Synthetic LV-Grid Models for Scientific Investigations

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0 Foreword

This document is an English version of the paper which was originally written in German[1]. In addition, this paper discusses a few more aspects especially on the planning process of distribution grids in Germany. Since there are special German vocabulary, it is not possible to give an exact translation all the time. We did our best.

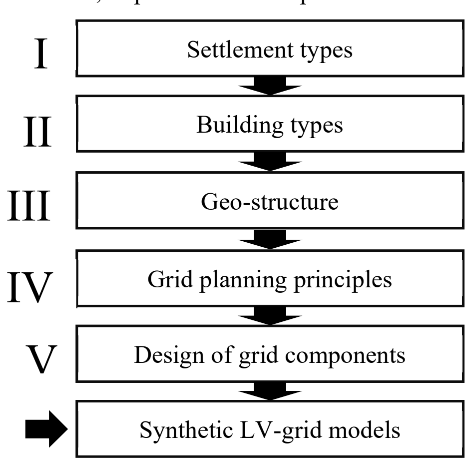
1 Motivation and Objectives

Due to the steadily increasing number of decentralized generation units, the upcoming smart meter rollout and the expected electrification of the transport sector (e-mobility), grid planning and grid operation at low-voltage (LV) level are facing major challenges. Therefore, many studies, research and demonstration projects on the above topics have been carried out in recent years, and the results and the methods developed have been published. However, the published methods usually cannot be replicated or validated, since the majority of the examination models or the scenarios used are incomprehensible to third parties. There is a lack of uniform grid models that map the German LV grids and can be used for comparative investigations, which are similar to the example of the North American distribution grid models of the IEEE [1].

In contrast to the transmission grid, whose structure is known with high accuracy, suitable grid models for LV grids are difficult to map because of the high number of LV grids and distribution system operators (DSOs). Furthermore, a detailed description of real LV grids is usually not available in scientific publications for data privacy reasons. For the investigations in [2], therefore, the most characteristic synthetic LV grid models have been created, which are based on common settlement structures and usual grid planning principles in Germany. In this work, these LV grid models, and their development are explained in detail. For the first time, comprehensible LV grid models for the middle European area are available to the public, which can be used as a benchmark for further scientific research and method developments.

2 Methodology

The development steps of the synthetic LV grids are shown in Figure 1. Step I involves the identification of the representative settlement structures with typical buildings and geo-structural features such as street layout and plot dimensions. In Step II, the building type is defined for each settlement structure, with the number of floors, the number of dwellings and building dimensions, and the derived usable roof areas. The roof areas are relevant to the later design of the PV systems. Step III includes the determination of the geo-structural features such as the typical grid feeder length, the distances between buildings and roads, the number of feeders at the local substation and the number of buildings or house connections. The determinations in steps I to III are based on an extensive literature research, in particular of the publications from the German construction industry.



In step IV line types, grid topologies and installation types of the lines for the various settlement structures are determined based on the standard grid planning principles. For this step, the authors co-operated closely with a medium-sized German DSO. As the result of step IV, basic grid models are created for each settlement structure in a commercial grid calculation program. In step V, the basic models are updated by the design of the components, i.e. the transformers and the cables. For this, normal planning procedures for LV grids are explained and applied. The equipment are selected from a catalogue of standard resources.

This process results in 14 different synthetic LV grid models, each with three variants in terms of their geographical extent.

Figure 1: Overview on development steps

[1] Wellssow et al,"Synthetische NS-Netzmodelle für wissenschaftliche Untersuchungen" (German) Online available: https://kluedo.ub.uni-kl.de/frontdoor/deliver/index/docId/5210/file/_Synthetische+NS-Netzmodelle+f%c3%bcr+wissenschaftliche+Untersuchungen.pdf (last check: 24.02.2022)

3 Developement steps

I. Identification of representative settlement structures

The settlement structure is defined as „*collections of buildings in which people live, including buildings for further purposes, facilities, traffic areas etc.*[2]" In the past, structural analysis of various sites [3 to 7] has combined characteristic settlements with defined structural features to form representative settlement structures. In [8], the settlement structures for grid investigations from [3] are modified. Table 1 shows the different settlement structures from the respective publications. Based on this, the representative settlement structures are derived in this article. Table 2 shows the established settlement structures with their abbreviations and their essential properties, with additional divisions into rural, suburban and urban areas.

Table 1: Overview of the settlement structures from the publications

	Publications					
	[3]	[4]	[5, S. 30]	[6, S. 26]	[7, S. 40]	[8, S. 64]
Rural settlement structures		X	X			X
Village centre and single-family housing estate	X					X
Single-family housing estate		X			X	
Freestanding inputs and Two-family houses	X		X	X		
One- and two-family houses as semi-detached houses			X	X	X	X
Row house	X	X	X	X	X	X
Row building medium density	X		X	X		X
Block building	X	X	X	X	X	X
Skyscraper	X	X		X	X	X
Historical old city	X					X
City buildings	X					X
Industrial and warehouse buildings	X					X

Table 2: Overview of the representative settlement structures in this article

Area	Title	Short ID.	Feature
Rual	Scattered settlement, scattered one-family houses	S1a	Detached house, far away from other buildings
	Scattered settlement with house cluster	S1b	Group of houses, far away from other groups
	Street village	S2a	Houses in the centre, arranged in a line
	Cross village	S2b	Houses in the centre, arranged as a cross
Suburban	Low-density one- or two-family housing	S3a	Houses in a low density structure, mostly inhabited by one family
	High-density one- or two-family housing	S3b	Houses in a high density structure, mostly inhabited by two families
	Semi-detatched settlement	S4a	Two houses on one property sharing one wall
	Row settlement	S4b	Row of identical houses, which share the side walls
Urban	Block of flats settlement	S5a	High buildings arranged in rows
	Residential high-rise buildings	S5b	High multi-storey buildings
	Block structure	S6a	Urban residential area surrounded by streets
	Historical old town	S6b	Historical old towns, mostly built during the Middle Ages

[2] Translation of the definition of a German dictionary
Online available: https://www.duden.de/suchen/dudenonline/Siedlung (last check: 24.02.2022)

II. Identification of the building types

Each representative settlement structure is assigned to a building type which can be defined by the following parameters:

1) Dimensions of the buildings
2) Number of floors
3) Number of apartments
4) Typical roof areas

To determine the parameters according to Table 3, rounded mean values of the data in [3 to 9] are used. The definition of the apartment is (free translation) *„externally locked, usually residential rooms in dwellings and other dwellings with living space, which allow the maintenance of a household of its own"*[3]. In the development of LV grid models, it is assumed that a household has one apartment.

Depending on the types of the buildings, different useable roof areas A_{pv} are considered for the installation of the PV modules. To calculate A_{pv}, a simplified equation based on the building dimensions is used:

$$A_{\mathrm{pv}} = \frac{A_{\mathrm{ge}}}{\cos\left(\alpha_{\mathrm{DN}}\right)} \cdot 0.5 \cdot f_{\mathrm{DN}} \quad (1)$$

The equation contains information of the building surface A_{ge}, the roof pitch angle α_{DN} and the roof utilization factor f_{DN}. Equation (1) assumes that only one side of the gable roof is used (factor 0.5). The roof pitch angle is set to α_{DN} = 30° for all settlement structures with an exception for S5b, where a flat roof is considered and α_{DN} is taken as 0°. The roof utilization factor considers that it is not possible to cover the entire area with the PV modules, which is also fixed at a flat rate of f_{DN} = 0.85.

Table 3: Parameters for the building types

	Building types	Building dimensions	Number of floors	Number of apartments	Usable roof area A_{pv}
S1a	Granny-flat	18 m x 10 m	1	1	88.33 m²
S1b		18 m x 10 m	1	1	88.33 m²
S2a	Bungalow	10 m x 16 m	1	1	78.52 m²
S2b		10 m x 16 m	1	1	78.52 m²
S3a	Single-family home	10 m x 12.5 m	1.25	1	61.34 m²
S3b	Double-family home	10 m x 12 m	2	2	58.89 m²
S4a	Townhouse	7.5 m x 10.7 m	2	1	39.26 m²
S4b		5.5 m x 10 m	2	1	26.99 m²
S5a	Row building	10 m x 24 m	5	10	117.78 m²
S5b	High-rise building	20 m x 24 m	12	48	204.00 m²
S6a	Block building	120 m x 140 m*	4	8	147.22 m ²*
S6b		60 m x 100 m*	3	6	122.69 m²*

* effective building dimension, see Figure 2

III. Identification of the geo-structural features

The determination of the geo-structural features is necessary for the determination of the line lengths and the size of the LV grid models, which are based on the following criteria:

1) Identification of the typical grid sizes (extensions) and the feeder lengths for each settlement structure
2) Geo-structural dimensions (the distance between two buildings, etc.)
3) Number of the feeders at the local sub station
4) Number of the buildings / house connections

[3] Free translation of a definition according German Government agency "Statistisches Bundesamt"
Online available: https://www.destatis.de/DE/Methoden/Klassifikationen/Bauwerke/bau-78v14-erl.pdf?__blob=publicationFile (last check: 24.02.2022)

The typical line lengths are determined based on various publications [8, 10] and in consultation with a German DSO (see Table 4). For the settlement structures S5a and S5b, no information of the typical grid feeder lengths is provided, since these are settlements or settlement parts with fixed geo-structure and number of nodes. The grid feeder lengths result here from the basic unit dimensions.

The number of floors (FAN) is used as the basis for determining the geo-structural dimensions. The FAN is part of the development plan and indicates the ratio of the floor area A_{ge} to plot area A_{gr}. According to [11] the FAN is defined as:

$$\mathrm{FAN} = \frac{A_{\mathrm{ge}}}{A_{\mathrm{gr}}}. \tag{2}$$

Due to the different digits of the FAN per settlement structure in various publications [3, 4, 6 to 8], three scenarios for the FAN of each settlement structure are considered: a maximum (max), a medium (mid) and a minimum (min) scenario of the resulting geographical extensions of the settlement. For that, min and max scenarios are taken from literature [3 to 8] by using the extreme values for each settlement structure. The mid scenario is generated by the mean value of all data.

With the FAN and the building dimensions from step two (Table 3), the plot dimensions are derived with which the distance between two buildings is determined, seen in Table 4. A high FAN value results in a small distance between two buildings.

The settlement structures S1a and S1b are special cases, as these are scattered. The value of the distance between two buildings (S1a) or between two house clusters (S1b) is set to 75 m ± 25 m according to the literature.

The distance between a building and the street is set as the values given in Table 4, which is in agreement with the DSO and with the consideration of the FAN. The width of the streets and the paths is based on the specifications in [8, p. 30].

Table 4: Overview of the geo-structural features

	Mean grid feeder length	FAN			Distance between adjacent house connections in m			Distance between building and street in m			Width of the street/ path in m	
		max	mid	min	min	mid	max	min	mid	max	str.	path
S1a	600 m	0.30	0.20	0..05	50	75	100	10	15	20	12.5	-
S1b	500 m	0.30	0.20	0.05	50	75	100	10	15	20	12.5	-
S2a	450 m	0.50	0.35	0.20	15	22.5	30	2	4	6	12.5	-
S2b	270 m	0.50	0.35	0.20	15	22.5	30	2	4	6	12.5	-
S3a	452 m	0.30	0.20	0.10	12	16	20	4	6	8	10	6
S3b	415 m	0.50	0.35	0.20	15	22.5	30	4	6	8	10	6
S4a	477.5 m	0.50	0.35	0.20	12	15.3	19	4	6	8	10	6
S4b	222.5 m	0.80	0.60	0.40	5.5	7.5	10.7	4	6	8	10	6
S5a	*	1.20	0.80	0.40	24	24	24	4	6	8	15	6
S5b	*	1.50	1.00	0.50	60	72	96	5	20	35	15	-
S6a	195 m	1.47	1.01	0.78	20	30	40	2	4	6	15	-
S6b	166 m	2.60	2.11	1.79	10	12.5	15	2	4	6	12.5	-

* Types of settlements with an fixed structure

Figure 2 shows the graphical representation of the buildings and the property dimensions for each scenario. If the building dimensions remain the same, the property dimensions are adjusted with the change of the FAN. Exceptions are the settlement structures S6a and S6b, where the building dimensions are almost the same as the plot dimensions. As the FAN decreases, the dimensions of the buildings and plots of land, as well as the usable roof area increase proportionally.

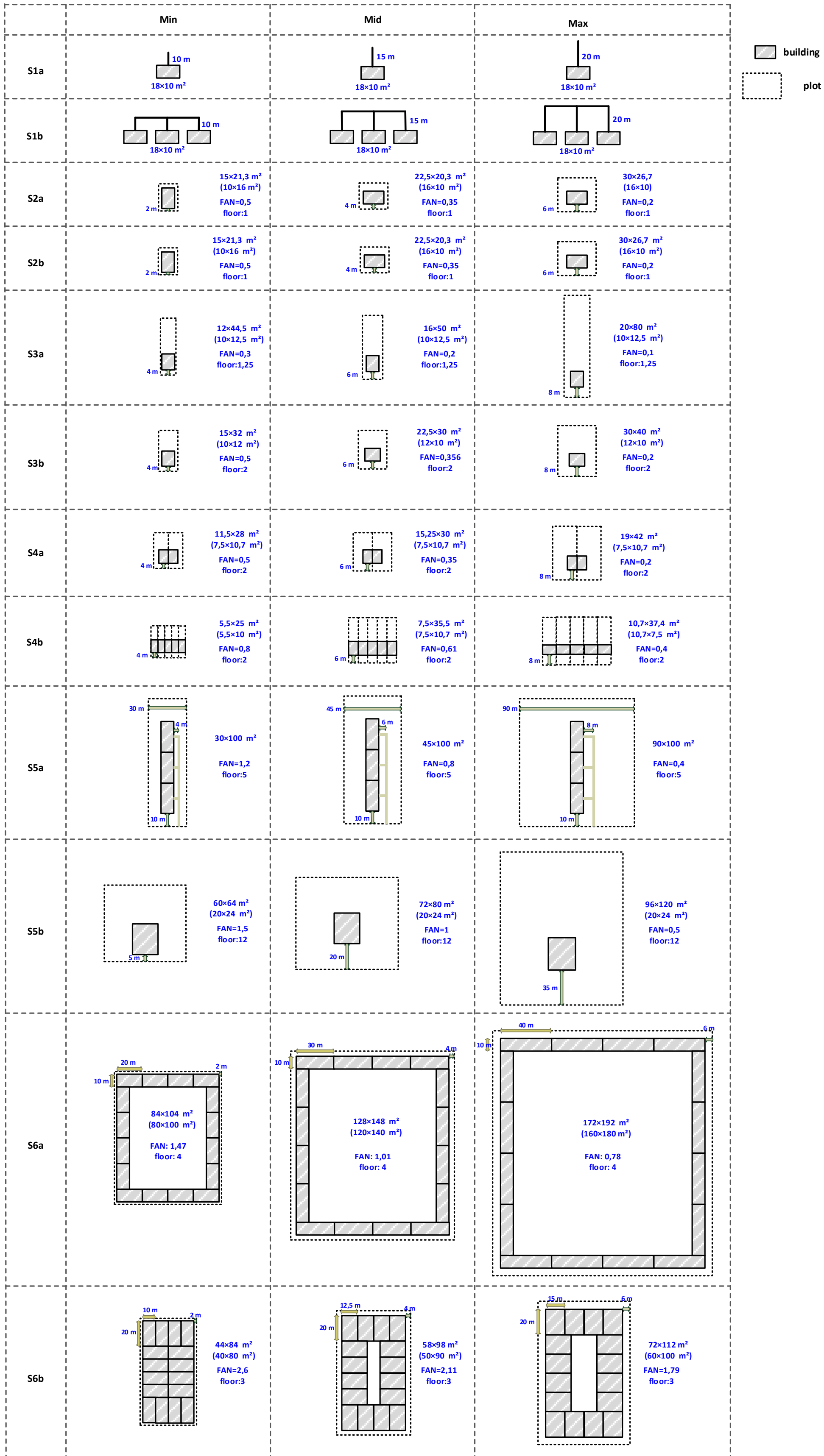


Figure 2: Graphical representation of the building and the property dimensions per dimension scenario

The number of outgoing feeders at the substation (number of grid feeders) also depends on the grid planning principles of the DSO. For this, the number of feeders is determined on the geo-structural features (e.g. streets) of typical grid sizes and the information from [8, 10] which is presented in Table 5. For some settlement structures (S3a, S3b and S4a), the number of grid feeders is changed after the grid components are designed with the standard grid planning principles (changing from one-sided to two-sided cable installations) to comply with the grid planning criteria.

The number of buildings (equal to the number of house connections) per feeder $N_{\mathrm{ge,grid}}$ is derived from the typical feeder length l_{grid} from Table 4 and the average value (per scenario) of the property dimensions along the feeder l_{gr}. The number of buildings is calculated using Eq. (3). The factor k serves as a multiplier, if a grid feeder supplies the houses on both sides of the street (k = 2) or only one side of the street (k = 1).

$$N_{\mathrm{ge,grid}} = k \cdot \frac{l_{\mathrm{grid}}}{l_{\mathrm{gr}}} \tag{3}$$

The number of dwellings per settlement structure is then calculated by multiplying the number of dwellings of the building types in Table 3 and the number of buildings. The number of dwellings is decisive for the load assumptions when designing the grid components. Table 5 shows all the information on the number of buildings and of dwellings per feeder. The number of buildings is recorded for the dimensioning scenarios (min/mid/max), while the feeder lengths decrease for the min scenario and increase for the max scenario.

Table 5: Number of buildings and of dwellings per feeder

	Number of grid feeders	k	Buildings per feeder $N_{\mathrm{ge,grid}}$.	Number of buildings N_{ge}	Number of dwellings N_{W}
S1a	1	2	18	18	18
S1b	1	2	30	30	30
S2a	2*	2	40	80	80
S2b	4	2	25	100	100
S3a	6	1	27	162	162
S3b	6	1	18	108	216
S4a	6	1	30	180	180
S4b	3	2	60	180	180
S5a	4	1	4	24	240
S5b	6	1	1	6	288
S6a	6	1	6	32	256
S6b	6	1	8	48	288

* Double the number of grid feeder for overhead line variant

IV. Application of standard grid planning principles

Grid planning principles are usually defined individually by each DSO. They usually include the following steps:

1) Selection of the grid topology
2) Selection of the line type
3) Selection of the cable laying scheme
4) Selection of the standard equipment

According to [12], there are three possible variants of the basic topologies for the LV grids:

- Radial grid
- Ring grid
- Mesh grid

The radial grid is the established basic topology of LV grids, especially in rural areas. There are also special forms of the radial grid, such as the radial grid with partially double installation, but these are not considered. Ring grids are usually operated with open rings, i.e. the rings are separated at one separation point. Ring grids with open rings can be treated like radial grids and are therefore not considered separately. Mesh grids are used in densely populated areas. Due to too low load density (S1a-S3a) or too small extension of the grid (S3b-S6b), the mesh grid is not considered either. Therefore, the radiation grid is used as the grid topology for all LV grid models as the standard design.

There are two variants for the line types:

- Overhead line (OHL)
- Buried cable (CB)

Overhead lines in Germany are generally used in rural areas with low load density. In suburban and urban areas, cables are generally used. Due to the different reactance-to-resistance ratio, the differentiation of these line types is relevant for the generation of synthetic LV grid models. Except for the settlement structures S1a and S1b, cables are used as the line type for all other settlement structures. For the settlement structures S2a and S3a, overhead lines are also considered as an additional variant.

There are two basic variants regarding the scheme of the cable laying:

- Single-sided cable installation
- Double-sided cable installation

If the cable is laid single-sided, the cable is laid on one side of the street. The house connections for the houses on the other side of the street are laid crosswise under the street. If a new house connection is required on this side of the street, construction work on the street is necessary. For this reason, the DSO prefers to lay cables on both sides of the street when the load density is high. The LV grid models described here are initially based on a single-sided cable installation. In some cases (S3a, S3b, S4a), the planning criteria are not met if the standard cables are used exclusively (see Step V: Design of grid components), which leads to a change to the two-sided cable installation.

There are also two variants for the installation of the overhead lines.

- Single-sided power pole
- Two-sided roof pole

In the first case, the houses on both sides of the street can be supplied by power poles at one side of the street, with cross-connections to the other side. In the second case, the overhead lines can be routed via roof poles, with parallel designs at both sides of the street. Figure 3 shows examples for each case. The variant using roof poles is more favourable but requires a sufficient proximity of the buildings. This variant is used for the settlement structures S2a and S3a. For the scattered boulders S1a and S1b, the variant of the single-sided poles is used. Table 6 shows the specifications regarding the grid planning principles for each settlement structure.

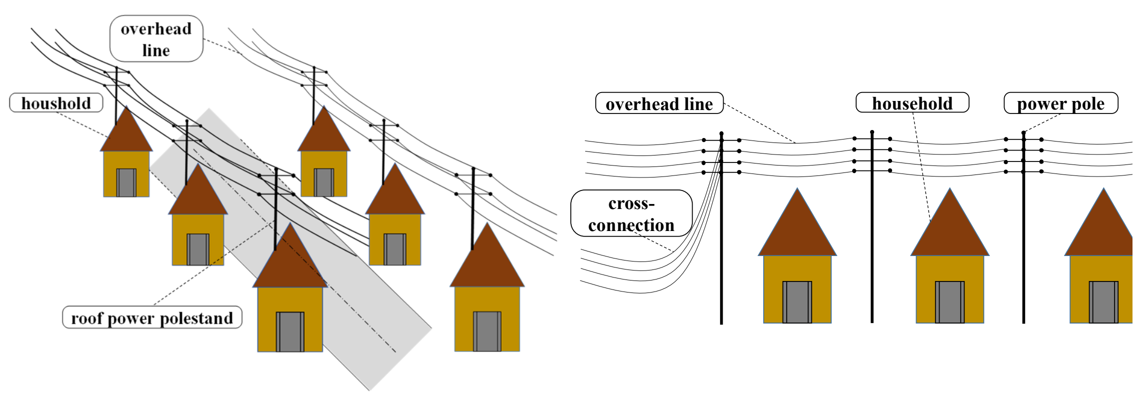


Figure 3: Examples of the two types of overhead line installation (left: roof pole, right: power pole)

Table 6: Used grid planning principles

	Line type	Grid topology	Installation type
S1a	OHL	radial grid	power pole
S1b	OHL	radial grid	power pole
S2a	CB & OHL	radial grid	one-sided cable installation & roof pole
S2b	CB	radial grid	one-sided cable installation
S3a	CB & OHL	radial grid	one-sided cable installation & roof pole
S3b	CB	radial grid	two-sided cable installation
S4a	CB	radial grid	two-sided cable installation
S4b	CB	radial grid	one-sided cable installation
S5a	CB	radial grid	one-sided cable installation
S5b	CB	radial grid	one-sided cable installation
S6a	CB	radial grid	one-sided cable installation
S6b	CB	radial grid	one-sided cable installation

Once the grid planning principles have been defined, the basic grid models of the LV grids are implemented in the grid calculation program. Figure 4 shows a graphic representation of the development steps using the example of the settlement structure S3a. After designing the grid components and setting the resulting parameters in the grid calculation program, the LV grid models are obtained.

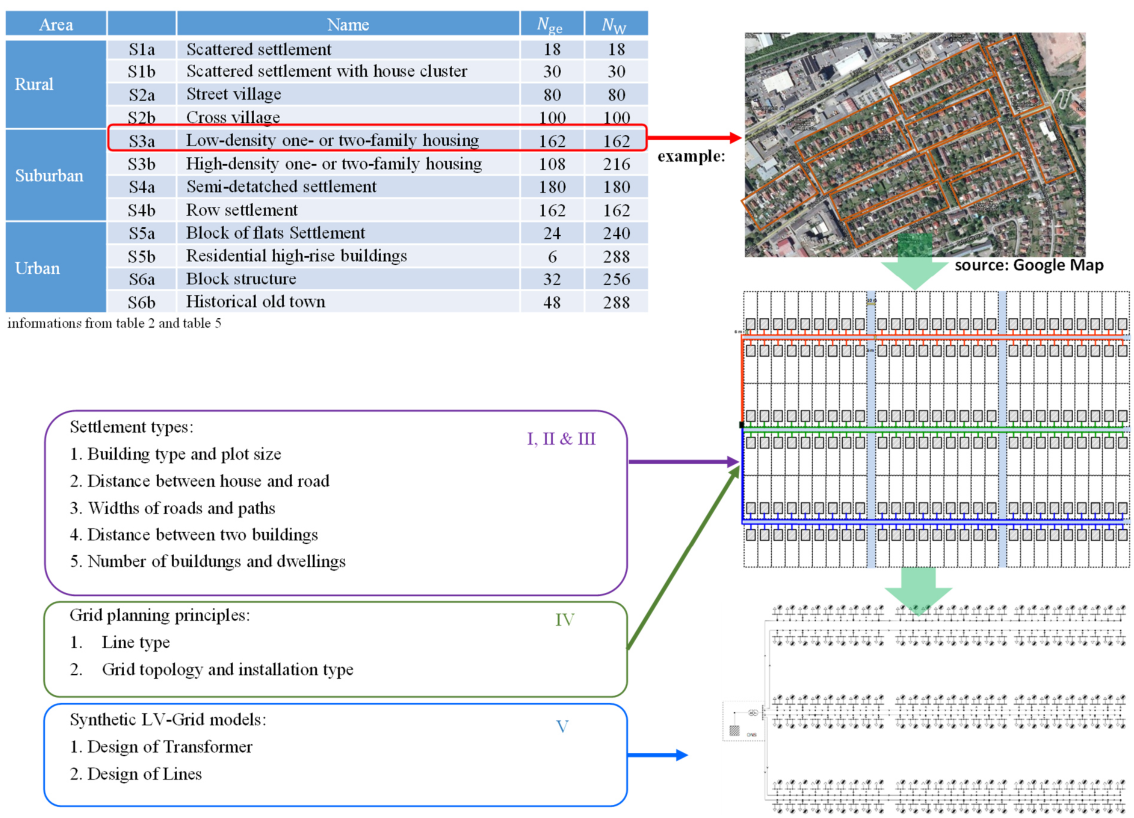


Figure 4: Example to illustrate the development steps

V. Grid planning criteria and design of the grid components

General planning process and criteria

The goal of the network planning process is to dimension the network components in such a way that compliance with the operational limits is guaranteed. Operational limits are on the one hand the thermal limits of the components, on the other hand the voltage compatibility level according to the DIN EN 50160 (European standard). According to the DIN EN 50160, the voltage should be within a ± 10 % tolerance band of the nominal voltage U_n most of the time. Since the distribution grids in Germany are normally not monitored or actively controllable (e. g.

by reactive power management like in the high voltage area), this $\pm$ 10 % U_n tolerance band is partitioned over all distribution voltage levels.

For this partition, the German DSOs must consider the standards VDE-AR 4110 (medium voltage, MV) and VDE-AR 4105 (LV). These standards specify the recommended values of voltage increase at full rated output of all the distributed generation units (DGUs) in the grid section. With full rated power output, the voltage increase in the whole grid section should not be higher than 2 % at MV level and 3 % at LV level. Note, that it can be deviated from these criteria, if the DSO provides proper measures against voltage problems.

Furthermore, VDE-AR 4110 and VDE-AR 4105 define that DGUs must disconnect from the grid if the voltage of a 10 min mean value exceeds 110 % of the nominal voltage U_n. Moreover, they allow the DGU a tolerance of $\pm$ 1 % for 10 min mean value, which means that in theory the DGUs can already be disconnected after a 10 min mean value of 109 % U_n.

Taking all this into account, the upper voltage band is fixed by the standards. Considering an active voltage controlled on-load tap changing transformer at the HV/MV substation, the voltage at the feeding MV busbar can be kept within a voltage regulation band. Therefore, the possible lower voltage band is defined and distributed across the MV and LV level.

Figure 5 shows the typical partition of a German DSO, which is used in this paper. The voltage regulation band at the substation is 2 % U_n and the set point is at 102.5 % U_n. The planned voltage drops for MV and LV level are 5 % U_n each. Due to a higher inductive part of the power flows during load cases, a higher voltage drop at the MV/LV transformer is considered as 1.5 % U_n compared to the feed-in case (0.5 % U_n). Note, that the voltage partition can differ from DSO to DSO.

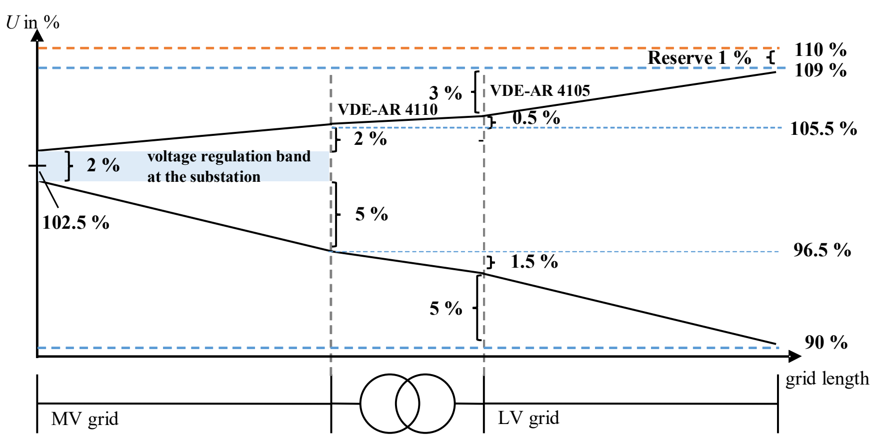


Figure 5: Voltage band partition for grid planning

According to the partition of Fig. 5, the grid planning criteria in this document for the LV grid are:

- The thermal current limit of the components
- The 5 % voltage drop in the load case
- The 3 % voltage raise in the feed-in case

For the verification, that the planning criteria are met, it is distinguished between load case and feed-in case. For all the verifications of the criteria, the slack node voltage is normally set to 100 % of the nominal voltage, while the slack node is located at the low voltage side of the substation.

For the load case, all the power infeeds of the DGUs are set to zero. All household loads are set to a grid-specific peak load share value P_G. To calculate this value a multiplier $M(N_\mathrm{W},\mathrm{EL})$ is determined depending on the selected electrification level (EL) and the number of apartments in the grid model according to [13, p. 35]

$$M(N_\mathrm{W},\mathrm{EL}) = 1 + \frac{\alpha(\mathrm{EL})}{{N_\mathrm{W}}^{\kappa}} = 1 + \frac{13{,}3}{N_\mathrm{W}}, \qquad (4)$$

with $\alpha(\mathrm{EL})$ and κ as the coefficients depending on regional conditions.

Without precise information on the regional conditions, standard values from the literature are used with $\kappa = 1$ and $\alpha(\mathrm{EL}) = 13.3$ for EL3 [13, S. 35]. The EL classifies apartments according to the installed electrical appliances. The four common degrees of EL are listed in Table 7 [12, p. 2–3, 13, p. 36, 13]. The peak load specified there is rarely reached, and it is uneconomical to design the LV grid for this capacity. Considering the simultaneity based on empirical values, a peak load share is allocated to each dwelling. Table 7 lists the empirical values of the peak load share $P_{\mathrm{G}\infty}$ for a very high number of flats (>1000). The grid-specific peak load share value P_{G} is calculated by multiplying $P_{\mathrm{G}\infty}$ and the multiplier as shown below:

$$P_{\mathrm{G}} = P_{\mathrm{G}\infty} \cdot M(N_{\mathrm{W}},\mathrm{EL}). \tag{5}$$

Table 7: Electrification level and peak loads for apartments [12, S. 2–3, 13, S. 36, 13]

EL	Description	Share of peak load $P_{\mathrm{G}\infty}$ for $N_{\mathrm{W}} \rightarrow \infty$
EL1	Light and small devices	0.7 … 0.9 kW/apartment
EL2	EL1 + electrical cooking	1.0 … 1.2 kW/apartment
EL3	EL2 +el. water heating	1.8 … 2.0 kW/apartment
EL4	EL3 + electrical heating	10 … 12 kW/apartment

It is also noted that many DSOs, based on the current grid planning, use a much higher peak load share $P_{\mathrm{G}\infty}$ for calculating load assumptions (e.g. 3.5 kW for EL3) in order to take into account the future electrification of vehicles.

For the feed-in case, the power of all loads are set to zero and the power output of the DGUs are set to the rated power. Different from the load case, the feed-in case needs to be analysed by an unbalanced power flow calculation since the DGUs are in general not symmetrically feeding-in and their connection is unbalanced as well.

If the DGUs have passive reactive power management, like the $\cos\varphi(P)$-characteristic described in VDE-AR 4105, this is considered too. In case of the $\cos\varphi(P)$-characteristic, the $\cos(\varphi)$ should be set for maximum active power feed-in.

For a grid planning from scratch, the first step is to determine the minimum rated power of the MV/LV transformer. To estimate the peak power at the MV/LV transformer in the load case, all the specific peak load share values are summed up:

$$P_{\Sigma}(N_{\mathrm{W}}) = N_{\mathrm{W}} \cdot P_{\mathrm{G}}. \tag{6}$$

For the feed-in case, all rated power outputs of the DGUs are summed up as well:

$$S_{\mathrm{DGU}} = \sum_i \frac{P_{\mathrm{DGU},i}}{cos(\varphi_{\mathrm{DGU},i})} \tag{7}$$

The variable w stands here for the three-line conductors.

The biggest of all these values are applied for the design of the minimum rated power $S_{\mathrm{rT,min}}$ of the MV/LV transformer. For this reason, the max-operator is applied to the values:

$$S_{\mathrm{rT,min}} = \max\left(\frac{P_{\Sigma}(N_{\mathrm{W}})}{cos(\varphi)}, S_{\mathrm{DGU}}\right). \tag{8}$$

The value applied for $\cos(\varphi)$ varies, depending on the DSO and the loads in the grid, between $\cos(\varphi) = 0.95...1$.

Planning process for the synthetic models

This section describes the selection of the grid component types used for the basic grid models. Since the installed power of the PV units highly depends on the scenario of a research (e.g. how many households have a PV unit), the grids are only designed for the load case. The working steps are as follows:

a) Estimation of the minimum rated power of the MV/LV transformer considering the simultaneity in the load assumption, see Eq. (8).
b) Selection of the type and rated power of the MV/LV transformer from the catalogue of standard equipment and selection in the grid calculation program accordingly (see Table 9).
c) Setting standard equipment types for the lines with the smallest cross-section in the grid calculation program (see Table 10).
d) Setting the output (load assumption) per house connection considering the peak load and the multiplier for simultaneity see Eq. (5).
e) Execution of the load flow calculation.
f) Check the compliance with the thermal current limits. If this is OK, check the compliance with the permissible voltage drop (< 5% U_{n}).
g) If all criteria are met, stop the process. If not fit, reinforce the cables and repeat steps e) to g). Reinforcement of the cable means to select the next greater cable cross section of the standard, see Table 10. If the maximum line cross section is reached, start with parallel lines by the lowest cross section. In the end, also the transformer rated thermal current should not be exceed too. Otherwise it must be replaced by a transformer with a higher rated power.

For the steps a) and d), the peak load share $P_{\mathrm{G}\infty}$ for the EL3 of 2 kW/housing is used.

In order to create the synthetic LV grid models, a cos(φ) = 0.99 is determined based on the empirical values and in consultation with the DSO. Table 8 shows the calculated values per settlement structure for the specific peak load shares P_{G} and the minimum rated power of the MV/LV transformer $S_{\mathrm{rT,min}}$.

Table 8: Calculated minimum rated power of the MV/LV transformer and peak load share per apartment

	Number of apartments N_{W}	Specific peak load share P_{G}	Minimum rated power $S_{\mathrm{rT,min}}$
S1a	18	3.478 kW	63.2 kVA
S1b	30	2.887 kW	87.5 kVA
S2a	80	2.333 kW	188.5 kVA
S2b	100	2.266 kW	228.9 kVA
S3a	162	2.164 kW	354.1 kVA
S3b	216	2.123 kW	463.2 kVA
S4a	180	2.148 kW	390.5 kVA
S4b	180	2.148 kW	390.5 kVA
S5a	240	2.111 kW	511.7 kVA
S5b	288	2.092 kW	608.7 kVA
S6a	256	2.104 kW	544.0 kVA
S6b	288	2.092 kW	608.7 kVA

Based on the values in Table 8, the local grid transformers with the next higher rated power are selected from a catalogue of standard equipment (see Table 9) and set in the grid calculation program. Lines are also selected and set from the catalogue of standard equipment (see Table 10), each with the initially small cross-section.

Table 9: Catalogue with standard equipment of MV/LV transformers

Voltage level	S_{rT}	u_{k}	u_{r}	X_0/X_1	R_0/R_1
20 kV / 0.4 kV	100 kVA	4 %	1 %	1	1
20 kV / 0.4 kV	250 kVA	4 %	1 %	1	1
10 kV / 0.4 kV	400 kVA	4 %	1 %	1	1
10 kV / 0.4 kV	630 kVA	4 %	1 %	1	1
10 kV / 0.4 kV	800 kVA	6 %	1 %	1	1

Table 10: Catalogue with standard equipment of lines

Type & material	Cross section	Reactance per km	Resistance per km	X_0/X_1	R_0/R_1	Thermal limiting current
OHL-AL	4x25 mm²	0.3988 Ω/km	1.2554 Ω/km	3 (or 4*)	2 (or 4*)	135 A
OHL-AL	4x 70 mm²	0.3667 Ω/km	0.4626 Ω/km	3 (or 4*)	2 (or 4*)	255 A
OHL-AL	4x 95 mm²	0.3557 Ω/km	0.3264 Ω/km	3 (or 4*)	2 (or 4*)	320 A
CB NAYY	4x 35 mm²	0.086 Ω/km	0.868 Ω/km	3 (or 4*)	2 (or 4*)	123 A
CB NAYY	4x 50 mm²	0.085 Ω/km	0.641 Ω/km	3.76	4	144 A
CB NAYY	4x 150 mm²	0.08 Ω/km	0.206 Ω/km	3.64	4	275 A
CB NAYY	4x 240 mm²	0.08 Ω/km	0.164 Ω/km	3.67	4	313 A

* for calculation of the minimal short circuit current

Subsequently, the load assumption per building or house connection is set, which is calculated by multiplying the specific peak load share per dwelling from Table 8 and the number of dwellings per building from Table 3. A load flow calculation is used to check the currents on the lines regarding the compliance with the thermal limit current. In case of overload, a larger cross section is selected based on Table 10. After a new load flow calculation, the compliance with the current thermal limit and the permissible voltage drop is checked again. As already mentioned, the grid planning criterion for the permissible voltage drop depends on the partition of the voltage band across the grid levels by the DSO. Usual values are between 5 % U_n [14] and 5.75 % U_n [15] of the voltage difference between the voltage at the busbar of the MV/LV transformer and the lowest voltage in the LV system. To create the synthetic LV grid models, the partition from Figure 5 is used, with a voltage drop of 5 % U_n. The lines are designed for the mid scenario. In the max scenario, with the higher grid feeder lengths, a higher voltage drop is likely to occur.

Table 11: Selection of the grid components

	Voltage level	Rated power S_{rT} in kVA	Overhead line	cable	House connection
S1a	20 kV / 0.4 kV	100	OHL 4x95	-	OHL 4x25
S1b		100	2x OHL 4x70	-	OHL 4x25
S2a		250	OHL 4x70	-	OHL 4x25
		250	-	NAYY 4x150	NAYY 4x35
S2b		250	-	NAYY 4x150	NAYY 4x35
S3a	10 kV / 0.4 kV	400	OHL 4x95	-	OHL 4x25
		400	-	NAYY 4x150	NAYY 4x35
S3b		630	-	NAYY 4x150	NAYY 4x35
S4a		400	-	NAYY 4x150	NAYY 4x35
S4b		400	-	NAYY 4x150	NAYY 4x35
S5a		630	-	NAYY 4x150	NAYY 4x35
S5b		630	-	NAYY 4x150	NAYY 4x35
S6a		630	-	NAYY 4x150	NAYY 4x35
S6b		630	-	NAYY 4x150	NAYY 4x35

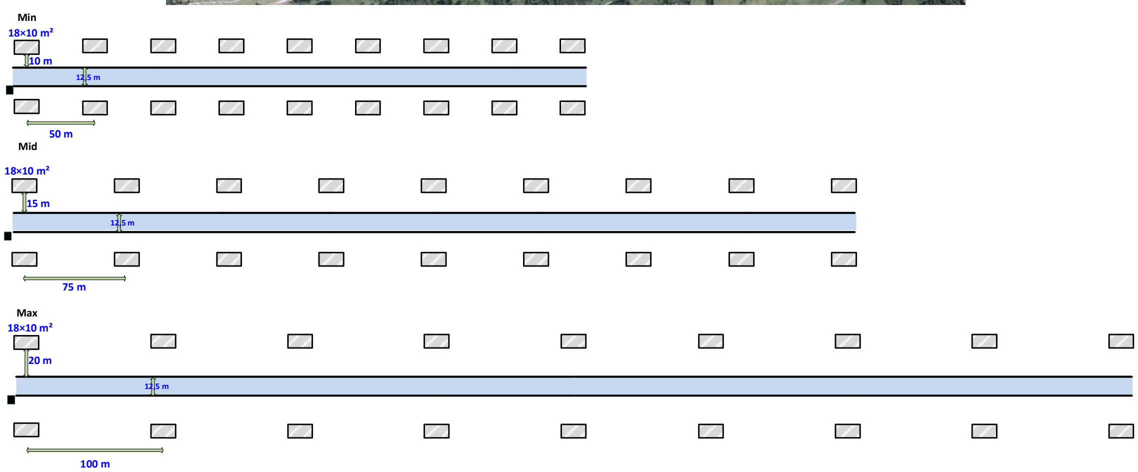
The grid components of the synthetic LV grid models are dimensioned to reflect the status quo of the LV grids, i.e. LV grids built in the 1970s and 1980s. They are not overdesigned which makes them to a suitable environment for testing new concepts and ideas to deal with a massive increase of new PV units and loads in the future.

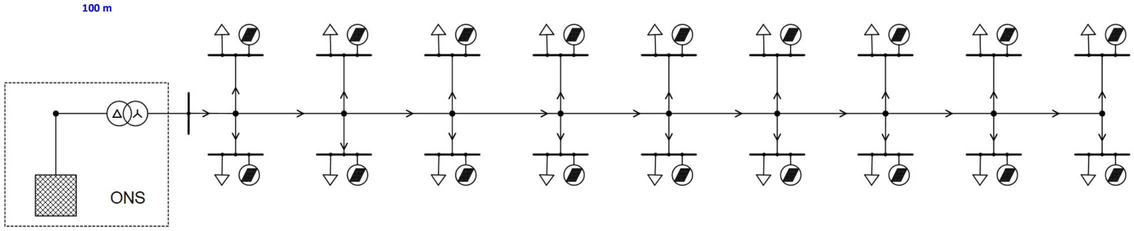
4 Synthetic LV-Grid models

In the following the synthetic LV grid models generated with the previous descriptions are presented. Each of them shows an extract from the online map service "Google Maps" as the real example of the settlement, the grid structure plan, the extract from the grid calculation program "PSS®Sincal" and some core data of the LV grid model. For the settlement structures S1a-S2b and S5a-S6b, the grid structure plans for the min, mid and max scenarios are shown, for all others only the mid scenario are presented.

Each building or house connection in the LV grid model is represented in the grid calculation program with one load and one generation unit. However, individual generation units can be taken out of operation to investigate different scenarios.

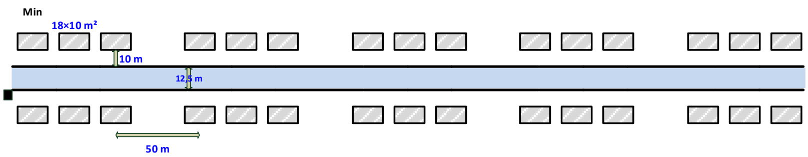
S1a Scattered settlement

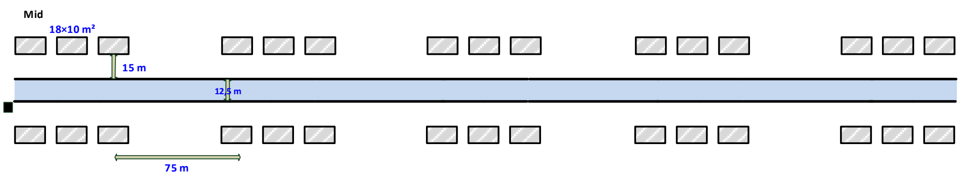


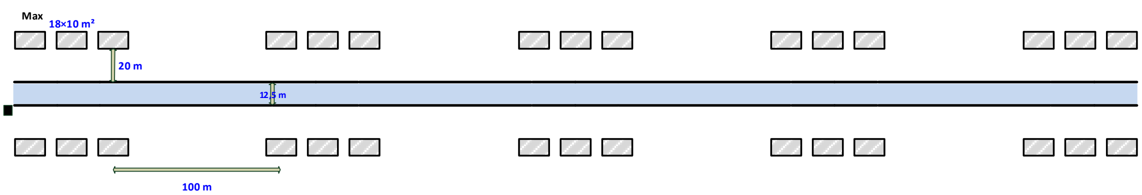


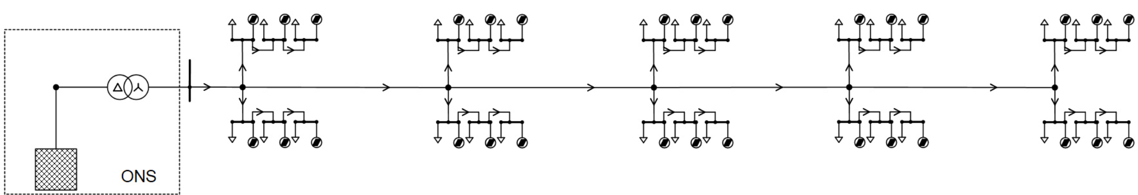
	S_{rT}	Line type	N_{ge}	N_W
S1a	100 kVA	OHL	18	18

S1b Scattered settlement with house cluster



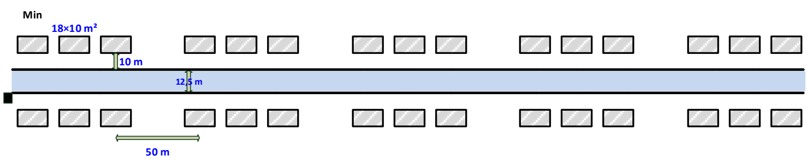


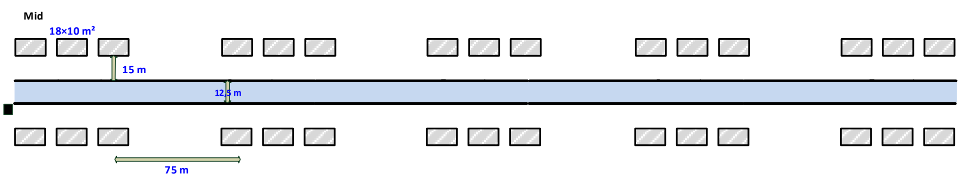


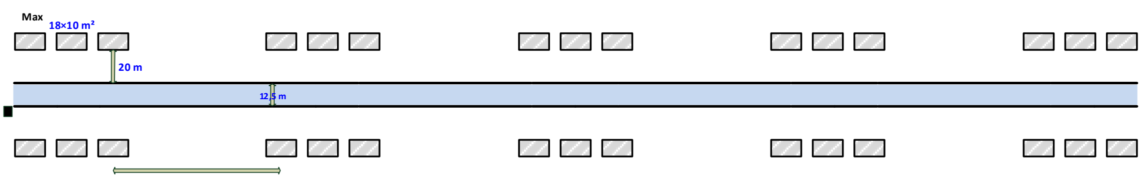


	S_{rT}	Line type	N_{ge}	N_W
S1b	100 kVA	OHL	30	30

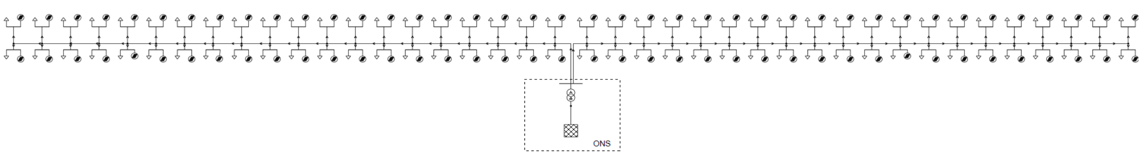
S2a Street village



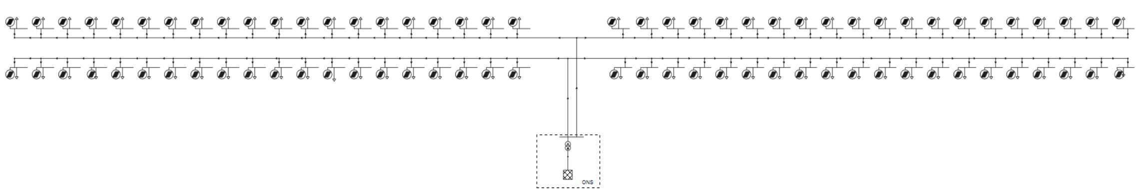




CB



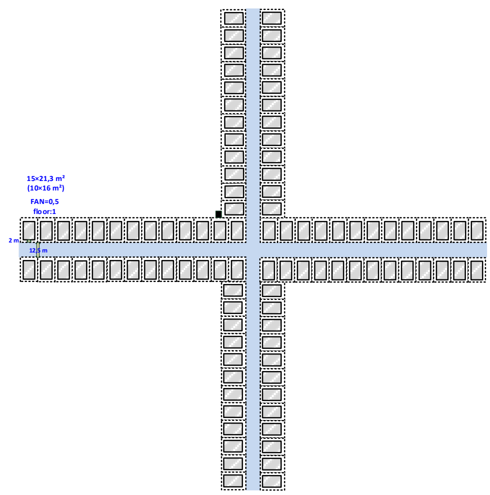
OHL

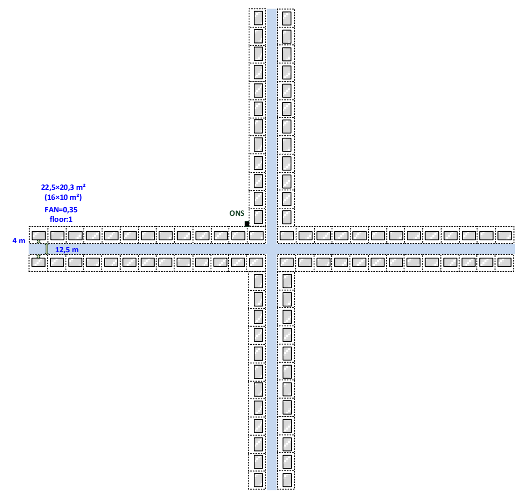


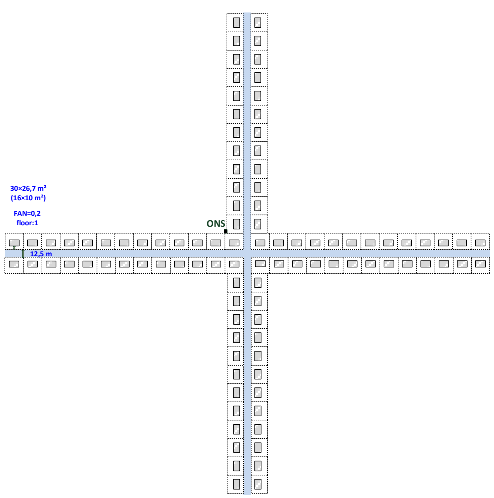
	S_{rT}	Line type	N_{ge}	N_{W}
S2a	250 kVA	CB & OHL	80	80

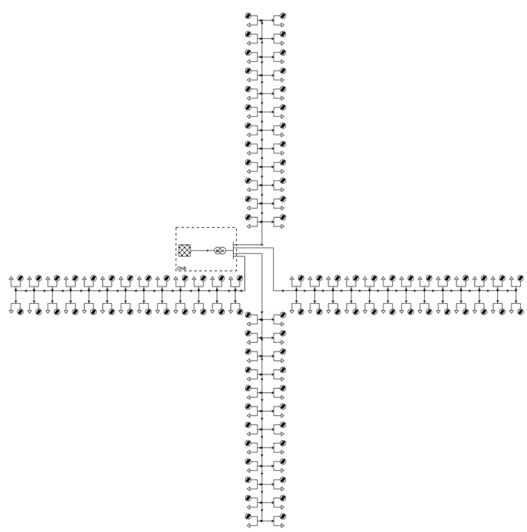
S2b Cross village

	S2b
S_{rT}	250 kVA
Line type	CB
N_{ge}	100
N_W	100

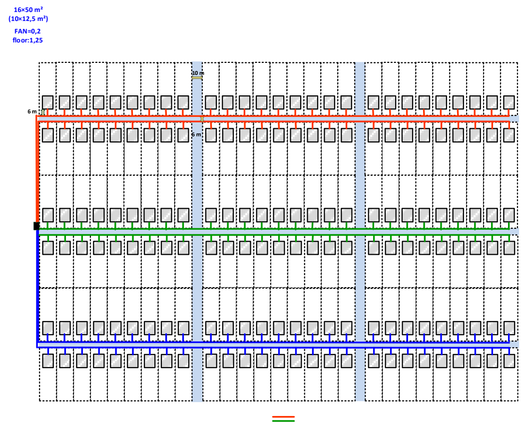




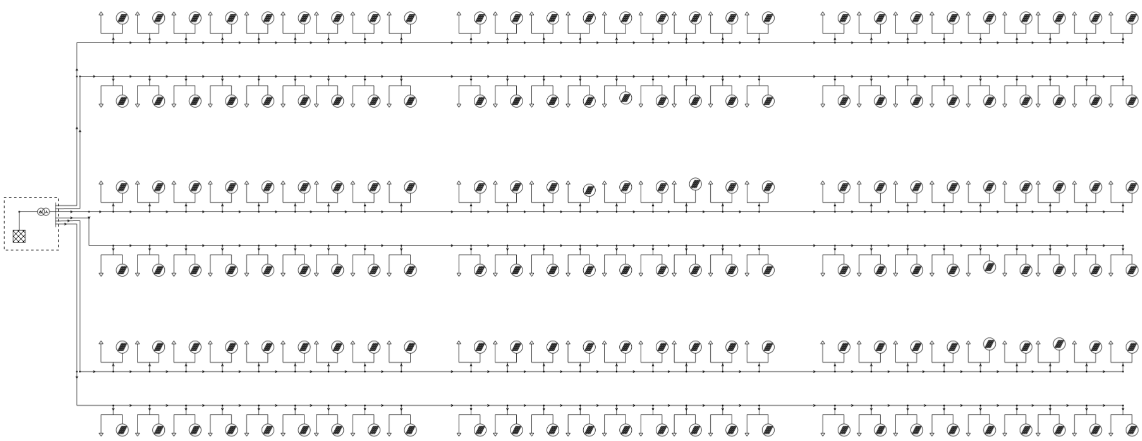




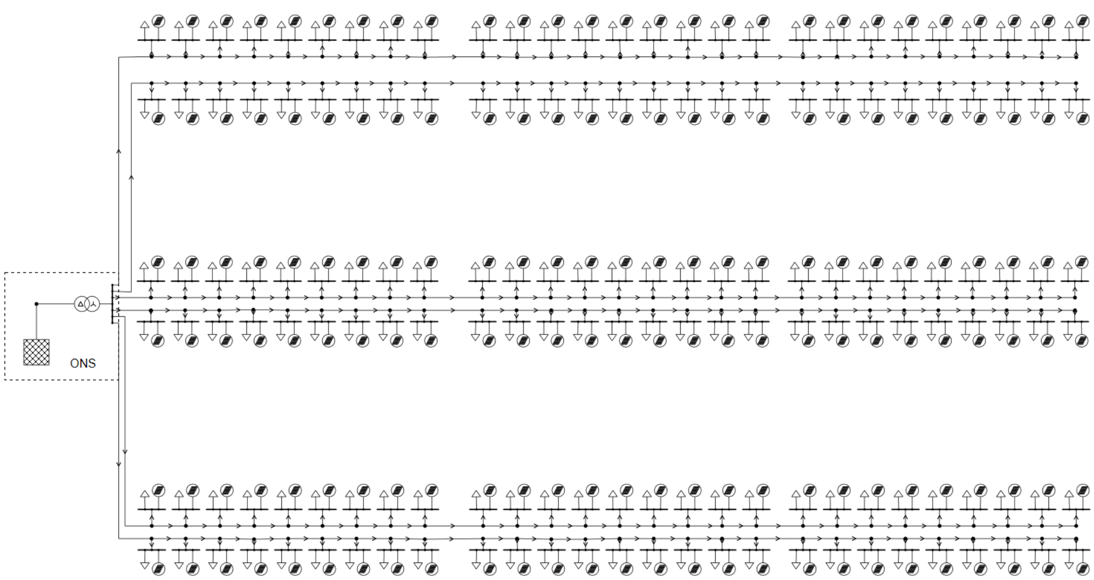
S3a Low density one or two family house settlement



CB

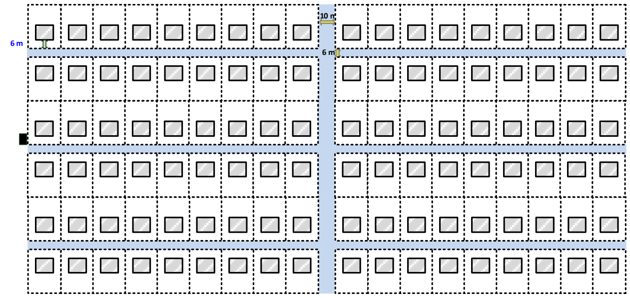


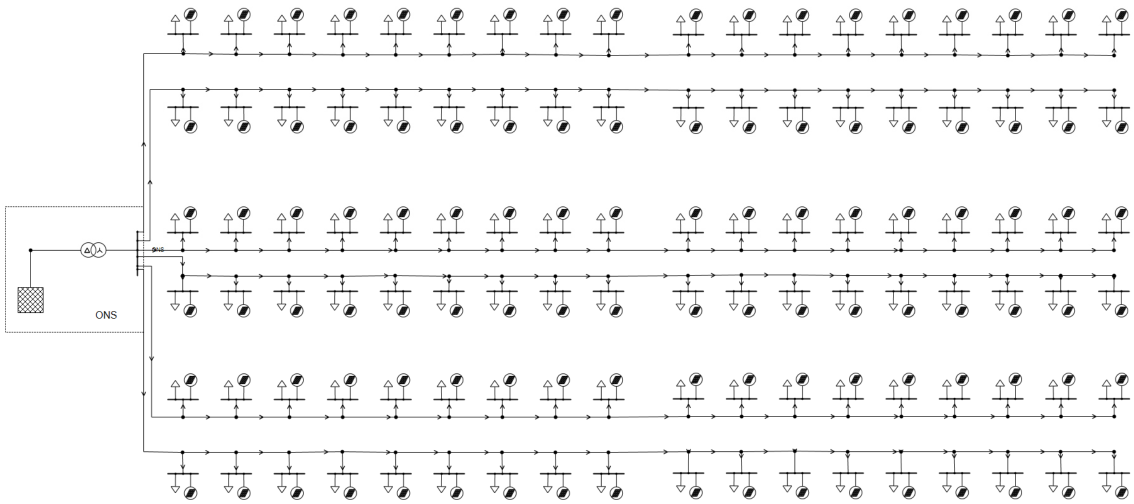
OHL



	S_{rT}	Line type	N_{ge}	N_{W}
S3a	400 kVA	CB & OHL	162	162

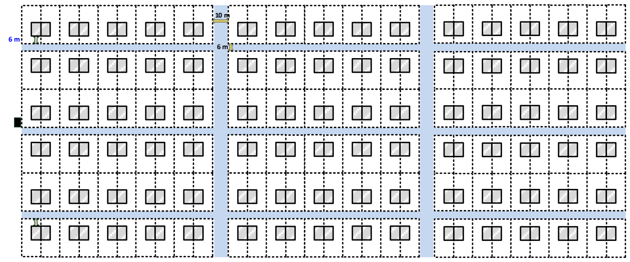
S3b High density one or two family house settlement

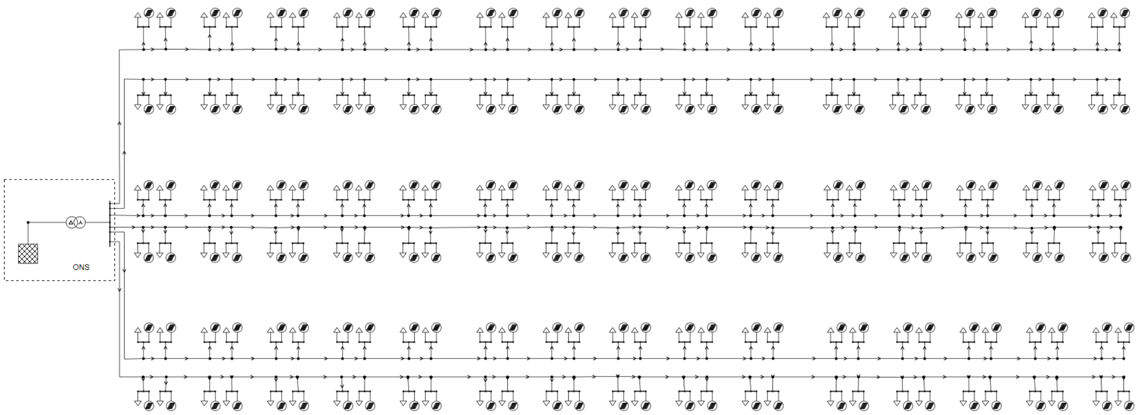




	S_{rT}	Line type	N_{ge}	N_{W}
S3b	630 kVA	CB	108	216

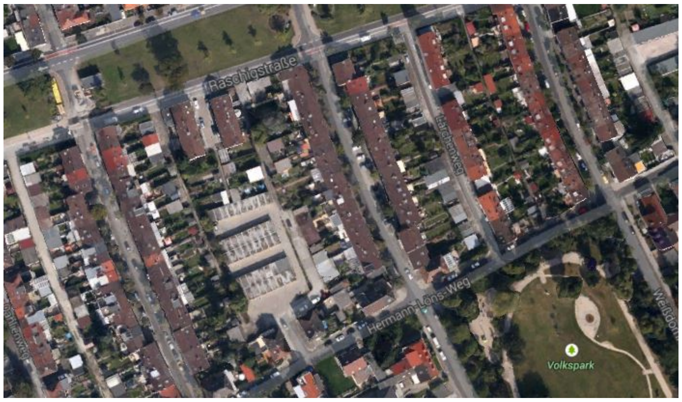
S4a Semi-detached house

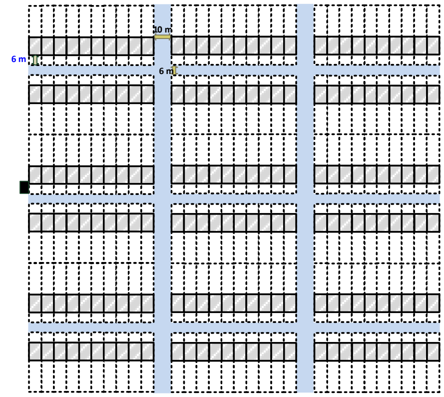


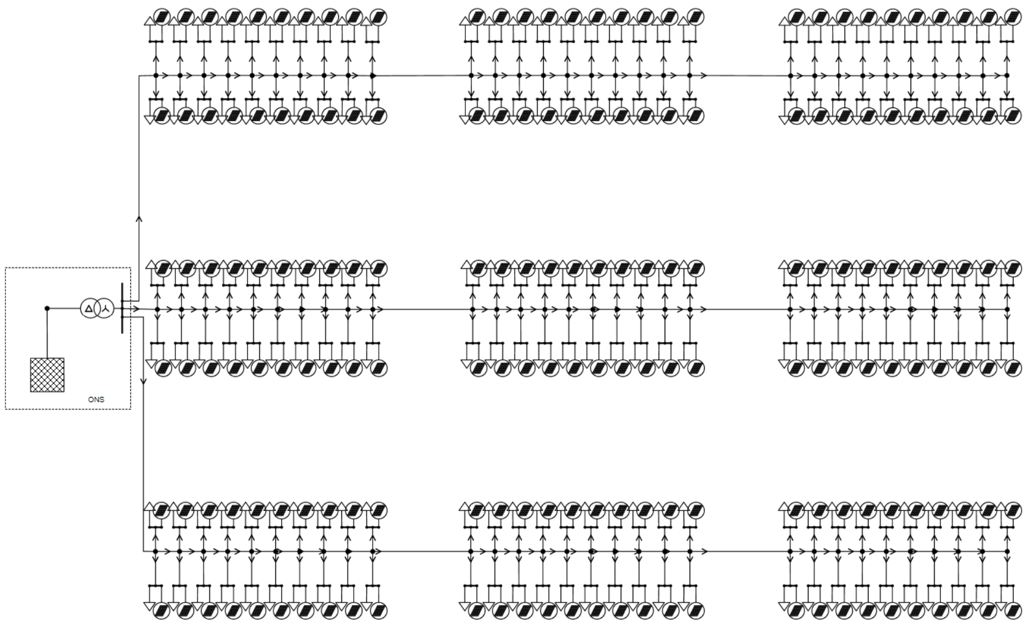


	S_{rT}	Line type	N_{ge}	N_W
S4a	400 kVA	CB	180	180

S4b Row house settlement

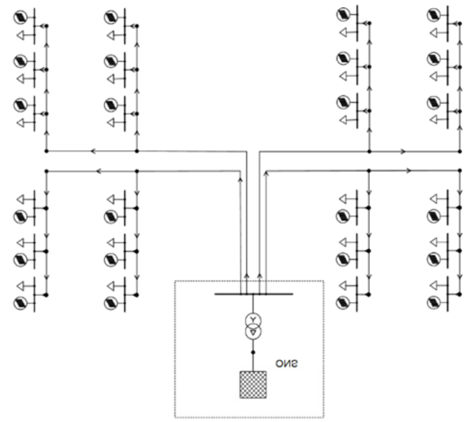






	S_{rT}	Line type	N_{ge}	N_{W}
S4b	400 kVA	CB	180	180

S5a Line structure



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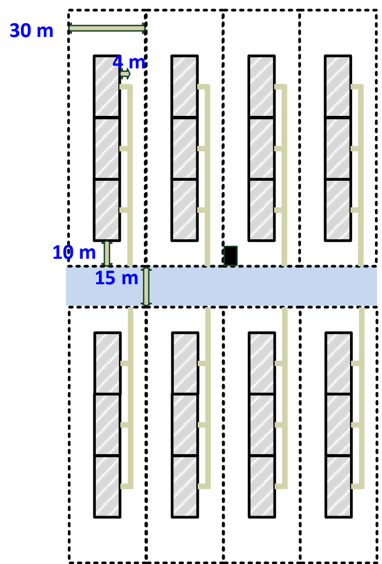

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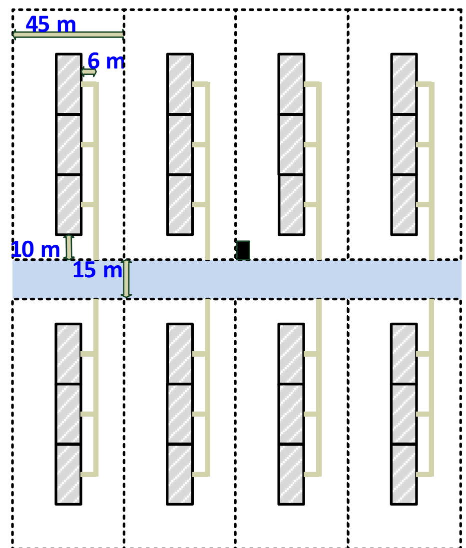

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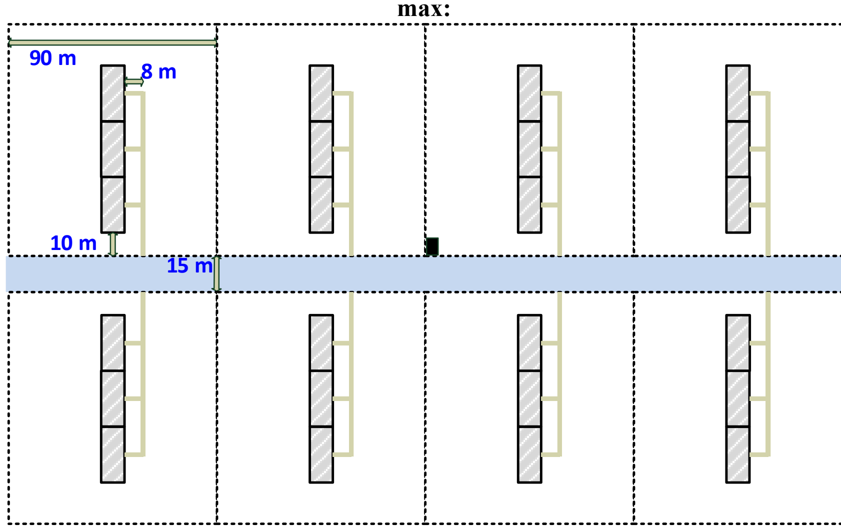
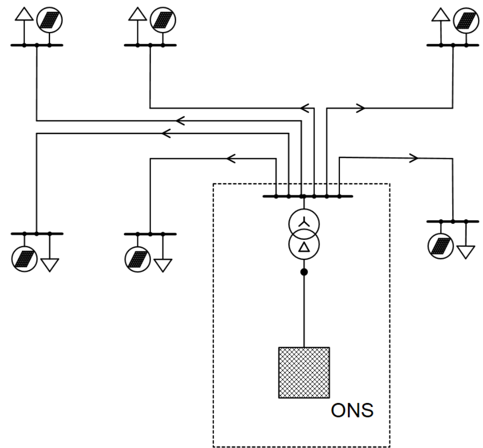


	S_{rT}	Line type	N_{ge}	N_{W}
S5a	630 kVA	CB	24	240

S5b Residential high-rise buildings



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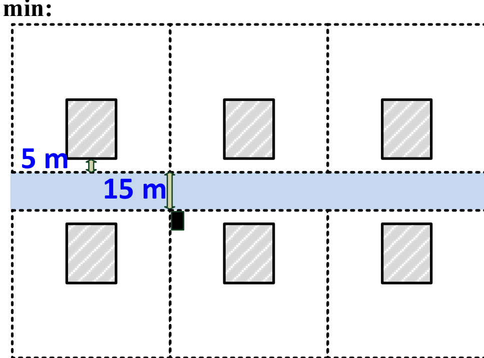

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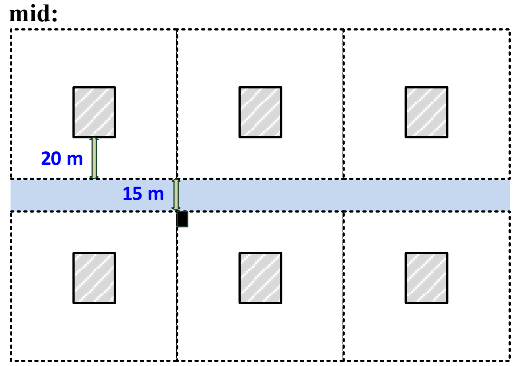

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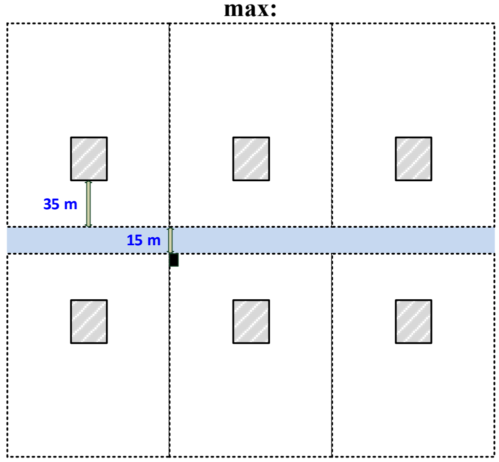
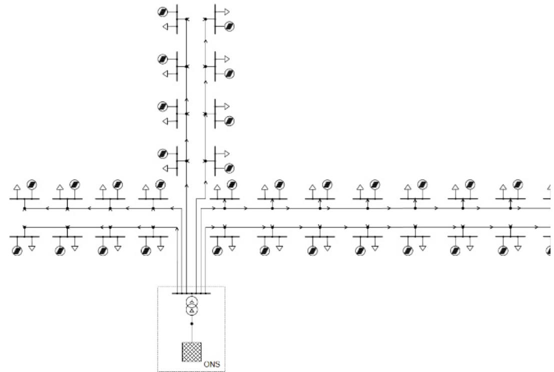
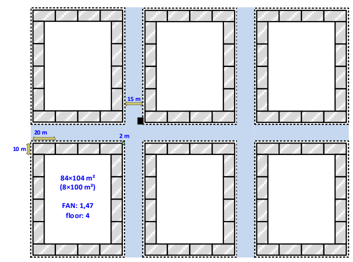
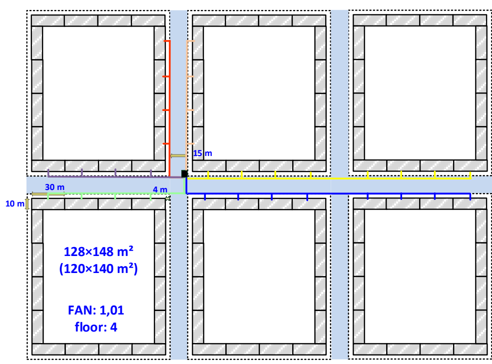


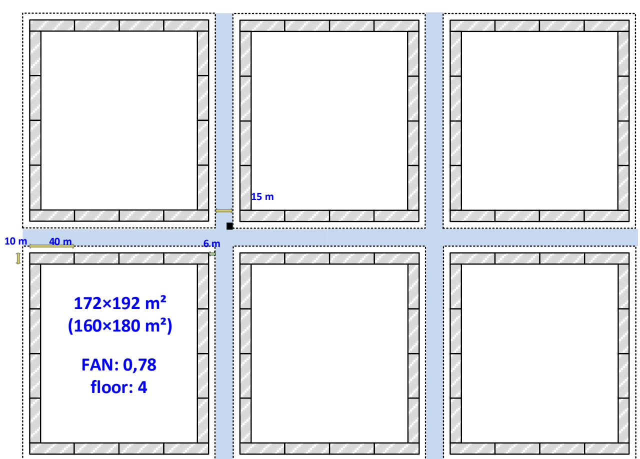
	S_{rT}	Line type	N_{ge}	N_W
S5b	630 kVA	CB	6	288

S6a Block structure







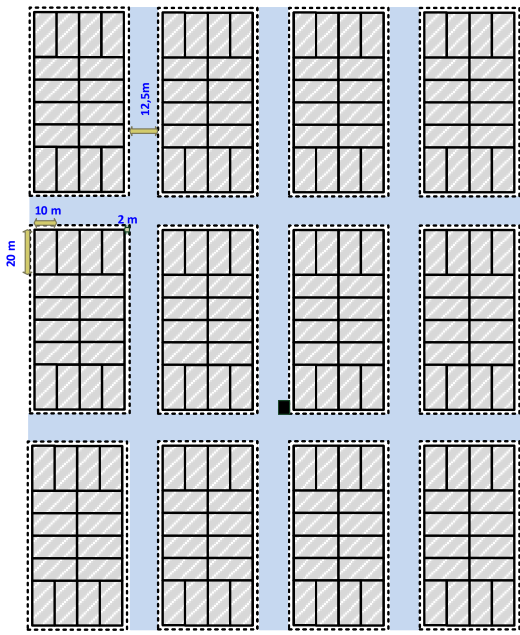


	S_{rT}	Line type	N_{ge}	N_{W}
S6a	630 kVA	CB	32	256

S6b Historical old town

	S6b
S_{rT}	630 kVA
Line type	CB
N_{ge}	48
N_W	288

min:



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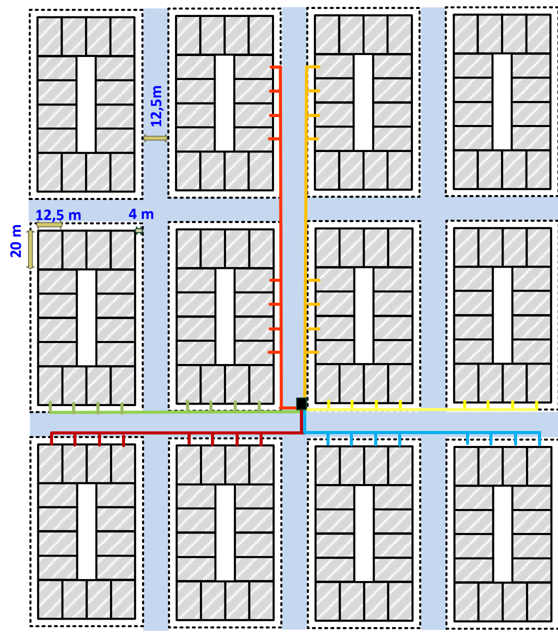

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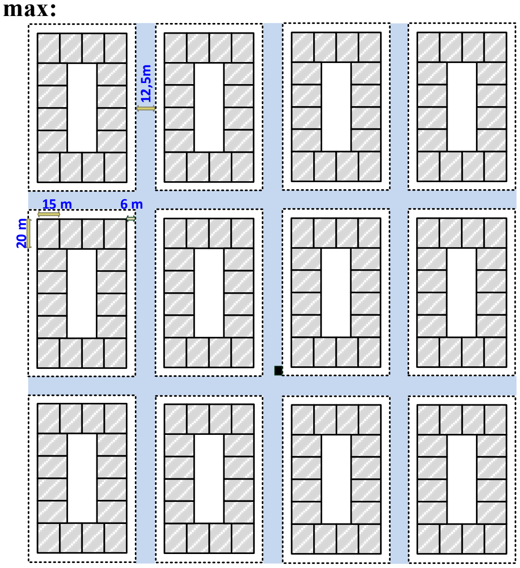

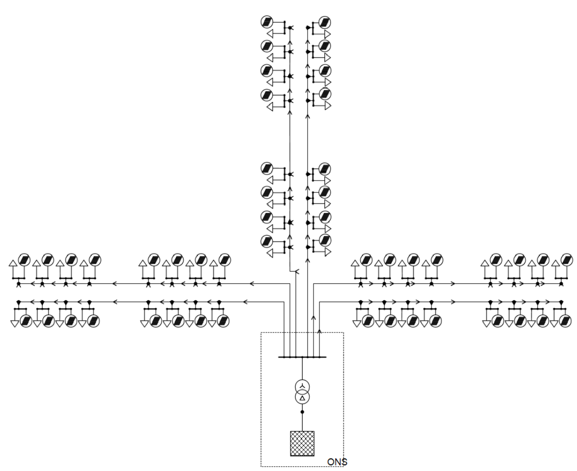

5 Summary and perspective

This paper presents the development of synthetic LV grid models for representative settlement structures and at the same time serves to document them. The definition of representative settlement structures and the derivation of the corresponding data of building types and geo structures are described. The used grid planning principles and the methodology of the grid planning procedures are explained. The grid structures and the most important characteristics of the resulting 14 synthetic LV grid models, each with three different geographical extensions, are presented individually. The LV grid models are based on the procedure for the investigations in [2].

This article provides all the information needed to create the LV grid models. For general use, the LV grid models documented in this article are available on request for the grid calculation programs "Matpower" and "PSS®Sincal".

The detailed documentation of the development steps, as well as the use of common grid planning procedures should promote the acceptance and the dissemination of these synthetic LV grid models and, in the long term, lead to more comparable scientific studies due to their increased use in professional communities.

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