WPP,t} \quad \forall t \in T \tag{5.16}$$

5.4.5 Solar Thermal System

Solar thermal systems generate thermal energy from solar radiation. The generated power $\dot{q}^{+}_{STS,t}$ is capped by the installed power of the solar thermal system $\dot{Q}_{STS,inst}$:

$$0 \leq \dot{q}^{+}_{STS,t} \leq \dot{Q}_{STS,inst} \quad \forall t \in T \tag{5.17}$$

The thermal power, that the solar thermal system produces, is coupled to the available power $\dot{Q}_{STS,t}$ by the efficiency $0 \leq \eta_{STS} \leq 1$:

$$\dot{q}^{+}_{STS,t} = \eta_{STS} \cdot \dot{Q}_{STS,t} \quad \forall t \in T \tag{5.18}$$

5.4.6 Battery Storage

Battery storages allow storing electrical energy over time. The decision variables of energy storages are the electrical power for discharging $p^{+}_{Bat,t}$ and charging $p^{-}_{Bat,t}$. The variables are capped by the installed power $P_{Bat,inst}+$ and $P^{-}_{Bat,inst}$ of the battery storage:

$$0 \leq p^{+}_{Bat,t} \leq P^{+}_{Bat,inst} \quad \forall t \in T \tag{5.19}$$

$$-P^{-}_{Bat,inst} \leq p^{-}_{Bat,t} \leq 0 \quad \forall t \in T \tag{5.20}$$

The stored energy is no direct decision variable in this formulation of an electrical storage. Nevertheless, the installed Capacity $E_{Bat,inst}$ has to be defined.

Efficiencies for charging $0 \leq \eta_{Bat,charge} \leq 1$ and discharging $0 \leq \eta_{Bat,discharge} \leq 1$ can be defined. Furthermore, an initial SoC $0 \leq SoC_{Bat,initial} \leq 1$ can be defined. The storage is constrained by:

$$-SoC_{Bat,initial} \cdot E_{Bat,inst} \leq \sum_{\tau=1}^{t} \eta_{Bat,charge} \cdot p^{-}_{Bat,\tau} + \frac{p^{+}_{Bat,\tau}}{\eta_{Bat,discharge}} \leq (1 - SoC_{Bat,initial}) \cdot E_{Bat,inst} \quad \forall t \in T \tag{5.21}$$

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5.4.7 Heat Storage

Heat storages allow storing thermal energy over time. The decision variables are the thermal power for charging $\dot{q}^-_{HS,t}$ and discharging $\dot{q}^+_{HS,t}$ and the energy stored in the storage at each time $q_{HS,t}$. The variables are capped by the installed power $\dot{Q}_{HS,inst}$ and the installed capacity $Q_{HS,inst}$:

$$0 \leq \dot{q}^+_{HS,t} \leq \dot{Q}_{HS,inst} \quad \forall t \in T \tag{5.22}$$

$$-\dot{Q}_{HS,inst} \leq \dot{q}^-_{HS,t} \leq 0 \quad \forall t \in T \tag{5.23}$$

$$0 \leq q_{HS,t} \leq Q_{HS,inst} \quad \forall t \in T \tag{5.24}$$

For every heat storage, an efficiency $0 \leq \eta_{HS,charge} \leq 1$ for charging and $0 \leq \eta_{HS,discharge} \leq 1$ for discharging has to be defined. Furthermore, self-discharging occurs defined by the efficiency $0 \leq \eta_{HS,selfdischarge} \leq 1$. The sub problem of a heat storage is constrained by:

$$q_{HS,t} = \eta_{HS,selfdischarge} \cdot q_{HS,t-1} + \eta_{HS,charge} \cdot \dot{q}^-_{HS,t} + \frac{\dot{q}^+_{HS,t}}{\eta_{HS,discharge}} \quad \forall t \in T \tag{5.25}$$

The initial charging of the storage can be defined as $0 \leq Q_{HS,initial} \leq Q_{HS,inst}$. The following constraint set the charging in the first time step to the initial charging:

$$q_{HS,0} = Q_{HS,initial} \tag{5.26}$$

5.4.8 Electric Vehicles

EVs allow charging the necessary energy for driving at any time. The decisions variables are the charging power $p^-_{EV,t}$, discharging power p^+_{EV} (for Vehicle to Grid (V2G)) and the stored energy $e_{EV,t}$. The power is capped by the installed power $P^+_{EV,inst} \geq 0$, $P^-_{EV,inst} \geq 0$ and the stored energy is capped by the installed capacity $E_{EV,inst} \geq 0$:

$$0 \leq p^+_{EV,t} \leq P^+_{EV,inst} \quad \forall t \in T \tag{5.27}$$

$$-P^-_{EV,inst} \leq p^-_{EV,t} \leq 0 \quad \forall t \in T \tag{5.28}$$

$$0 \leq e_{EV,t} \leq E_{EV,inst} \quad \forall t \in T \tag{5.29}$$

If V2G shall not be used by an EV, the discharging power is constrained by:

$$p^-_{EV,t} = 0 \quad \forall t \in T \tag{5.30}$$

EVs can be either at the entities building, driving or in a different location. Therefore, they just can be charged at the entities building, if they are there. The location and whether the car is plugged in can be defined in a parameter $L_{EV,t} \in \{0;1\}$. Whereby $L_{EV,t} = 0$ means that the EV can not be charged at the time t and $L_{EV,t} = 1$ means that the EV can be charged at the time t. The charging power and discharging power is then constrained by:

$$p^+_{EV,t} \leq P_{EV,inst} \cdot L_{EV,t} \quad \forall t \in T \tag{5.31}$$

$$p^-_{EV,t} \geq -P_{EV,inst} \cdot L_{EV,t} \quad \forall t \in T \tag{5.32}$$

(5.33)

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When EVs drive, they use electrical energy. This can be defined by the parameter $P_{EV,t} \geq 0$. Charging and discharging are possible with an efficiency $0 \leq \eta_{EV,charge} \leq 1$ and $0 \leq \eta_{EV,discharge} \leq 1$. The storage of the EV is then constrained by:

$$e_{EV,t} = e_{EV,t-1} + \eta_{EV,charge} \cdot p^{-}_{EV,t} + \frac{p^{+}_{EV,t}}{\eta_{EV,discharge}} - P_{EV,t} \quad \forall t \in T \tag{5.34}$$

5.4.9 Electrical Heating Rod

Electrical heating rods allow converting electrical energy to thermal energy. They can be modelled by their electrical power $p^{-}_{EHR,t}$ and thermal power $\dot{q}^{+}_{EHR,t}$. The electrical power is capped by the installed electrical power $P_{EHR,inst}$:

$$-P_{EHR,inst} \leq p^{-}_{EHR,t} \leq 0 \quad \forall t \in T \tag{5.35}$$

The electrical and thermal power are coupled by an efficiency $0 \leq \eta_{EHR} \leq 1$:

$$-\eta_{EHR} \cdot p^{-}_{EHR,t} = \dot{q}^{+}_{EHR,t} \quad \forall t \in T \tag{5.36}$$

5.4.10 Heat Pump

Electrical heating rods allow converting electrical energy to thermal energy. Thereby, they utilise surrounding thermal energy from the air or soil. They can be modelled by their electrical power $p^{-}_{HP,t}$ and thermal power $\dot{q}^{+}_{HP,t}$. The electrical power is capped by the installed electrical power $P_{HP,inst}$:

$$-P_{HP,inst} \leq p^{-}_{HP,t} \leq 0 \quad \forall t \in T \tag{5.37}$$

The electrical and thermal power are coupled by an Coefficient of Performance $\varepsilon_{HP} \geq 1$:

$$-\varepsilon_{HP} \cdot p^{-}_{HP,t} = \dot{q}^{+}_{HP,t} \quad \forall t \in T \tag{5.38}$$

5.4.11 Gas Heat Boiler

Gas Heat Boilers allow converting chemical energy from methane to thermal energy. They can be modelled by their chemical power $w^{-}_{CH2,GHB,t}$ and thermal power $\dot{q}^{+}_{GHB,t}$. The chemical power is capped by the installed electrical power $\dot{W}_{GHB,inst}$:

$$-W_{GHB,inst} \leq \dot{w}^{-}_{CH2,GHB,t} \leq 0 \quad \forall t \in T \tag{5.39}$$

The electrical and thermal power are coupled by an efficiency $0 \leq \eta_{GHB} \leq 1$:

$$-\eta_{GHB} \cdot \dot{w}^{-}_{CH2,GHB,t} = \dot{q}^{+}_{GHB,t} \quad \forall t \in T \tag{5.40}$$

5.4.12 Combined Heat and Power Plant

CHPs convert chemical energy from gas to electrical and thermal energy. According to subsection 2.7.3, CHP-plants will be modelled as back-pressure turbines, extraction condensing turbines or gas turbines in the DES. Independent of the type, the sub problem for CHP-plants have the decision variables $\dot{w}^{-}_{h,CHP,t}$, $p^{+}_{CHP,t}$ and $\dot{q}^{+}_{CHP,t}$ whereby h is indicating whether hydrogen or methane is used. The electrical power is capped by the installed power $P_{CHP,inst}$:

$$0 \leq p^{+}_{CHP,t} \leq P_{CHP,inst} \quad \forall t \in T \tag{5.41}$$

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The consumption of chemical energy and the production of electrical energy in back-pressure turbines and gas turbines are coupled by the electrical efficiency $0 \leq \eta_{CHP} \leq 1$:

$$-\eta_{CHP,el} \cdot \dot{w}^{-}_{h,CHP,t} \geq p^{+}_{CHP,t} \quad \forall t \in T \tag{5.42}$$

Electrical and thermal power are coupled by the back-pressure coefficient $M_{CHP,b} \geq 0$.

In back-pressure turbines, electrical and thermal power is coupled directly:

$$p^{+}_{CHP,t} = M_{CHP,b} \cdot \dot{q}_{CHP,t} \quad \forall t \in T \tag{5.43}$$

In gas turbines, the electrical power forms an upper bound for the thermal power:

$$p^{+}_{CHP,t} \geq M_{CHP} \cdot \dot{q}_{CHP,t} \quad \forall t \in T \tag{5.44}$$

In condensing extraction turbines, the chemical energy is coupled to the electrical power and thermal power with the electrical efficiency η_{CHP} and the loss of electricity generation per unit of heat generated at fixed fuel input $M_{CHP,v} \geq 0$:

$$-\eta_{CHP} \cdot \dot{w}^{-}_{h,CHP,t} = p^{+}_{CHP,t} + M_{CHP,v} \cdot \dot{q}^{+}_{CHP,t} \quad \forall t \in T \tag{5.45}$$

The ratio of produced electrical energy and thermal energy can be set freely within certain restrictions:

$$p^{+}_{CHP,t} \geq M_{CHP,b} \cdot \dot{q}^{+}_{CHP,t} \quad \forall t \in T \tag{5.46}$$

$$p^{+}_{CHP,t} \leq P_{CHP,inst} - M_{CHP,v} \cdot \dot{q}^{+}_{CHP,t} \quad \forall t \in T \tag{5.47}$$

All types of CHP-plants can be constrained by ramps. This can be modelled by a ramping constant $0 \leq R_{CHP} \leq 1$:

$$-R_{CHP} \cdot P_{CHP,inst} \leq p^{+}_{CHP,t} - p^{+}_{CHP,t-1} \leq R_{CHP} \cdot P_{CHP,inst} \quad \forall t \in T \tag{5.48}$$

5.4.13 Electrolyser

Electrolysers transform electrical energy to Hydrogen. They use electrical power $p^{-}_{Ele,t}$ and produce chemical power $\dot{w}^{+}_{H2,Ele,t}$. The electrical power is capped by the installed electrical power $P_{Ele,inst}$:

$$-P_{Ele,inst} \leq p^{-}_{Ele,t} \leq 0 \quad t \in T \tag{5.49}$$

The electrical and chemical power are coupled by the efficiency $0 \leq \eta_{Ele} \leq 1$:

$$-\eta_{Ele} \cdot p^{-}_{Ele,t} = \dot{w}^{+}_{H2,Ele,t} \quad \forall t \in T \tag{5.50}$$

5.4.14 Fuel Cell

Fuel cells transform chemical energy from hydrogen to electrical energy. Fuel cells can be modelled as back-pressure turbines or gas turbines (comp. CHP plants).

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5.5 Coordination Mechanisms

So far, just technical submodels have been explained for the operational planning. These models allow generating or using energy of one commodity or converting energies of commodities. However, every entity has to be able to deploy energy they require and to sell energy they generate. Otherwise, the entities could often not satisfy their consumption.

The deployment and selling of energy can be provided by CMs. Within the context of PlaMES, CMs can be very simple methodologies to allow trading energy, such as deployment contracts. In deployment contracts, an entity can sell or purchase energy for a fixed price to the slack, such as the utility or the network operator. However, more sophisticated CMs will be considered in PlaMES, too. One of them are LEMs. In LEMs, entities can trade energy among each other. This allows the use of flexibilities to increase the profit margin of each entity while reducing the energy shifted to the slack (which is the substation).

5.5.1 Deployment Contracts

Deployment contracts describe the status quo of energy deployment. End customers (households, CTS) conclude contracts with companies such as utilities to deploy energy for a fixed energy price. Larger companies, such as utilities or industrial companies with high consumption can also purchase energy directly on the central energy market. If an entity produces energy through RES' or a CHP plant, they can sell it for fixed prices (households and CTS) or to the central energy market (utilities and industry). This can be valid for all energy carries electricity, gas and heat.

The decision variables of such an optimisation problem for one entity and their price parameters are depicted in Table 5.4.

Variable	Price Parameter	Sale / Purchase	Energy Carrier
$p^+_{DC,t}\ \forall t \in T$	$C^+_{el,t}\ \forall t \in T$	Purchase	Electricity
$p^-_{DC,t}\ \forall t \in T$	$C^-_{el,t}\ \forall t \in T$	Sale	Electricity
$\dot{q}^+_{DC,t}\ \forall t \in T$	$C^+_{th,t}\ \forall t \in T$	Purchase	Heat
$\dot{q}^-_{DC,t}\ \forall t \in T$	$C^-_{th,t}\ \forall t \in T$	Sale	Heat
$\dot{w}^+_{h,DC,t}\ \forall t \in T, h \in \{H2, CH2\}$	$C^+_{h,t}\ \forall t \in T, h \in \{H2, CH2\}$	Purchase	Gas
$\dot{w}^-_{h,DC,t}\ \forall t \in T, h \in \{H2, CH2\}$	$C^-_{h,t}\ \forall t \in T, h \in \{H2, CH2\}$	Sale	Gas

Table 5.4: Variables and parameters of deployment contract models

The variables are defined according to the variables in section 5.4:

$$p^+_{DC,t} \geq 0 \quad \forall t \in T \tag{5.51}$$

$$p^-_{DC,t} \leq 0 \quad \forall t \in T \tag{5.52}$$

$$\dot{q}^+_{DC,t} \geq 0 \quad \forall t \in T \tag{5.53}$$

$$\dot{q}^-_{DC,t} \leq 0 \quad \forall t \in T \tag{5.54}$$

$$\dot{w}^+_{h,DC,t} \geq 0 \quad \forall t \in T, h \in \{H2, CH2\} \tag{5.55}$$

$$\dot{w}^-_{h,DC,t} \leq 0 \quad \forall t \in T, h \in \{H2, CH2\} \tag{5.56}$$

For one single entity, the electrical Deployment Contract could be influenced by a power price. This is a price that has to be sold for the maximal used power. Therefore, a decision variable $p_{DC,max,j}$ is defined representing the maximal sold or purchased power in the Deployment Contract over the whole time frame T. The maximal sold or purchased power $p_{DC,max,j}$ of one entity $j \in J$ is defined as:

$$p_{DC,max,j} \geq 0 \tag{5.57}$$

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The maximal power is bound to a power price $C_{el,max,j} \geq 0$. The objective function of the sub problem for a Deployment Contract for one entity $j \in J$ is then given as:

$$\begin{aligned}\min p_{DC,max,j} \cdot C_{el,max,j} + \sum_{t\in T} (p^{+}_{DC,t} \cdot C^{+}_{el,t} + p^{-}_{DC,t} \cdot C^{-}_{el,t} \\ + \dot{q}^{+}_{DC,t} \cdot C^{+}_{th,t} + \dot{q}^{-}_{DC,t} \cdot C^{-}_{th,t} \\ + \dot{w}^{+}_{H2,DC,t} \cdot C^{+}_{H2,t} + \dot{w}^{-}_{H2,DC,t} \cdot C^{-}_{H2,t} \\ + \dot{w}^{+}_{CH2,DC,t} \cdot C^{+}_{CH2,t} + \dot{w}^{-}_{CH2,DC,t} \cdot C^{-}_{CH2,t})\end{aligned} \tag{5.58}$$

The maximal electrical power of one entity $j \in J$ is coupled to the sold and purchased power by a set of constraints:

$$p^{+}_{DC,j,t} \leq p_{DC,max,j} \quad \forall t \in T \tag{5.59}$$

$$-p^{-}_{DC,j,t} \leq p_{DC,max,j} \quad \forall t \in T \tag{5.60}$$

All cost parameters can be defined freely. Furthermore, for each energy carrier, multiple deployment contracts can be defined. This can be necessary, when an entity owns a CHP and a PV-system. As an example, in Germany, there are two different feed-in tariffs for these systems. By that, two deployment contract sub problems will be required. One sub problem for the feed-in of PV-power and one sub problem for CHP-power.

In case of the deployment contracts CM, no coupling constraint (compare section 5.2) between various entities models exists. Every entity optimises its own profit without of any inter-dependency between the entities.

5.5.2 Local Energy Markets

LEMs allow customers to trade energy between each other. Thereby, entities can have access to a LEM and deployment contracts or just have access to a LEM. The formulation of a LEM in PlaMES is based on an economic dispatch formulation.[1]

For the sub problem of LEMs, two decision variables exist: $p^{+}_{LEM,t}$ is the decision variable for purchasing electrical energy on the LEM. $p^{-}_{LEM,t}$ is the decision variable for selling electrical energy on the local energy market. The variables for one entity $j \in J$, where J is the set of all entities, are defined as:

$$p^{+}_{LEM,j,t} \geq 0 \quad \forall t \in T \tag{5.61}$$

$$p^{-}_{LEM,j,t} \leq 0 \quad \forall t \in T \tag{5.62}$$

(5.63)

For one single entity, the LEM could be influenced by a power price. This is a price that has to be sold for the maximal used power. Therefore, a decision variable $p_{LEM,max,j}$ is defined representing the maximal sold or purchased power in the LEM over the whole time frame T. The maximal sold or purchased power $p_{LEM,max,j}$ of one entity $j \in J$ is defined as:

$$p_{LEM,max,j} \geq 0 \tag{5.64}$$

The maximal power is bound to a power price $C_{el,max,j} \geq 0$. The objective function of the sub problem for a LEM for one entity $j \in J$ is then given as:

$$\min p_{LEM,max,j} \cdot C_{el,max,j} \tag{5.65}$$

1. Wilhelm Cramer et al., "Engaging Prosumers in Local Energy Market Business Models," in *Proc. of the 25th International Conference on Electricity Distribution (CIRED 2019)* (AIM, 2019), ISBN: 978-2-9602415-0-1, doi:10.34890/555.

The maximal power of one entity $j \in J$ is coupled to the sold and purchased power by a set of constraints:

$$p^{+}_{LEM,j,t} \leq p_{LEM,max,j} \quad \forall t \in T \tag{5.66}$$
$$-p^{-}_{LEM,j,t} \leq p_{LEM,max,j} \quad \forall t \in T \tag{5.67}$$

Next to the LEM, the entities can also sell and purchase energy in deployment contracts.

The matching of the LEM is performed by the optimisation problem of the economic dispatch which maximises the welfare in the market. Mathematically, this can be formulated as a coupling constraint. This coupling constraint couples all selling and purchasing decision variables of the LEM:

$$\sum_{j\in J} p^{+}_{LEM,j,t} + p^{-}_{LEM,j,t} = 0 \quad (\pi_{LEM,t}) \quad \forall t \in T \tag{5.68}$$

The dual variable $\pi_{LEM,t}$ can be identified as the marginal change in the welfare of the whole LEM by changing the allowed sold energy. This can be interpreted as the market clearing price of the LEM and is the price, that every entity sells or buys its energy for from the market.

When solving the model, the solver can be indifferent in who should trade with each other. Often, multiple entities have equal marginal costs. Thereby, it may occur that just a few entities trade high amounts with each other which may affect the distribution grid negatively. A further sub problem can be added ensuring a fair distribution of traded energy between all entities.

Therefore, a overall maximal traded energy $p_{LEM,max,t}$ and small power costs $C_{LEM,max} \geq 0$ are defined:

$$p_{LEM,max,t} \geq 0 \quad \forall t \in T \tag{5.69}$$

The objective function for the sub problem for fair trading minimises the overall paid power prices:

$$\min \sum_{t\in T} p_{LEM,max,t} \cdot C_{LEM,max} \tag{5.70}$$

The maximal traded power for each time step is coupled to the traded power of each entity $j \in J$:

$$p^{+}_{LEM,j,t} \leq p_{LEM,max,t} \quad \forall j \in J, \forall t \in T \tag{5.71}$$
$$-p^{-}_{LEM,j,t} \leq p_{LEM,max,t} \quad \forall j \in J, \forall t \in T \tag{5.72}$$

Further CMs could be investigated in PlaMES. One possible CM is a VPP. In a VPP, multiple RES and flexibilities can be combined to a larger portfolio. Thereby, constraints of every end customer have to be considered. Furthermore, grid-supporting CMs can be investigated. One simple CM could be a use of power prices. The modelling of power prices has been described in subsection 5.5.1 and subsection 5.5.2. By that, the maximal grid usage of each entity is minimised reducing in less stress on the distribution grid.

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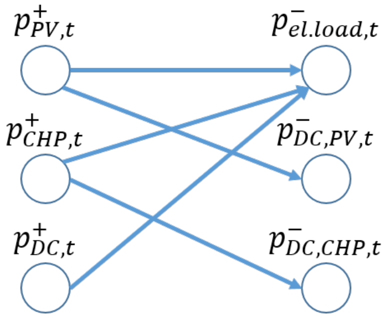

Figure 5.3: Exemplary coupling for electricity for an entity with one PV-system, one CHP, one electrical load, one deployment contract for purchasing energy and two deployment contracts for selling energy.

5.6 Entity Coupling Constraints

In the operational planning, a coupling between all sub problems is required. Thereby, a pure energy equilibrium based coupling is not sufficient. It is possible, that entities have multiple sub problems for deployment contracts for one energy carrier. With an energy equilibrium constraint, the deployment contract with the highest feed-in tariff would be used. To avoid those problems, a flow-based coupling is required. This coupling is exemplary depicted in Figure 5.3.

The illustration shows that each sub problem $i \in I$ has limited sets of sub problems $k \in K_{p,i} \forall i \in I$, $k \in K_{w,i} \forall i \in I$ and $k \in K_{q,i} \forall i \in I$ that it can give energy to or take energy from. This leads to decision variables:

$$p_{i \to k} \geq 0 \quad \forall i \in I, \forall k \in K_i \tag{5.73}$$

$$\dot{w}_{i \to k} \geq 0 \quad \forall i \in I, \forall k \in K_i \tag{5.74}$$

$$\dot{q}_{i \to k} \geq 0 \quad \forall i \in I, \forall k \in K_i \tag{5.75}$$

indicating the power shifted from sub problem i to sub problem k. The coupling constraints are then given as:

$$p_i = \sum_{k \in K_{p,i}} p_{i \to k} - \sum_{k | i \in K_{p,k}} p_{k \to i} \quad \forall i \in I \tag{5.76}$$

$$\dot{w}_i = \sum_{k \in K_{w,i}} \dot{w}_{i \to k} - \sum_{k | i \in K_{p,k}} \dot{w}_{k \to i} \quad \forall i \in I \tag{5.77}$$

$$\dot{q}_i = \sum_{k \in K_{q,i}} \dot{q}_{i \to k} - \sum_{k | i \in K_{p,k}} \dot{q}_{k \to i} \quad \forall i \in I \tag{5.78}$$

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Chapter 6

Distribution Network Expansion Planning

The Distribution Network Expansion Planning is focused on the strategic planning approach of Distribution System Operators (DSOs). The distribution system operator is responsible for operating, maintaining and developing the regional electric distribution grid infrastructure. DSOs have to ensure the long term ability of the system to provide reasonable capacity for the distribution of electricity. DNEP focuses on the new challenges within future distribution grids triggered through higher penetration of volatile renewable energy sources, usage of flexibilities and new electric loads through sector coupling, such as the growing electrification of the mobility and heat sector. The Distribution Network Expansion Planning will provide an economic assessment and strategic planning solution for distribution system operators on the long term effects of future supply tasks. In this regard DNEP focuses on the assets within the authority of DSOs.

6.1 Electric Grid Topology

To enable DNEP, the electric distribution grid topology has to be modelled. While the Central Energy Systems focuses on the transregional energy transport, distribution system planning covers the regional electric distribution grid topology. The Electric Grid Topology for the distribution grid planning approach is described in the following sections.

6.1.1 Voltage Levels

The investigated voltage levels in DNEP are the MV Level (10kV-30kV) and LV Level (less than 1kV). For the modelling of the Decentral Energy System especially in regard to the feedback through the Decentral Energy System Aggregation within PlaMES the High Voltage Level (110kV) needs to be considered as well. The grid topology depends on regional and structural differences as well as the respective voltage level, which need to be considered within the topology modelling.

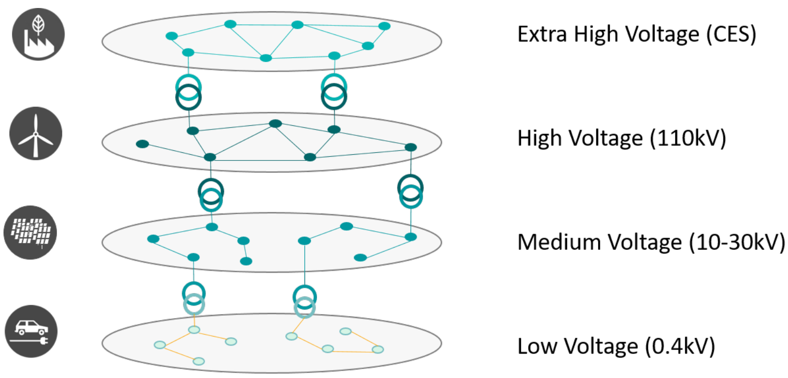

Figure 6.1: Voltage Levels

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6.1.2 Distribution Grid Structure

The topology of electric distribution grids differs in their structure. There are different topologies in which grid users are connected to the grid.

Radial Grids

The lines in a radial grid branch from a feeding substation and connect underlying stations and consumers. In this grid topology, several consumers are connected to one line in series. The radial grid is mostly used in low voltage networks (0.4 kV) with locally high consumer density. This design results in a very clear and cost-effective network structure. The disadvantage is the security of supply: In the event of a fault in one string, all the consumers connected to it are taken off the grid.

Ringed Grids

Ringed network offers a higher level of security with regard to the voltage supply. The lines run in a ring from one to a second supply transformer. During normal operation, the rings are separated and thus operated as individual lines, which in case of a fault prevents the failure of an entire ring. In the event of a fault, the ring is cut open at the fault location and the previously open separation point is closed. In this way the cut-off consumers can be quickly resupplied. Ringed networks are often used in medium voltage networks.

Meshed Grids

In Meshed Networks the lines are galvanically linked by switchgear (nodes). This results in a high level of security of supply from each feeding point in the network to the consumers as well as a balanced voltage profile as in radial networks. Switching operation in the event of an error is carried out automatically and often takes just a few milliseconds. Due to these advantages, the extra-high voltage networks and almost all high-voltage networks are operated as a meshed network to ensure the stability of voltage and frequency even in the event of a fault. This also prevents locally extensive power failures and thus minimises the risk of a blackout.

6.1.3 Grid Model

In order to be able to consider the electrical grid in the planning process, the grid assets and their individual parameters for modelling must be described. Therefor to adequately model the electric distribution grid within PlaMES, the pandapower grid model is used. Pandapower is an open source tool for modelling, analysing and optimising electric power systems. To facilitate modelling of grid assets, pandapower provides Standard Type Libraries. Lines and transformers have to different categories in pandapower. One category describes parameters which are element specific (e.g. length of line) and asset specific (resistance per kilometre line). The Standard Type Library provides a database of different types of lines and transformers, so that not all parameters have to be defined individually.[1]

Lines

Power is mainly transmitted using two different types of lines: overhead lines and cables. The cross-section of the cables varies with the power and voltage level in which the line is used. The decision which type is used depends mainly on the costs and local conditions. With the pandapower Standard Type Library the basic modelling parameters for each line can be set accordingly.

Transformers

In the planning process, the modelling of transformers has to reflect the concrete requirements and thus design relevant parameters. These include, among others, the nominal power, nominal voltage and the voltage control range. The voltage

1. Leon Thurner et al., "Pandapower—An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems," *IEEE Transactions on Power Systems* 33, no. 6 (2018): 6510–6521, ISSN: 0885-8950, doi:10.1109/TPWRS.2018.2829021.

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control range has to be chosen according to the networks to be connected and the maximum voltage deviation in these networks. Normally the maximum operational flexibility within the voltage band limits and the control range of the transformer is ± 15-20 %. As well for transformers pandapower provides Standard Type assets.

6.2 Planning and Operation Principles

A planning variant is valid if it enables safe and reliable grid operation. In order to guarantee this, there are various technical criteria and boundary conditions within the framework of grid planning. Within the scope of the Distribution Network Expansion Planning the reliable grid operation will be ensured while approaches to use grid technologies for flexible operation of the grid are considered within the planning process.

Normal Operation

Electric distribution grids must be designed in a way in which the maximum load capacity of equipment is not exceeded in any of the load cases expected in the future. For the connection points of all grid users in the grid, the maximum permissible deviations from the nominal voltage under normal operating conditions are defined at ± 10 % following industry standards. Besides the voltage constraints, it has to be ensured to operate assets within their current limits. The maximum allowed currents are defined through rated power of transformers or maximum thermal current of lines.

N-1 Criterion

The N-1 or single contingency criterion specifies that all loads still can be serviced after the event of an outage of one grid asset in the grid. Two basic outage events are the fault of a transformer or a line. In the event of an transformer outage, it has to be ensured, that an redundant transformer is installed and as well can transmit the additional capacities. In the event of a line outage as well the constraints of normal operation have to be ensured.

Fault Currents

In the event of grid faults, transient short circuit currents can occur. These currents can excess the permitted currents of normal operation. Due to high thermal and mechanical stress on grid assets fault currents have to be considered in the planning process, to ensure that possible faults can be detected and cut of safely.

6.3 Grid Analysis

On basis of Planning and Operation Principles, an automated grid analysis is necessary to enable the planning process. In this way the grid structure is evaluated with regard to the planning principles of distribution system operators. To enable the grid analysis, the DSOs grid data needs to be prepared to ensure correct calculations in DNEP. In order to prepare a DSO grid model for the requirements of the calculations in DNEP and to ensure a realistic representation of the grid, network plans or existing grid models of the DSO have to be reviewed and adapted. Furthermore, current planning statuses can be taken into account in the preparation of the grid model. Typical input data for the preparation are:

- stations: Position, busbars per station, switchgear, equipment with circuit breakers and disconnectors
- line corridors: Location and length of existing actual line corridors, pre-planned lines and current line allocation
- Lines and transformers: Electrical parameters (resistivity, capacitance etc.) of current or possibly planned equipment, technical restrictions (currents, voltages).

The prepared grid model represents the calculation basis for the subsequent calculations. On the basis of the grid model, power flow calculations for grid snapshots of the supply task are enabled. The results of the power flow calculations are currents in each line and voltages at each station.

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6.4 Distribution Grid Planning

To enable Distribution Grid Planning in PlaMES a target grid planning approach will be used. This grid planning methodology is used to automate the planning process within the Distribution Network Expansion Planning. It describes an efficient way to facilitate long term strategic planning tasks in distribution grids. On basis of a long term prognosis of the supply task an optimised target grid is developed using a static planning task. Such target grid planning is a good way of increasing efficiency in existing network areas. A historically grown distribution grid can thus be restructured cost-effectively. This approach will focus on the future integration of RES and new loads to the considered grid topology.

At first, a scenario for the target period is chosen in the planning process. In the next step, the grid model of the existing network is adapted. Loads and feeder,s that have not yet been connected to the existing grid, are integrated and corresponding time series are assigned to network nodes. On this basis, use cases, on which the grid will be expanded for, are defined. On the grid model then the future power flow situation is calculated for the target year. The resulting power flows and node voltages in the network are evaluated with regard to occurring network congestion (equipment overloads and voltage band violations). This serves as a starting point for the subsequent determination of investment candidates which can then be economically assessed.[2]

6.4.1 Nomenclature

The mathematical formulation is presented using several sets, parameters, variables and indices being defined in the following.

Sets

Following the Sets used in the formulation of the DNEP and the DESA are shown. All sets are defined by capital letters in combination with an corresponding index.

Set	Indices	Description
Ω_K	k,m	Set of nodes
Ω_L	l,km	Set of Edges
Ω_I	i	Set of Investment Candidates
Ω_U	u	Set of Grid Snapshots
Ω_P	p^-, p^+	Set of generation and loads
Ω_F	f	Set of degree of operational Freedom
Ω_G	g	Set of Grids
Ω_S	s	Set of Scenarios
Ω_T	t	Set of Timesteps
Ω_A	a	Set of Network Areas

Table 6.1: Sets used within the formulation of the DNEP and DESA model.

2. Leon Thurner, "Structural Optimizations in Strategic Medium Voltage Power System Planning" (PhD thesis, University of Kassel, 2018).

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Parameters

Parameters are described by capital letters or by greek letters used in the literature for corresponding variables.

Parameter	Description
α	Annual discount factor
C	Cost coefficient
η	efficiency factor

Table 6.2: Parameters used within the formulation of the DNEP and DESA model.

Variables

Variables are indicated by lower case letters. To distinguish between continuous and binary variables, binary variables are characterised by the letter x.

Variable	Description
p	Active power
q	Reactive power
θ	Voltage angle
x	Expansion status (binary variable)
y	operating variable
v	voltage variable
g	active conductance
b	susceptance

Table 6.3: Variables used within the formulation of the DNEP and DESA model.

Indices

Indices are used for specifying the parameters and the variables shown above.

Indices	Description
$+, -$	increase, reduction
max, min	maximum value, minimum value
0	initial state
gs	grid storage system
c_l	line cost
c_t	transformer cost
c_{gs}	grid storage cost
t_n	new transformer
l_n	new line
l_r	line reinforcement

Table 6.4: Indices used within the formulation of the DNEP and DESA model.

6.4.2 Scenario

To have a detailed approach to adequately develop a scenario for the Distribution Network Expansion Planning the Decentral Energy System Disaggregation and Decentral Energy System Operation acts as basis for the allocation of generation

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and load within each network area. On the basis of the future supply task the scenario describes the long term prognosis on which the strategic grid planning will be carried out.

$$p^{-}_{t,k,s} = P_{el.load,t,s,k} \qquad \forall t \in \Omega_T, \forall s \in \Omega_S, \forall k \in \Omega_K \tag{6.1}$$

$$p^{+}_{t,k,s} = P_{el.gen,t,s,k} \qquad \forall t \in \Omega_T, \forall s \in \Omega_S, \forall k \in \Omega_K \tag{6.2}$$

$$P_{el.load,t,s,k}, P_{el.gen,t,s,k} \in \Omega_{P_{s,k,t}} \tag{6.3}$$

6.4.3 Grid Snapshot Definition

To define the energetic parameters to adequately evaluate the network expansion, in practice typical network use cases are defined. These use cases consist of load and generation patterns at each node in the grid model and thus represent supply tasks of the network. This step is crucial to limit simulation time in the planning problem. Typical use cases will be defined in PlaMES by evaluating decentral operational planning for each time step in the target period including all electric generation and load units. The resulting grid utilisation enables the clustering of relevant time steps which can be used for the following grid planning process. This process can involve techniques such as down sampling or heuristic approaches of clustering extreme periods.[3] In a further step, this temporal aggregation is used to define grid snapshots to be used in the subsequent planning process.

$$p^{u}_{t,k} \in P_{t,k,s} \qquad \forall t \in \Omega_T, \forall s \in \Omega_S, \forall k \in \Omega_K \tag{6.4}$$

6.4.4 Formulation of Planning Methodology

For the automated target grid planning approach in the Distribution Network Expansion Planning the Electric Grid Topology and operational constraints need to be integrated into an economic objective within the formulation of the planning Problem.[4]

Objective Function

The objective function is to minimise the sum of the annuity costs of investment measures and the approximated operating costs:

$$\min C^{TOTEX} = C^{CAPEX} + C^{OPEX} \tag{6.5}$$

CAPEX:
Cost of investment candidates

$$C^{CAPEX}(x) = \alpha_i \cdot \sum_{i \in \Omega_I} c_i^{\Omega_I} \cdot x_i \tag{6.6}$$

OPEX:
Operational Cost of grid infrastructure.

$$C^{OPEX} = C^{OPEX,M} + \sum_{t \in \Omega_T} C_t^{OPEX,O} + C_t^{OPEX,F} \tag{6.7}$$

3. Leander Kotzur et al., "Impact of different time series aggregation methods on optimal energy system design," *Renewable Energy* 117 (2018): 474–487, ISSN: 09601481, doi:10.1016/j.renene.2017.10.017.

4. Simon Koopmann, "Planung von Verteilungsnetzen unter Berücksichtigung von Flexibilitätsoptionen" (PhD thesis, RWTH Aachen University, 2016); Thurner, "Structural Optimizations in Strategic Medium Voltage Power System Planning."

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OPEX Maintenance:
Cost for repairing and maintaining the grid infrastructure.

$$C^{OPEX,M}(x) = \sum_{t \in \Omega_T} C_t^{OPEX,O}(v,\theta) \cdot x_i \tag{6.8}$$

OPEX Operation:
Costs for the procurement of network losses.

$$C^{OPEX,O}(v,\theta) = C^{OPEX,loss}(x) \cdot \sum_{k \in \Omega_K} \sum_{m \in \Omega_K} p_{km,t}(u,\theta) + p_{mk,t}(v,\theta) \tag{6.9}$$

OPEX Flexibility Options:
Costs for the use of grid flexibility options.

$$C^{OPEX,F}(y) = \sum_{f \in F} C_{f,t}^{OPEX,F} \cdot y_{f,t} \tag{6.10}$$

The optimisation problem comprises as decision variables the possible investment measures x (investment variables), the operational degrees of freedom through flexibility options y (operational variables) as well as the grid state variables v (voltage amounts) and θ (voltage angle). The investment and operating costs depend on the characteristics of these variables.

The investment costs are the sum of the investment costs of all selected individual measures x_i in the grid area. Quantity Ω_I is the quantity of all possible investment candidates, which include investments in grid expansion projects as well as investments for the connection of grid flexibility options. Each investment measure x_i is associated with individual investment costs $C_i^{\Omega_I}$. In order to achieve comparability between investment costs with long-term effects and annual operating costs, the investment costs are converted to annuity costs using the annuity factor α_i.

The operating costs are made up of three cost components. Costs for the repair and maintenance of grid assets, costs for the procurement of network losses and costs for the use of flexibility options. Additional maintenance and repair costs are only incurred for investment measures that have actually been carried out. Therefore, there is a direct dependency on the investment variables x_i. The costs for the procurement of grid losses depend on the grid utilisation (power flows $p_{km,t}$ via the line km in time step t) and thus on the grid state variables u and θ for all time steps t of the grid snapshots considered. The costs for the use of flexibility options $C_{f,t}^{OPEX,F}$ are determined by the extent to which flexibility is used. The extent of flexibility usage is represented by the operating variable y. The quantity Ω_F comprises all degrees of freedom that represent the use of flexibility options in network operation at every time step t in Ω_T. These degrees of freedom include, for example, the regulation of reactive power through cos(ϕ) or selected injection and withdrawal capacities of grid storage systems. Every intervention in the operation of the system causes technology-specific and time-dependent costs $C_{f,t}^{OPEX,F}$.

The investment variables x_i are integer variables, as each investment candidate can only be carried out in full or not at all (e.g. the construction of a transformer). Operating variables, on the other hand, are defined as continuous within the respective technical limits.

6.4.5 Topological and Operational Constraints:

The topological and operational constraints of the Distribution Network Expansion Planning can be grouped into the following categories.

- Operational Constraints
- Operational Flexibility Constraints
- Technology Constraints

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Operational Constraints

To enable the network expansion planning to consider the technical limits of the assets in the grid, voltage band, voltage angles or maximum transmittable power have to be formulated as grid constraints. The grid constraints apply to all lines and grid nodes of existing grid infrastructure as well as for investment decisions in additional grid assets. Compliance with the technical limits of network operation permitted for network planning is formulated subsequently. For each time step t of the grid snapshots, the permissible voltage bands and voltage angles as well as the maximum transmittable power of the equipment must be kept. This applies to all lines and grid nodes in the existing network as well as to all additional grid assets added through investment decisions. This results in restrictions for the network state variables. The following formulas represent the constraints, where the set Ω_K comprises all network nodes and the set Ω_L all edges (i.e. lines and transformers) of the network model. $p_{t,km}$ and $q_{t,km}$ represent the active and reactive power flows on the lines:

$$V_k^{min} \leq v_{t,k} \leq V_k^{max} \quad \forall t \in \Omega_T, \forall k \in \Omega_K \tag{6.11}$$

$$\theta_k^{min} \leq \vartheta_{t,k} \leq \theta_k^{max} \quad \forall t \in \Omega_T, \forall k \in \Omega_K \tag{6.12}$$

$$p_{t,km}^2 + q_{t,km}^2 \leq (S_{km}^{max})^2 \quad \forall t \in \Omega_T, \forall km \in \Omega_L \tag{6.13}$$

In this regard, S refers to the complex power. The dependency between voltage v and angle θ as well as active and reactive power flows is given by the non-linear power flow equations.

$$p_{t,km} = v_{t,k}^2 g_{km} - v_{t,k} \cdot v_{t,m} \cdot [g_{km} cos(\theta_{t,km}) + b_{km} sin(\theta_{t,km})] \quad \forall t \in \Omega_T, \forall km \in \Omega_L \tag{6.14}$$

$$q_{t,km} = -v_{t,k}^2 (b_{km} + g_{km}) + v_{t,k} \cdot v_{t,m} \cdot [b_{km} cos(\theta_{t,km}) - g_{km} sin(\theta_{t,km})] \quad \forall t \in \Omega_T, \forall km \in \Omega_L \tag{6.15}$$

$$p_{t,k} = v_{t,k} \sum_{m \in K_k} v_{t,m} \cdot [G_{km} cos(\theta_{t,km} + B_{km} sin(\theta_{t,km}] \quad \forall t \in \Omega_T, \forall k \in \Omega_K \tag{6.16}$$

$$q_{t,k} = v_{t,k} \sum_{m \in \Omega_{K_k}} v_{t,m} \cdot [G_{km} sin(\theta_{t,km} - B_{km} cos(\theta_{t,km}] \quad \forall t \in \Omega_T, \forall k \in \Omega_K \tag{6.17}$$

$$with : \theta_{t,km} = \theta_{t,k} - \theta_{t,m} \tag{6.18}$$

g_{km} represents the active conductance and b_{km} the susceptance of the line from node k to node m. G_{km} and B_{km} are the corresponding elements of the node admittance matrix. The set Ω_{K_k} comprises all network nodes that are connected to the node k via a line. The active power $p_{t,k}$ or reactive power $q_{t,k}$ fed in at each node corresponds to the sum of all active or reactive power flowing out via the connected lines. The power fed in at each node is the sum of all feeds minus all loads.

Operational Flexibility Constraints

The usage of grid technology options and grid asset flexibility are subject to technology-specific restrictions. These are reflected in the constraints for the operating variables y. The limitation of operating variables also depend on the chosen investment candidates. For example, the use of flexibility options is only possible if the corresponding measure x_i is selected for the application of flexibility. For grid storage systems, the limits of the operating variables also depend on the selected storage size. The connection between investment and operating variables is formulated in general terms in the following formulas.

$$y_{f,t}^{min} \leq y_{f,t} \leq y_{f,t}^{max} \forall f \in \Omega_F, t \in \Omega_T \tag{6.19}$$

$$y_{f,t}^{min} = n_{f,t}(x) \forall f \in \Omega_F, t \in \Omega_T \tag{6.20}$$

$$y_{f,t}^{max} = o_{f,t}(x) \forall f \in \Omega_F, t \in \Omega_T \tag{6.21}$$

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Here $y_{f,t}^{min}$ and $y_{f,t}^{max}$ denote the upper and lower limits for the variable of the operational degree of freedom f at time t. Both the upper and lower limits for each operational variable are a time and technology dependent function $n_{f,t}(x)$ $o_{f,t}(x)$ of the vector of the investment variable x_i and illustrate the dependence on the investment decision.

Technology Constraints

Conventional grid expansion measures include the construction of new transformer stations, transformers, overhead lines and cable circuits on new corridors. Reinforcement measures include new line construction in existing corridors and an exchange of transformers and other equipment. The typical expansion measures are identified through power flow analysis and converted into suitable investment candidates for the optimisation process on the basis of various criteria. The reinforcement of existing lines or the replacement or addition of a transformer describe the basic approach in the Distribution Network Expansion Planning. Expansion and Reinforcement Candidates Constraints describe the technological and operational constraints to be taken into account. The following constraints are formulated.

- New Reinforcement and New Lines
- New Transformer
- Grid Technology Options (Grid Storage System)

The investment in a new line, in a new transformer or a line reinforcement has to comply with the operational constraints, previously described. For the grid storage system additional operational constrains are formulated.

Line Reinforcement and New Lines:
To eliminate a network congestion, there are two options on lines. One possibility is to reinforce only individual existing lines. Reinforcement implies replacing existing lines or laying a new parallel line. In this approach all lines in all outgoing feeders, in which equipment overloads or voltage band violations were determined in the power flow analysis, are defined as candidates for reinforcement. The other possibility is the investment in a new line on a new line corridor. To consider new line corridors the grid topology has to be.
The investment to a line reinforcement is depending on it's length $d_{k,m}$.

$$C_i^{l_r} = C_{c_l}^{l_r} \cdot d_{k,m} \forall k,m \in \Omega_K, i \in \Omega_I \tag{6.22}$$

$$C_i^{l_n} = C_{c_l}^{l_n} \cdot d_{k,m} \forall k,m \in \Omega_K, i \in \Omega_I \tag{6.23}$$

The respective investment cost in the objective function results in:

$$C_i^{\Omega_I} = C_i^{l_r} \forall i \in \Omega_I \tag{6.24}$$

$$C_i^{\Omega_I} = C_i^{l_n} \forall i \in \Omega_I \tag{6.25}$$

New Transformer:
If a transformer has inadmissible loads according to the power flow analysis, an additional transformer or the replacement of the transformer is determined as an investment candidate.
The investment to a new transformer is depending on it's installed rated power $P_k^{inst,nt}$.

$$C_i^{nt} = C_{c_t}^{t_n} \cdot P_k^{inst,nt} \forall k \in \Omega_K, i \in \Omega_I \tag{6.26}$$

The respective investment cost in the objective function results in:

$$C_i^{\Omega_I} = C_i^{c_t} \forall i \in \Omega_I \tag{6.27}$$

Grid Technology Options:
Grid technology options are taken into account to reduce the classical network expansion measures. This approach follows

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the directive of primarily consider network operation enhancements before expanding or reinforcing network infrastructure. The operational grid technology options includes cos(ϕ)-control and Q(V)-control as reactive power management solutions as well as Voltage Regulated Distribution Transformer (VRDT) which automatically adjust the transmission ratio between voltage levels. VRDTs are equipped with an integrated on load tap-changers and are able to adjust the transformation ratio between the high and low voltage side in small steps under load. Due to this decoupling of the voltage levels,the VRDT makes it possible to use the complete voltage band with a voltage quality in accordance with the standard. Grid technology options are taken under consideration within grid analysis to determine the investment candidates. In this regard the Grid Storage System is described in further detail.

Grid Storage System:
Grid storage systems can both feed power into the grid and draw power. Correspondingly, modelling is performed using decision variables for charging $p_{t,k}^{-,gs}$ and discharging $p_{t,k}^{+,gs}$ per time step t and grid node k. SOC refers to the state of charge of the battery. Since electrical storage devices are connected to the grid via inverters, there are also degrees of freedom with regard to the provision of reactive power. Therefore, the reactive power supply can be modelled as a further decision variable $q_{t,k}^{gs}$ per time step.

Limitation of the charging and discharging capacity by the installed capacity:

$$0 \le p_{t,k}^{-,gs} \le P_k^{max,gs} \tag{6.28}$$

$$0 \le p_{t,k}^{+,gs} \le P_k^{min,gs} \tag{6.29}$$

Limitation of the provision of reactive power:

$$q_{t,k}^{gs} = p_{t,k}^{gs} \cdot \tan(\phi_k^{gs}) \tag{6.30}$$

$$P^{max,gs} \cdot \tan(\phi_k^{gs}) \le q_{t,k}^{gs} \le P^{min,gs} \cdot \tan(\phi_k^{gs}) \tag{6.31}$$

$$with : \tan(\phi_k^{gs}) = \tan(\arccos(\cos(\phi_k^{gs}))) \tag{6.32}$$

Limitation of the storage level between the minimum and the maximum permissible state of charge:

$$SOC_k^{gs,min} \le SOC_k^{gs,0} + 1/n_T \cdot \left[\sum_{\tau=1}^{t} p_{\tau,k}^{-,gs} \cdot \eta_k^{-,gs} - p_{\tau,k}^{+,gs} / \eta_k^{-,gs} \right] \le SOC_k^{gs,max} \tag{6.33}$$

The investment to a grid storage system is depending on it's installed capacity $P_k^{max,gs}$.

$$C_i^{gs} = C_{c_{gs}}^{gs} \cdot P_k^{max,gs} \forall k \in \Omega_K, i \in \Omega_I \tag{6.34}$$

The respective investment cost in the objective function results in:

$$C_i^{\Omega_I} = C_i^{gs} \forall i \in \Omega_I \tag{6.35}$$

The investment candidates are automatically determined by the procedure in accordance with the criteria described above. In addition, the user of the procedure can manually define further expansion projects as investment candidates.

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Chapter 7

Decentral Energy System Aggregation

While modelling central structures, the Decentral Energy System also needs to be considered. The granularity and complexity of the energy system grows with the depth of detail and hence the requirements for the central modelling in PlaMES. Therefore an interface between the Central Energy Systems and the Decentral Energy System is required. The Decentral Energy System Aggregation focuses on providing an economic impact assessment on decentral energy system structures. To enable the Central Energy Systems to take the cost of the integration of electric generation and load technologies into account, the Decentral Energy System Aggregation will provide the aggregated cost of multiple considered areas. The Decentral Energy System Aggregation will act as a streamline for multi-sectoral and infrastructural parameters to picture the underlying area of each Decentral Energy System considered in the Central Energy Systems.

7.1 Decentral Energy System Topology

The Decentral Energy System Topology in the Decentral Energy System Aggregation is modelled in a way to enable the feedback of future energy scenarios on regional level to a transregional planning instance. This requires georeferenced data handling for multiple regions to capture the heterogeneity of decentral energy systems.

7.1.1 Network Areas

To enable the modelling of the spacial distributed generation and loads in different areas and grid voltage levels to simulate the impact of future scenarios on multiple decentral energy systems, the modelling and definition of network areas is necessary.[1] In this approach network areas are defined to enable the modelling of synthetic grid infrastructure in the respective areas. The modelling of network areas and synthetic grid infrastructure enables the allocation of electric loads and generation capacities to the modelled voltage levels. In this way an meaningful aggregation of the impact of integrated new load and generation capacities to the Decentral Energy System is enabled.

The modelling of network areas goes along with the electric grid infrastructure and uses open source data which is available especially through OSM.[2] Network areas are modelled in three levels, the sub-transmission level, the medium-voltage level, and the low voltage level. To model the sub-transmission level the EHV/HV-substations at first need to be identified. These substations function as interconnection between the Central Energy Systems and the Decentral Energy System in PlaMES. Once the EHV/HV substations are identified and allocated geographically the underlying areas associated to the EHV/HV substation have to be identified. To identify the associated areas to the sub-transmission level, the HV/MV substations need to be geographically allocated, as well as the MV/LV substations. While this step happens under data scarcity substations are also allocated heuristically if necessary. Once the substations are allocated geographically, community boarders (of i.e.

1. Ludwig Hülk et al., "Allocation of annual electricity consumption and power generation capacities across multiple voltage levels in a high spatial resolution: 79-92 Pages / International Journal of Sustainable Energy Planning and Management, Vol 13 (2017) / International Journal of Sustainable Energy Planning and Management, Vol 13 (2017)," 2017, doi:`10.5278/IJSEPM.2017.13.6`.
2. OpenStreetMap contributors, *Planet dump retrieved from https://planet.osm.org*, `https://www.openstreetmap.org`, 2017.

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postal code or community areas) function as boarders of the network areas. To aggregate areas from the low-voltage level to medium-voltage level a suitable procedure is the application of the Voronoi-Method. The underlying areas are aggregated and assigned to the superordinate substation. The same procedure is used for the aggregation of medium-voltage areas to sub-transmission areas which then are assigned to the EHV/HV substation and therefor the interconnection pont between the Central Energy Systems and the Decentral Energy System. The georeferenced areas and the data available for the areas enable spacial aggregation in the modelling approach presented.

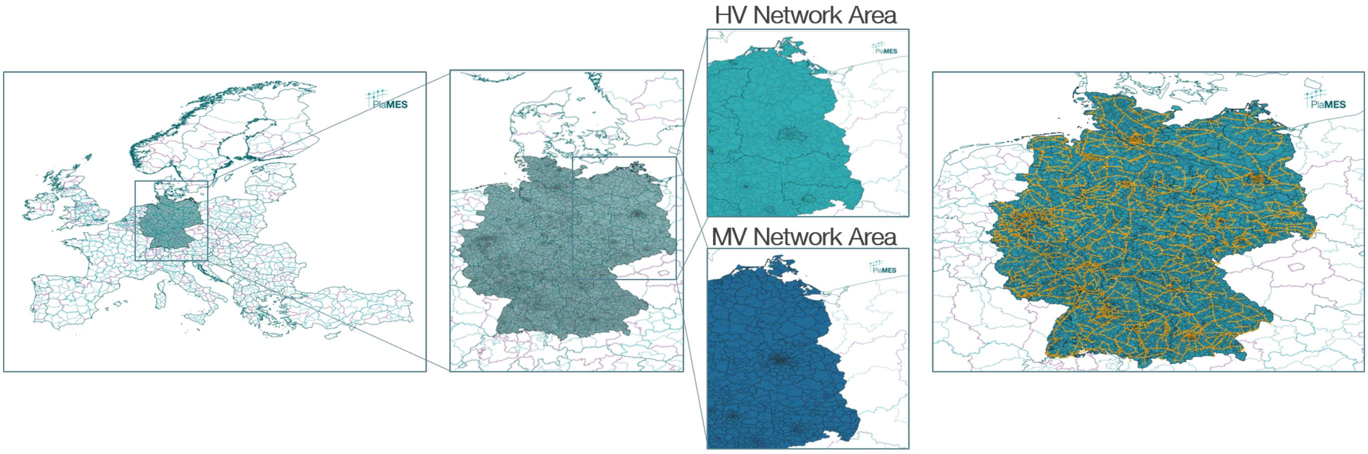

Figure 7.1: Network Area modelling in PlaMES

7.1.2 Electric Distribution Grid

The Electric Distribution Grid is modelled for all defined Network Areas. Since data of electric distribution grids is not publicly available, the electric distribution grid needs to be modelled synthetically. The approach using the defined Network Areas enables the simulation of Decentral Energy Systems for a Central Energy Systems Planning under data scarcity. While for most of the transmission and sub-transmission systems in Europe already network models exist (either open-source or within the institutions working on this project) the electric distribution grid (medium-voltage level and low-voltage level) has to be modelled without real network data available.

Therefore synthetic distribution grids representing the status quo supply task are modelled and assigned to the defined Network Areas to represent the regional heterogeneity of the distribution grid.

7.2 Decentral Aggregation Methodology

The Decentral Energy System Aggregation will focus on determining a cost indicator for the integration cost of decentral generation and load technologies on the decentral electric grid infrastructure. In this regard the Central Energy Systems optimisation process includes the cost of dispatch decisions and therefor future supply tasks on decentral electric grid infrastructure in the central planning process. Requirement for the indicator is to include regional resolution, multi-energy technology integration scenarios on basis of regional integration potential and the respective economic impact assessment.

7.2.1 Planning and Operation Principles

Like in the Distribution Network Expansion Planning a planning variant is valid if it enables safe and reliable grid operation. In order to guarantee this as well in the Decentral Energy System Aggregation, there are various technical criteria and boundary conditions within the framework of grid planning. This involves the system to be designed to ensure normal operation as described in 6.2.

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7.2.2 Energy Scenarios

The approach to adequately develop a scenario for the Decentral Energy System Aggregation, the Decentral Energy System Disaggregation and Decentral Energy System Operation in Chapter 4 and Chapter 5 acts as basis for the allocation of generation and load. Since synthetic network models will be used, multiple possible allocations of electric generation and load within a synthetic network have to be considered. On the basis of the future supply task within a considered grid area one energy scenario in the Decentral Energy System Aggregation describe the possible future supply task on which a strategic grid planning can be carried out. As well as in the Distribution Network Expansion Planning the future asset structure needs to be considered within the scenario creation. The asset structure for the synthetic grids will match the average asset structure of the areas covered by the Central Energy Systems Planning.

$$p^{-}_{t,k,s} = P_{el.load,t,s,k} \qquad \forall t \in \Omega_T, \forall s \in \Omega_S, \forall k \in \Omega_K \tag{7.1}$$

$$p^{+}_{t,k,s} = P_{el.gen,t,s,k} \qquad \forall t \in \Omega_T, \forall s \in \Omega_S, \forall k \in \Omega_K \tag{7.2}$$

$$P_{el.load,t,s,k}, P_{el.gen,t,s,k} \in \Omega_{P_{s,k,t}} \tag{7.3}$$

7.2.3 Grid Snapshot Definition

For the Decentral Energy System Aggregation the energetic parameters to adequately evaluate the network expansion are derived in a similar way to the Grid Snapshot Definition within the Distribution Network Expansion Planning. The typical use cases will be defined by automatically evaluate grid operation for each time step in the target period. Since the process of the grid snapshot definition within the Decentral Energy System Aggregation will be automated, the level of detail given to each considered DES can not be as granular as the process in the Distribution Network Expansion Planning.

$$p^{u}_{t,k} \in \Omega_{P_{t,k,s}} \qquad \forall t \in \Omega_T, \forall s \in \Omega_S, \forall k \in \Omega_K \tag{7.4}$$

7.2.4 Network expansion and network reinforcement

The network expansion and reinforcement measures in the Decentral Energy System Aggregation include the same expansion measures as formulated in Distribution Network Expansion Planning. For DESA the reinforcement measures include as well new line construction in existing lines and an exchange of transformers and other equipment. The approach to determine network expansion and reinforcement candidates to be taken into account in the planning approach is the same as in the Distribution Network Expansion Planning.

7.2.5 Grid Planning Methodology

To automate the grid planning procedure in the Decentral Energy System Aggregation the target grid planning approach developed in the Distribution Network Expansion Planning will be executed on the basis of the energy scenarios and grid snapshots on the synthetic grid models. The approach follows the mathematical formulation in 6.4.

The objective function is to minimise the sum of the annuity costs of investment measures and the approximated operating costs as well as in the Distribution Network Expansion Planning approach but for multiple grids g in Ω_G:

$$\min C_g^{TOTEX} = C_g^{CAPEX} + C_g^{OPEX} \tag{7.5}$$

CAPEX:
Cost of investment candidates.

$$C_g^{CAPEX}(x) = \alpha_i \cdot \sum_{i \in \Omega_I} c_i^{\Omega_I} \cdot x_i \tag{7.6}$$

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OPEX:
Operational Cost of grid infrastructure.

$$C_g^{OPEX} = C_g^{OPEX,M} + \sum_{t \in \Omega_T} C_{t,g}^{OPEX,O} + C_{t,g}^{OPEX,F} \tag{7.7}$$

OPEX Maintenance:
Cost for repairing and maintaining the grid infrastructure.

$$C_g^{OPEX,M}(x) = \sum_{t \in \Omega_T} C_{t,g}^{OPEX,O}(v,\theta) \cdot x_i \tag{7.8}$$

OPEX Operation: Costs for the procurement of network losses.

$$C_g^{OPEX,O}(v,\theta) = C_g^{OPEX,loss}(x) \cdot \sum_{k \in \Omega_K} \sum_{m \in \Omega_{K_k}} p_{km,t}(v,\theta) + p_{mk,t}(v,\theta) \tag{7.9}$$

OPEX Flexibility Options: Costs for the use of grid flexibility options.

$$C_g^{OPEX,F}(y) = \sum_{f \in F} c_{f,t}^{OPEX,F} \cdot y_{f,t} \tag{7.10}$$

The constraints for the planning process in DESA follows the same conceptual structure as in DNEP. To ensure solutions for the aggregation the DNEP approach might be simplified.

7.2.6 Economic Assessment

The Economic assessment for multiple scenarios and automated target grid planning on the synthetic grid infrastructure in the Decentral Energy System Aggregation approach enables the derivation of a cost factor for each area and scenario. Since spatial aggregation and clustering of typical network areas might be necessary to keep acceptable calculation times, extrapolation of costs will be the means of choice.

$$C_{s,a}^{TOTEX} = \sum_{g \in \Omega_{G_A}} C_{g,s}^{TOTEX} \forall g \in \Omega_{G_A}, a \in \Omega_A, \forall s \in \Omega_S \tag{7.11}$$

7.2.7 Indicator for Central Energy System

As described, the streamline process should result in indicators for each area, which represent the integration costs of the installed capacity for each technology considered in the Central Energy Systems on the electric distribution grid. These indicators then enable the optimisation process in the Central Energy Systems to consider the cost of the integration of technologies to the existing decentral infrastructure.

$$C^{Indicator} = C_{s,a}^{TOTEX} \forall a \in \Omega_A, \forall s \in \Omega_S \tag{7.12}$$

In order to ensure the adequate representation of the impact of technology integration in decentral structures this indicator has to reflect multiple technology dimensions and the respective integration cost. While the integration of wind power plants may resolve in higher expansion costs in the electric distribution grid, the use of flexible technologies such as storage systems reduces the costs. DESA provides the possibility to analyse multiple technology options and derives a cost indicator for the consideration within the central planning approach in chapter 2.

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Chapter 8

Next steps

The target of this deliverable was describing the mathematical formulation and the functionality of the PlaMES tools. The overall target - an integrated planning of multimodal energy systems - has been split in six tools. Each tool can be run on its own providing its own value but depends on each the other tools to be able to answer the research questions of PlaMES.

In the previous work, the optimisation problems have been described mathematically. Now, a prototype of the PlaMES tools will be developed and implemented. Therefore, each tool will be implemented to be able to solve the explained problem. Furthermore, the tools need to be coordinated. A workflow coordination and a shared database system will be developed.

The mathematical problems described in this deliverable have various mathematical problem structures. CES and DESOP are formulated as LP without of any binary variable. However, the problem structure and size of the problems may be big when trying to plan large central energy systems, such as the European energy system or when planning large decentral energy system consisting of more than 100,000 buildings. TEP and DNEP are formulated as MILP with a large set of binary investment decisions. To reduce the complexity of solving those optimisation problems, solution methods and decomposition approaches will be developed in Work Package 4 "Development of solution methods".

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Bibliography

Cramer, Wilhelm, Maria Vasconcelos, Carlo Schmitt, Andreas Armstorfer, Nauman Beg, and Florian Heringer. “Engaging Prosumers in Local Energy Market Business Models.” In *Proc. of the 25th International Conference on Electricity Distribution (CIRED 2019)*. AIM, 2019. ISBN: 978-2-9602415-0-1. doi:10.34890/555.

Franken, Marco, Hans Barrios, Alexander Schrief, and Albert Moser. “Transmission Expansion Planning via Power Flow Controlling Technologies.” *IET Generation, Transmission & Distribution*, 2020. ISSN: 17518687. doi:10.1049/iet-gtd.2019.1897.

Franken, Marco, Alexander B. Schrief, Hans Barrios, Ralf Puffer, and Albert Moser. “Co-Optimization of Multi-Stage Transmission Expansion Planning and Grid Operation.” In *21st Power Systems Computation Conference (PSCC), accepted for publication*. 2020.

Franken, Marco, Alexander B. Schrief, and Albert Moser. “Planung elektrischer Übertragungsnetze unter Berücksichtigung netzbetrieblicher Flexibilitäten.” In *16. Symposium Energieinnovation*. 2020.

Hülk, Ludwig, Lukas Wienholt, Ilka Cußmann, Ulf Philipp Müller, Carsten Matke, and Editha Kötter. “Allocation of annual electricity consumption and power generation capacities across multiple voltage levels in a high spatial resolution: 79-92 Pages / International Journal of Sustainable Energy Planning and Management, Vol 13 (2017) / International Journal of Sustainable Energy Planning and Management, Vol 13 (2017),” 2017. doi:10.5278/IJSEPM.2017.13.6.

Koopmann, Simon. “Planung von Verteilungsnetzen unter Berücksichtigung von Flexibilitätsoptionen.” PhD thesis, RWTH Aachen University, 2016.

Kotzur, Leander, Peter Markewitz, Martin Robinius, and Detlef Stolten. “Impact of different time series aggregation methods on optimal energy system design.” *Renewable Energy* 117 (2018): 474–487. ISSN: 09601481. doi:10.1016/j.renene.2017.10.017.

OpenStreetMap contributors. *Planet dump retrieved from https://planet.osm.org*. https://www.openstreetmap.org, 2017.

Rahmani, Mohsen, Gabriela Hug, and Amin Kargarian. “Comprehensive power transfer distribution factor model for large-scale transmission expansion planning.” *IET Generation, Transmission & Distribution* 10, no. 12 (2016): 2981–2989. ISSN: 1751-8687. doi:10.1049/iet-gtd.2015.1573.

Thurner, Leon. “Structural Optimizations in Strategic Medium Voltage Power System Planning.” PhD thesis, University of Kassel, 2018.

Thurner, Leon, Alexander Scheidler, Florian Schafer, Jan-Hendrik Menke, Julian Dollichon, Friederike Meier, Steffen Meinecke, and Martin Braun. “Pandapower—An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems.” *IEEE Transactions on Power Systems* 33, no. 6 (2018): 6510–6521. ISSN: 0885-8950. doi:10.1109/TPWRS.2018.2829021.

Van den Bergh, Kenneth, Erik Delarue, and William D’haeseleer. *DC power flow in unit commitment models*. University of Leuven - Energy Institute, Leuven, May 2014. Accessed May 26, 2020. https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wpen2014-12.pdf.

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Abbreviations

AC	Alternating Current
CAPEX	Capital Expenditures
CES	Central Energy System
CCS	Carbon Capture Storage
CHP	Combined Heat and Power
CM	Coordination Mechanism
CTS	Commerce, Trade and Service
DC	Direct Current
DES	Decentral Energy System
DESA	Decentral Energy System Aggregation
DESD	Decentral Energy System Disaggregation
DESOP	Decentral Energy System Operation
DNEP	Distribution Network Expansion Planning
DSO	Distribution System Operator
EV	Electric Vehicle
GEP	Generation Expansion Planning
HH	Household
HP	Heat Pump
HV	High Voltage
HVDC	High Voltage Direct Current
LEM	Local Energy Market
LP	Linear Problem
LV	Low Voltage
MILP	Mixed Integer Linear Programming
MV	Medium Voltage
MW	Megawatt
MWh	Megawatt-hour
OPEX	Operational Expenditures
PlaMES	Integrated Planning of Multi Energy Systems
PST	Phase Shifting Transformer
PTDF	Power Transfer Distribution Factor
PV	Photovoltaik
RES	Renewable Energy Sources

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SoC	State of Charge
TCSC	Thyristor Controlled Series Compensator
TEP	Transmission Expansion Planning
UC	Unit Commitment
V2G	Vehicle to Grid
VPI	Virtual Power Injection
VPP	Virtual Power Plant
VRDT	Voltage Regulated Distribution Transformer
WPP	Wind Power Plant