Article

Comparison of the Use of Energy Storages and Energy Curtailment as an Addition to the Allocation of Renewable Energy in the Distribution System in Order to Minimize Development Costs

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Abstract: This paper presents a comparison of the efficiency of energy storage and energy curtailment as an addition to the allocation of renewable energy in the distribution system in order to minimize development costs using a Mixed Integer-Linear Programming (MILP). Energy sources and energy storages are selected, sized and allocated under operational circumstances such as grid congestions and weather conditions. Loads and power units are modeled by daily consumption and generation profiles respectively, to reflect the intermittent character of renewable generation and consumption of energy. The optimization is carried out for a one-year time horizon using twenty-four representative days. The method is verified on three main simulation scenarios and three sub-scenarios for each of them, allowing for the comparison of the efficiency of each used tool. The main scenarios differ in their share of energy from renewable energy sources (RES) in total consumption. In the sub-scenarios, different tools (RES sizing and allocation, energy storages (ES) sizing and allocation and energy curtailment) are used. The results of this research confirm that energy curtailment is a more efficient additional tool for RES sizing and allocation than energy storages. This method can find practical application for Distribution System Operators in elaborating grid development strategies.

Keywords: MILP optimization; allocation; renewable energy sources; system modeling; energy storages; energy curtailment

1. Introduction

Under the increasing installed power of renewable energy sources (RES), the purpose of distribution grids is shifting from passive energy delivery only, to energy delivery and energy production, increasing the role and imposing new duties for Distribution System Operators (DSOs) [1]. One of these duties imposes an obligation on DSOs for the elaboration of development plans, which is a key measure for increasing distribution systems' capacity host for increasing RES penetration. Presently, the location of the renewable connection with the distribution network relates to local weather conditions or mounting capabilities. Therefore, wind turbines are usually located in distant places from household areas, while photovoltaics (PVs) are commonly installed on the top of roofs. As a result, energy generation and consumption are not correlated and power flows are increased in both directions. This is especially visible in the case of residential prosumers equipped with PV systems. In the summer, PV peak generation occurs from 12 p.m. to 2 p.m., and it falls to zero when the sun is setting. This is in opposition to the energy consumption pattern in households where demand peaks in the evening and from 12 p.m. to 2 p.m. are low, because usually, most of the consumers are away from their houses. Consequently, the PV energy is not consumed locally, and instead it is injected to the grid, to be transmitted and consumed, i.e., by commercial and

industrial loads, which are often distant from residential areas. This power flow inflicts additional losses, because energy is lost twice: In the evening, due to increased demand, and midday, because of PV generation. This leads to grid infrastructure overdevelopment and stranded cost problems for DSOs and power balancing issues for Transmission System Operators (TSO) and utilities which, even now, face the problem of dynamic load changes (residual load curve variation) resulting in increased re-dispatching costs and reduced power system reliability [1]. These aspects are usually omitted in the research of DG allocation, which usually focuses on power loss minimization or the improvement of voltage stability.

The above-presented problems can be inexpensively solved by the proper allocation of the RES and energy storages (ES) in the distribution system and its operation. If the generation profile of the energy source is adjusted to the demand profile, the majority of the DG generation is self-consumed locally and allows for the avoidance of power losses. An example of such a principle can be seen in an office equipped with a rooftop PV system. Peak demand for commercial type load is correlated with PV generation, due to the working hours and intensity of devices, such as air conditioners.

This paper presents a method for the minimization of distribution system development costs through the optimal allocation of renewable power units, energy storages and the operation of them, including operational features of various types of generation units and consumption of versatile load types. Strong points lie in the complex approach for solving the local problem by:

> the modelling of loads and power-generating units by energy consumption/generation profiles reflecting operational conditions;
> the modelling of optimization variables allowing for the selection of the type of RES, energy storages (ES), its size and connection point in the grid and its operation.

The paper consists of seven sections, starting with the introduction, followed by the state of the art on methods of RES allocation in power systems. The third chapter presents the method proposed by the author, while the fourth section includes assumptions and fifth section includes simulation scenarios. Simulation results and discussions are presented in the sixth section. The paper ends with conclusions and recommendations for further research and Appendix A which displayed capacity structure for each scenario.

2. State of the Art on the Distribution System Development

This section provides an overview of methods for DG allocation under the following criteria: objective function formulation, variables selection, time horizon, resolution, approach (technical, economic, environmental, etc.), problem formulation and used solving methods.

Power loss minimization is one of the most common objective function formulations implemented for DG allocation problems [2–7]. Equally frequently applicable methods take into account aspects of the quality of supply also, including voltage improvement in an objective function [8–16] or setting constraints on voltage distortion [17,18] while others include the reduction of harmonics distortions as well [19,20]. Power loss reduction and the improvement of voltage are also presented in [21], however these measures are represented by sensitivity factors. Another approach is more energy consumer-oriented maximizing welfare [22] (including minimisation of energy costs and carbon emissions) or minimizing costs of power losses, load not supplied and DG installation O&M costs [23,24]. A similar method—minimizing power losses and energy generation costs—is presented in [25], while in [24,26], air pollutants are minimized as well. Some of the papers present methods using DG allocation for the improvement of supply reliability [27–29]. In [30], the authors propose a restoration matrix that presents the priority of supply from DG. Reference [31] also includes a reduction of the grid upgrade costs. Some papers present a multistep approach, hence, in the first step of the method presented in [12], optimization maximizes the benefits from the node point of view, while in the second step, the optimization maximizes the benefits from the entire considered network. In [32], the first step determines localization only, while the second provides an optimal

capacity of each DG. The original approach is presented in [33], where authors maximize system loadability (usage of the network infrastructure). The objective of the optimization in [34] is nodal voltage stabilization. Nevertheless, the most common approach focusses on power loss minimization and voltage improvement, which are optimized in many approaches. This is presented in [35], where a much wider review on the optimization of DG allocation methods is provided.

Novelty of the Paper

The novelty of this research lies in the complex long-term optimization of a distribution system using RES sizing and allocation simultaneously, ES sizing and allocation and energy curtailment. Furthermore, the technical aspects of distribution system operation such as generation and consumption profiles, power flows, power losses or voltage levels are included.

The above-listed objectives can be obtained by the allocation of DG which can be carried out in several ways, including versatile types of variables. The significant majority of optimisation methods focus on the DG sizing and placing only [9,17–19,22,25,36,37]. Some methods also consider the selection of the DG type [3,7,20,22,23,31,38] but none of the mentioned methods combine the allocation of RES and ES or the allocation of RES and energy curtailment.

Optimization can be carried out for different time horizons and with different time resolutions. Most of the papers present methods optimising the DG structure for a single moment, omitting the dimension of time [2,5,8–11,17–19,22,23,25,36,39–41]. This static approach does not allow us to include crucial aspects of daily demand changes or intermittent RES generation, which are included in the presented paper. In papers where intermittent RES generation is included—[4] and [7]—there is a lack of long-time planning.

In papers [3,7,20,42,43], which present methods for long-time planning, no distribution system costs were minimized.

Most of the research already performed focuses on technical aspects, such as power line constraints [16] or nodal voltage limits, and only a few of them include economic aspects such as investment and O&M costs [17,23] or total cost of energy [19,22]. Only one of the papers reviewed includes different types of loads connected to considered systems [9]. This is another novel aspect of the paper that combines technical and economic aspects of distribution system operating, including different types of loads and generation units also.

Research also exists which combines the allocation of renewable energy sources and energy storages in the distribution system [44–46]. Other papers describe different approaches to energy curtailment: Turning off generation sources [47], limiting generation to a constant level [48], generation constraints adapted to technical constraints [49] or proportional generation reduction for the whole analyzed period [50]. None of the mentioned papers, however, combine the allocation of RES and ES or the allocation of RES and energy curtailment. Furthermore, none of the papers compare which distribution development strategy is more efficient.

3. Problem Formulation

The objective of the method presented is to provide the structure of the RES and ES allocation in the distribution system along with its operation, ensuring minimal costs of the distribution system development without violating the technical standard of the grid operation. Three types of RES (wind turbine (WT), photovoltaic (PV) and biogas (BG)) can be connected in each node with rated power depending on the value of typical units. RES units are represented by representative generation profiles, reflecting typical operating conditions. Due to the grid, overloads can be identified and eliminated by proper RES allocation and curtailment and energy storing. The optimization is performed, preserving technical constraints. Technical constraints refer to the network transmission capacity, nodal voltage standards and power exchange with the transmission system. Power flow in each line is calculated for each time step. The generation for RES is calculated as a product of the installed capacity and

generation profile and load consumption is calculated similarly. Power exchange with the transmission system depends on the power of each transformer which connects these two systems.

The optimization model, which is described in the next section, consists of general mathematical formulations for mixed-integer linear problems which can be used by other optimization software.

3.1. Optimization Model

The minimization of the total costs of the distribution system development in relation to one year (installation and operating RES and energy storages) is the objective function. Total costs consist of three elements:

Fixed costs (CAPEX and OPEXfix) of new RES,
Fixed costs (CAPEX and OPEXfix) of new energy storages,
Operating costs (OPEXvar).

CAPEX there are investment costs connected with equipment and construction works costs. OPEXfix there are costs intended for taxes, maintenances and salaries. OPEXvar are the costs of fuels.

$$\min\left\{\sum_{n\in N}\left(\sum_{d\in D}\left(\sum_{r\in R}\left(p_{n,d,r} * P_{d,r} * FC_{d,r}^{RES}\right)\right) + p_n^{ES} * C^{ES} * FC^{ES} + \sum_{d\in D}\left(E_{n,d} * VC_{d,r}^{RES}\right)\right)\right\} \tag{1}$$

subject to

$$\forall_{n\in N} \quad \forall_{d\in D} \quad \forall_{r\in R} \quad p_{n,d,r} \in N \tag{2}$$

The DG generation in each node for each type of RES ($E_{n,d}$) is calculated as a sum of energy generation of each DG type in one node for the entire year.

$$\forall_{n\in N} \quad \forall_{d\in D} \quad E_{n,d} = \sum_{t\in T} E_{n,d,t}^{GEN\_RES} \tag{3}$$

The DG generation in each time period ($E_{n,d,t}^{GEN\text{-}RES}$) is a function of the optimization variable $p_{n,d,r}$ and is calculated a product of the RES rated power ($P_{d,r}$), current power utilization level (according to the generation profile $P_{d,r}^{avail}$), optimization variable $p_{n,d,r}$ and minus energy curtailment ($e_{n,d,t}^{curt}$). The $p_{n,d,r}$ is a three-dimension variable, where dimension n refers to the number of the node, dimension d refers to the RES technology type (i.e., PV) and dimension r refers to the rated power (2). Energy curtailment ($e_{n,d,t}^{curt}$) is a variable which curtails the generation from the reference generation profiles for each node (n), RES type (d) and each time period (t).

$$\forall_{n\in N} \quad \forall_{d\in D} \quad \forall_{t\in T} \quad E_{n,d,t}^{GEN\_RES} = \sum_{r\in R}\left(\left(P_{d,r}\cdot p_{n,d,r}\right)\cdot P_{d,t}^{avail}\right) - e_{n,d,t}^{curt} \tag{4}$$

Another important parameter is the generation in the entire node ($E_{n,t}^{GEN\_node}$) which depends on the sum of DG generation for each RES type in single node and energy exchange with energy storages that are installed in the node.

$$\forall_{n\in N} \quad \forall_{t\in T} \quad E_{n,t}^{GEN\_node} = \left(\sum_{d\in D}\left(E_{n,d,t}^{GEN\_RES}\right) - e_{n,t}^{toES} + e_{n,t}^{fromES}\right) \tag{5}$$

The typical RES sizes of each renewable technology are predefined and are included in the two-dimension matrix $P_{d,r}$ (4). As a result of multiplication of variable matrix $p_{n,d,r}$ and parameters matrix $P_{d,r}$ the installed power of all RES in every node is calculated.

$$\underset{d \in D}{\forall} \quad \underset{r \in R}{\forall} \quad P_{d,r} = \overbrace{\begin{bmatrix} P_{1,d_1} & P_{1,d_2} & P_{1,d_3} \\ P_{2,d_1} & P_{2,d_2} & P_{2,d_3} \\ \vdots & \vdots & \vdots \\ P_{r,d_1} & P_{r,d_2} & P_{r,d_3} \end{bmatrix}}^{\text{dimmension } D} \left.\vphantom{\begin{bmatrix} P_{1,d_1} \\ P_{2,d_1} \\ \vdots \\ P_{r,d_1} \end{bmatrix}}\right\} \text{dimmension } R \tag{6}$$

The optimization model in general is formulated as for an integer programming, however, it includes some non-linear elements such as power losses or voltage drops. In order to improve computation time and reformulate the original problem to the Mixed Integer-Linear Programming (MILP), non-linear components are linearized. The quadratic power losses are linearized by the spline of five linear functions—Figure 1. Each linear function was created for different values of power flow in relation to power line capacity. The first function was created for power flow in rage 0–100% of line capacity. The rest of the functions were designed for power flow in range: *f2*: 20%–100%, *f3*: 40%–100%, *f4*: 60%–100% and *f5*: 80%–100% of line capacity. The final power losses were created as a sum of all mentioned linear functions.
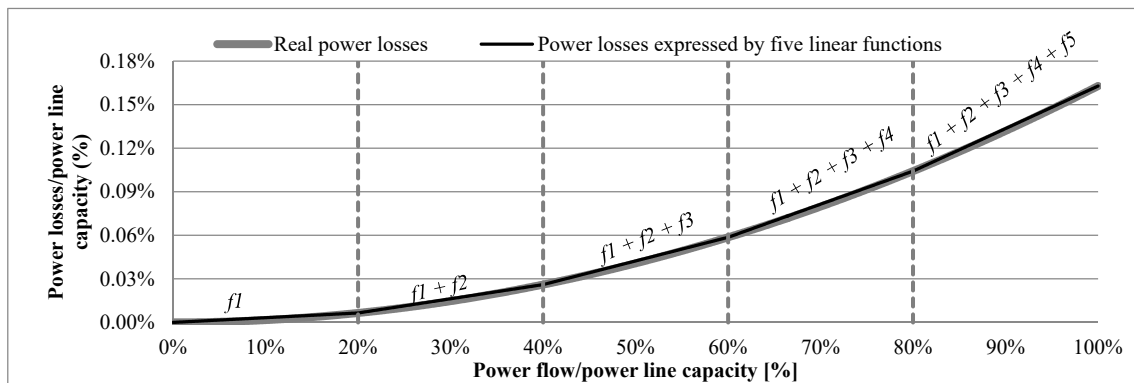

Figure 1. Power losses linearization—spline function consisting of five linear functions.

Each linearising function refers to power line capacity, this is applicable for every power line of the grid model (7)–(11).

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad f1_{n,w,t} = 0.2 * \frac{Line.const_{n,w} * R_{n,w}}{U_{n,t}{}^2} * PF_{n,w,t} \tag{7}$$

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad f2_{n,w,t} = 0.4 * \frac{Line.const_{n,w} * R_{n,w}}{U_{n,t}{}^2} * PF_{n,w,t} - 0.08 * \frac{Line.const_{n,w}^2 * R_{n,w}}{U_{n,t}{}^2} \tag{8}$$

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad f3_{n,w,t} = 0.4 * \frac{Line.const_{n,w} * R_{n,w}}{U_{n,t}{}^2} * PF_{w,k,t} - 0.16 * \frac{Line.const_{n,w}^2 * R_{n,w}}{U_{n,t}{}^2} \tag{9}$$

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad f4_{n,w,t} = 0.4 * \frac{Line.const_{n,w} * R_{n,w}}{U_{n,t}{}^2} * PF_{w,k,t} - 0.24 * \frac{Line.const_{n,w}^2 * R_{n,w}}{U_{n,t}{}^2} \tag{10}$$

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad f5_{n,w,t} = 0.4 * \frac{Line.const_{n,w} * R_{n,w}}{U_{n,t}{}^2} * PF_{w,k,t} - 0.32 * \frac{Line.const_{n,w}^2 * R_{n,w}}{U_{n,t}{}^2} \tag{11}$$

Consequently, the energy lost on the power lines in each time step is as in (12),

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad P^{losses}_{n,w,t} = f1_{n,w,t} + f2_{n,w,t} + f3_{n,w,t} + f4_{n,w,t} + f5_{n,w,t} \tag{12}$$

while the total power losses in the entire time horizon are as (13).

$$\underset{t \in T}{\forall} \quad P^{losses}_t = \sum_{n,w \in N} \left(P^{losses}_{n,w,t} \right) \tag{13}$$

The same assumption of constant nodal voltages and omission of reactive power and reactance allows for the linearization of voltage drops (14).

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad \Delta U_{n,w,t} = \frac{PF_{n,w,t} * R_{n,w}}{U_{n,t}} \tag{14}$$

Power flow in a power line, as well as nodal voltage, depends on power balance in each node depending on the grid structure and temporary power generation and demand. While the generation depends on weather conditions and generation structure, the demand for power in each time period depends on the load size and its type (referring to user behaviors).

$$\underset{n \in N}{\forall} \quad \underset{t \in T}{\forall} \quad \sum_{n \in N} (PF_{n,w,t}) = E^{GEN\_node}_{n,t} - \sum_{l \in L} \left(Load_{n,l} * P^{DEM}_{l,t} \right) \tag{15}$$

3.2. Constraints

Two types of constraints are included: technical and economic. Technical constraints include power balances in grid nodes (16), power lines capacity (17) and nodal voltage limitations (18).

$$\underset{t \in T}{\forall} \quad \sum_{n \in N} \left\{ \sum_{l \in L} \left(Load_{n,l} * P^{DEM}_{l,t} \right) \right\} - P^{res}_t + TS^{exchange}_t + PF_{n,w,t} = 0 \tag{16}$$

$$\underset{t \in T}{\forall} \quad \underset{n,w \in N}{\forall} \quad -Line.const_{n,w} \leq PF_{n,w,t} \leq Line.const_{n,w} \tag{17}$$

$$\underset{t \in T}{\forall} \quad \underset{n \in N}{\forall} \quad 0.9 * Unominal \leq \underline{U}_{n,t} \leq 1.1 * Unominal \tag{18}$$

In the model, there are also assumed constraints related to the operation of energy storages like: level of charge, which depends on energy exchange between energy storage and node and efficiency of this exchange.

$$n \in N, \forall t \in T \quad CL_{n,t} = CL_{n,t-1} + \eta^{ES} * p^{doES}_{n,t} - \left(\frac{1}{\eta^{ES}} \right) * p^{zES}_{n,t} \tag{19}$$

The model assumes that annual energy production minus total losses in lines must be equal or greater than the assumed share (*k*) in the annual demand in the distribution system (20).

$$\sum_{n \in N} \left\{ \sum_{d \in D} E_{n,d} - \sum_{t \in T} P^{losses}_t \right\} \geq k * \sum_{n \in N} \left\{ \sum_{l \in L} \left(\sum_{t \in T} Load_{n,l} * P^{DEM}_{l,t} \right) \right\} \tag{20}$$

4. Assumptions

Since the model includes natural (non-negative integer) and real variables and all functions are linear, the optimization problem is modeled as a Mixed Integer-Linear Programming (MILP).

The natural variable $p_{n,d,r}$ indicates the type of RES selected from the set of three technologies D: PV systems, wind turbines and biogas thermal units (21).

$$D = \{d_1, d_2, d_3\} = \{pv, wt, bg\} \tag{21}$$

The rated power of each type of the RES is retrieved from the impact assessment to polish regulation on renewable energy sources from 2015 [51], displayed in Table 1. In the case of PV, the author realized that due to modular structure, PV systems are fully configurable, although they are assumed as three predefined values, to reduce the calculation effort. Nevertheless, the method allows for the application of any set of parameters.

Table 1. Rated power of the renewable energy sources (RES).

Type Series	PV	WT	BG
1	10 kW	10 kW	200 kW
2	100 kW	100 kW	500 kW
3	1000 kW	500 kW	2000 kW

There was one assumed type of energy storage with a capacity of 10 kWh, power of 5 kW and efficiency of energy exchange with the grid on the level of 90%.

Generation profiles are divided into three parts of the year: summer, winter and spring/autumn together. For each part of the year, there were created two profiles for WT and PV (high and low generation) based real data retrieved from the website of German and PolishTSOs. Generation profile for BG is assumed as constant for the whole year.

Three types of loads are included: residential, commercial and industrial. Each type of load is also characterized by a different energy consumption profile. Consumption profiles are also divided into three parts of the year and for each part, two profiles were created for working and non-working days. Load location is predefined (Figure 2).
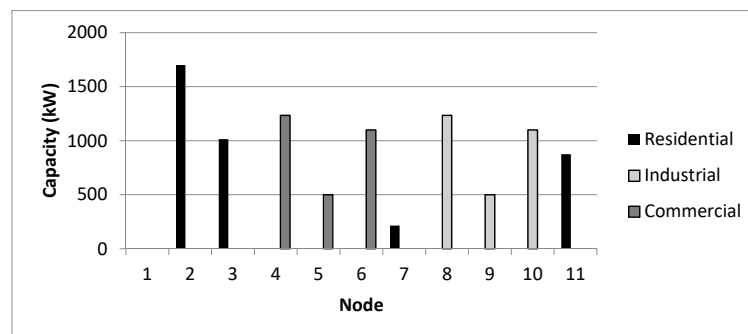
Figure 2. Structure of loads connected to the benchmark network model. Own study.

Simulations were carried out for twenty-four representative days which were created as a total combination of generation profiles and consumption profiles, and according to real data, there was an analysis of how many times each combination occurred in the year, and based off of this, the whole year is modeled.

The modified MV benchmark network model consisting of eleven nodes is used for the simulation—Figure 3. Lines are characterized as connections between nodes, and for each of them, capacity and resistance are assumed. There is one exception, which is between nodes one and two and it is a transformer which connects the transmission (node 1) and the distribution system (node 2). The resistance for the transformer is assumed as 0 ohms, because this part of the system is not the aim of this research.
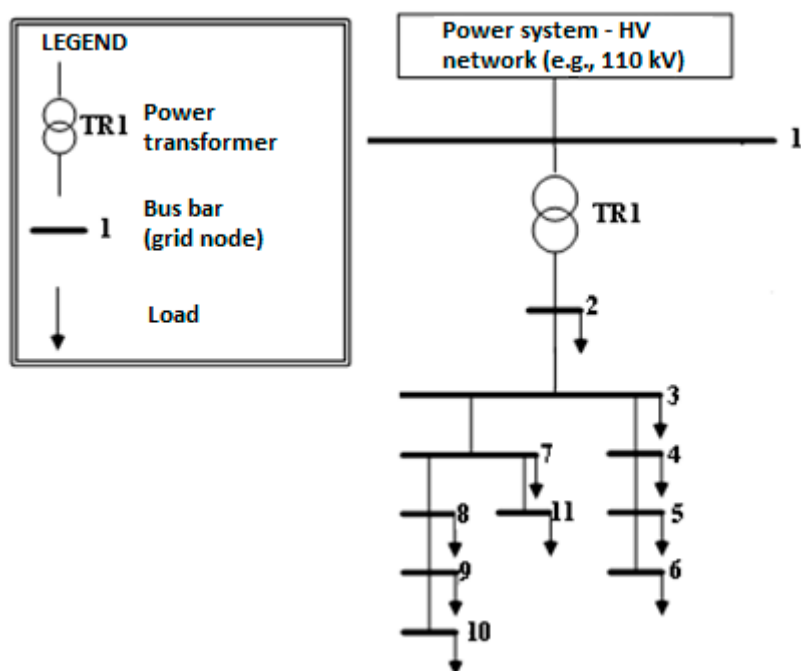
Figure 3. Benchmark model of medium voltage distribution network.

Power lines capacity and resistance are taken from the real data—Table 2.

Table 2. Power lines parameters.

Line	Connection between Nodes	Line Capacity (MW)	Line Resistance (Ω)
1	1–2	40	0 *
2	2–3	7.3	1.21
3	3–4	5.9	0.77
4	3–7	5.9	0.77
5	4–5	5.9	2.89
6	5–6	5.9	1.77
7	7–8	5.9	0.36
8	7–11	5.9	1.77
9	8–9	5.9	0.29
10	9–10	5.9	0.19

* resistance of a power transformer is negligible and assumed as equal to 0.

One of the factors affecting the power balance of the distribution system is power exchange with the transmission system. In this research, it is assumed that power flow is allowed only in one direction—from the transmission to the distribution system. This means that in the period when energy consumption is higher than generation, the difference between them is covered by power supplied by external generation units from the transmission system. However, power cannot flow from the distribution to transmission system. This causes the sum of generation to be lower than the sum of demand in the whole system. This assumption is made arbitrarily and can be removed without affecting the method principle. This will result only with the higher local capacity host for DG.

CAPEX and OPEX (Table 3) depend on the type and the size of a power unit and are assumed on impact assessment to polish the regulation of RES [51].

Table 3. Costs of RES installation.

Type of Cost	Type of RES								
	PV 10	PV 100	PV 1000	WT 10	WT 100	WT 500	BG 200	BG 500	BG 1000
CAPEX [thous. €/MW_year]	84	84	81	110	110	99	214	198	188
OPEXfix [thous. €/MW_year]	27	27	24	36	36	45	144	183	181
OPEXvar [€/MWh]	0	0	0	0	0	0	91	78	70

5. Simulation

5.1. Scenarios

The method is examined in three main simulation scenarios which differ in the share of energy from RES in total demand in the analyzed distribution system. In the first scenario, the share of energy from RES is 30%, in the second 40%, and in the last scenario 50%. Furthermore, each major scenario has three sub-scenarios that were created to display the differences between approaches to the development of distribution systems. In Sub-scenario A, only the sizing and allocation of RES were used, in Sub-scenario B, the sizing and allocation of RES and ES were used, and in the last sub-scenario, C, the sizing and allocation of RES and energy curtailment were used.

Main scenarios:

30% share of energy from RES in total demand,
40% share of energy from RES in total demand,
50% share of energy from RES in total demand.

Sub-scenarios:

sizing and allocation of RES,
sizing and allocation of RES and ES,
sizing and allocation of RES and EC.

5.2. Revision of the Strucure

The minimization of total costs of the distribution system development in relation to one year (installation and operating RES and energy storages) is the objective function. Simulations are performed using a network consisting of eleven nodes, where the node number one represents the transmission system and the rest of the nodes represent the distribution system. In nodes 2–11, generation units and ES can be connected. The connection between nodes is represented by resistance and line capacities. The generation from RES is calculated as a product of the RES rated power, current power utilization level (according to the generation profile), number of units and minus energy curtailment. It is also possible that energy can be stored in an energy storage, which is connected to the nodes.

6. Results

This section provides the simulation results presented in two parts that compare approaches to the development of distribution systems. The first part displays capacity structure for each scenario and the second one displays the overall cost of system development. In each part, the results consist of three charts that present the results for a different share of energy from RES in total demand. All of the results are obtained using FICO®Xpress v. 8.6. optimization software and all graphs are created using Microsoft Excel 365.

Based on Figures 4–6, it can be seen that additional tools to RES sizing and allocation, like energy curtailment (EC) allocation or energy curtailment, allows a user to install more wind turbines, which are the cheapest renewable energy sources, without violating grid technical standards. Energy storages shift energy from one moment to another, which prevents the over-generation from RES. Energy curtailment, on the other hand, fits the generation profile to demand.
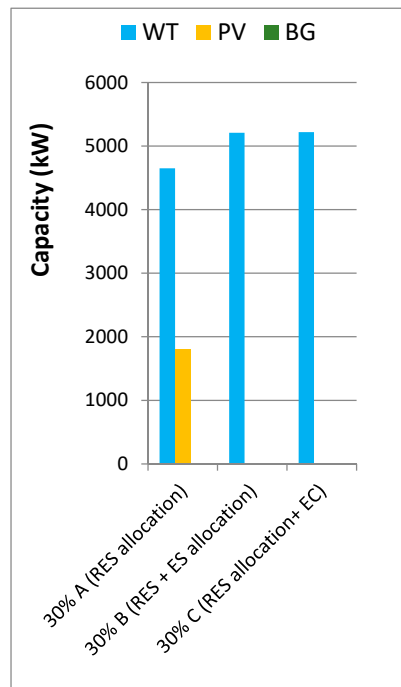
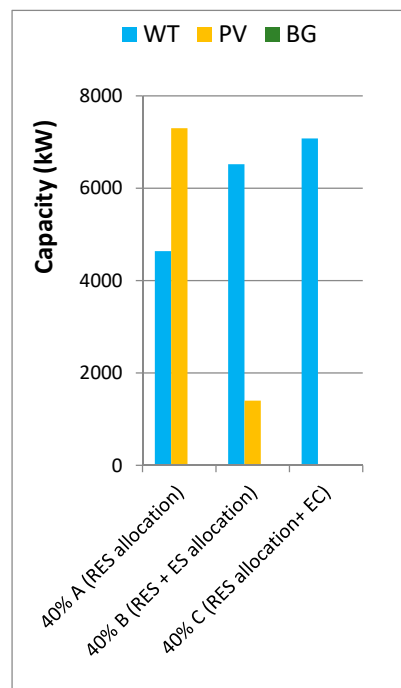**Figure 4.** Structure of capacity for main scenarios—1.

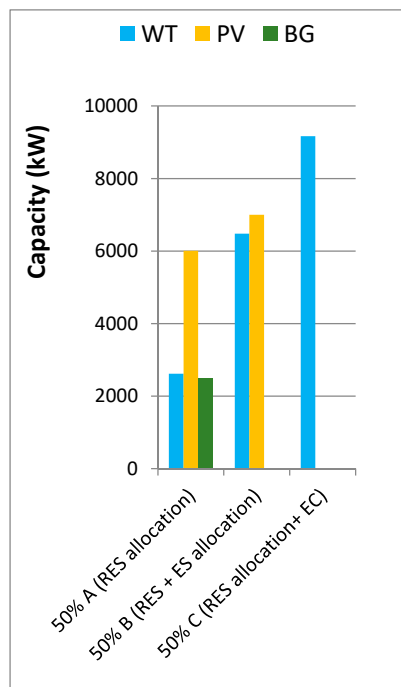**Figure 5.** Structure of capacity for main scenarios—2.

Figure 6. Structure of capacity for main scenarios—3.

Based on Figures 7–9 (all costs are compared to the highest one which is for 50% share for RES with RES sizing and allocation only), it can be observed that the combination of RES sizing and allocation and another additional tool reduces the overall cost of the distribution system development (at least 12% for 30% share). It can also be seen that, together with an increasing share of energy from RES in total demand, the energy curtailment became more efficient than energy storages.
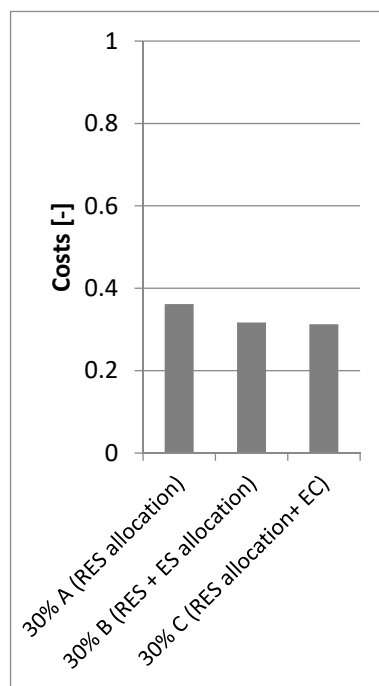
Figure 7. Costs for main scenarios—1.
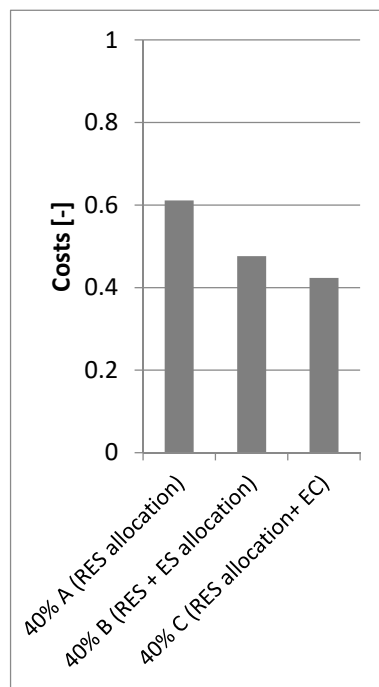
Figure 8. Costs for main scenarios—2.
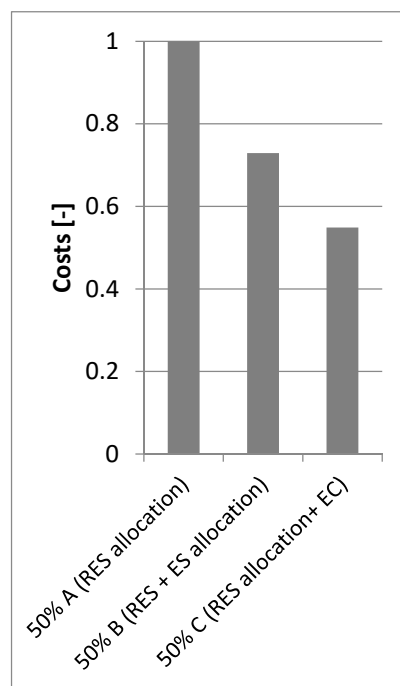
Figure 9. Costs for main scenarios—3.

In Table 4, computation time and the number of variables are displayed for each of the analyzed scenarios.

Table 4. Computation time and number of variables.

Scenario	Computation Time [s]	Number of Variables
30% (RES allocation)	249	17,532,417
30% (RES + ES allocation)	641	17,594,652
30% (RES allocation + EC)	81	17,672,385
40% (RES allocation)	88	17,532,417
40% (RES + ES allocation)	607	17,594,652
40% (RES allocation + EC)	36	17,734,620
50% (RES allocation)	109	17,532,417
50% (RES + ES allocation)	173	17,594,652
50% (RES allocation + EC)	156	17,672,385

Results Discussion

The allocation and sizing of RES allows for the better use of existing infrastructure. This operation consists of choosing the type of renewable energy sources, the number of sources from a given power series and the node in which the units are to be built. Taking into account the generation profiles of individual RES, loads profiles and capacity of existing lines, it is possible to locate such generating units that do not violate the technical parameters of the network, and allow the achievement of the set level of their annual generation at the lowest possible cost total.

The allocation and sizing of energy storage allows for their distribution in the network and the selection of capacity, which will allow them to support RES at times when their generation exceeds the total demand in the system. Energy storage allows for energy storage at times when the generation from generating units exceeds the demand (usually, these are the night demand valleys) and putting this energy into the network at the peak of demand.

Energy curtailment allows a user to reduce energy production at times when their generation exceeds the total demand, which makes it possible to adjust the generation to the demand in these periods.

7. Conclusions

The optimization method for RES, ES allocation and energy curtailment under the criterion of minimization costs of distribution system development is presented. The novelty lies in comparing energy storages (ES) and energy curtailment (EC) as additional tools to RES sizing and allocation.

This combination of mentioned tools allows for the achievement of a desirable target (reducing costs of distribution system development). Due to the modelling of power units with energy generation or consumption profiles, it is possible to consider specific operational cases and select the best structure and location of renewables.

The results also show that energy curtailment is more efficient than energy storages with the growth of the share of energy from RES in total demand. This is due to the high prices of the ES and its limitation connected to the efficiency and level of charge. It shows that energy curtailment can be an efficient tool to control the operation of RES.

Conflicts of Interest: Author declare no conflict of interest.

Abbreviations

Sets

$n, w \in N$	sets of indices n, w representing number of nodes in distribution network
$d \in D$	set of indices d representing type of renewable energy sources (RES) technology—$D = [d_1, \ldots d_3]$, where d_1 is the first possible technology and d_3 is the last one
$l \in L$	set of indices l representing number of possible load type. $L = [l_1, \ldots l_3]$, where l_1 is the first possible type and l_3 is the last one
$r \in R$	set of indices r representing type of rated power for each type of possible RES technology

Coefficients

$E_{n,d}$	annual energy production from each type of RES r in each node n
$E_{n,d,t}^{GEN\_RES}$	total production from RES type d in node n in time t
$E_{n,t}^{GEN\_node}$	total production from RES in node n in time t
P_t^{losses}	total power losses in distribution system in time t
$P_{n,w,t}^{losses}$	power losses in a power line between nodes w and k in time t
$P_{d,r}$	rated power of RES technology d for the power unit series type r
$P_{d,t}^{avail}$	generation profile for RES technology d in time t
$P_{n,w,t}^{active}$	active power flow between nodes n and w in time t
$Load_{n,l}$	nominal power of load type l in node n
$P_{l,t}^{DEM}$	ergy consumption profile (discretized with hourly resolution) of load type l in time t
$PF_{n,w,t}$	linearized power flow between nodes n and w in time t
$TS_t^{exchange}$	energy exchange between distribution and transmission system in time t
$Line.const_{n,w}$	capacity of power line between nodes n and w
$U_{nominal}$	nominal voltage for distribution system (in this paper assumed as a 30 kV)
$R_{n,w}$	resistance of power line between nodes n and w
$U_{n,t}$	active voltage in node n in time t
$\Delta U_{n,w,t}$	linearized value of voltage drop between nodes n and w in time t
$FC_{d,r}^{RES}$	fixed cost of each type and rated power of renewable energy sources
FC^{ES}	fixed cost of energy storages
$VC_{d,r}^{RES}$	variable cost of each type d and rated power r of renewable energy sources
C^{ES}	nominal capacity of single energy storage
$CL_{n,t}$	level of charge of energy storages in node n in time t
η^{ES}	efficiency of energy exchange between nodes and energy storages

Decision variable

$p_{n,d,r}$	number of units in node n for RES type d and rated power r
p_n^{ES}	number of units in node n for energy storages
$e_{n,d,t}^{curt}$	energy curtailment of RES type d in node n in time t
$e_{n,t}^{toES}$	energy which flow from grid to energy storage in node n in time t
$e_{n,t}^{fromES}$	energy which flow from energy storage to grid in node n in time t

Acronyms

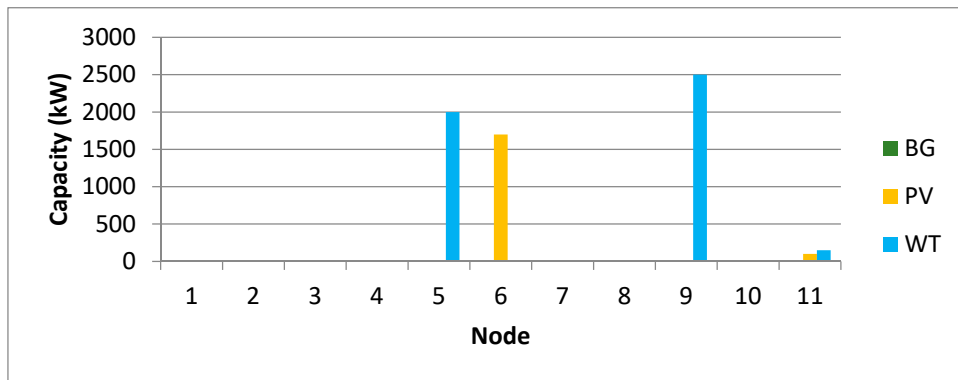|	
WT	wind turbine
PV	photovoltaic installation
BG	biogas power plant
RES	renewable energy sources
ES	energy storages
EC	energy curtailment

Appendix A

Figure A1. Capacity structure for 30% share of energy from RES in total demand with sizing and allocation of RES only.
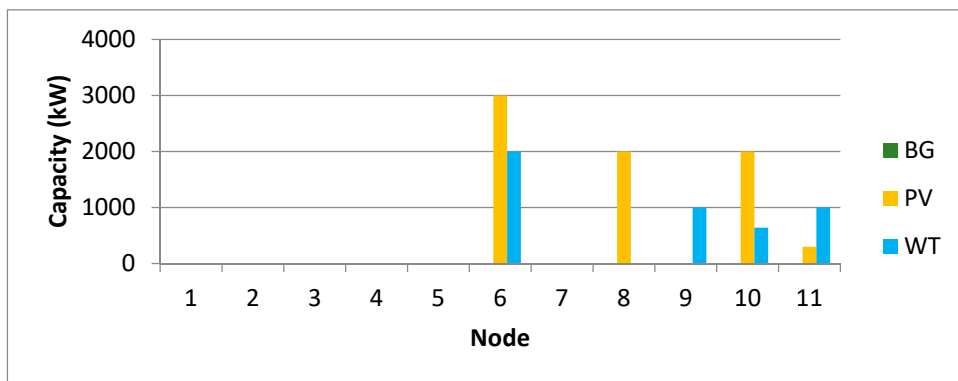

Figure A2. Capacity structure for 40% share of energy from RES in total demand with sizing and allocation of RES only.
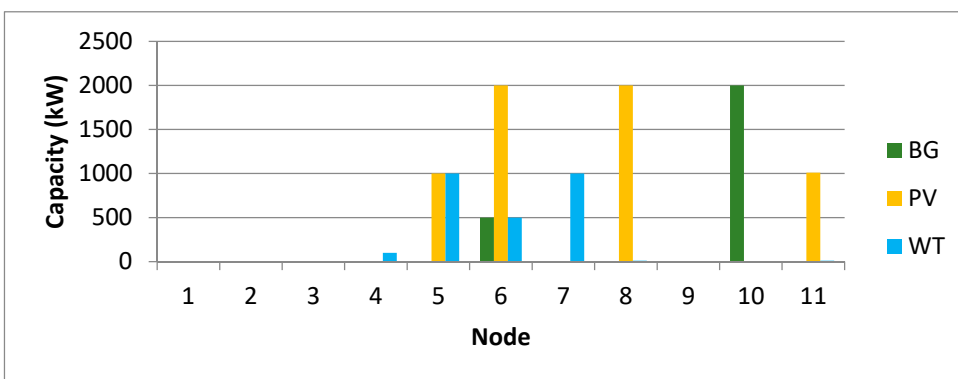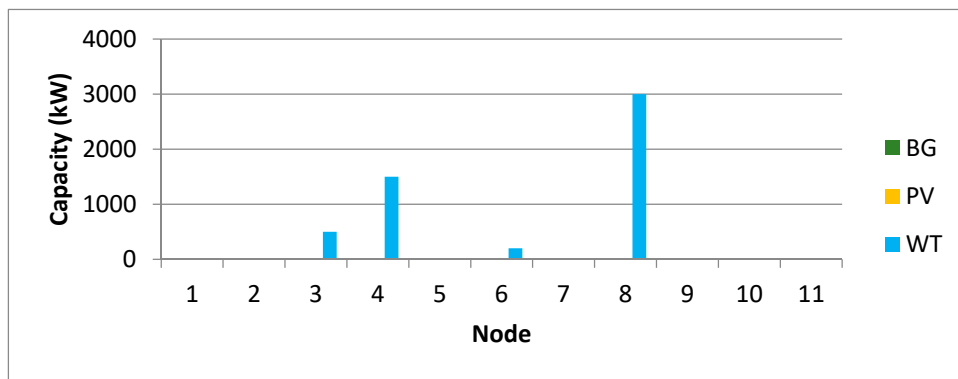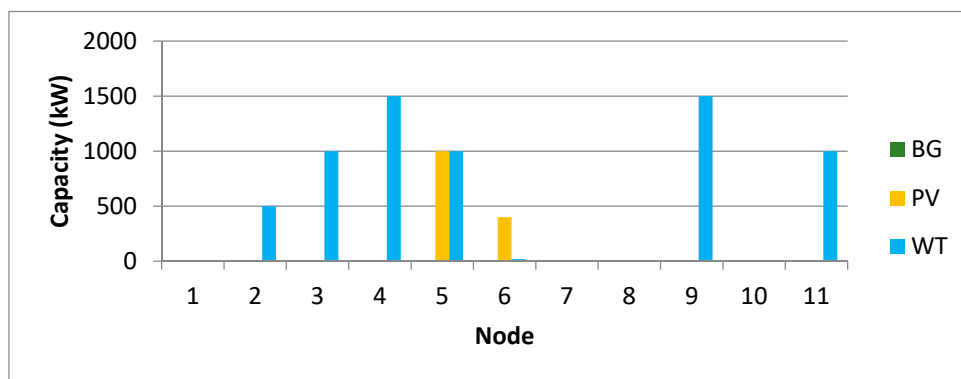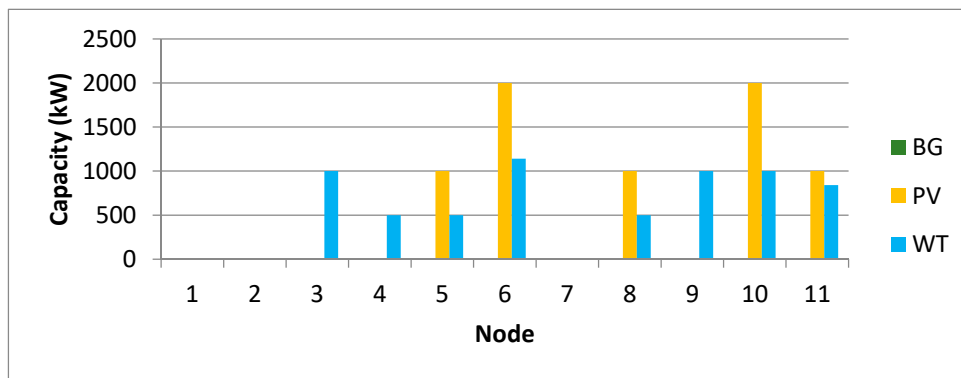

Figure A3. Capacity structure for 50% share of energy from RES in total demand with sizing and allocation of RES only.

Figure A4. Capacity structure for 30% share of energy from RES in total demand with sizing and allocation of RES and energy storages (ES).

Figure A5. Capacity structure for 40% share of energy from RES in total demand with sizing and allocation of RES and ES.

Figure A6. Capacity structure for 50% share of energy from RES in total demand with sizing and allocation of RES and ES.
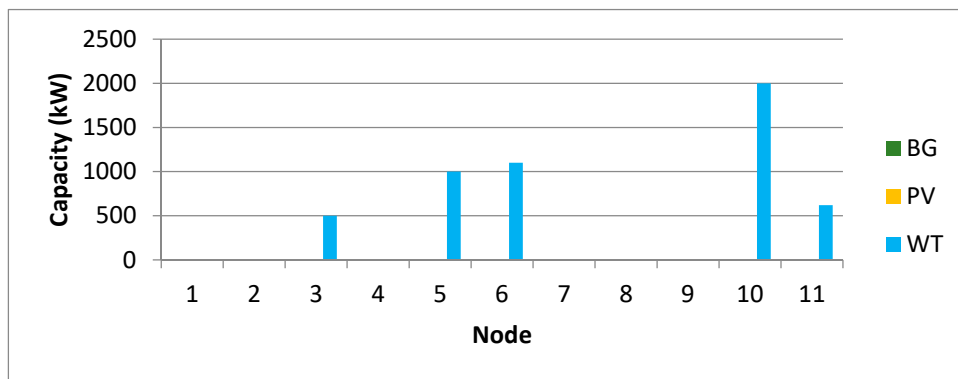
Figure A7. Capacity structure for 30% share of energy from RES in total demand with sizing and allocation of RES and Energy Curtailment (EC).
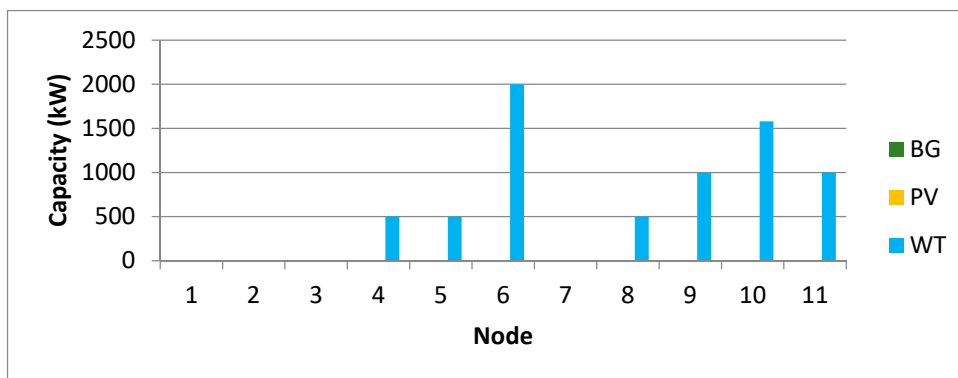

Figure A8. Capacity structure for 40% share of energy from RES in total demand with sizing and allocation of RES and EC.
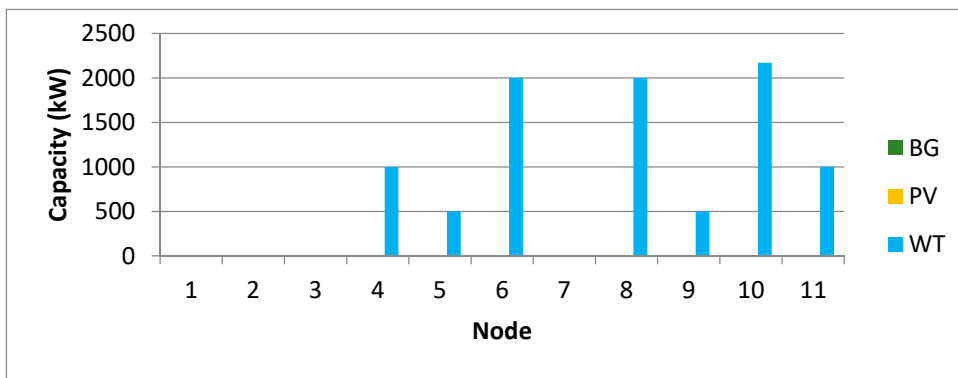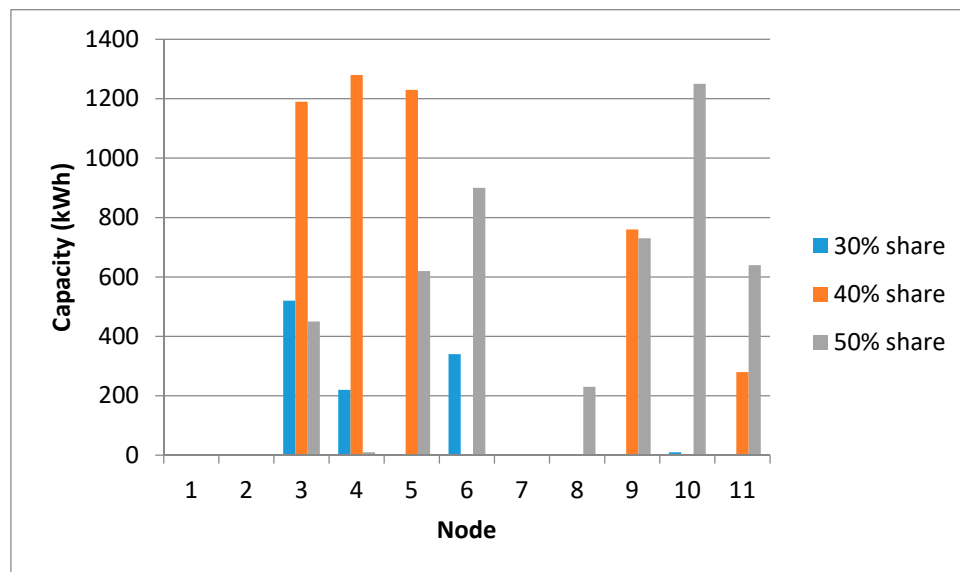

Figure A9. Capacity structure for 50% share of energy from RES in total demand with sizing and allocation of RES and EC.

Figure A10. Capacity structure for energy storages in the context of share of energy from RES in total demand.

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